U.S.NRC
United States Nuclear Regulatory Commission
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RIL2023-05

PROCEEDINGS OF THE EIGHTH ANNUAL PROBABILISTIC FLOOD HAZARD ASSESSMENT RESEARCH WORKSHOP

March 21-24, 2023

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U.S. Nuclear Regulatory Commission
Rockville, MD 20852

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Research Information Letter
Office of Nuclear Regulatory Research

Disclaimer

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ABSTRACT

These conference proceedings transmit the agenda, abstracts, and presentation slides for the Eighth Annual Nuclear Regulatory Commission (NRC) Probabilistic Flood Hazard Assessment Research (PFHA) Workshop held at NRC Headquarters in Rockville, Maryland on March 21–24, 2023. The workshop offered both in-person and virtual participation. Participants included NRC staff, NRC licensees, nuclear industry staff and consultants, staff from U.S. federal and state agencies, regulators and consultants from other countries, staff of international agencies, as well as, participants from academia and members of the public. The workshop began with an introductory session that included perspectives and research program highlights from NRC Office of Research (RES), the Nuclear Energy Agency's working group on external hazards, and the Federal Emergency Management Agency. This introductory session was followed by technical sessions on climate and weather, intense precipitation, riverine flooding, coastal flooding, as well as external hazard operational experience and probabilistic risk assessment. Most workshop sessions were followed by a panel discussion featuring the session's presenters.

The PFHA Research Workshops support the NRC/RES PFHA Research Program. This multiyear, multi project research program to enhance the NRC's risk-informed and performance-based regulatory approach regarding external flood hazard assessment and safety consequences of external flooding events at nuclear power plants. RES has presented annual PFHA research workshops to communicate results, assess progress, collect feedback, and chart future activities. These workshops have brought together NRC staff and management from RES and user offices, technical support contractors, interagency and international collaborators, and industry and public representatives.

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1 INTRODUCTION

This research information letter (RIL) details the Eighth Annual U.S. Nuclear Regulatory Commission (NRC) Probabilistic Flood Hazard Assessment (PFHA) Research Workshop, which took place from March 21–24, 2023 at NRC Headquarters in Rockville, Maryland. These proceedings include presentation abstracts, slides, as well as summaries of the questions and answers from individual presentations as well as panel discussions. The workshop offered both in-person and virtual participation options. Attendees included NRC staff, NRC licensees, industry consultants, Federal and State agencies, National Labs, regulatory counterparts from other countries, international agencies, academia, and the public.

The workshop began with an introduction from Ray Furstenau, Director, NRC Office of Nuclear Regulatory Research (RES). Following this introduction, Thomas Aird from RES provided an overview of the current progress and next steps in NRC's PFHA research program. Minkyu Kim, from the Korea Atomic Energy Research Institute, then provided an overview of external hazard efforts (including flooding) underway by the Nuclear Energy Agency, Committee on the Safety of Nuclear Installations (CSNI), Working Group on External Events (WGEV). Next, staff from the Federal Emergency Management Agency (FEMA) presented information on the FEMA Resilience Analysis Planning Tool (RAPT).

Technical sessions followed the introduction session over the course of the four-day workshop; sessions covered climate and weather, intense precipitation, riverine flooding, coastal flooding, as well as external hazard operational experience and PRA. Most sessions consisted of a series of technical presentations on similar topic, followed by a panel of all speakers, who discussed the session topic in general. A "poster session" also took place, which consisted of a series of shorter technical presentations encompassing the range of topics listed above.

1.1 Background

The NRC is conducting the multiyear, multi project PFHA Research Program. It initiated this research in response to staff recognition of a lack of guidance for conducting PFHAs at nuclear facilities that required staff and licensees to use highly conservative deterministic methods in regulatory applications. The staff described the objective, research themes, and specific research topics in the "Probabilistic Flood Hazard Assessment Research Plan," Version 2014-10-23, provided to the Commission in November 2014 (Agencywide Documents Access and Management System (ADAMS) Accession Nos. ML14318A070). The NRC Office of Nuclear Reactor Regulation and the former Office of New Reactors endorsed the PFHA Research Plan in a joint user need request. This program is designed to support the development of regulatory tools (e.g., regulatory guidance, standard review plans) for permitting new nuclear sites, licensing new nuclear facilities, and overseeing operating facilities. Specific uses of flooding hazard estimates (i.e., flood elevations and associated affects) include flood-resistant design for structures, systems, and components (SSCs) important to safety and advanced planning and evaluation of flood protection procedures and mitigation.

The lack of risk-informed guidance with respect to flooding hazards and flood fragility of SSCs constitutes a significant gap in the NRC's risk-informed, performance-based regulatory approach to the assessment of hazards and potential safety consequences for commercial nuclear facilities. The probabilistic technical basis developed will provide a risk-informed approach for improved guidance and tools to give staff and licensees greater flexibility in evaluating flooding hazards and potential impacts to SSCs in the oversight of operating facilities (e.g., license amendment requests, significance determination processes, notices of enforcement discretion) as well as the licensing of new facilities (e.g., early site permit applications, combined license applications), including proposed small modular reactors and advanced reactors. This methodology will give the staff more flexibility in assessing flood hazards at nuclear facilities so the staff will not have to rely on the use of the current deterministic methods, which can be overly conservative in some cases.

The main focus areas of the PFHA Research Program are to (1) leverage available frequency information on flooding hazards at operating nuclear facilities and develop guidance on its use, (2) develop and demonstrate a PFHA framework for flood hazard curve estimation, (3) assess and evaluate the application of improved mechanistic and probabilistic modeling techniques for key flood-generating processes and flooding scenarios, (4) assess potential impacts of dynamic and nonstationary processes on flood hazard assessments and flood protection at nuclear facilities, and (5) assess and evaluate methods for quantifying reliability of flood protection and plant response to flooding events. Workshop organizers used these focus areas to develop technical session topics for the workshop.

1.2 Workshop Objectives

The Annual PFHA Research Workshops serve multiple objectives: (1) inform and solicit feedback from internal NRC stakeholders, partner Federal agencies, industry, and the public about PFHA research being conducted by RES, (2) inform internal and external stakeholders about RES research collaborations with Federal agencies, the Electric Power Research Institute (EPRI), and the IRSN, and (3) provide a forum for presentation and discussion of notable domestic and international PFHA research activities.

1.3 Workshop Scope

The scope of the workshop presentations and discussions included the following:

- overview of flooding research programs of the NRC, other Federal agencies, and selected international organizations
- climate influences on flooding hazards
- precipitation processes and modeling
- riverine flooding processes and modeling
- coastal flooding processes and modeling
- external hazard operational experience and probabilistic risk assessment

1.4 Organization of Workshop Proceedings

Section 2 provides the agenda for this workshop. The agenda is also available from NRC's Agencywide Documents Access and Management System (ADAMS) at Accession No. ML23177A151.

Section 3 presents the proceedings from the workshop, including abstracts and presentation slides and abstracts for submitted posters.

The summary document of session abstracts for the technical presentations is available at ADAMS Accession No. ML23177A150. The complete workshop presentation package is available at ADAMS Accession No. ML23177A135.

Section 4 lists the workshop attendees and Section 5 summarizes the workshop.

1.5 Related Workshops

Proceedings of previous NRC Annual PFHA Research Workshops have been published as NRC Research Information Letters (RILs) on the agency's public Web site as listed below:

- 1st Annual NRC PFHA Research Workshop, October 14–15, 2015 (RIL 2020-01, Part 1)
- 2nd Annual NRC PFHA Research Workshop, January 23–25, 2017 (RIL 2020-01, Part 2)
- 3rd Annual NRC PFHA Research Workshop, December 4–5, 2017 (RIL 2020-01, Part 3)
- 4th Annual NRC PFHA Research Workshop, April 30–May 2, 2019 (RIL 2020-01, Part 4)
- 5th Annual NRC PFHA Research Workshop, February 19–21, 2020 (RIL 2021-01)
- 6th Annual NRC PFHA Research Workshop, February 22–25, 2021 (RIL 2022-02)
- 7th Annual NRC PFHA Research Workshop, February 15-18, 2022 (RIL 2022-10)

In addition, an international PFHA workshop took place January 29–31, 2013. The workshop was devoted to sharing information on PFHAs for extreme events (i.e., annual exceedance probabilities (AEPs) much less than $2x10^{-3}$ per year) from the Federal community. The NRC issued the proceedings as NUREG/CP-0302, "Proceedings of the Workshop on Probabilistic Flood Hazard Assessment (PFHA)," in October 2013 (ADAMS Accession No. ML13277A074).

2 WORKSHOP AGENDA

Day 1 (March 21, 2023) Oral Presentations

*** denotes speaker**

Session 1A: Introduction

Session Chair: Joseph Kanney, NRC/RES

1A-0	10:00 - 10:10	Meeting and Webinar Logistics	Kenneth Hamburger*, NRC/RES
1A-1	10:10 - 10:20	Opening Remarks	Ray Furstenau*, Director, NRC Office of Research
1A-2	10:20 - 10:35	NRC PFHA Research Program Update	Tom Aird*, NRC/RES
1A-3	10:35 - 11:00	Presentation and Training: Resilience Analysis and Planning Tool (RAPT)	Karen Marsh, Benjamin Rance, Scott Mahlik*; Federal Emergency Management Agency (FEMA)
1A-4	11:00 - 11:25	Committee on the Safety of Nuclear Installations (CSNI) Working Group on External Events (WGEV)	Minkyu, Kim*, Korea Atomic Energy Research Institute, Division of Structural and Seismic Safety (WGEV Chair)
	11:25 - 11:40	**Break**	

Session 1B: Climate and Weather

Session Chair: Elena Yegorova, NRC/RES

1B-1	11:40 - 12:05	Overview of the U.S. Global Change Research Program	Michael Kuperberg*, Executive Director, U.S. Global Research Program
1B-2	12:05 - 12:30	A Coastal Flood Regime Shift Is on the Horizon	William Sweet*, NOAA National Ocean Service
	12:30 - 13:30	**Lunch**	
1B-3	13:30 - 13:55	Observation-based Trajectory of Future Sea Level for the Coastal United States Tracks Near High-end Model Projections	Benjamin Hamlington*[1], Don Chambers[2], Thomas Frederikse[1], Soenke Dangendorf[3], Severine Fournier[1], Brett Buzzanga[1,2], R. Steven Nerem[4]; [1]NASA Jet Propulsion Laboratory, [2]University of South Florida, [3]Tulane University, [4]University of Colorado, Boulder
1B-4	13:55 - 14:20	National Weather Service Forecasts for the late December 2022 to mid-January 2023 West Coast Atmospheric Rivers	Mark Fresch*[1], Alex Lamers*[2]; [1]NOAA National Weather Service Office of Water Prediction, [2]NOAA National Weather Service Weather Prediction Center
	14:20 - 14:30	**Break**	

1B-5	14:30 - 14:55	Sharpening of cold-season storms over the western United States	Xiaodong Chen, L. Ruby Leung*, Yang Gao, Ying Liu, Mark Wigmosta; Pacific Northwest National Laboratory
1B-6	14:55 - 15:20	2022 U.S. Billion-dollar Weather and Climate Disasters Analysis and Tools	Adam Smith*, NOAA National Centers for Environmental Information (NCEI)
1B-7	15:20 - 15:40	Climate and Weather Panel Discussion	All Presenters
1C	15:40 - 15:50	**Day 1 Wrap-up**	

Day 2 (March 22, 2023) Oral Presentations

*** denotes speaker**

Session 2A: Precipitation

Session Chair: Joseph Kanney, NRC/RES

2A-1	10:00 - 10:25	NOAA's Exploration of Future Probable Maximum Precipitation Datasets and Methods	Kelly Mahoney*[1], Janice Bytheway[2], Diana Stovern[2], James Correia[3], Sarah Trojniak[3], Ben Moore[1]; [1]NOAA Physical Sciences Laboratory (PSL), [2]NOAA PSL/University of Colorado Boulder & Cooperative Institute for Earth System Research and Data Science (CIESRDS), [3]University of Colorado Boulder & CIESRDS, NOAA/NWS/Weather Prediction Center
2A-2	10:25 - 10:50	The "Perfect Storm": Can Atmospheric Models Improve Confidence in Probable Maximum Precipitation (PMP)?	Emilie Tarouilly*, University of California, Los Angeles
2A-3	10:50 - 11:15	Improving the Reliability of Stochastic Modeling of Short-Duration Precipitation by Characterizing Spatiotemporal Correlation Structure and Marginal Distribution	Giuseppe Mascaro*[1], Simon Papalexio[2], Daniel Wright[3]; [1]Arizona State University, [2]University of Calgary, [3]University of Wisconsin-Madison
	11:15 - 11:25	**Break**	
2A-4	11:25 - 11:50	Stochastic Design Storm Sequence in the Lower Mississippi River Basin	Yuan Liu*, Daniel Wright; University of Wisconsin-Madison
2A-5	11:50 - 12:15	An Update to the NOAA Atlas 14 National Precipitation Frequency Standard	Michael St Laurent*, Sandra Palovic, Carl Trypaluk, Dale Unruh, Fernando Salas; NOAA National Weather Service Office of Water Prediction
2A-6	12:15 - 12:35	Precipitation Panel Discussion	All Presenters
	12:35 - 13:30	**Lunch**	

Session 2B: Riverine Flooding

Session Chair: Joseph Kanney, NRC/RES

2B-1	13:30 - 13:55	Lowering the Barriers to Process-Based Probabilistic Flood Frequency Analysis using the NextGen Water Modeling Framework	Daniel, Wright*[1], Ankita Pradhan[1], Mohammad Sadegh Abbasian[1], Benjamin Fitzgerald[1], Gary Aaron[1], Fred Ogdan[2], Mathew Williamson[2]; [1]University of Wisconsin-Madison, [2]NOAA National Water Service Office of Water Prediction
2B-2	13:55 - 14:20	Towards the Development of a High-Resolution Historical Flood Inundation Reanalysis Dataset for the Conterminous United States	Sudershan Gangrade*[1], Ganesh Ghimire[1], Shih-Chieh Kao[1], Mario Morales-Hernandez[2], Michael Kelleher[1], Alfred Kalyanapu[3]; [1]Oak Ridge National Laboratory, [2]University of Zaragoza (Spain), [3]Tennessee Technological University
2B-3	14:20 - 14:45	Quantifying Uncertainty for Local Intense Precipitation and Riverine Flooding PFHA at Critical Structures on the Idaho National Labs Property	Ryan Johnson*[1], Shaun Carney[1], Paul Micheletty[1], Debbie Martin[1], Bruce Barker[2]; [1]RTI International, [2]MGS Engineering
	14:45 - 14:55	**Break**	
2B-4	14:55 - 15:20	Back to the Future: Paleoflood Hydrologic Analyses Provide Insights into Extreme Flood Risk in the Tennessee River Basin	Lisa Davis*[1], Ray Lombardi[2], Matthew Gage[1]; [1]University of Alabama, [2]University of Memphis
2B-5	15:20 - 15:45	Testing New Approaches to Integrating Sediment-Based Flood Records into Flood Frequency Models	Ray Lombardi*[1], Lisa Davis[2], Tessa Harden[3,4], John F. England, Jr.[5]; [1]University of Memphis, [2]University of Alabama, [3]Thomas College, [4]U.S. Geological Survey, [5]U.S. Army Corps of Engineers, Risk Management Center
2B-6	15:45 - 16:10	Using Paleoflood Analyses to Improve Hydrologic Loading for USACE Dam Safety Risk Assessments: A Nationwide Approach	Keith Kelson*[1], Justin Pearce[2], Amy LeFebvre[2], Ryan Clark[3], Bryan Freymuth[4], Nathan Williams[5], John England[2]; [1]US Army Corps of Engineers (USACE), South Pacific Division Dam Safety Production Center, [2]USACE Risk Management Center, [3]USACE Dam Safety Modification Mandatory Center of Expertise, [4]USACE Northwest Division Risk Cadre, [5]USACE Lakes and Rivers Division Risk Cadre
2B-7	16:10 - 16:30	Riverine Flooding Panel Discussion	All Presenters

2C 16:30 - 16:40 **Day 2 Wrap-up**

Day 3 (March 23, 2023) Poster Presentations

*** denotes speaker**

Session 3A: Posters

Session Chair: Thomas Aird, NRC/RES

3A-1	10:00 - 10:15	Identifying and Cataloging Major Storm Events from Gridded Quantitative Precipitation Estimates for use in Stochastic Storm Transposition	Alyssa Dietrich*, Eric King, Seth Lawler; Dewberry
3A-2	10:15 - 10:30	A Bayesian Network and Monte Carlo Simulation PRA Approach for External Flood Probabilistic Risk Assessments at Nuclear Power Plants	Joy Shen*, Michelle Bensi, Mohammad Modarres; University of Maryland, College Park
3A-3	10:30 - 10:45	Probabilistic Compound Flood Hazard Assessment Using Two-Sided Conditional Sampling	Somayeh Mohammadi*[1], Ahmed Nasr[2], Muthukumar Narayanaswamy[1], Celso Ferreira[1], Arslaan Khalid[1]; [1]Michael Baker International Inc, [2]University of Central Florida
3A-4	10:45 - 11:00	Estimation of Probabilistic Flood Hazard Curve at the NPP Site Considering Storm Surge	Beom-Jin Kim*, Minkyu, Kim; Korea Atomic Energy Research Institute (KAERI)
3A-5	11:00 - 11:15	Compound Flood Risk Assessment of the Coastal Watersheds of Long Island and Long Island Sound in Connecticut and New York	Liv Herdman*, Robert Welk, Robin Glas, Salme Cook, Kristina Masterson; U.S. Geological Survey New York Water Science Center
	11:15 - 11:25	**Break**	
3A-6	11:25 - 11:40	Steps Toward Extensions of Existing Probabilistic Coastal Hazard Analysis for Coastal Compound Flood Analysis Leveraging Bayesian Networks	Ziyue Liu*[1], Michelle, Bensi[1], Meredith Carr[2], Norberto Nadal-Caraballo[2], Madison Yawn[2], Luke Aucoin[2]; [1]University of Maryland, College Park, [2]U.S. Army Corps of Engineers, Engineer R&D Center, Coastal & Hydraulics Laboratory
3A-7	11:40 - 11:55	Assessing Uncertainty Associated with Hurricane Predictions and Duration to Inform Probabilistic Risk Assessments for Nuclear Power Plants	Kaveh Faraji Najarkolaie*, Michelle Bensi; University of Maryland, College Park

3A-8	11:55 - 12:10	Assessment of Uncertainty Associated with the Development of Intensity Duration Frequency Curves under Changing Climate for the State of Maryland	Azin Al Kajbaf*[1], Michelle Bensi[2], Kaye Brubaker[2]; [1]Johns Hopkins University, [2]University of Maryland, College Park
	12:10 - 13:10	**Lunch**	

Day 3 (March 23, 2023) Oral Presentations

*** denotes speaker**

Session 3B: Coastal Flooding

Session Chair: Joseph Kanney, NRC/RES

3B-1	13:10 - 13:35	Flood Inundation Modelling on Nuclear Power Plant Site due to Complex Disasters	Byunghyun Kim*[1], Jaewan Yoo, Beomjin Kim[2], Minkyu Kim[2]; [1]Kyungpook National University, [2]Korea Atomic Energy Research Institute
3B-2	13:35 - 14:00	Probabilistic Flood Hazard Assessment for a Coastal Nuclear Power Plant Using Climate Change Projections	Gorkem Gungor*, Zeynep Arslan; Minstry of Energy and Natural Resources, Turkey
3B-3	14:00 - 14:25	Probabilistic Coastal Compound Flood Hazard Analysis Pilot Study	Victor M. Gonzalez[1], Meredith L. Carr*[1], Luke Aucoin[1], T. Chris Massey[1], Ning Lin[2], Dazhi Xi[2], Norberto C. Nadal Caraballo[1], Karlie Wellls[1]; [1]U.S. Army Corps of Engineers, Engineer Research and Development Center, Coastal and Hydraulics Laboratory, [2]Princeton University
	14:25 - 14:35	**Break**	
3B-4	14:35 - 15:00	HEC-RAS Modeling Framework and Lessons Learned from Coastal Flooding PFHA Pilot Study: Coupling and Automation of HEC-HMS and ADCIRC Outputs to 2D HEC-RAS Model Using Python	Kathleen Harris*, Chase Hamilton, Waleska Echevarria-Doyle, Meredith Carr, Victor M. Gonzalez; U.S. Army Corps of Engineers, Engineer Research and Development Center, Coastal and Hydraulics Laboratory
3B-5	15:00 - 15:25	An Overview of a Multi-Agency Modeling Effort to Quantify Future Conditions in the Great Lakes	Margaret Owensby*[1], T. Chris Massey[1], Robert Jensen[1], Norberto Nadal-Caraballo[1], Madison Yawn[1], David Bucaro[2], Johnna Potthoff[2], Kaitlyn McClain[2]; [1]U.S. Army Corps of Engineers, Engineer Research and Development Center, Coastal and Hydraulics Laboratory, [2]U.S. Army Corps of Engineers, Chicago District
3B-6	15:25 - 15:45	Coastal Flooding Panel Discussion	All Presenters
3C	15:45 - 15:55	**Day 3 Wrap-up**	

Day 4 (March 24, 2023) Oral Presentations

*** denotes speaker**

<u>Session 4A: Operational Experience</u>

Session Chair: Tom Aird, NRC/RES

4A-1	10:00 - 10:20	PRA Modeling the FLEX Strategies for External Hazards	John Hanna*, U.S. Nuclear Regulatory Commission, Office of Nuclear Reactor Regulation
4A-2	10:20 - 10:40	Failure to Verify Flood Restoration Times at Millstone Unit 2	Dave Werkheiser*, U.S. Nuclear Regulatory Commission, Region 1
4A-3	10:40 - 11:00	Impact of the 2022 Lake Erie Seiche the Davis-Besse Nuclear Power Station	Daniel Mills*[1], Russ Cassara[1], John Hanna[2]; [1]U.S. Nuclear Regulatory Commission, Davis Bessie Resident Inspector, [2]U.S. Nuclear Regulatory Commission, Office of Nuclear Reactor Regulation
4A-4	11:00 - 11:15	Operational Experience Panel Discussion	All Presenters
	11:15 - 11:25	**Break**	

<u>Session 4B: Wrapping Up</u>

Session Chair: Tom Aird, NRC/RES

4B-1	11:25 - 11:50	On Fuzzy-Systems Modeling of Ponded Infiltration, as Analogue to Flooding, in Fractured-Porous Subsurface Media	Boris Faybishenko*; Lawrence Berkeley National Laboratory
	11:50 - 13:00	**Lunch**	
4B-2	13:00 - 13:25	Probabilistic Flood Hazard Assessment for Local Intense Precipitation at Nuclear Power Plant Sites – A Pilot Study	Rajiv Prasad*[1], Arun Veeramany[1], Rajesh K. Singh[1], Joseph Kanney[2]; [1]Pacific Northwest National Laboratory, [2]U.S. Nuclear Regulatory Commission
4B-3	13:25 - 13:50	Research Activities on Extreme External Hazard Risk Assessment of Korean NPP	Minkyu Kim*, Daegi, Hahm; Korea Atomic Energy Research Institute (KAERI)
	13:50 - 14:00	**Break**	

4B-4	14:00 - 14:25	External Flooding PRA Guidance	Marko Randelovic*[1], Raymond Schneider*[2]; [1]Electric Power Research Institute, [2]Westinghouse Company
4B-5	14:25 - 14:50	A Proposal for Paradigm Shift in Hydrological Ensemble Predictions: From Parameter Inference to Probabilistic Error Estimation	Vinh Ngoc Tran[1], Valeriy Y. Ivanov*[1], Donghui Xu[1], Jongho Kim[2]; [1]University of Michigan, [2]University of Ulsan, South Korea
4C	14:50 - 15:10	**Workshop Wrap-up**	

3 PROCEEDINGS

3.1 Day 1: Session 1A – Introduction

Session Chair: Joseph Kanney, NRC/RES

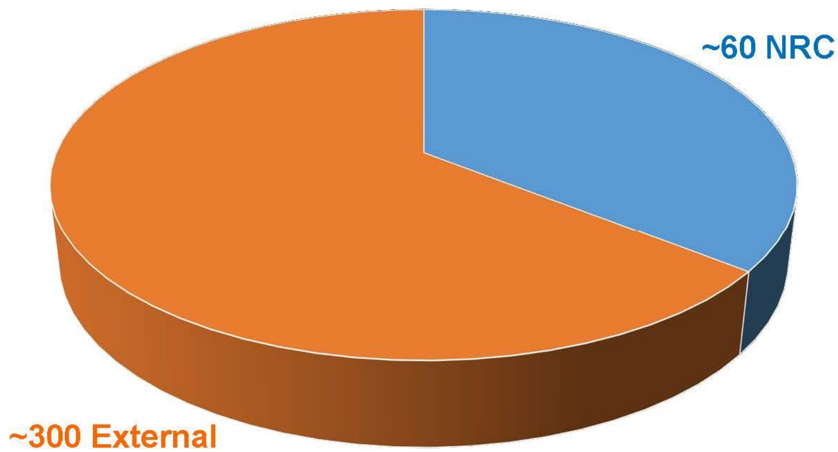
3.1.1 Presentation 1A-1: Opening Remarks

Speaker: Raymond Furstenau, Director, NRC Office of Nuclear Regulatory Research

3.1.1.1 Presentation (ADAMS Accession No. ML23177A152)

Workshop Participation

~360 Participants (~75% fully remote)



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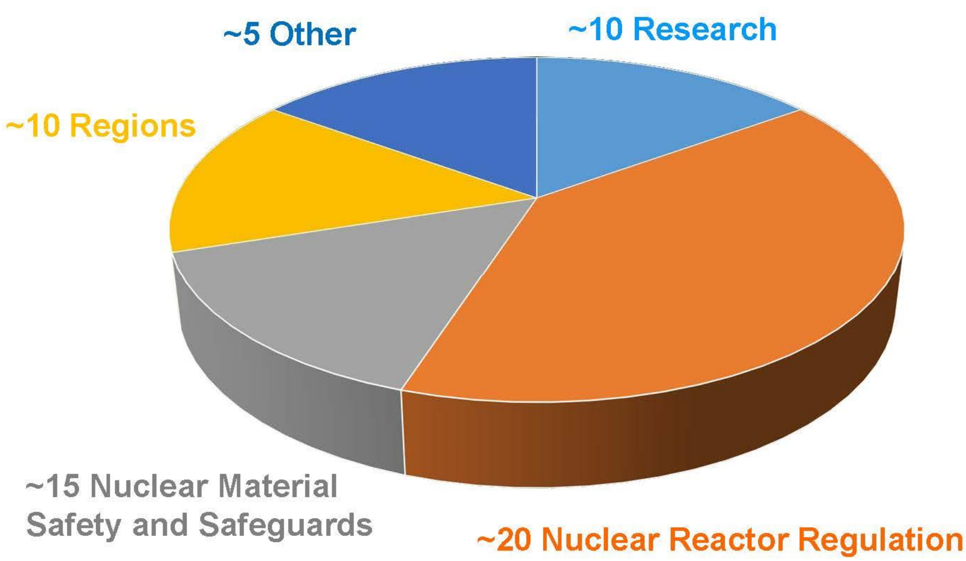
NRC Participation (~60)



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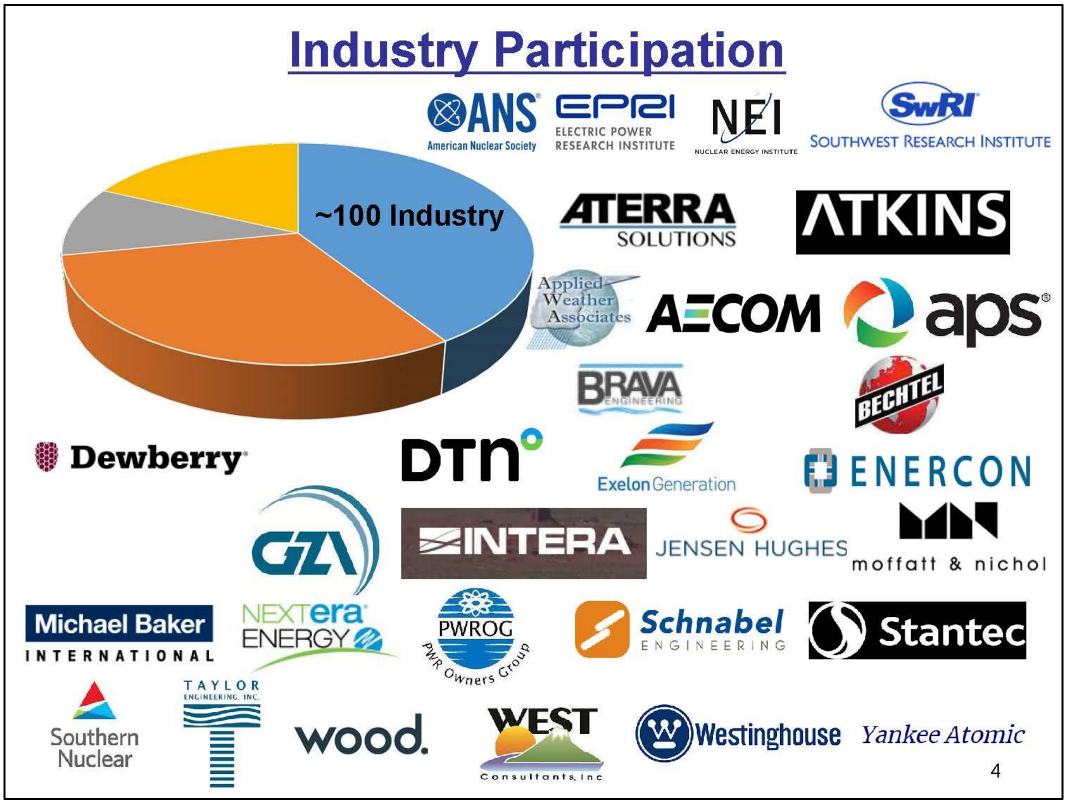
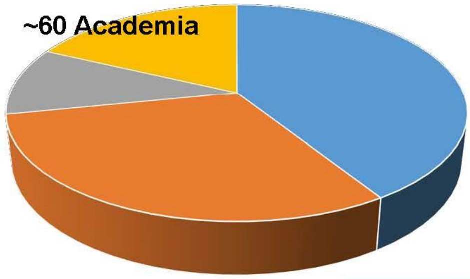

Industry Participation
~100 Industry
ANS
American Nuclear Society
EPRI
ELECTRIC POWER RESEARCH INSTITUTE
NEI
NUCLEAR ENERGY INSTITUTE
SwRI
SOUTHWEST RESEARCH INSTITUTE
ATERRA SOLUTIONS
ATKINS
Applied Weather Associates
AECOM
aps
BRAVA ENGINEERING
BECHTEL
Dewberry
DTN
Exelon Generation
ENERCON
GZA
INTERA
JENSEN HUGHES
moffatt & nichol
Michael Baker INTERNATIONAL
NEXTera ENERGY
PWROG
PWR Owners Group
Schnabel ENGINEERING
Stantec
Southern Nuclear
TAYLOR ENGINEERING, INC.
wood.
WEST Consultants, Inc
Westinghouse
Yankee Atomic
4


Non-NRC Government Participation
~80 Government (Non-NRC)
US Army Corps of Engineers.
TVA
Idaho National Laboratory
OAK RIDGE National Laboratory
Pacific Northwest NATIONAL LABORATORY
BERKELEY LAB
NASA
FEMA
USGS
science for a changing world
BUREAU OF RECLAMATION
NIST
National Institute of Standards and Technology
U.S. Department of Commerce
NCEI
NATIONAL CENTERS FOR ENVIRONMENTAL INFORMATION
NOAA
NATIONAL WEATHER SERVICE
CO
DNR
Office of the State Engineer
Interstate Stream Commission
DEPARTMENT OF WATER RESOURCES
STATE OF CALIFORNIA
5

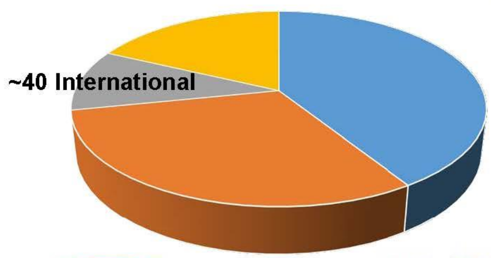
Academic Participation



Arizona State University
AUBURN UNIVERSITY
Boulder
UNIVERSITY OF MICHIGAN
UNIVERSITY OF MARYLAND 1856
VIRGINIA COMMONWEALTH UNIVERSITY MCV RPI 1838
HARVARD VE RI TAS
KYUNGPOOK NATIONAL UNIVERSITY
FURMAN UNIVERSITY
UCLA
Idaho State University
JOHNS HOPKINS UNIVERSITY
NC STATE UNIVERSITY
NCAR
THE UNIVERSITY OF IOWA
Creighton UNIVERSITY School of Medicine
NATIONAL CHENG KUNG UNIVERSITY
UNIVERSITY OF NEVADA RENO 1874
THE UNIVERSITY OF OKLAHOMA 1890
GCU Glasgow Caledonian University
WISCONSIN UNIVERSITY OF WISCONSIN–MADISON
WASCAL West African Science Service Centre on Climate Change and Adapted Land Use
PURDUE UNIVERSITY
DRI Desert Research Institute
ORTA DOĞU TEKNİK ÜNİVERSİTESİ MIDDLE EAST TECHNICAL UNIVERSITY

6

International (Non-Academic)



ATOMIC ENERGY COUNCIL EXECUTIVE YUAN
CNSC CCSN
IAEA
ONR Office for Nuclear Regulation
SNC·LAVALIN
NATIONAL NUCLEAR REGULATOR
ENGIE Electrabel
FANR Federal Authority for Nuclear Regulation
REPUBLIC OF TÜRKİYE MINISTRY OF ENERGY AND NATURAL RESOURCES
GRS
EDF
IRSN INSTITUT DE RADIOPROTECTION ET DE SÛRETÉ NUCLÉAIRE
Government of India AERB Atomic Energy Regulatory Board
AMAZUL
STCU SCIENCE & TECHNOLOGY CENTER IN UKRAINE
KINS
RATEN ICN PITEŞTI INSTITUTUL DE CERCETĂRI NUCLEARE
BC Hydro Power smart
TEPCO
NEA NUCLEAR ENERGY AGENCY
KAERI Korea Atomic Energy Research Institute
NUCLEARELECTRICA
anav
Joint Research Centre JRC
OECD

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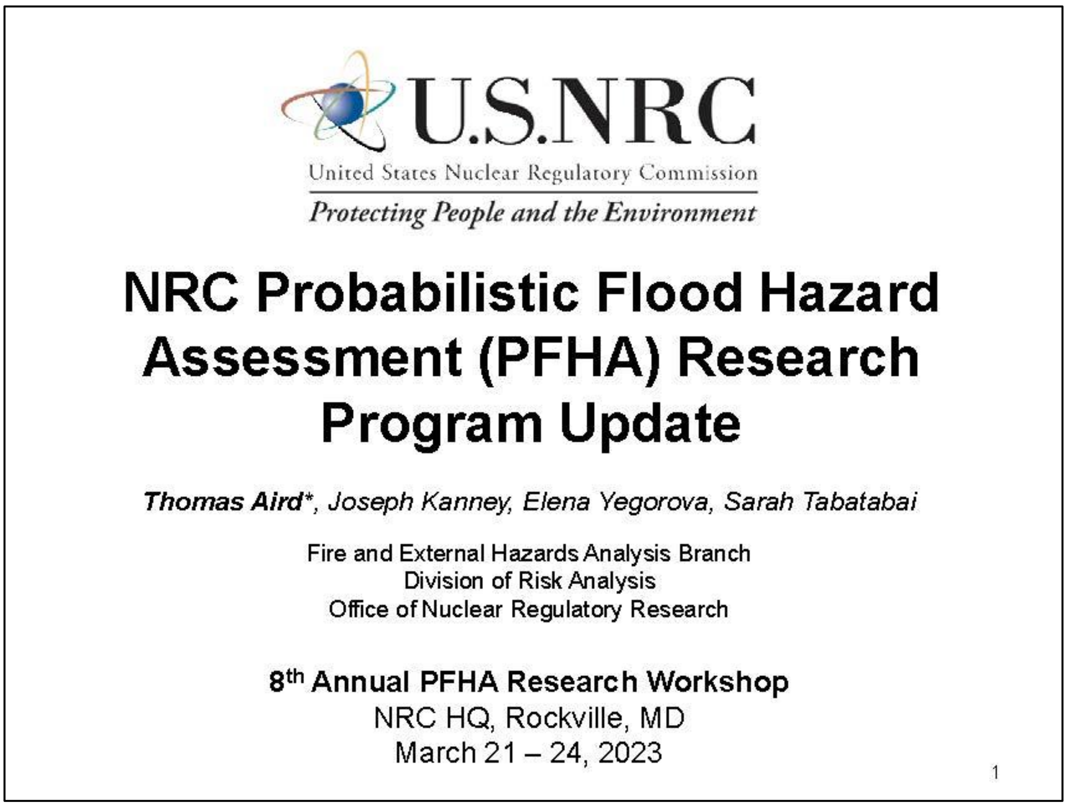
3.1.2 Presentation 1A-2: NRC Probabilistic Flood Hazard Assessment Research Program Overview

Author: Thomas Aird, NRC Office of Nuclear Regulatory Research
Speaker: Thomas Aird

3.1.2.1 Abstract

This presentation will provide an update on the NRC probabilistic flood hazard assessment (PFHA) research program. Topics will include the completion of Phase 1 (technical basis research) and Phase 2 (pilot studies) and the status of Phase 3 (guidance development).

3.1.2.2 Presentation (ADAMS Accession No. ML23177A153)



Outline

- Objectives, key challenges, approach
- Phase 1 Overview (Technical Basis)
- Phase 2 Projects (Pilot Studies)
- Phase 3 (Guidance)

2

PFHA Research Objectives

- Develop resources, tools and selected guidance to:
  - Address significant gap in the technical basis for guidance for probabilistic assessment of external hazards
    - Probabilistic: seismic, high winds
    - Deterministic: flooding
  - Support risk-informed licensing and oversight activities involving assessment of flooding hazards and potential consequences
    - Licensing and oversight in operating reactor program
    - Design basis flood hazard assessments for new facilities
      - Readiness for licensing of advanced reactors

3

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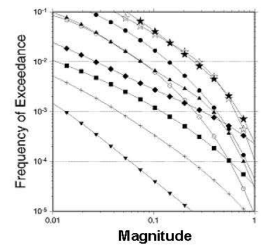
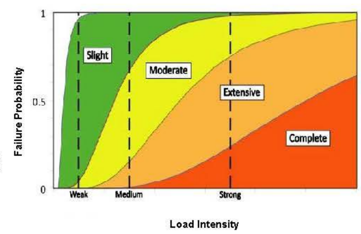
Protecting People and the Environment

Key Challenges

- Hazard Estimation
  - Range of annual exceedance probabilities (AEPs)
    - Moderately rare to extreme floods
  - Multiple flooding mechanisms
    - Coincident and correlated mechanisms
  - Uncertainty characterization and estimation
    - Aleatory (e.g., storm recurrence rates)
    - Epistemic (e.g., model structure, parameters)
- Fragility
  - Information on reliability of flood protection features and procedures is sparse
  - Cliff-edge effects





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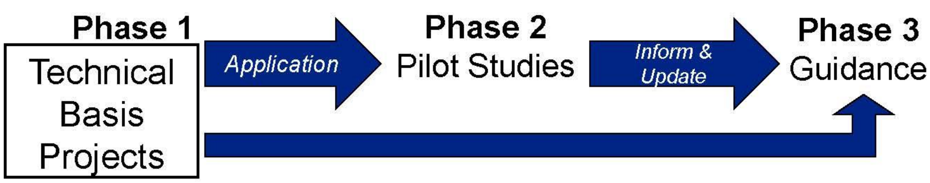
Protecting People and the Environment

Phased Research Approach



- Phase 1 – Technical Basis Research - ***Complete***
  - *Climate and precipitation*
  - *Mechanistic, statistical and probabilistic modeling of flooding processes*
  - *Reliability of flood protection features and procedures*
  - *Modeling Frameworks*
  - *Natural Hazard Information Digest (NHID)*
- Phase 2 – Pilot Studies - ***In Progress***
  - *Local Intense Precipitation (LIP) Flooding - **Complete***
  - *Riverine Flooding - **Complete***
  - *Coastal Flooding – **In Progress***
- Phase 3 – Develop Guidance - ***In Progress***

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Phase 1 Technical Basis Research

- **Climate**
  - *Historical trends and future projections for U.S. regions*
- **Mechanistic, statistical and probabilistic modeling of flooding processes**
  - *Extreme precipitation*
  - *Riverine flooding*
  - *Coastal flooding*
- **Methods for Estimating Joint Probabilities of Coincident and Correlated Flooding Mechanisms**
  - *Riverine flooding*
  - *Coastal flooding*
- **Reliability of flood protection features and procedures**
  - *Flood barriers (seals, etc.)*
  - *Environmental effects on manual actions*
- **Modeling Frameworks**
  - *Structured hazard assessment committee process for flooding (SHAC-F)*
  - *Dynamic analysis of flooding events*
  - *USACE HEC-WAT*
- **Natural hazards information digest (for internal NRC staff use)**
  - *Collect and organize natural hazard information for operating reactors*

For more details on Phase 1 completion see Digital Exhibit #11 at the 34th Annual Regulatory Information Conference (RIC), March 8-10, 2022:
https://www.nrc.gov/public-involve/conference-symposia/ric/index.html

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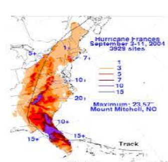
Phase 2: Pilot Studies

Objective: **Synthesize results from technical basis research**
- **Multiple flooding mechanism contribution to hazard curves**
- **Quantify key aleatory variabilities and epistemic uncertainties**

- LIP Flooding PFHA Pilot
  - **PNNL**
  - ***Completed in October 2022***
- Riverine Flooding PFHA Pilot
  - **USACE/HEC**
  - ***Completed in January 2022***
- Coastal Flooding Pilot PFHA Pilot
  - **USACE/ERDC/CHL**
  - ***In Progress; completion expected in May 2023***



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Phase 2: LIP Pilot Study

- **Objectives**
  - *Inform guidance development for probabilistic assessment of site-scale flooding hazards due to local intense precipitation*
  - *Synthesize results from technical basis research*
  - *Incorporate site-scale features (curbs, buildings, drains)*
- **Key elements**
  - *Point rainfall (aleatory variability) based on NOAA Atlas 14*
  - *Sensitivity study to identify key epistemic uncertainties wrt site features*
  - *Propagation of uncertainties to construct hazard curve families for selected flood hazard metrics (e.g., depth, velocity, duration)*
  - *Monte Carlo simulation with stratified sampling*
- **More detailed information:**
  - *Presentation 4B-2 (Friday at 13:00)*

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Phase 2: Riverine Pilot Study

- **Objectives**
  - *Inform guidance development for probabilistic assessment of riverine flooding hazards*
  - *Synthesize results from technical basis research*
  - *Incorporate multiple flooding mechanism contributions to hazard curves*
- **Key elements**
  - *Stochastic rainfall model (aleatory variability)*
  - *Epistemic uncertainties in hydrologic (runoff and routing), reservoir, and hydraulic models*
  - *Multiple dam failure scenarios*
  - *Propagation of uncertainties to construct hazard curve families for selected flood hazard metrics (e.g., elevation, velocity, duration)*
  - *Monte Carlo simulation approach using HEC-WAT*
- **More information:**
  - *Final Report (in publication)*
  - *PFHA-WS7 Proceedings*
    - *Presentation 2B-4, Posters 3A-4 and 3A-5*

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Phase 2: Coastal Pilot Study

- **Objectives**
  - *Inform guidance development for probabilistic assessment of coastal flooding hazards*
  - *Synthesize results from technical basis research*
  - *Incorporate multiple flooding mechanism contributions to hazard curves*
- **Key elements**
  - *Tropical cyclone rainfall model (aleatory variability)*
  - *Epistemic uncertainties in hydrodynamic (surge), hydrologic (runoff and routing), and hydraulic models*
  - *Flooding due to surge and rainfall-induced riverine discharge*
  - *Propagation of uncertainties to construct hazard curve families for selected flood hazard metrics (e.g., elevation, velocity)*
  - *USACE Probabilistic Coastal Hazard Assessment (PCHA) framework*
- **More detailed information:**
  - *Presentation 3B-3 (Thursday at 14:00)*
  - *Presentation 3B-4 (Thursday at 14:35)*

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Phase 3: PFHA Guidance

- **FY23:**
  - **Develop draft guidance based on:**
    - *Technical basis research*
    - *Pilot projects*
    - *User office needs*
    - *Stakeholder & public interests*
  - **Publish draft guidance for public comment**
- **FY24:**
  - **Finalize guidance based on public comment**


U.S. Nuclear Regulatory Commission
REGULATORY GUIDE
Office of Nuclear Regulatory Research

A. INTRODUCTION

11

Past Workshops

- Proceedings of 1st-4th Annual NRC PFHA Research Workshops
  - *NRC Research Information Letter (RIL) 2020-01*
- Proceedings of 5th Annual NRC PFHA Research Workshop
  - *RIL 2021-01*
- Proceedings of 6th Annual NRC PFHA Research Workshop
  - *RIL 2022-02*
- Proceedings of 7th Annual NRC PFHA Research Workshop
  - *RIL 2022-10*

NRC Research Information Letters are available at:
https://www.nrc.gov/reading-rm/doc-collections/index.html#ril

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Questions?

Contacts:
Joseph.Kanney@nrc.gov
Thomas.Aird@nrc.gov
Elena.Yegorova@nrc.gov

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3.1.2.3 Questions and Answers

Comment:

We did not hear much about nonstationarity.

Answer:

Joseph Kanney: That’s a good comment. Some of the work that we have done, specifically in flood frequency analysis, has touched on nonstationarity issues. To the person who submitted that commentonline: if you send me an email, I can point you to the research reports where we have looked at some aspects of nonstationarity. I won’t claim that we have solved the nonstationarity issue in its entirety though, obviously.

3.1.3 Presentation 1A-3: Moving FEMA towards Presentation and Training: Resilience Analysis and Planning Tool (RAPT)

Authors: Karen Marsh, Benjamin Rance, Scott Mahlik, Federal Emergency Management Agency (FEMA)

Speaker: Scott Mahlik

3.1.3.1 Abstract

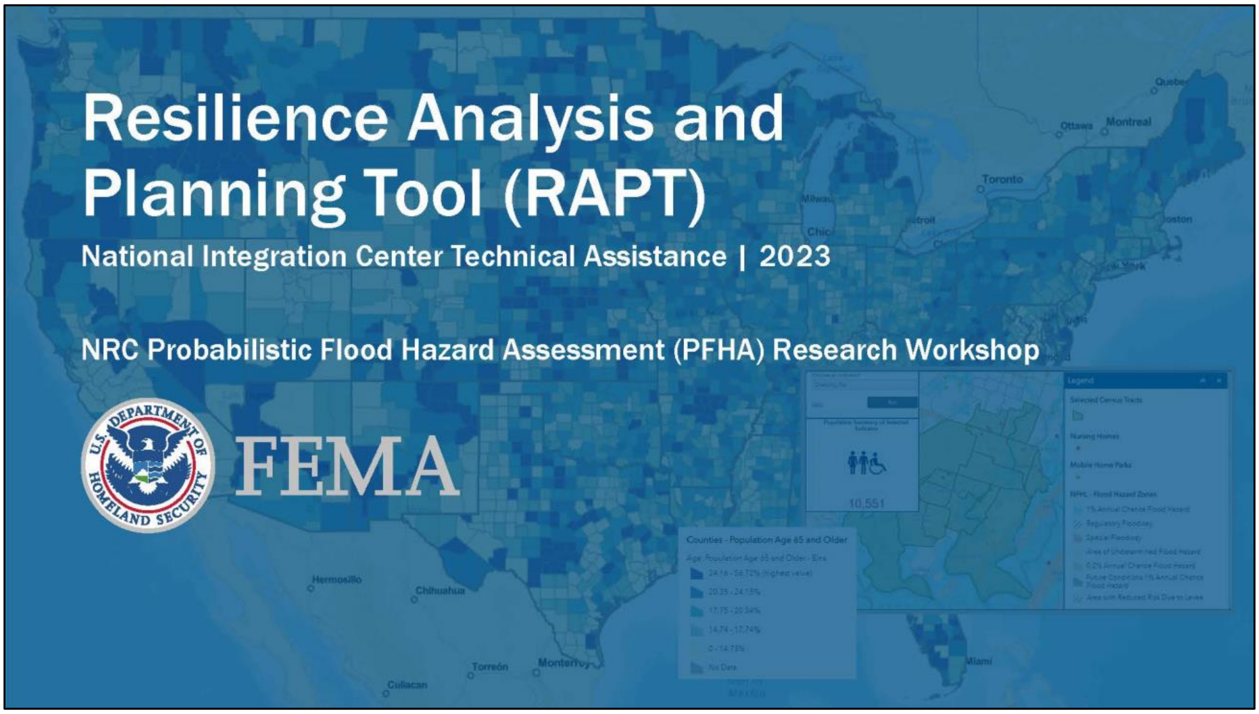
Many of the utilities that own nuclear generating facilities and the relevant off-site response organizations (ORO) can benefit from the Resilience Analysis and Planning Tool (RAPT), as there is an increased focus on equity in emergency management, including a need for federal, state and local governments, utility companies and disaster support organizations to better understand the community and population demographics in areas surrounding these facilities.

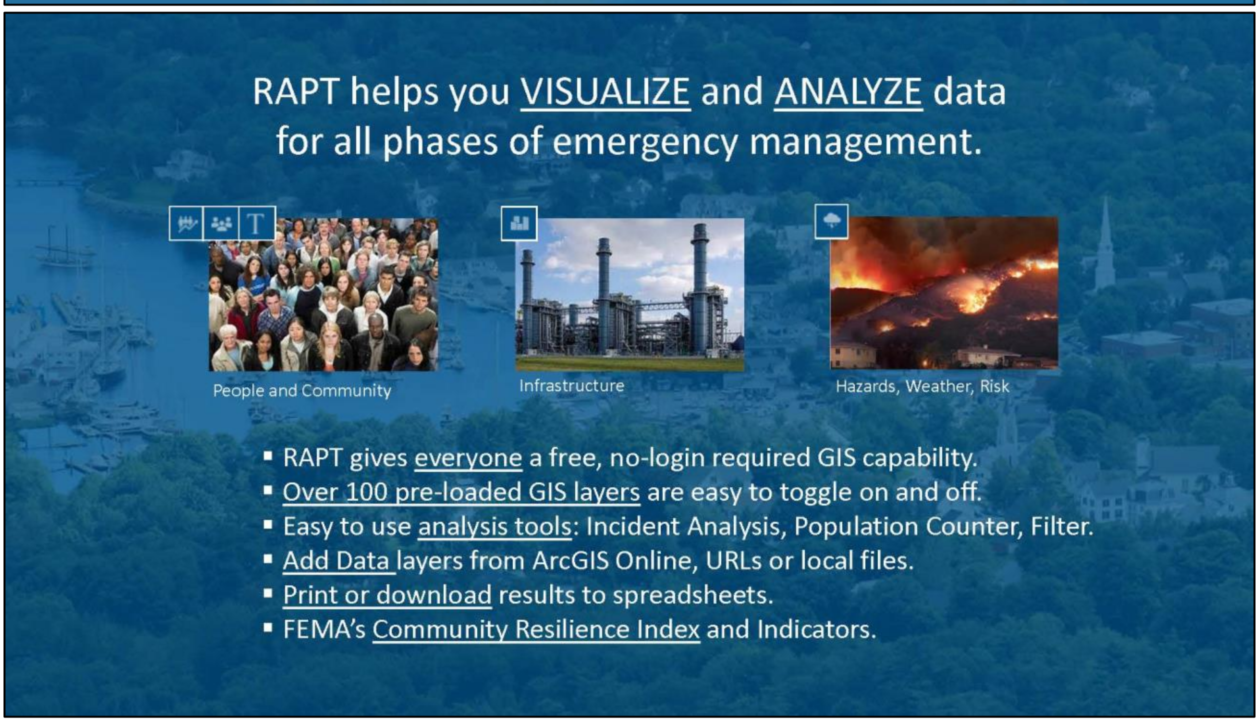
FEMA’s National Integration Center would like to present the updated and improved RAPT, a free GIS web map that allows users to examine the interplay of census data, infrastructure locations, and hazards. RAPT helps users visualize and analyze data about their community to inform resilience, response, and recovery actions. Participants will learn how to use RAPT to understand their community and the populations that may have more difficulty receiving an alert and/or following the proscribed protective action, such as those with limited English, individuals without access to a vehicle, or with a disability.

The RAPT includes information from FEMA’s Community Resilience Index (CRI), derived from the science-based Community Resilience Indicator Analysis report. The CRI allows users to identify areas of the community with greater potential challenges to resilience while also providing census-tract level information on each of the indicators that contribute to the CRI. In addition to the community and population demographic information, the session will also provide an overview of unique analysis tools that allow users to isolate specific incident areas and identify, summarize, and export information as needed. The information in RAPT can benefit all stakeholders and we hope to facilitate discussion and collaboration amongst attendees.

In addition to a presentation, we would also provide an in-depth, interactive demonstration of the tool to participants. This demonstration will show participants demographic information for their specific communities, demonstrate the powerful analysis tools in RAPT and examine local data layers. We believe this presentation opportunity would help participants use RAPT to understand community dynamics and demographics in areas surrounding nuclear facilities.

3.1.3.2 Presentation (ADAMS Accession No. ML23177A154)





RAPT Community Demographics Data Layers

** County data only; ** County and Tribal only; ^ County and Census Tract only; + Census Tract only*

Population Characteristics
- Population without a High School Education
- Population 65 and Older
- Population with a Disability
- Population by Race and Hispanic Origin^

Household Characteristics
- Households without a Vehicle
- Households with Limited English
- Single-Parent Households
- Households without a Smartphone
- Households without Broadband Subscription+

Housing
- Mobile Homes as Percentage of Housing
- Owner-Occupied Housing
- Rental Housing Costs^
- Residential Structures in SHFA with Flood Insurance*

Healthcare
- Number of Hospitals*
- Medical Professional Capacity**
- Population without Health Insurance
- Medicare Recipients with Power-Dependent Devices*

Economic
- Population Below Poverty Level
- Median Household Income
- Unemployed Labor Force
- Unemployed Women Labor Force
- Income Inequality
- Workforce in Predominant Sector

Connection to Community
- Presence of Civic and Social Organizations*
- Population without Religious Affiliation*
- Percentage of Inactive Voters*
- Population Change*

FEMA

County and Census Tract Community Resilience Index (CRI) combining 22 indicators.

Infrastructure Layers: Homeland Infrastructure Foundation-Level Data Open

- Hospitals
- Nursing Homes
- Pharmacies
- Urgent Care Facilities
- Dialysis Centers
- Mobile Home Parks
- Fire Stations
- Local Law Enforcement Locations
- Public Health Departments
- 911 Service Area Boundaries
- SNAP Authorized Retailers

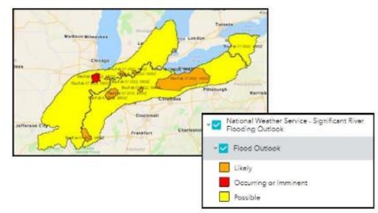
- Places of Worship
- Colleges and Universities
- Private Schools
- Public Schools
- Prison Boundaries
- Power Plants
- Electric Transmission Lines
- Wastewater Treatment Plants
- Solid Waste Landfills
- High-Hazard Dams

FEMA

Federal Emergency Management Agency 4

Hazards, Weather, Risk

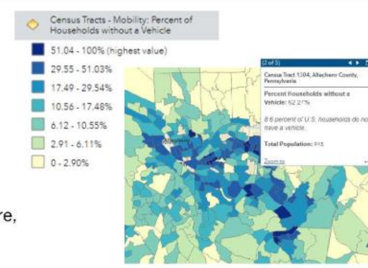
- Live Stream Gauges
- Flood Hazard
- Hurricane Tracks (1990+)
- Historical Tornado Tracks
- Wildfires – Current Incidents (Points)
- Wildfires – Current incidents (Perimeters)
- Seismic Hazard
- National Risk Index Census Tracts
- NOAA Sea Level Rise (4-6 ft.)
- NWS Severe Weather Watches and Warnings
- NWS Severe Weather Outlook
- NWS Atlantic/Caribbean Tropical Cyclones
- NWS Eastern Pacific Tropical Cyclones
- NWS Excessive Rainfall Outlook
- NEXRAD Real-Time Weather Radar

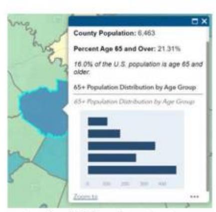


FEMA

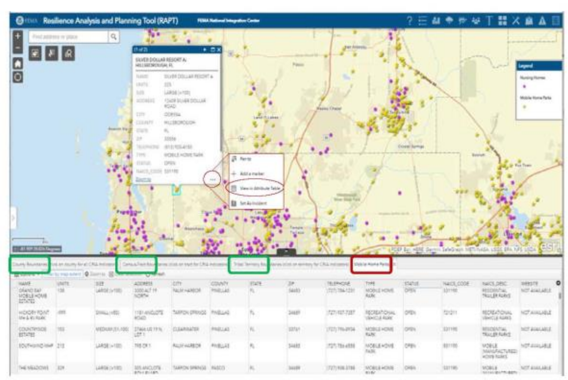
Data Binning, Pop-Up Boxes and Attribute Tables

- **Data Binning:**
  County = 5 bins
  Census Tract = 7 bins
  Tribal = 5 bins
- **Pop-up boxes:**
  Additional information for each data point: population, infrastructure, and hazards
- **Attribute tables:**
  - By map extent
  - By FEMA region, state, county, zip code
  - Select rows





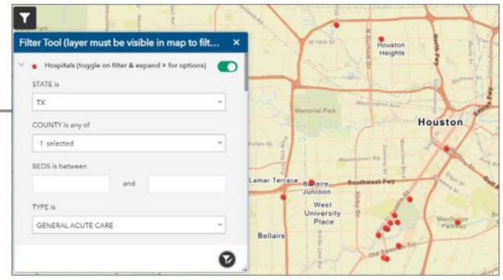
age, disabilities, language, race

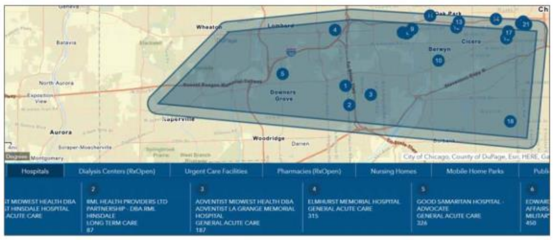


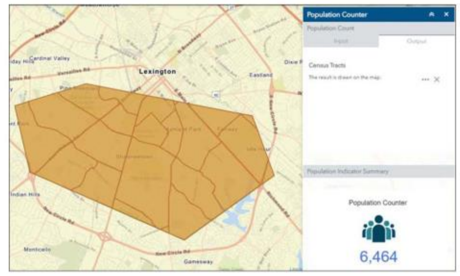
FEMA

Analysis Tools

- Analysis Tools
  - Add Data
  - Filter Tool
  - Population Counter
  - Incident Analysis Tool







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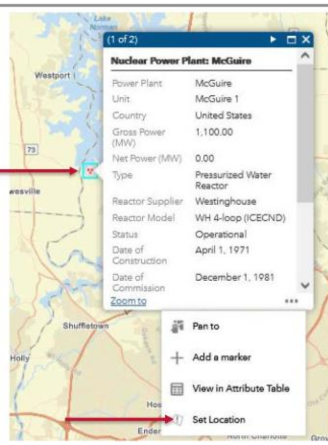
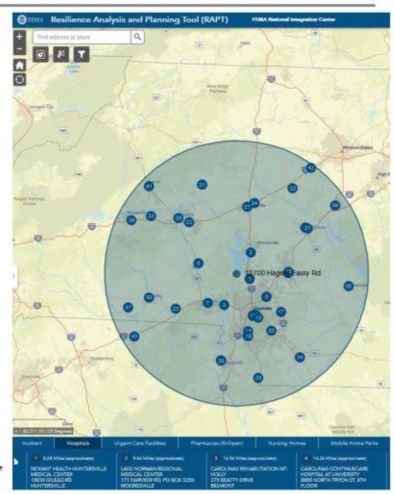
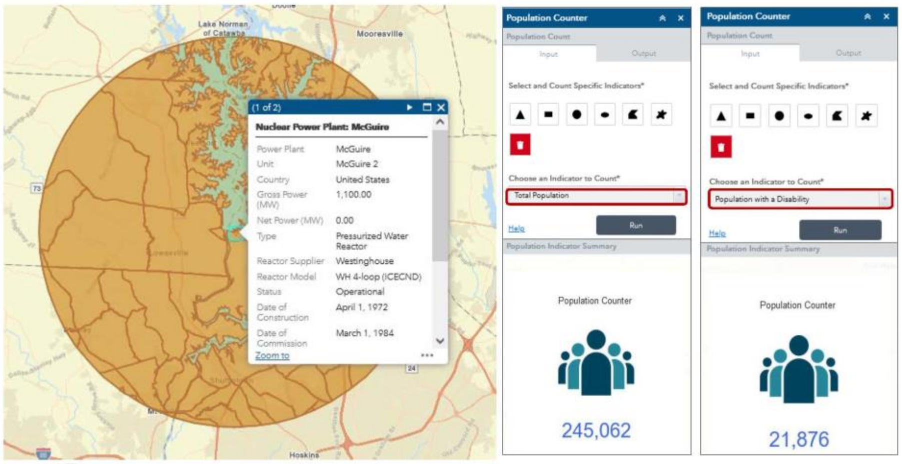
Add Data and Incident Analysis





FEMA

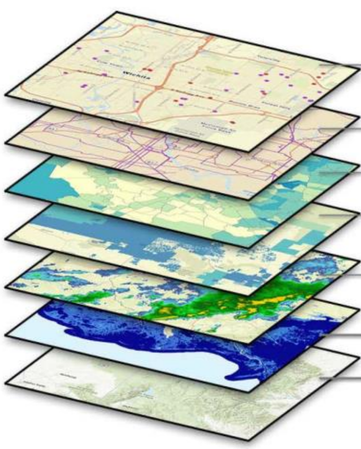
Population Counter



Total Population
Population without HS Diploma
Population Unemployed
Population with a Disability
HH with Limited English
HH without a Vehicle
Population Age 65 and Over
Population without Health Insurance
Single Parent HH
HH without Smartphone
Population Living Below Poverty Level
Population Living in Mobile Homes

FEMA

RAPT Analysis through Layer Combinations



Infrastructure Point Locations
(Hospitals, Nursing Homes etc.)

Infrastructure Lines
(Transmission lines, High Hazard dam lines)

County/Census Tract Indicators
(Population over 65, lack of health insurance)

Tribal Boundary Indicators
(Population over 65, lack of health insurance)

Real-time Hazards (NWS)
(Radar, Severe Watches & Warnings, Tropical Cyclones)

Future Climate conditions
(Sea Level Rise)

Basemap

RAPT combines multiple data sets and analysis tools to support situational awareness for all phases of emergency management.

FEMA

Evacuation Planning

Planning for evacuation and how to deliver reliable and actionable information to surrounding communities, including people without access to a vehicle and people with limited English proficiency.

Population Demographics:

% population with a disability
% households without a vehicle
% population with limited English proficiency

Analysis Tools:

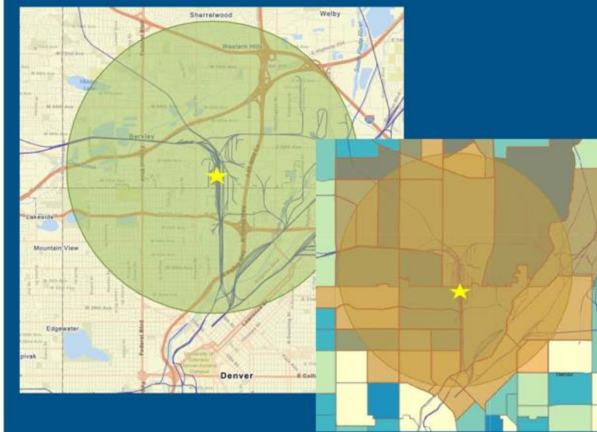
Population Counter- draw projected area based on 2-mile buffer zone around incident

- Calculate # of people affected
- Calculate # of people with a disability
- Calculate # of people without a vehicle
- Calculate # of people with limited English Proficiency

Add Data:

Railroad lines: HIFLD Open North American Rail Lines

FEMA



Population Summary of Selected Indicators

Population: 141,087
people with disability: 15.931
people without vehicle: 12,160
people with limited English: 8,095

Census Tracts - Disability: Percent of the Population with a Disability

- 0 - 7.54%
- 7.55 - 10.27%
- 10.28 - 12.86%
- 12.87 - 15.64%
- 15.65 - 18.94%
- 18.95 - 23.60%
- 23.61 - 100%

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RAPT Resource Center

- RAPT overview
- Use Cases
- Indicator Analysis
- Data Sources
- User Guide and FAQs
- Instructional video
- Contact us email: FEMA-TARequest@fema.dhs.gov

Send Us Your Use Cases!!

FEMA

Federal Emergency Management Agency 12

Climate Risk & Resilience Portal (ClimRR): Goals

- Provide free and equitable access to leading, peer-reviewed climate datasets.
- Empower non-technical individuals, organizations, planners and officials at state, local, tribal, and territorial governments to analyze climate risk to support decision-making and adaptation efforts.
- Contextualize how climate risks factor into equity considerations and barriers to community and infrastructure disaster resilience.
- ClimRR is the outgrowth of a public-private partnership between Argonne National Laboratory, FEMA, and AT&T.

CENTER FOR
CLIMATE RESILIENCE
AND DECISION SCIENCE
Argonne National Laboratory

FEMA

AT&T

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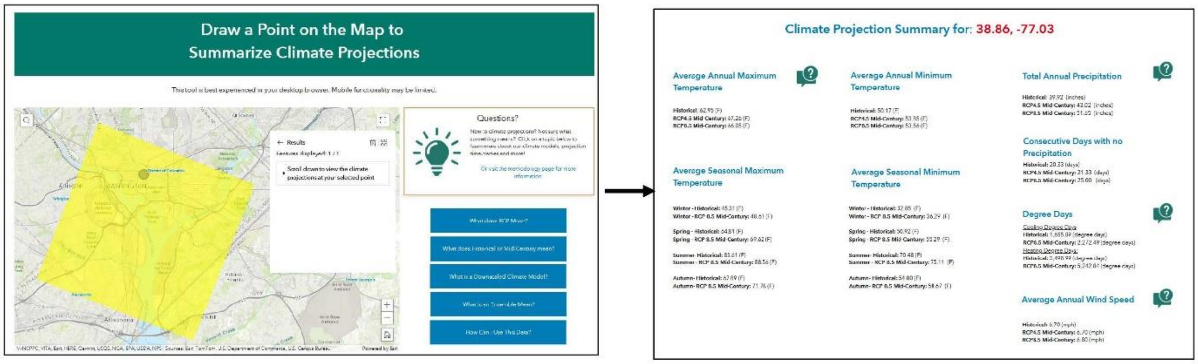
Dynamical DOWNSCALING

- From coarse resolution (100-200km) to high resolution, community-level data (12km)
- Downscaled data are an *ensemble mean* of three different global climate models
- Physics-based models that address non-stationarity
- Two scenarios: RCP8.5 (high emissions) + RCP4.5 (~Paris accords)
  - Useful for infrastructure protection and disaster planning
- Scientific transparency: widely published and peer reviewed modeling and outcomes
- Future release will be 9 times more precise (4km)

Location Summaries

Quickly summarize all variables for a single location



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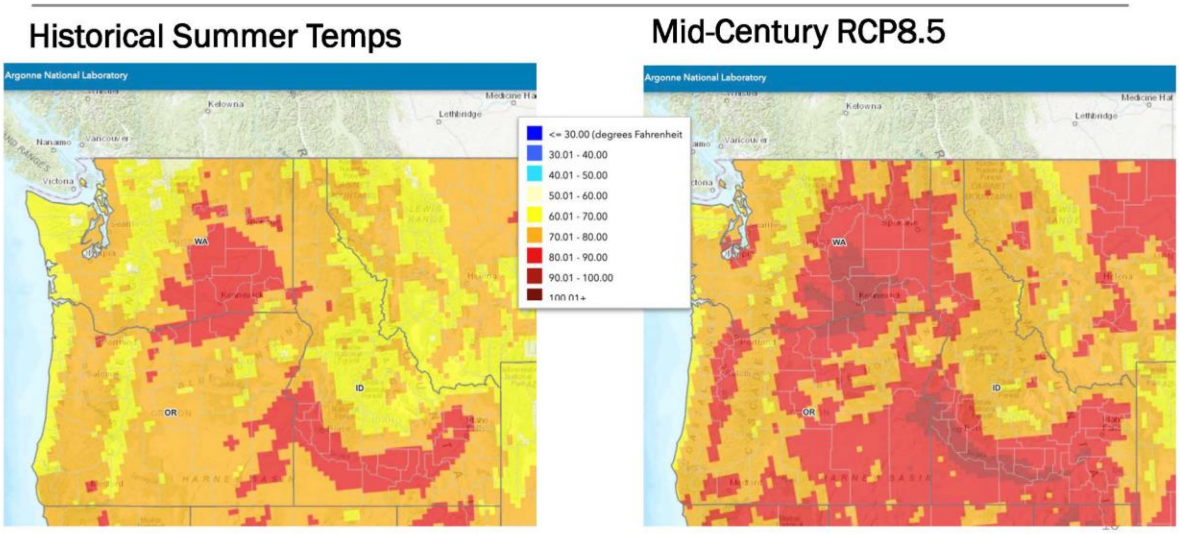
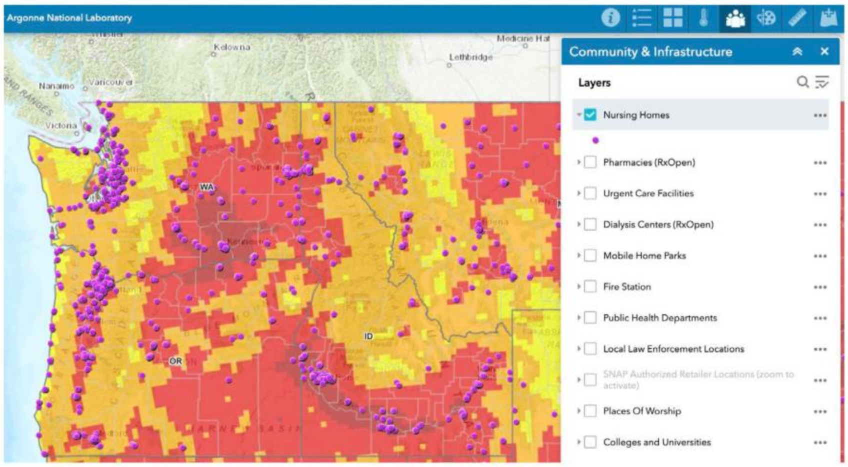
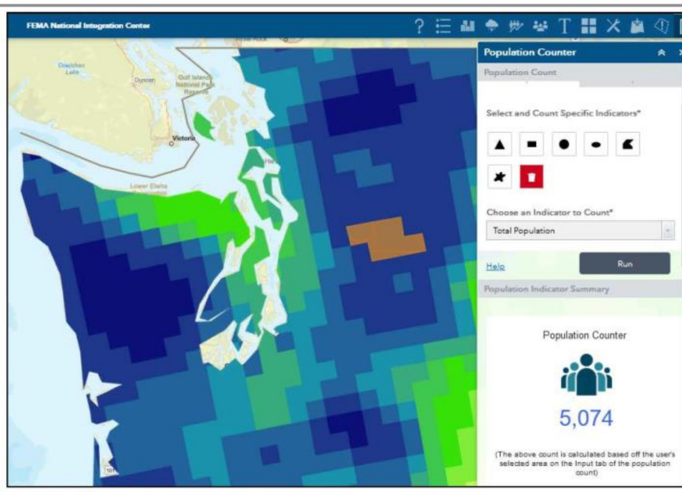
Data Explorers

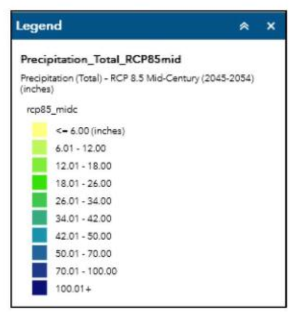


RAPT data in ClimRR



ClimRR Data in RAPT





3.1.3.3 Questions and Answers

Question:

How do you deal with deep uncertainty in extreme rainfall when using dynamical downscaling?

Answer:

Diane Cooper: If you are familiar with any of the atmospheric models, we are using the using the WRF[1]; they [Argonne National Laboratory] are running hourly simulations and then identifying that over longer periods, which is why you need supercomputing capacity to be able to be able to create this gridded output. We are at least getting in some of the orographic elements that maybe aren't well represented in the climate models because your grid scale is too large. The WRF has a much finer resolution and does have the topography included as well as the water information from the oceans, bays, Great Lakes that is going to be a little bit more defined than what you would have in the traditional climate models.

Question:

Any plans to add CMIP6[2] to ClimRR[3]?

Answer:

Diane Cooper: I believe that this is in the conversation for one of our future releases, but not sure of the timing.

Question:

[1] Weather Research and Forecasting (WRF) model
[2] Coupled Model Intercomparison Project (CMIP) Phase 6
[3] Climate Risk and Resilience Portal

Two questions: 1) Do you have plans to integrate this with Hazus; and 2) do you have the constituent components of the National Resilience Index in there or is it just the final index value?

Answer:

Scott Mahlik: The Hazus team isn't in the federal insurance and mitigation administration, but they are, obviously, our colleagues and partners. We haven't talked specifically about adding the ClimRR data yet, but definitely something we will consider and is on the plate as this data should be incorporated into many different places. We do have the have the index values and constituent components in there.

Question:

Is there timing information provided in RAPT? Some context for the question is when we look at core damage frequency (CDF) scenarios and large early release frequency (LERF) scenarios for our plants, the LERF answers are largely dependent on whether we can get the population evacuated before that large and early release happens. Does RAPT include that kind of timing where you could either use the emergency planning zone (EPZ) or draw a polygon around a plant and say what is the distribution of the time for evacuation for this area?

Answer:

Scott Mahlik: Unfortunately, no for the timing. That would have to be an "add data." It's not pre-loaded into RAPT so that's something that you would have to add, unfortunately. You can get the context of how many people are in the area but not an evacuation timing. That would be something you'd have to add.

Diane Cooper: There are evacuation studies that have been done along the coast from a hurricane perspective and the timeframes that would be needed for that, which have been done in very close concert with the local emergency management. I suggest that, for whatever facility you are concerned about, you would need to work with those local emergency managers who would initiate those evacuations. We offer technical assistance in a workshop format to emergency management on how to word that information to the public.

Question:

RAPT is clearly a great planning tool, but what kind of capabilities does it have for real time events, for trying to conduct evacuations?

Answer:

Scott Mahlik: We are using data that are estimates (e.g., population demographics change over time). It is the latest data, but it is by no means giving you real-time information. You can add traffic layers, which are real-time, and those are brought in through ESRI that would be through the Add Data tool. So, you can get some real time information, but it depends. If you were a county or a state using RAPT to make decisions, you would want to make sure that you understand what data is uploaded and what the limitations are. For example, some of the data pre-loaded into RAPT is real-time (e.g., information from the national weather service is real-time), but that is not true for all layers. So be sure you understand whether a layer you are looking at is real-time or stored data.

Question:

You just talked about the real-time hazard information, and I was curious about what you have there in terms of forecasts. What about forecasts like precipitation forecasts or river flooding forecasts? Are those included or if they aren't, do you have plans to include them?

Answer:

Scott Mahlik: We do have excessive rainfall outlooks pre-loaded. We do have stream gages also pre-loaded. That will give you the real-time, but you can add future or forecast conditions from the National Weather Service as well. The tool is configured so that whatever problem that you want to solve, you can bring data in as necessary. It can be added and we that's why we do a lot of work with folks who are using RAPT. So, send an e-mail fema-trequestthatfema.dhs.gov. We have really focused on customer support to make sure if you want to use it for something, we can help you do that.

3.1.4 Presentation 1A-4: Committee on the Safety of Nuclear Installations (CSNI) Working Group on External Events (WGEV)

Author: Minkyu Kim, Korea Atomic Energy Research Institute, Division of Structural and Seismic Safety (WGEV Chair)

Speaker: Minkyu Kim

3.1.4.1 Abstract

The March 2011 accident at the Fukushima Daiichi nuclear power plant triggered discussions about the natural (external) events that are low-frequency but high-consequence. To address these issues and determine which events would benefit from international co-operative work, the Working Group on External Events (WGEV) was established in CSNI. WGEV is composed of a forum of experts for the exchange of information and experience on external events in member countries, thereby promoting co-operation and maintenance of an effective and efficient network of experts.

WGEV already finalized some international collaboration works as below; severe weather and storm surge, examination of approaches for screening external hazards, riverine flooding - hazard assessment and protection of NPPs, concepts, and definitions for flooding protective measures, benchmark exercise to validate hazard frequency and magnitude for external events risk assessment. Also, WGEV now performing several activities for high wind and tornado - hazards assessment and protection of Nis, combined external hazards, uncertainties in the assessment of natural hazards (Excluding Earthquakes), sources of uncertainties and methods to deal with uncertainties, and local intense precipitation.

3.1.4.2 Presentation (ADAMS Accession No. ML23177A155)

OECD BETTER POLICIES FOR BETTER LIVES — Nuclear Energy Agency — NEA NUCLEAR ENERGY AGENCY

CSNI Working Group on External Events (WGEV)

Minkyu KIM (Chair of WGEV)

8th Annual PFHA Research Workshop
March 21-24 2023, USNRC

 1

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Working Group on External Events

- Background of WGEV
  - After Fukushima Daiichi nuclear power plant accident, many activities were initiated in the countries with nuclear energy to assess the robustness of nuclear power plants with respect to earthquakes, tsunamis and floods originating from the sea
  - CSNI established TGNEV (Task Group on Natural External Events) in 2013 to cover other natural events which might also pose hazards to the safe operation of nuclear installations
  - TGNEV to review natural external events that are low-frequency, but high-consequence, and determine whether there are activities that would benefit from international cooperative work
  - WGEV is established in 2014

 2

Working Group on External Events

- The main mission
  - to improve the understanding and treatment of external hazards that would support the continued safety performance of nuclear installations, and improve the effectiveness of regulatory practices in member countries.
  - To focus on external hazards that are of sufficient common interest to allow sharing of approaches for analysis, oversight, and facility design and operation

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Working Group on External Events

- Meeting
  - Regulators, TSOs, research institutes, operators
  - Twice per year (last meeting in October
  - Activities decided by member states
  - Sharing significant external events which affected or could affect safety operation of NIs
- Activities
  - Experience sharing
  - Workshop, Report

What WGEV has discussed so far

- Severe Weather Events with High Winds and Flooding
- Examination of approaches for screening external hazards
- Riverine Flooding –Hazard Assessment and protection of NPPs
- Concepts and Definitions for Protective Measures in Response to External Flooding Hazards
- Benchmark on External Events Hazard Frequency and Magnitude Statistical Modelling

WGEV in 2022

- Start One CAPS
  - **Characterization in Local Intense Precipitation** was approved by CSNI in June 2022
- Two Workshop
  - High Winds and Tornado (March 2022, virtual)
  - Uncertainties in the assessment of natural hazards *(phase 1-sources of uncertainties)* (April 2022, virtual)
- Cooperation with IAEA
  - Start to discuss to develop a template to develop a database for external events

Ongoing Activities

	Title	Leader	Approval
1	High Wind and Tornado - Hazard Assessment and Protection of NIs	France	2019
2	Combinations of External Hazards – Hazard and Impact Assessment and PSA for Nis (WGEV/WGRISK Joint project)	Czech Rep (WGEV) Hungary (WGRISK)	2019
3	Uncertainties in the assessment of natural hazards – phase 1 (sources of uncertainties)	Germany USA	2020
4	Uncertainties in the assessment of natural hazards – phase 2 (methods to deal with uncertainties)	Germany USA	2020
5	Characterization of Local Intense Precipitation	Canada	2022

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Ongoing Activities (1/5)

High Wind and Tornado – Hazard Assessment and Protection of NIs

- **Objectives**
  - Collecting information from WGEV member states with respect to current regulatory practices and technical approaches, methods and models used to confirm the adequacy of protection of NIs against high wind and tornadoes
  - Identifying key issues regarding high wind and tornado hazard assessment (both deterministic and probabilistic) and dedicated protection

- **Milestones**
  - Technical note was finalized (March 2021)
  - **Virtual Workshop (March 2022)**
  - Endorsement of workshop proceedings by CSNI – June 2023

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Ongoing Activities (2/5)

Combinations of External Hazards – Hazards and Impact Assessment and Probabilistic Safety Analysis (PSA) For Nuclear Installations ***(Joint project with WGRISK, Working Group on Risk Assessment)***

- **Objectives**
  - Collecting information on current regulatory practices as well as technical approaches and methods applied in hazard assessments for nuclear installations with respect to combinations of external hazards and integrated hazard impacts. Based on the evaluation of this information, key issues impacts will be identified.
  - Providing an overview of the current state-of-art with respect to risk analysis of hazard combinations of external hazards and to review the methods applied for these analyses in order to provide a basis for advances in this area.
- **Milestones**
  - Finalization of survey task report – March 2023
  - **Common WGEV/WGRISK workshop – 11-13 September 2023 (IRSN, France)**
  - Endorsement of workshop proceedings by CSNI – June 2024

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Ongoing Activities (2/5)

Combinations of External Hazards – Hazards and Impact Assessment and Probabilistic Safety Analysis (PSA) For Nuclear Installations ***(Joint project with WGRISK, Working Group on Risk Assessment)***

- **Workshop on Combinations of External Hazards**
  - 11-13th September 2023, IRSN (Pairs, France)
  - Kick-off meeting of Organizational Committee meeting (21th Nov) *(Members from WGEV & WGRISK)*
  - Official announcement would be in March 2023
    - call for the contribution for the workshop
    - Registering would start from March

Ongoing Activities (3/5)

- **Title**
  - ***Uncertainties in the Assessment of Natural Hazards (Excluding Earthquakes) – Phase 1 (Sources of Uncertainties)***
- **Objectives**
  - (overall objective) Developing an understanding of the state of practice with respect to the consideration of uncertainties in natural hazards assessments. The result will serve as a basis for the identification of areas that could benefit from future collaborative efforts and as an input to the work of CNRA.
  - (Phase 1) Providing an overview of the various types of uncertainties that need to be considered depending on the type of natural hazards, the data sources and the assessment approaches.
- **Milestones**
  - **Virtual Workshop (April 2022)**
  - Approval of the workshop proceedings by CSNI - June 2023
  - Finalization of the **report** – September 2023
  - Approval of the report by CSNI – December 2023

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Ongoing Activities (4/5)

- **Title**
  - ***Uncertainties in the Assessment of Natural Hazards (Excluding Earthquakes) – Phase 2 (Methods to Deal with uncertainties)***
- **Objectives**
  - (Phase 2) Providing an overview of recommendable methods to account – either qualitatively or quantitatively – for uncertainties in assessments for a set of natural hazards as specified in Phase 1 of the activity.
- **Milestones**
  - Writing and discussing (WGEV meetings) – 2023~
  - Approval of the report by CSNI – June 2024
  - Workshop – September 2025
  - Approval of workshop proceedings by CSNI – June 2026

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Ongoing Activities (5/5)

- **Title**
  - ***Characterization of Local Intense Precipitation***

- **Objectives**
  - collecting information from WGEV member states with respect to current regulatory guidance and operators' practices as well as best available technical approaches and methods in assessing and characterizing LIP for use in flood hazard assessment(FHA) for nuclear installations. Based on the evaluation of the obtained information, best practice and knowledge gaps will be identified.

- **Milestones**
  - Developing and distributing survey – Dec 2022
  - Answers to the survey by working group members – Feb 2023
  - Finalization of technical note – March 2024
  - **Workshop – Sep 2024**
  - Approval of workshop proceedings by CSNI – June 2025

Nuclear Energy Agency

Topics for the Future

- **Cooperation with IAEA**
  - IAEA has cooperated with WGIAGE to analyse the effect of external events in earthquake, and would like to expand to other external events
  - WGEV is going to prepare a CAPS to develop the template on effect of the external events (to be approved by CSNI June 2023)
  - WGEV will share external events in their countries during the meetings and decide what to share with IAEA
  - IAEA will share significant external events in IAEA countries

NEA NUCLEAR ENERGY AGENCY — OECD BETTER POLICIES FOR BETTER LIVES

INTERNATIONAL EXPERT WORKSHOP ON THE SAFETY ASSESSMENT OF NUCLEAR INSTALLATIONS FOR COMBINATIONS OF EXTERNAL HAZARDS

Fontenay-aux-Roses, France, September 11 – 13, 2023

IRSN

Hosted by the Institut de Radioprotection et de Sûreté Nucléaire (IRSN)

Key Dates

12th May 2023	*Deadline for Abstract Submission*
16th June 2023	*Notification to Authors*
14th July 2023	*Deadline for Attendance Registration*
28th August 2023	*Deadline for Presentation Submission*
11th -13th September 2023	*Workshop*

- **Suggested Workshop Topics**
  - Regulatory environment related to assessing combinations of external hazards
  - Supporting data and uncertainties as well as operational experience regarding combinations of external hazards
  - Selection and assessment of combined external hazards;
  - Assessment of integrated hazard impact
  - Risk assessment (PSA) for combined external hazards
  - Overall experience from safety assessment for combined external hazards

https://www.oecd-nea.org/jcms/pl_78713/international-expert-workshop-on-the-safety-assessment-of-nuclear-installations-for-combinations-of-external-hazards

Thank you for your attention!

3.1.4.3 Questions and Answers

Question:

Is tsunami considered a seismic hazard in this context?

Answer:

Our working group is WGEV. Another working group, WGIAGE[4], considers seismic hazards, but they don't consider flooding. We consider flood (and tsunami)

***Question**:*

Do the proceedings from the various meetings and workshops, do they get released publicly?

Answer:

Yes, they become publicly available if CSNI approves the proceedings they will be published and made publicly available. They can be found on the NEA[5] website.

3.2 Day 1: Session 1B –Climate and Weather

Session Chair: Elena Yegorova, NRC/RES

3.2.1 Presentation 1B-1: Overview of the U.S. Global Change Research Program

Author: Michael Kuperberg, Executive Director, U.S. Global Research Program

Speaker: Michael Kuperberg

3.2.1.1 Abstract

The U.S. Global Change Research Program (USGCRP) is a federal program mandated by Congress to coordinate federal research and investments in understanding the forces shaping the global environment, both human and natural, and their impacts on society. USGCRP facilitates collaboration and cooperation across its 14 federal member agencies to advance understanding of the changing Earth system and maximize efficiencies in federal global change research. Together, USGCRP and its member agencies provide a gateway to authoritative science, tools, and resources to help people and organizations across the country manage risks and respond to changing environmental conditions. This presentation will provide an overview of USGCRP, its structure and major responsibilities.

[4] Working Group on Integrity and Ageing of Components and Structures

[5] Nuclear Energy Agency (https://www.oecd-nea.org/)

3.2.1.2 Presentation (ADAMS Accession No. ML23177A156)

Coordinating Global Change Research Across the U.S. Government

U.S. Nuclear Regulatory Commission
Probabilistic Flood Hazard Assessment (PFHA) Research Workshop

21 March 2023

U.S. Global Change Research Program

About USGCRP

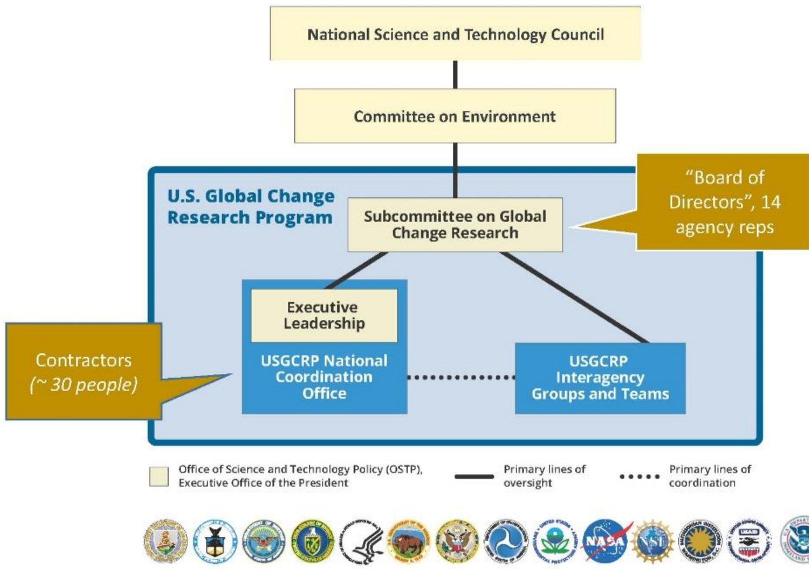
- Began as a Presidential Initiative in 1989
- Mandated by Congress in the GCRA
- 14 member agencies
- FY2021 budget crosscut approx. $3.3 Billion
- Interagency Distributed Cost Budget supports the National Coordination Office (NCO) and activities of the organization

"[A] comprehensive and integrated United States research program which will assist the Nation and the world to understand, assess, predict and respond to human-induced and natural processes of global change"

(P.L. 101-606)

U.S. Global Change Research Program

USGCRP Oversight & Coordination



FY2021 USGCRP budget cross-cut

Funding amounts are shown in millions of dollars ($M) and are rounded to the nearest millions (totals reflect the rounded sum of the unrounded agency amounts).

Agency	FY 2020 Enacted ($M)	FY 2021 Enacted ($M)	FY 2022 President's Budget ($M)
Department of Agriculture	111	128	405
Department of Commerce	306	444	731
Department of Energy	256	305	366
Department of Health and Human Services	10	19	154
Department of the Interior	38	207	461
Department of Transportation	0	1	52
Environmental Protection Agency	18	20	51
National Aeronautics and Space Administration	1,469	1,617	1,827
National Science Foundation	246	521	762
Smithsonian Institution	8	8	13
TOTAL (USGCRP)	**2,461**	**3,270**	**4,822**

USGCRP interagency groups

Approximately 400 individuals participate in USGCRP groups

- Tuning in to teleconferences
- Participating in assessment development
- Active membership in interagency groups, **open to all federal agencies**

Current Interagency Groups	
Carbon Cycle	International Activities
Observations	Sustained Assessment
Integrated Modeling	Indicators
Human Health	Integrated Water Cycle
Social Science	Adaptation and Resilience
Coasts	Climate Engagement and Capacity Building

U.S. Global Change Research Program

5

National Global Change Research Plan

"[The Program] shall develop a 10-year National Global Change Research Plan for implementation of the Program" (GCRA)

- New decadal plan (2022-2031) released in December 2022
- Four Plan Pillars:
  - Advancing Science
  - Engaging the Nation
  - Informing Decisions
  - Collaborating Internationally

U.S. Global Change Research Program

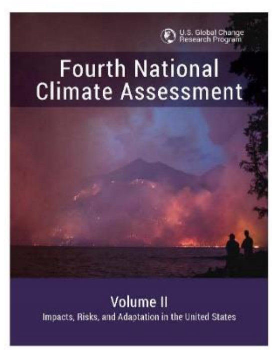
Our Changing Planet

"Each year at the time of submission to the Congress of the President's budget [the Program] shall submit to the Congress a report on the activities conducted by the Committee" (GCRA)

- *Our Changing Planet,* USGCRP's annual report to Congress, includes:
  - Summary of the program's achievements for the past year
  - Priorities for future global change research
  - Budget cross-cut

The National Climate Assessment Mandate

- *"Not less frequently than every 4 years [the Program] shall prepare and submit to the President and Congress an assessment which:*
  - *Integrates, evaluates, and interprets the findings [of the Program] and discusses the scientific uncertainties associated with such findings;*
  - *Analyzes the effects of global change on the natural environment, agriculture, energy production and use, land and water resources, transportation, human health and welfare, human social systems, and biological diversity;*
  - *Analyzes current trends in global change, both human-induced and natural, and projects major trends for the subsequent 25 to 100 years."*



NCA4

The Fifth National Climate Assessment

Coming in late 2023. Chapters include:

- Overview/Summary Findings
- Earth System Processes
- Climate Trends
- Water
- Energy
- Land Cover and Land Use
- Forests
- Ecosystems and Biodiversity
- Coastal Effects
- Oceans and Marine Resources
- Agriculture
- Built Environment
- Transportation
- Air Quality
- Human Health
- Tribal and Indigenous Peoples
- International
- Complex Systems
- Economics*
- Human Social Systems*

*new chapters

International context of the GCRA

- Promote international cooperation on global change research
- Coordinate U.S. activities with the programs of other nations and international organizations
- Involve developing country scientists and decision-makers in this research while also building capacity abroad in the realm of global change science

To these ends, USGCRP develops international partnerships that advance program priorities, link to program areas, and leverage investments by other entities

Recent Priority Topics of Interest

- Expanding USGCRP Participation and Membership
  - Lots of interest from non-member agencies
  - DHS became the 14th member in February 2023
- Fulfilling USGCRP's full "global change" mandate
  - National Nature Assessment (E.O. 14072)
- Expanding Role in Providing Climate Services
  - Involved in an emerging Federal climate services framework
  - Climate information and validation
- Climate Security
  - Collaboration with ODNI
  - Linkages to Climate Security Working Group

U.S. Global Change Research Program

11

Thank you

Mike Kuperberg
mkuperberg@usgcrp.gov

Connect with us:

@usgcrp

usgcrp

GlobalChange.gov

U.S. Global Change Research Program

3.2.1.3 Questions and Answers

Question:

Is the peer review with the National Academies mandated somewhere or is that something that you decided to do?

Answer:

The law requires that we partner with the National Academies for the development of our strategic plan. There is also an OMB policy that defines something called a highly influential scientific assessment (HISA). The national climate assessment is a HISA and has to go to external peer review. Because we have an existing relationship with the National Academies through our strategic plan, we use them as our external peer review body for the national climate assessment. So, it's mandated that we have an external peer review. It doesn't say that is has to be the National Academies. We see the National Academies as the gold standard on external peer review and so we use them in that way.

Question:

How does the private sector participate or give information or their position on things to USGCRP? Is this strictly a federal group talking to other federal members or is there some mechanism for the private sector to have some involvement?

Answer:

There are mechanisms. We work with the private sector through open public venues. However, we are mindful of and we work within the Federal Advisory Committee Act, which makes it difficult to work with external bodies if they are not established. The National Academies has a standing committee that we support, that provides us with advice as well as input on our strategic plan and the review of the National Climate Assessment. So that is a body, it's essentially our advisory committee, a federally chartered group, the National Academy, that meets regularly and does provide ongoing advice to us.

All the activities that we are working on, the National Nature Assessment that I mentioned earlier, the National Climate Assessment, have a very strong external input process. The National Climate Assessment will have gone through three or four federal register notices where we put out open comment on a pre-prospectus, the full prospectus, and then the third draft of the National Climate Assessment went out for public comment. So, we work within the rules that govern the federal government. We work as closely as we can with the external community, and that's not just academia. We invite and encourage input from the private sector as well. The National Climate Assessment will have authors. Approximately 50% of the authors are from outside the federal government. Many of those are academic, but you don't have to be. We can and like having private sector folks involved in the National Climate Assessment.

Question:

How does the National Climate Assessment relate to Intergovernmental Panel on Climate Change (IPCC) reports?

Answer:

The IPCC is the United Nations body that assesses climate change (it's a big international assessment).
These bodies, whether it is the National Climate Assessment or the IPCC, assess the scientific literature. They don't do new research or create new findings. They assess the existing scientific

literature and make broad statements about what we know, what we understand, what we expect, and what we project into the future. The U.S. National Climate Assessment focuses on the United States. Even in the international chapter it looks at the impact of international climate change on the United States. The IPCC is an international assessment. North America is a region for the IPCC. It's very similar science and the numbers are very similar (e.g., temperature projections or precipitation projections into the future) because they all come from the same place. They all come from the output of global climate models and the consolidated scientific literature that is available.

Question:

Does the USGCRP develop any policy recommendations?

Answer:

No, USGCRP is staunchly policy neutral. Our goal is to provide information that informs policy.

Question:

IPCC says we have a small window of opportunity to reduce greenhouse gases. Does USGCRP agree? Will NCA5 reflect that?

Answer:

Yes, USGCRP agrees with that finding. You will find that same finding in the 4th National Climate Assessment. I believe you will find that more starkly in the 5th National Climate Assessment.

3.2.2 Presentation 1B-2: A Coastal Flood Regime Shift Is on the Horizon

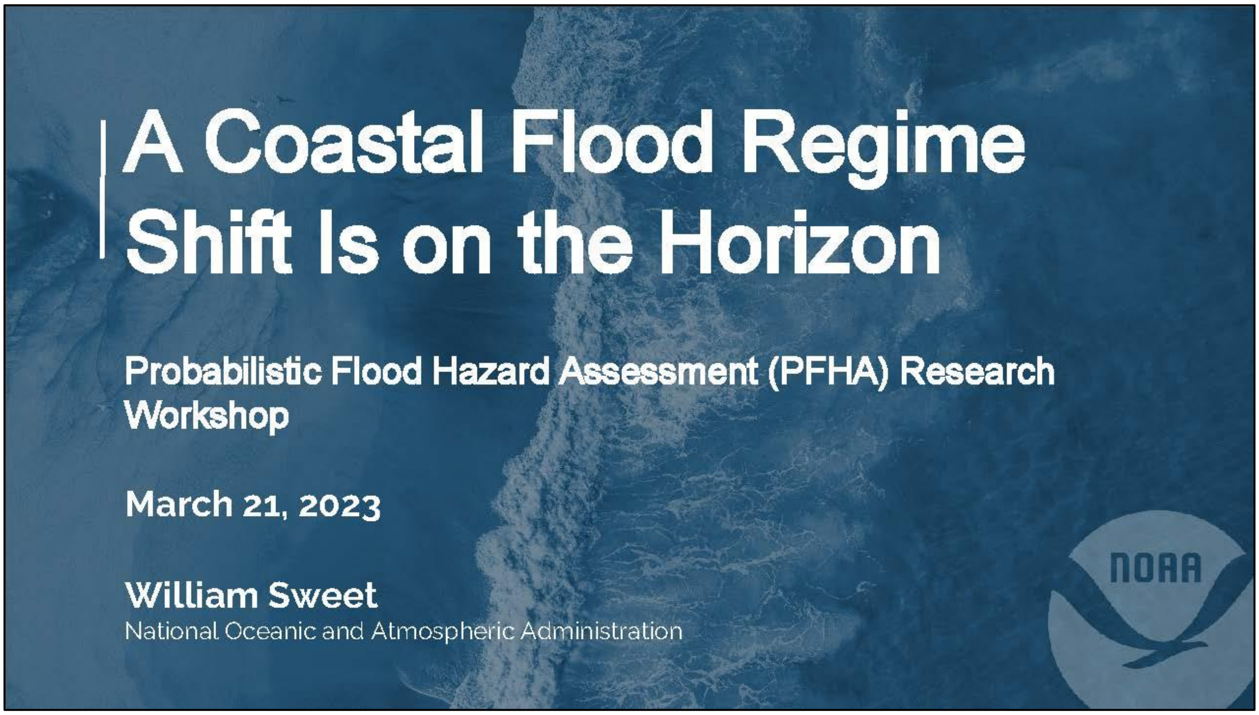
Authors: William Sweet, NOAA National Ocean Service

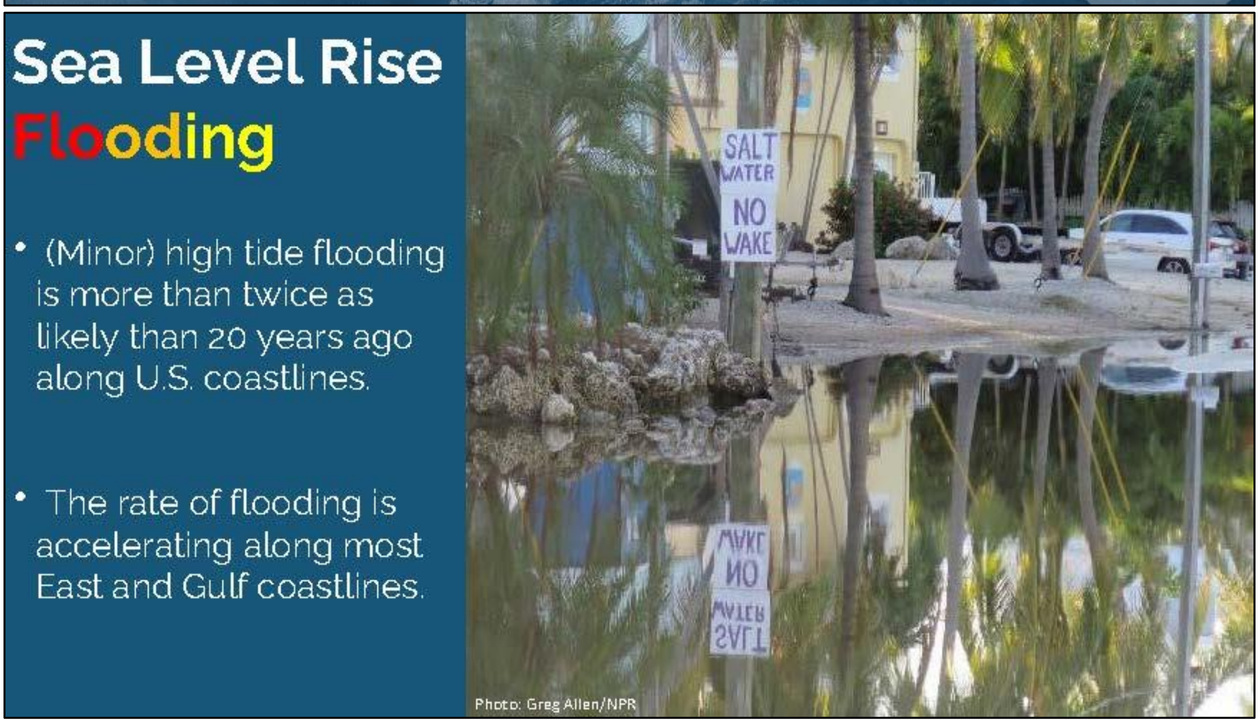
Speakers: William Sweet

3.2.2.1 Abstract

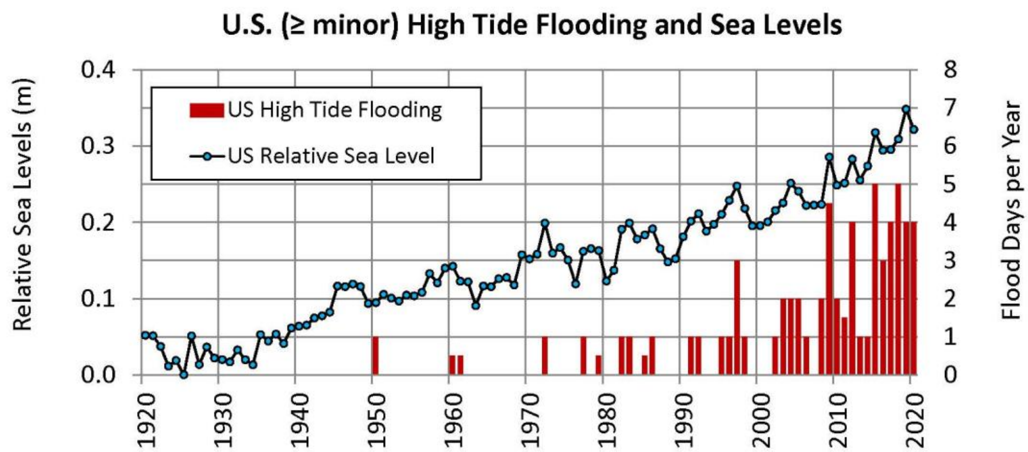
The US Interagency Sea Level Rise Task Force recently released their 2022 report that 1) updated the 2017 sea level rise scenarios for the U.S., 2) provided extreme water level probabilities based upon a regional frequency analysis of tide gauge data and 3) assessed how minor, moderate, and major flood probabilities associated with contemporary infrastructure-vulnerability and emergency-response criteria will change in the coming decades unless action is taken. This talk will review the findings of the 2022 report and discuss some next steps to continue to quantify coastal flood risk today and tomorrow.

3.2.2.2 Presentation (ADAMS Accession No. ML23177A157)





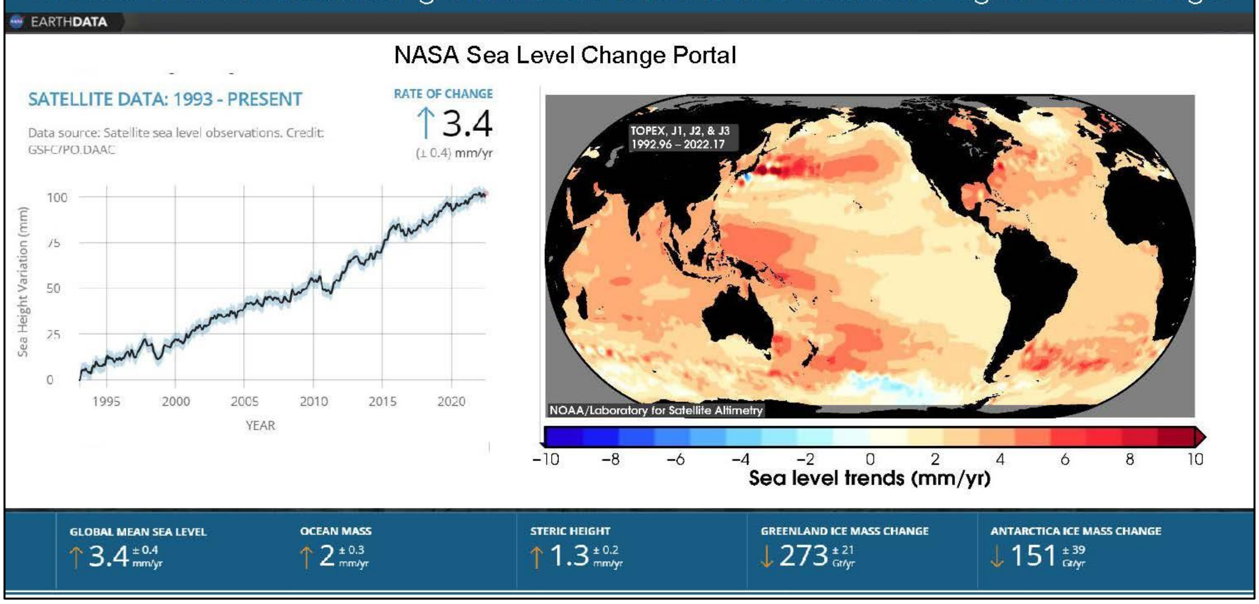
Effects of Sea Level Rise: Doubling of (minor) High Tide Flood Risk



NOAA/Sweet et al. (2021): 2021 State of High Tide Flooding and Annual Outlook

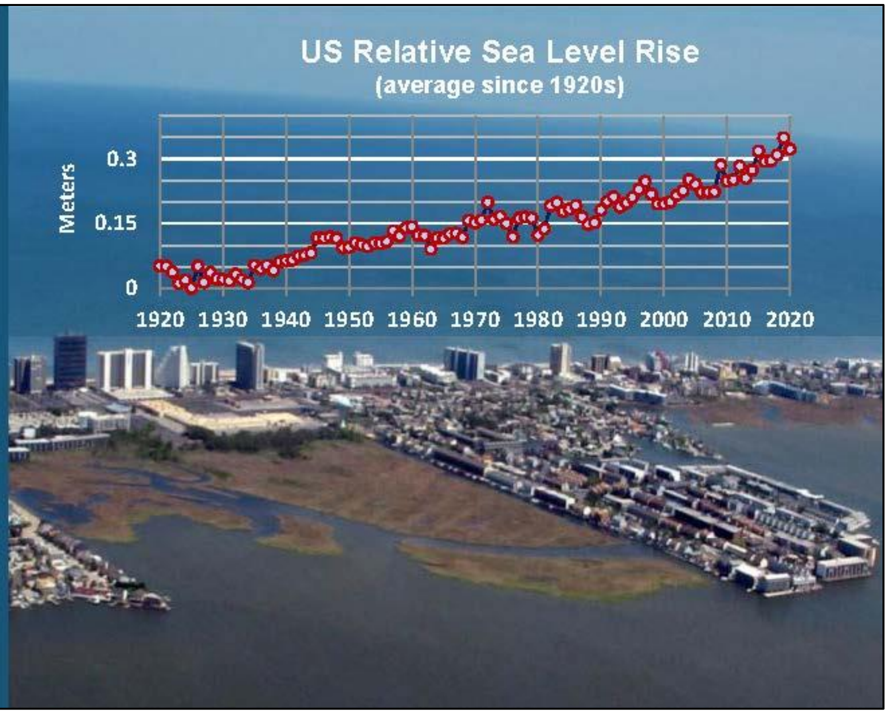
Sea Level Rise

The rate of rise is accelerating and the U.S East and Gulf Coasts are higher than average.



Sea Level Rise

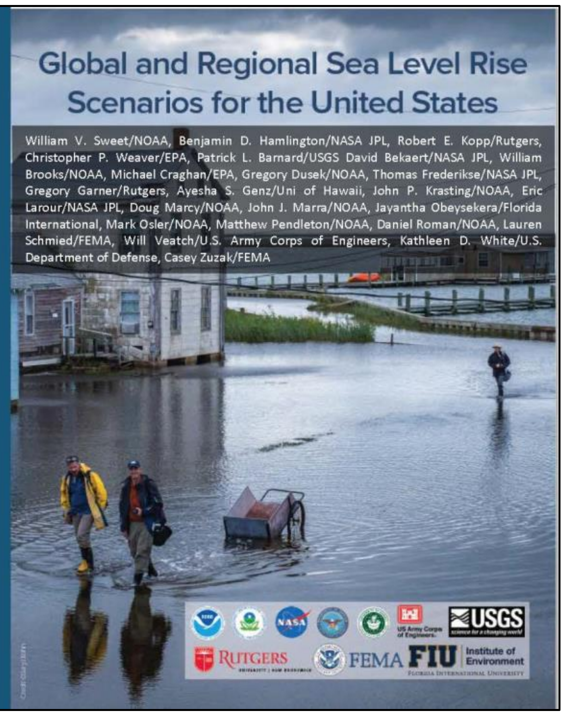
- About 1 foot (0.3 m) of rise over the last 100 years along the US coastline
- The rate of rise has been accelerating over the last 50 years…**where is it going**?



2022 Interagency Sea Level Rise Report

- How much sea level rise should the U.S. expect by 2050?
- How much could sea levels rise by 2100 or 2150?
- What is the risk of a:
  - 2-foot (disruptive) flood
  - 3-foot (typically damaging) flood
  - 4-foot (often-destructive) flood

  now and by 2050?



What are Sea Level Rise Scenarios?

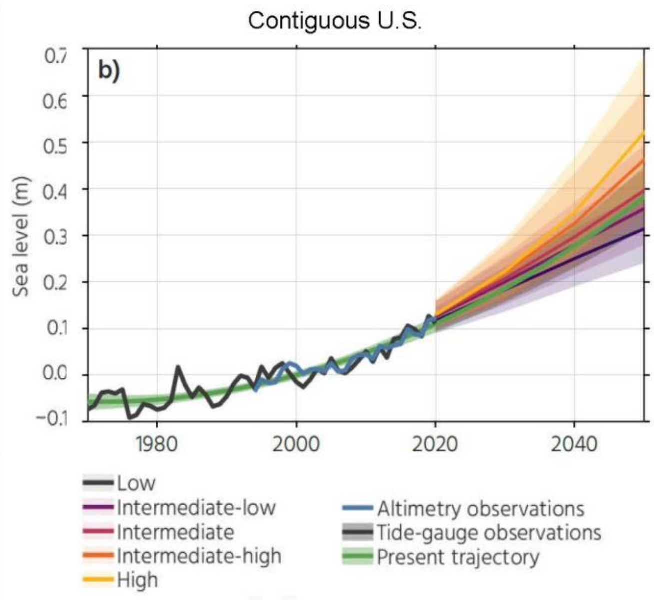
- Assess the plausible future range using AR6
- Incorporate future emissions, warming and our current scientific understanding
- 5 possibilities from Low to High (1 to 6.5 ft by 2100)

Sea Level Scenario in this Report (2100 Value)	Low Emissions Low Warming	High Emissions High Warming	Considers Possible Rapid Ice Sheet Loss
Low (0.3 m)	Large		
Intermediate-Low (0.5 m)	Medium	Medium	
Intermediate (1 m)	Small	Large	Medium
Intermediate-High (1.5 m)	Small	Large	Large
High (2m)		Large	Large

Small Contribution Medium Contribution Large Contribution

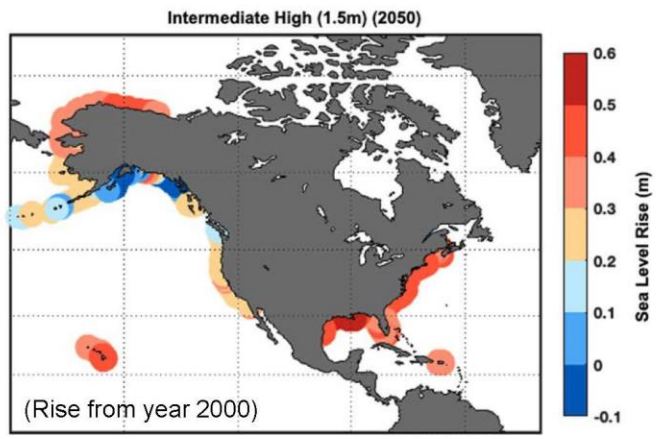
U.S. sea levels expected to be, on average, 10-12 in. higher in the next 30 years (2020-2050)

- Equals rise from the past 100 years
- Observations agree with models
- Smaller range across scenarios and greater confidence in the potential SLR in next 30 years



Sea Level Rise Scenarios Differ Geographically

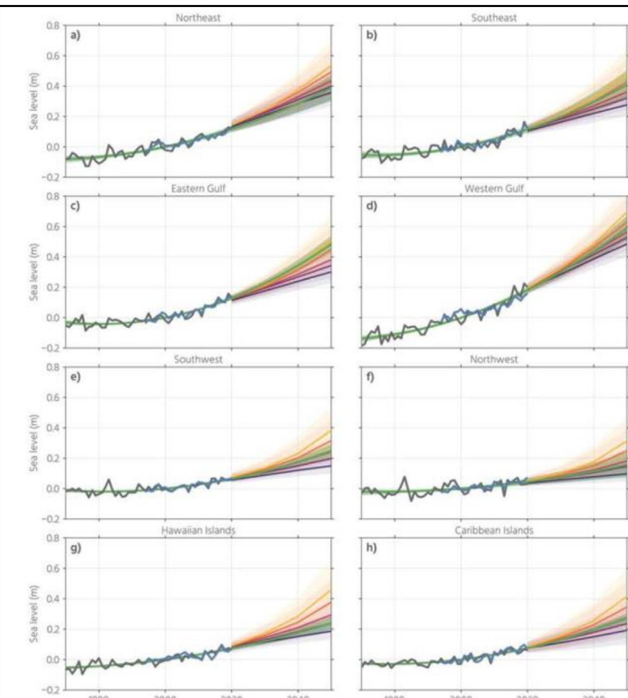
- Physical processes affect U.S. coastlines differently:
  - Vertical land motion
  - Heating/Circulation
  - Where ice melts
- Higher sea levels projected along East and Gulf vs. West Coasts
- Observations and models agree



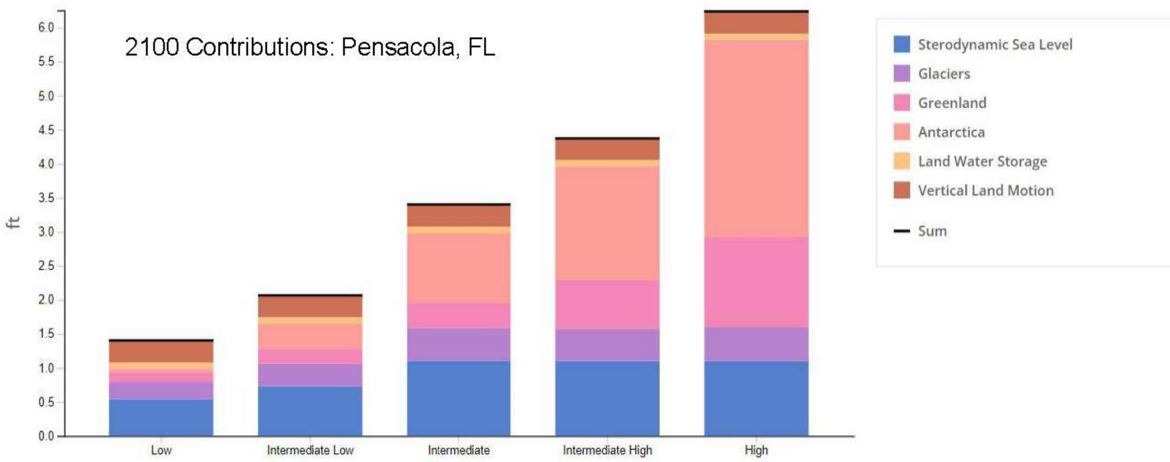
Regionally, U.S. sea level rise will be different.

By 2050, sea levels are expected to be higher (2020-2050):

- 0.25 - 0.35 m for the East coast
- 0.35 - 0.45 m for the Gulf coast
- 0.1 - 0.2 m for the West coast
- 0.2 - 0.25 m for the Caribbean
- 0.15 - 0.2 m for the Hawaiian Islands
- 0.2 - 0.25 m for northern Alaska



NASA Site Providing the Sea Level Data



High Tide Flood Risk Communication

(Minor flooding is about 1.75', **moderate** is **2.75'** and **major** is **4'** above high tide)

Beginning to graduate risk within FEMA's coastal floodplain

Minor is usually only disruptive

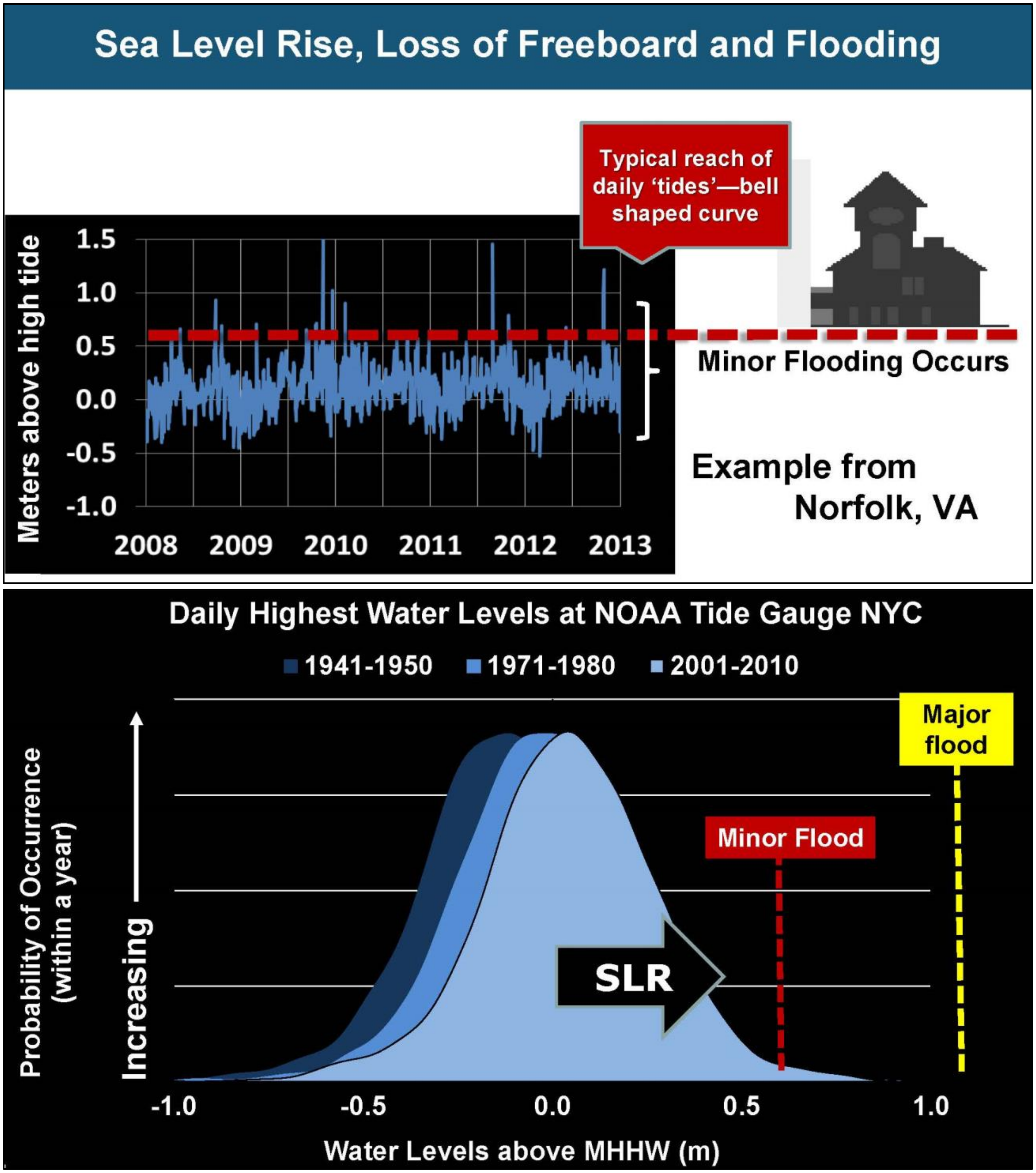
- **Shallow flooding** in the most vulnerable locations near the waterfront and shoreline resulting in a **low threat of property damage.**
- **Up to 1 foot of inundation** in shoreline and vulnerable areas.

Moderate is typically damaging

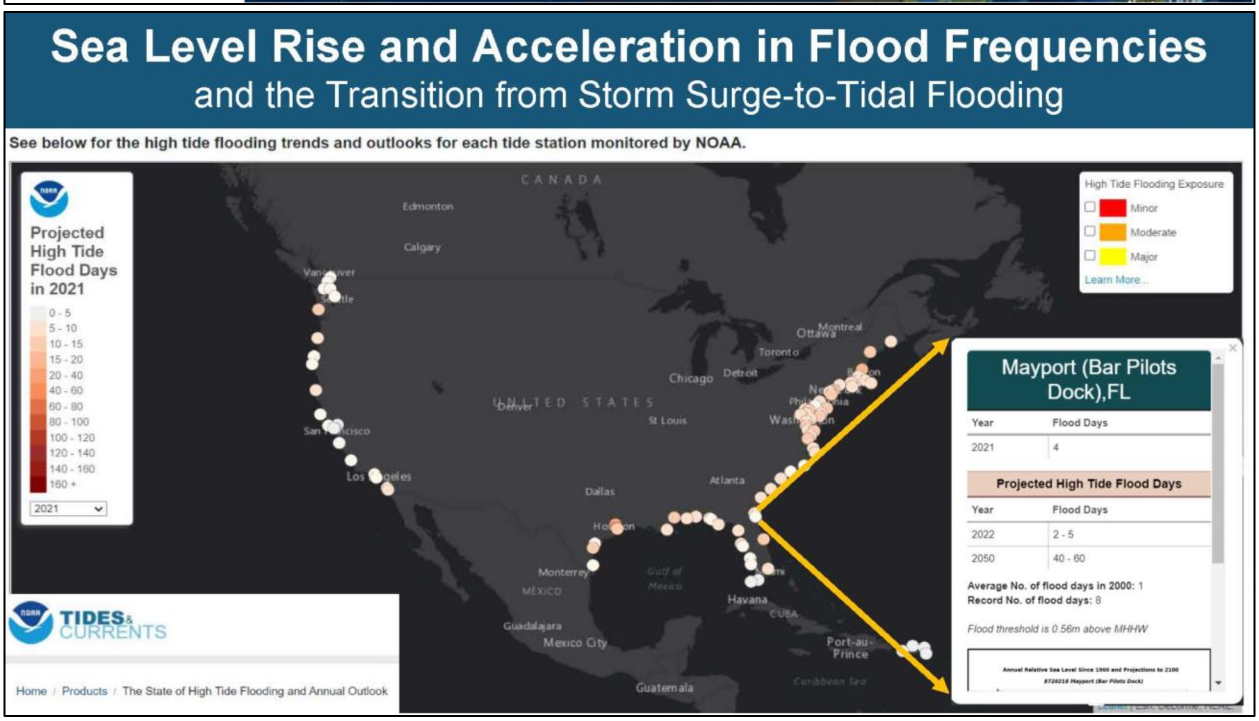
- **Widespread flooding** of vulnerable areas will result in an **elevated threat of property damage.**
- **1 to 2 feet of inundation** primarily in shoreline and vulnerable areas.

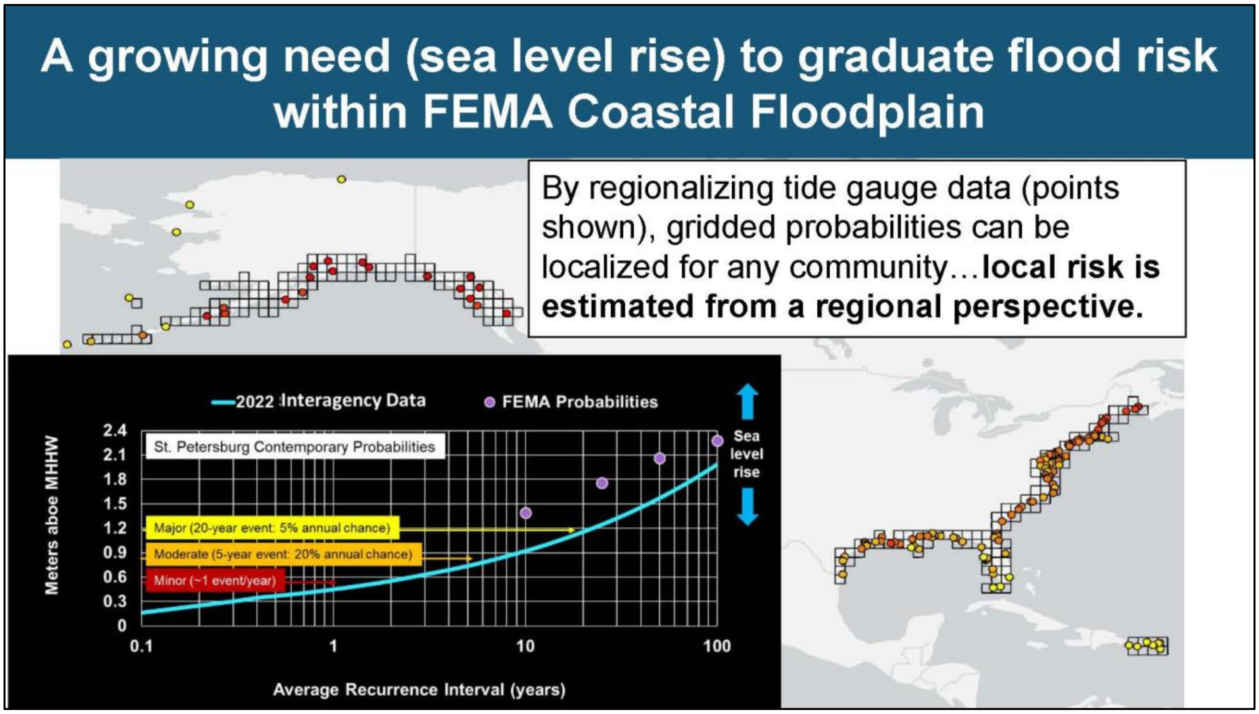
Major is often destructive

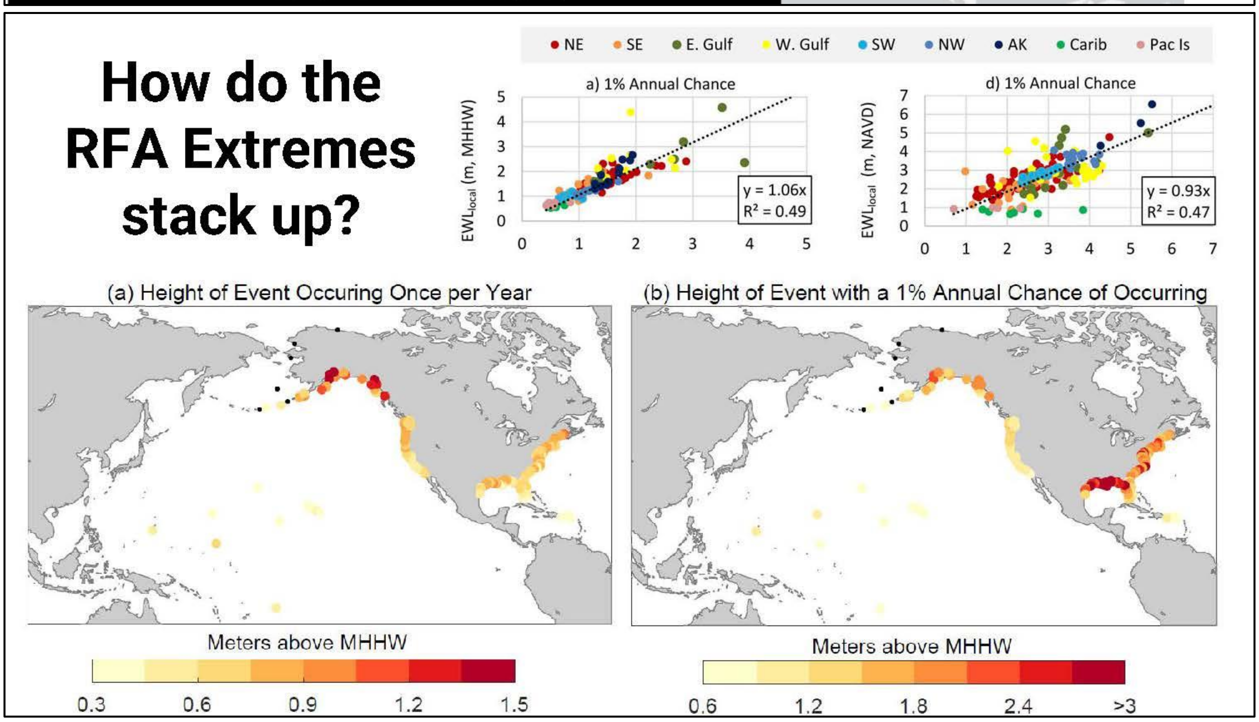
- **Severe flooding** will cause extensive inundation and flooding of numerous roads and buildings resulting in a **significant threat to property and life.**
- **2 to 3 feet or more of inundation.**

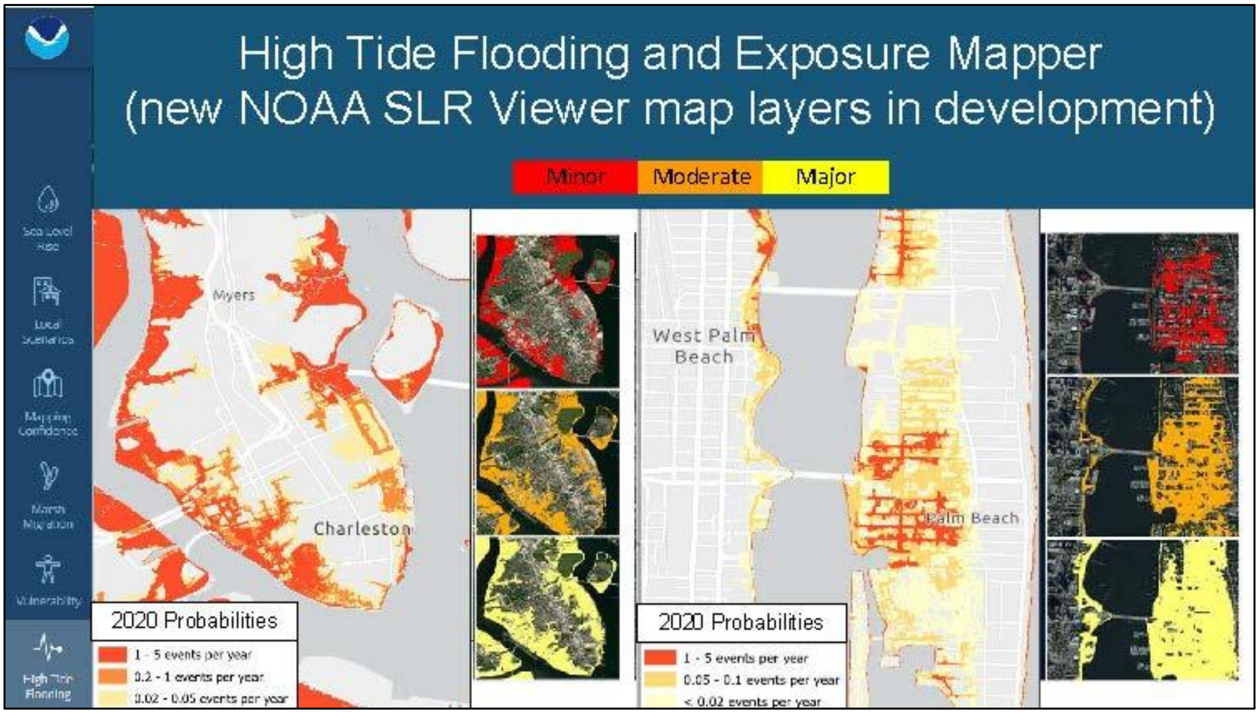

Sea Level Rise, Loss of Freeboard and Flooding
Typical reach of daily 'tides'—bell shaped curve
Meters above high tide
1.5
1.0
0.5
0.0
-0.5
-1.0
2008
2009
2010
2011
2012
2013
Minor Flooding Occurs
Example from Norfolk, VA
Daily Highest Water Levels at NOAA Tide Gauge NYC
1941-1950
1971-1980
2001-2010
Probability of Occurrence (within a year)
Increasing
Major flood
Minor Flood
SLR
-1.0
-0.5
0.0
0.5
1.0
Water Levels above MHHW (m)


High tide flood risk Alerts
NOAA Coastal Inundation Dashboard
Coastal Inundation Dashboard
About
Station List
Share Map
Legend
Latest Data
Multi-Station View
Patch.com (photo: Annapolis Office of Emergency Management)
CANADA
UNITED STATES
MEXICO
CUBA
Display Time: Wed, Apr 6, 2022 9:12 am (EDT)


Sea Level Rise and Acceleration in Flood Frequencies
and the Transition from Storm Surge-to-Tidal Flooding
See below for the high tide flooding trends and outlooks for each tide station monitored by NOAA.
Projected High Tide Flood Days in 2021
0 - 5
5 - 10
10 - 15
15 - 20
20 - 40
40 - 60
60 - 80
80 - 100
100 - 120
120 - 140
140 - 160
160 +
2021
High Tide Flooding Exposure
Minor
Moderate
Major
Learn More...
Mayport (Bar Pilots Dock),FL
Year
Flood Days
2021
4
Projected High Tide Flood Days
Year
Flood Days
2022
2 - 5
2050
40 - 60
Average No. of flood days in 2000: 1
Record No. of flood days: 8
Flood threshold is 0.56m above MHHW
TIDES & CURRENTS
Home / Products / The State of High Tide Flooding and Annual Outlook

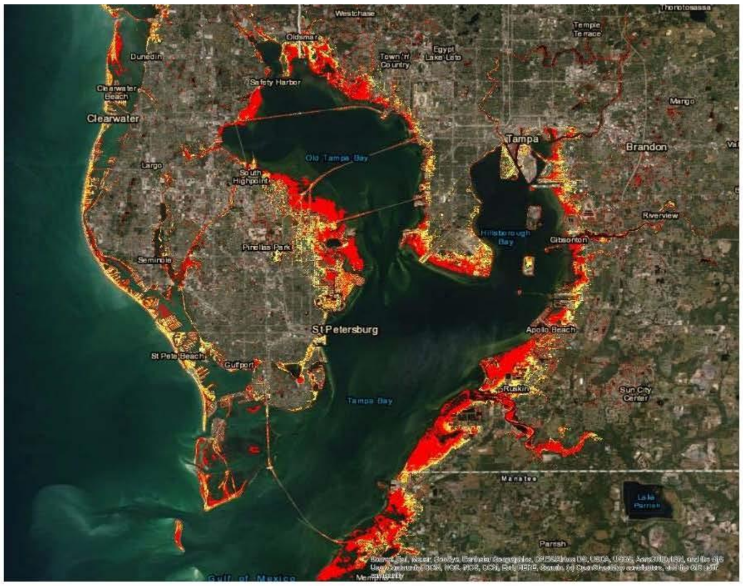

A growing need (sea level rise) to graduate flood risk within FEMA Coastal Floodplain
By regionalizing tide gauge data (points shown), gridded probabilities can be localized for any community…local risk is estimated from a regional perspective.
2022 Interagency Data
FEMA Probabilities
St. Petersburg Contemporary Probabilities
Major (20-year event: 5% annual chance)
Moderate (5-year event: 20% annual chance)
Minor (~1 event/year)
Sea level rise
Meters aboe MHHW
2.4
2.1
1.8
1.5
1.2
0.9
0.6
0.3
0
0.1
1
10
100
Average Recurrence Interval (years)


How do the RFA Extremes stack up?
NE SE E. Gulf W. Gulf SW NW AK Carib Pac Is
a) 1% Annual Chance
y = 1.06x
R² = 0.49
d) 1% Annual Chance
y = 0.93x
R² = 0.47
(a) Height of Event Occuring Once per Year
(b) Height of Event with a 1% Annual Chance of Occurring
Meters above MHHW
0.3 0.6 0.9 1.2 1.5
Meters above MHHW
0.6 1.2 1.8 2.4 >3



What does 2050 hold with 30 more years of SLR?

A coastal flood regime shift with significant consequences to coastal infrastructure, communities, and ecosystems without additional risk reduction measures.



In 2050:

St. Petersburg/Tampa Bay (w/ 0.35 m of additional rise):

- **Minor: >50 days/year (1 'event'/year in 2020)**
- **Moderate: 1-5 events/year (5-year event in 2020)**
- **Major: 5-year event (20-year event in 2020)**

Summary Points

- Nationally, sea levels are headed about 1 foot higher in the next 30 years (2020-2050) and at least 2 feet or more by 2100.
- Lower emissions = lower sea levels by 2100+
- Without action, US headed for a ~2050 coastal flood regime shift: 1 foot separates minor (~2'), moderate (3') and major (4') flood severity levels.
- Elevation matters—lower elevations are at greater risk.
- Heavier rains, **stronger storms** and rising groundwater tables are compounding factors.

3.2.2.3 Questions and Answers

Question:

So, if I understand correctly, a flood that was happening every once every 10 years can now be expected maybe once a year and something that was happening once every 100 years we could now expect every 10 years. Is that understanding correct?

Answer:

More or less. The idea is that the storms may not be changing, but the water levels that are associated with the let's say 1% or 5% chance event will become more frequent as sea level rises. A lesser storm can produce a similar water level height, as it's referenced to ground, looking forward with higher sea levels. So yes, as sea level increases, there would be an increase in flood frequency or the likelihood of flooding without any changes in storms.

Question:

If we go way out on the tail, can I extrapolate and say something that I'd expect once in a million years would now happen once in a hundred thousand years?

Answer:

That is of interest, but to get out there to those low probabilities like the 10,000-year event, we need to think about ways of assessing risk, like what is the sedimentary evidence? There's evidence that the hurricane Sandy storm surges have happened in New York maybe 3 or 4 times in the last 500 years if we start using other records. So that really gets into data exploration. You really need to up your sample size to understand. Mathematically, you can extend the tail of those plots I showed you out to a million years. Would I have faith in it? The confidence intervals would explode. That's an emerging science to say how can we actually get more data sets involved to give us more robust very rare event water level probability.

Question:

Have coastal reclamation, estuary dam construction, etc., been taken into account in assessing sea level rise?

Answer:

Yes. We pulled directly from the IPCC AR6. Groundwater pumping is contributing now. Impoundment was definitely something that helped retain water on land in the fifties, sixties, seventies, but it's a small contribution, maybe 5%. It varies, but has been factored in. It's a small contribution about 5%. A much smaller contributor than melting of ice sheets and thermal expansion.

3.2.3 Presentation 1B-3: Observation-based Trajectory of Future Sea Level for the Coastal United States Tracks Near High-end Model Projections

Authors: Benjamin Hamlington[1], Don Chambers[2], Thomas Frederikse[1], Soenke Dangendorf[3], Severine Fournier[1], Brett Buzzanga[1,2], R. Steven Nerem[4]; [1]NASA Jet Propulsion Laboratory, [2]University of South Florida, [3]Tulane University, [4]University of Colorado, Boulder

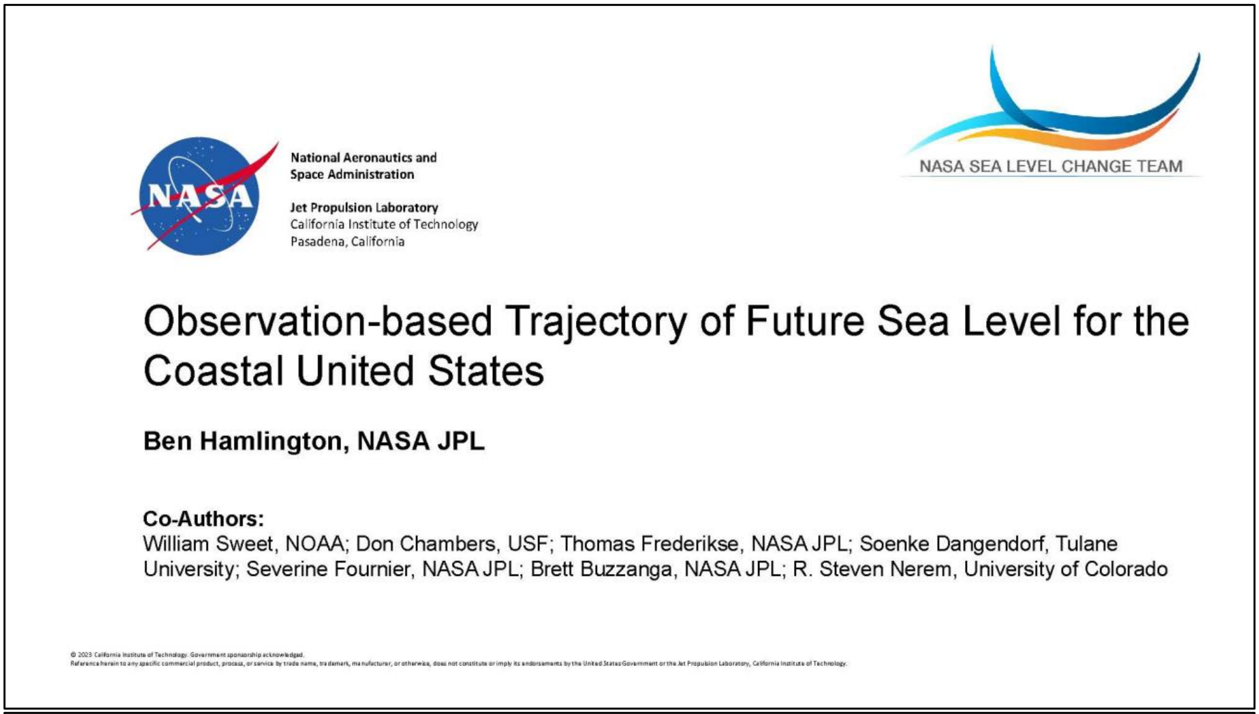
Speaker: Benjamin Hamlington

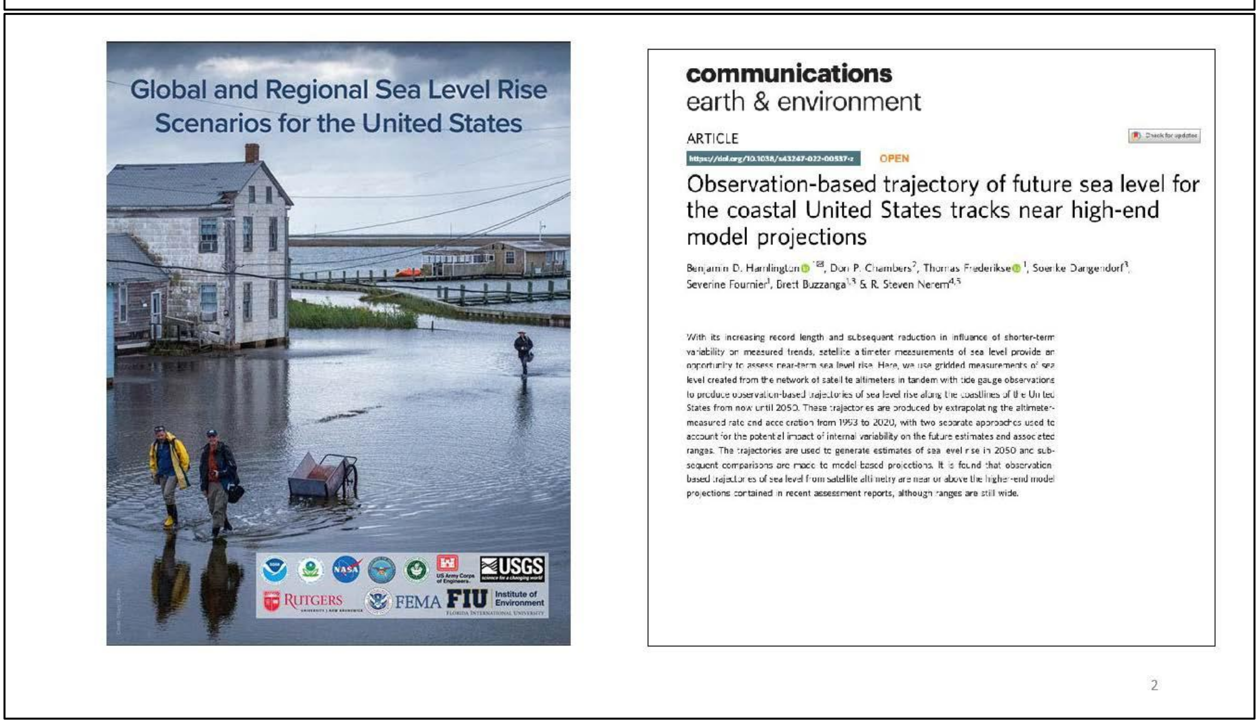
3.2.3.1 Abstract

With its increasing record length and subsequent reduction in influence of shorter-term variability on measured trends, satellite altimeter measurements of sea level provide an opportunity to assess near-term sea level rise. Here, we use gridded measurements of sea level created from the network of satellite altimeters in tandem with tide gauge observations to produce observation-based trajectories of sea level rise along the coastlines of the United States from now until 2050. These trajectories are produced by extrapolating the altimeter-

measured rate and acceleration from 1993 to 2020, with two separate approaches used to account for the potential impact of internal variability on the future estimates and associated ranges. The trajectories are used to generate estimates of sea level rise in 2050 and subsequent comparisons are made to model-based projections. It is found that observation-based trajectories of sea level from satellite altimetry are near or above the higher-end model projections contained in recent assessment reports, although ranges are still wide.

3.2.3.2 Presentation (ADAMS Accession No. ML23177A158)





Evolution of Observations, Sea Level Projections and Planning

Observations

- Records of sea level are getting longer, overlapping with projected time periods, and showing significant accelerations.

Projections

- With the updated science that is covered in the IPCC AR6 report, the potential for high amounts of sea-level rise from rapid ice sheet loss has been assessed to occur further into the future.

Planning Horizons

- As a result of a) the sea-level rise already experienced, b) the impacts already being felt, c) the uncertainty of future sea-level rise on long timescales, important planning horizons have shifted to the near-term.

3

Global and Regional Scenarios Sea Level Rise Scenarios for the United States

What's in this report?

- SLR Scenarios for U.S. at regional (1-degree gridded) and local level (tide gauges) from 2020 to 2150
- Trajectories of SLR from 2020 to 2050 based on tide gauge observations from 1970-2020

What's new?

- Scenarios updated using science from IPCC 6th Assessment Report
- Comparisons of models vs. tide gauge and altimeter observations
- Increased focus on near-term time period (2020-2050)

Observation-Based Extrapolations/Trajectories

Motivation:
- As a result of increasing observational record lengths, there an opportunity to use tide gauge and satellite observations to assess near-term sea-level rise.

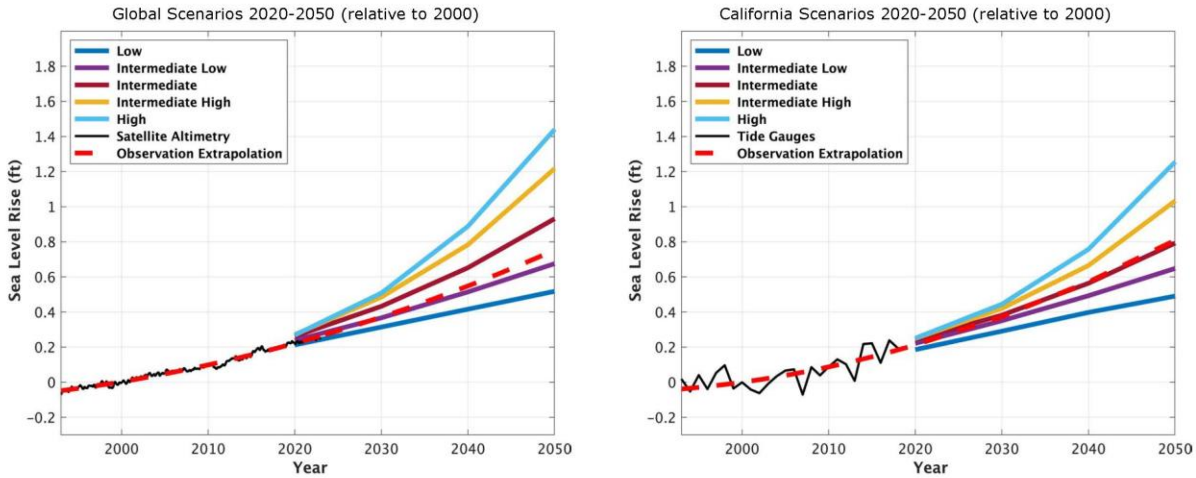
What are we producing?
- Observation-based extrapolations from tide gauge observations from 1970-2050 at the global, national, regional and local levels.

How are these used?
- Serve as an independent comparison to the scenarios.
- Provides information on current trajectory and which scenario we might currently be following.

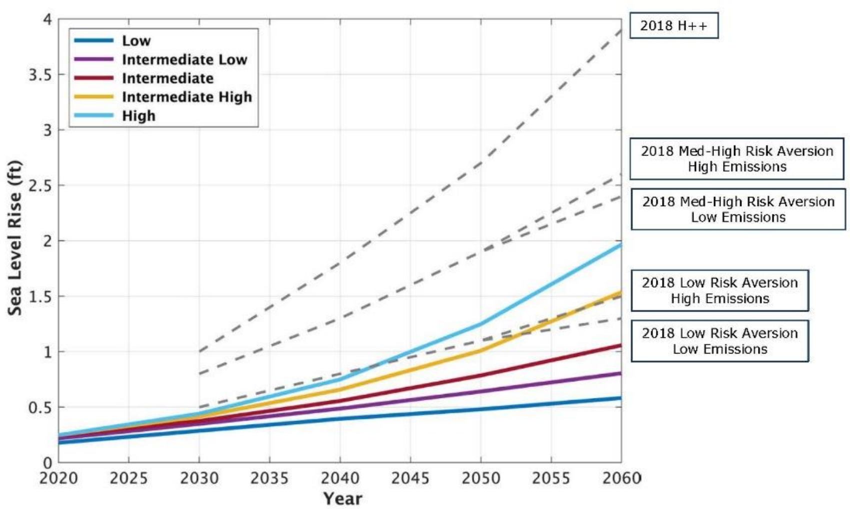
Observation-Based Extrapolated Projections

Procedure:
1. Eleven separate regions are chosen around the U.S. coastlines to minimize the effects of highly localized VLM and natural variability.
2. The tide gauges in each region are grouped and combined to generate a monthly time series of relative sea level from 1920 to present.
3. Natural variability is partially removed through regression analysis using climate indices representing El Niño-Southern Oscillation, Pacific Decadal Oscillation and North Atlantic Oscillation.
4. The rate and acceleration from 1970 to present is computed and the uncertainty on each term is assessed accounting for the influence of remaining natural variability.
5. The rates, accelerations and uncertainties are used to generate an ensemble extrapolations with a baseline year of 2000 and extending to 2050. Median projections and a likely (17th-83rd) range are computed from this ensemble.

Observation Trajectories vs. Scenarios



Narrower Range in Near-Term: Southwest U.S.



Observation Trajectories vs. Scenarios

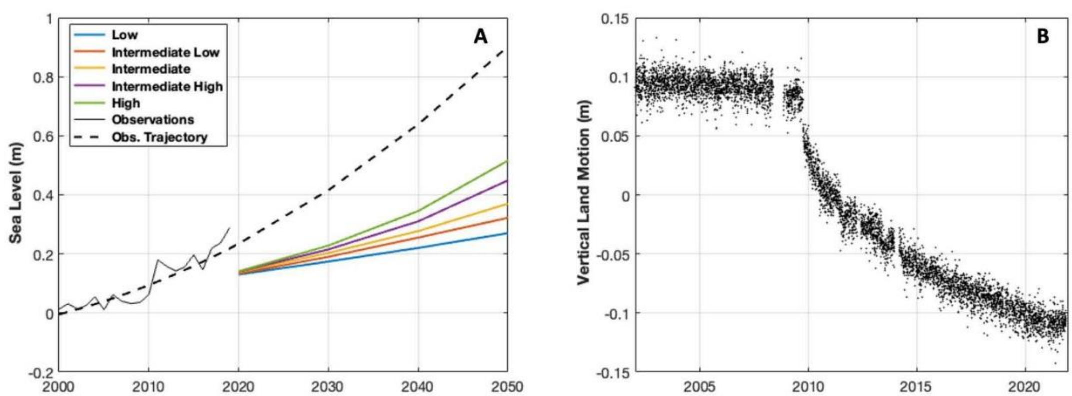
Regional/Local vs. Global

- Interpretation of trajectories is different on local, regional and global scales.
- The influence of natural variability on trajectories increases.
- Vertical land motion becomes a key driver of future scenarios.
- Largest spatial scale possible should be used for comparison between observations and scenarios.

Observation Extrapolations	Low	Intermediate-Low	Intermediate	Intermediate-High	High	Median Bounding Scenarios
Northeast						
0.40 [0.30, 0.47]	0.36 [0.27, 0.45]	0.40 [0.31, 0.49]	0.43 [0.34, 0.54]	0.49 [0.38, 0.64]	0.54 [0.40, 0.69]	Int-Low
Southeast						
0.41 [0.32, 0.50]	0.28 [0.20, 0.35]	0.32 [0.25, 0.40]	0.36 [0.28, 0.46]	0.43 [0.32, 0.58]	0.49 [0.35, 0.64]	Int–Int-High
Eastern Gulf						
0.48 [0.43, 0.54]	0.30 [0.22, 0.38]	0.34 [0.26, 0.42]	0.38 [0.30, 0.48]	0.45 [0.34, 0.60]	0.51 [0.38, 0.68]	Int-High–High
Western Gulf						
0.59 [0.51,0.67]	0.49 [0.41, 0.57]	0.53 [0.44, 0.62]	0.57 [0.47, 0.67]	0.63 [0.51, 0.79]	0.69 [0.56, 0.87]	Int–Int-High
Southwest						
0.24 [0.20,0.29]	0.15 [0.10, 0.20]	0.20 [0.14, 0.26]	0.24 [0.18, 0.32]	0.31 [0.22, 0.45]	0.38 [0.26, 0.54]	Intermediate
Northwest						
0.16 [0.08, 0.24]	0.10 [0.05, 0.15]	0.15 [0.09, 0.20]	0.18 [0.12, 0.26]	0.25 [0.15, 0.39]	0.31 [0.19, 0.47]	Int-Low–Int
Hawaiian Islands						
0.24 [0.20, 0.28]	0.19 [0.13, 0.24]	0.24 [0.18, 0.31]	0.29 [0.22, 0.39]	0.38 [0.27, 0.53]	0.46 [0.31, 0.64]	Int-Low
Caribbean						
0.28 [0.24, 0.31]	0.19 [0.10, 0.29]	0.24 [0.14, 0.33]	0.28 [0.18, 0.39]	0.35 [0.22, 0.51]	0.42 [0.27, 0.59]	Intermediate

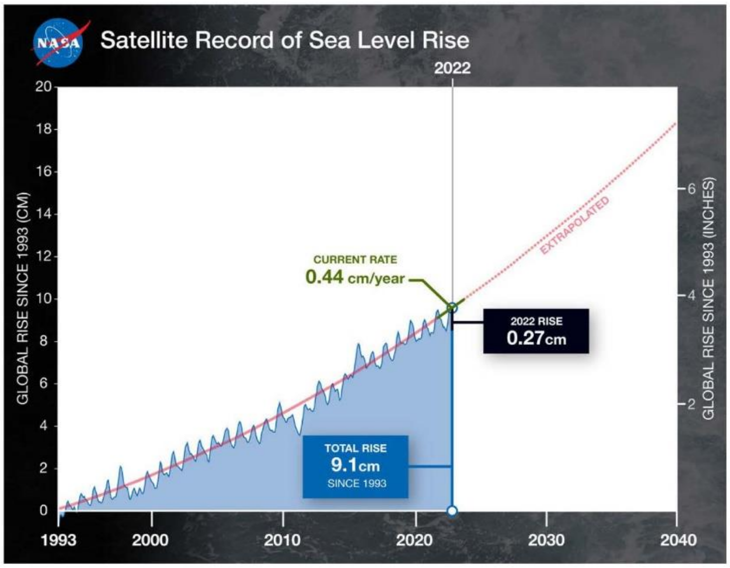
Sweet et al. (2022)

Observation Trajectories vs. Scenarios

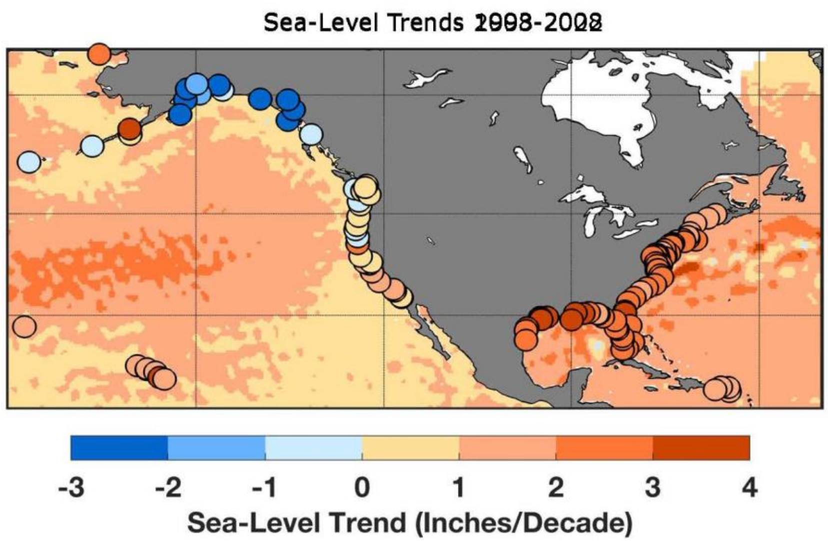


(A) Scenarios and observed trajectory of sea level rise for Pago Pago, American Samoa, from Sweet et al. (2022), showing disagreement between observations and the range of future projections. (B) Vertical land motion measured at the ASPA GPS station in Pago Pago. Adapted from Collini et al. (2022).

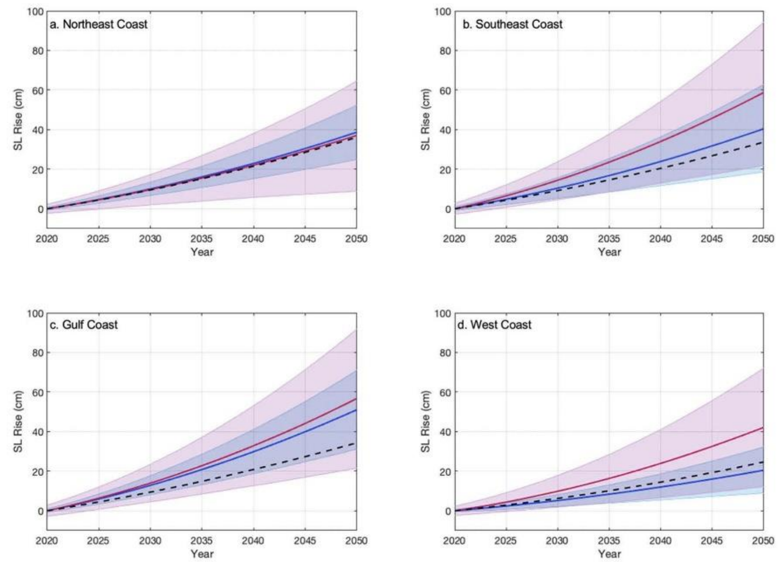
Using Satellite Altimeters to Assess Trajectory



Using Satellite Altimeters to Assess Trajectory

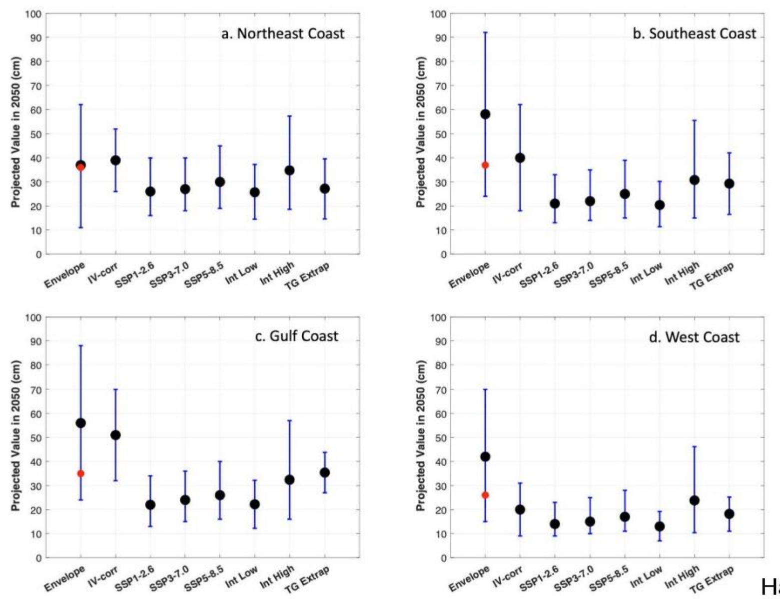


Using Satellite Altimeters to Assess Trajectory



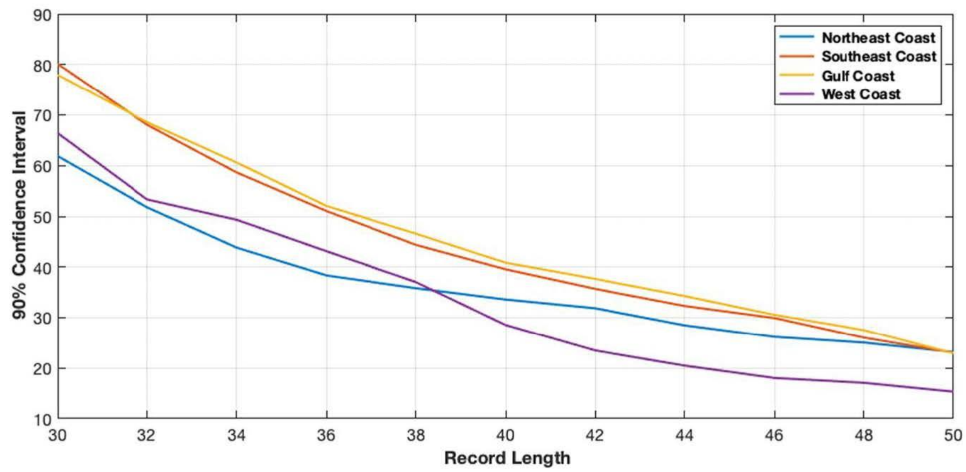
Hamlington et al. (2022)

Using Satellite Altimeters to Assess Trajectory



Hamlington et al. (2022)

Using Satellite Altimeters to Assess Trajectory



Hamlington et al. (2022)

Summary

Observations

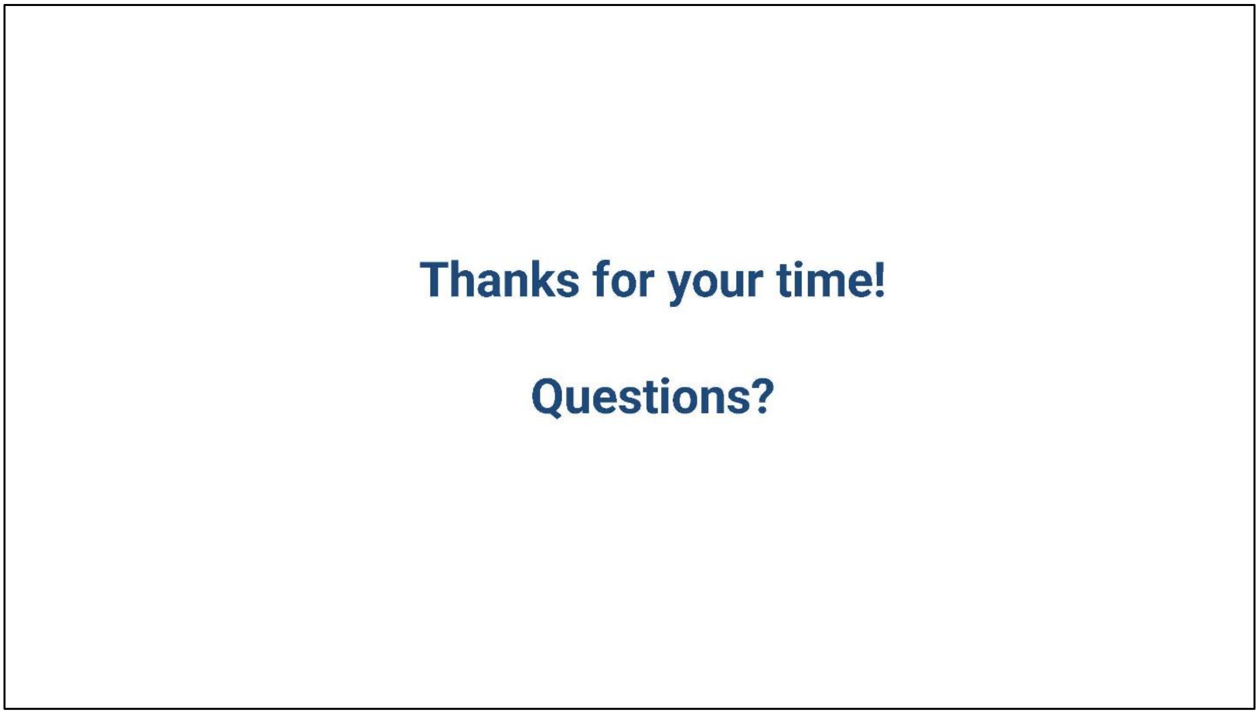
- Records of sea level are getting longer, overlapping with projected time periods, and showing significant accelerations → **can be informative of trajectory of sea-level rise in "near-term".**

Projections

- With the updated science that is covered in the IPCC AR6 report, the potential for high amounts of sea-level rise from rapid ice sheet loss has been assessed to occur further into the future → **smaller range in the "near-term".**

Planning Horizons

- As a result of a) the sea-level rise already experienced, b) the impacts already being felt, c) the uncertainty of future sea-level rise on long timescales, important planning horizons have shifted to the near-term → **need better information and a focus on the "near-term".**



3.2.3.3 Questions and Answers

Question:

How does the sea level rise model consider ocean-atmosphere coupling?

Answer:

Not very well at this point. There are certainly simplifications that are made within the projections. The scenarios that Billy and I have both talked about really connect to the AR6. The foundation of those scenarios is within the IPCC AR6 report and the way those projections are built up are by integrating across different processes, so the ice sheet models incorporate a certain amount of information and the CMIP5 and CMIP6 provide the ocean side of things. But there are definitely limitations in how well certain processes are captured with the ocean atmospheric coupling being one of those.

Question:

How can you check the quality of observational data in predicting sea level rise using observed data?

Answer:

It’s a difficult thing to do if we think about these trajectories going forward from our observations. We have an associated likely range with those, where we try our best to capture the uncertainties in the rates in accelerations what we can estimate from the observations themselves. But any inference or interpretation of those observations must be considered alongside those likely ranges, those uncertainties. So, I don’t know if there is a good way to check. We can compare our observations to the models, but if there is misalignment it tells us either we are not capturing something in the observational uncertainties or there is something missing in the models. It requires additional research to find out where the problem might sit.

Question:

On the whisker plot slide, what do the red dots represent? Are they projections based on observed data?

Answer:

That's right. They are projections based on observed data. I kind of glossed over this, but we actually took a couple of different approaches to correct for the natural variability and its influence on rates and accelerations and that was one of those specific ways of doing that. That does go back to the other question. Trying to figure out ways to understand the separation of natural variability from the forced response to isolate that trend that we want to project out into the future within the observations is a really key part of this work and something that is ongoing in terms of research.

3.2.4 Presentation 1B-4: National Weather Service Forecasts for the late December 2022 to mid-January 2023 West Coast Atmospheric Rivers

Authors: Mark Fresch[1], Alex Lamers[2]; [1]NOAA National Weather Service Office of Water Prediction, [2]NOAA National Weather Service Weather Prediction Center

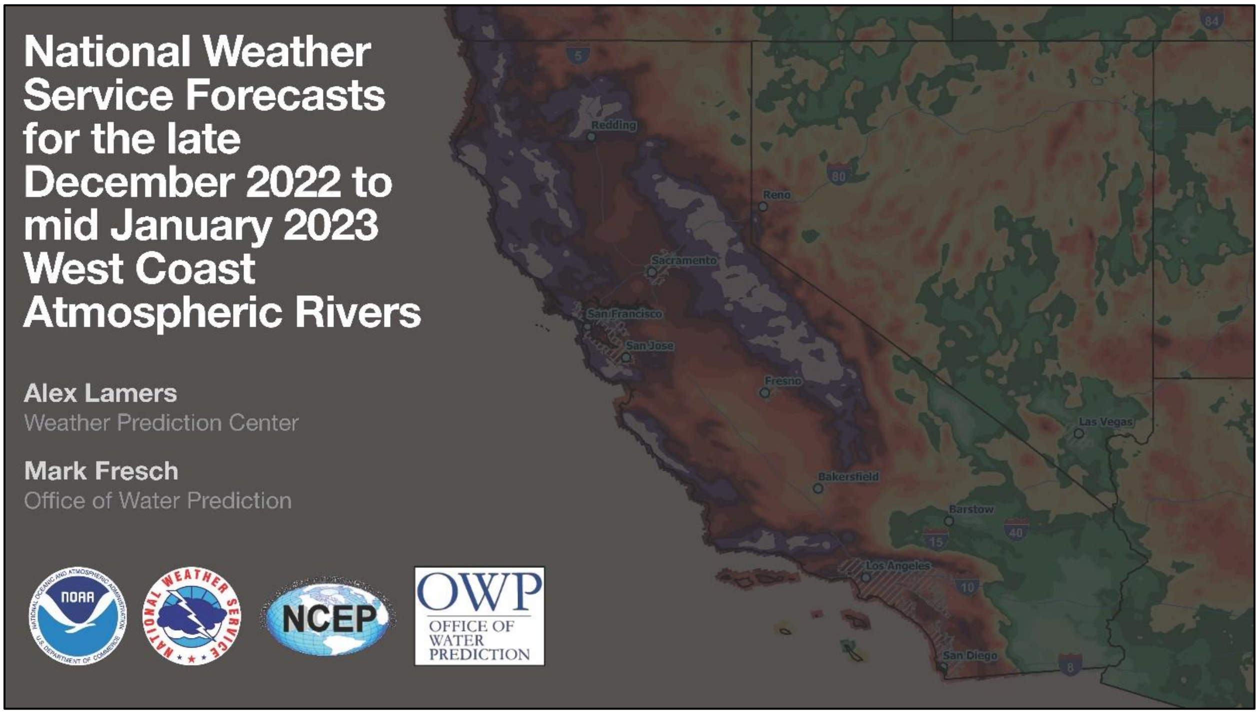
Speakers: Mark Fresch, Alex Lamers

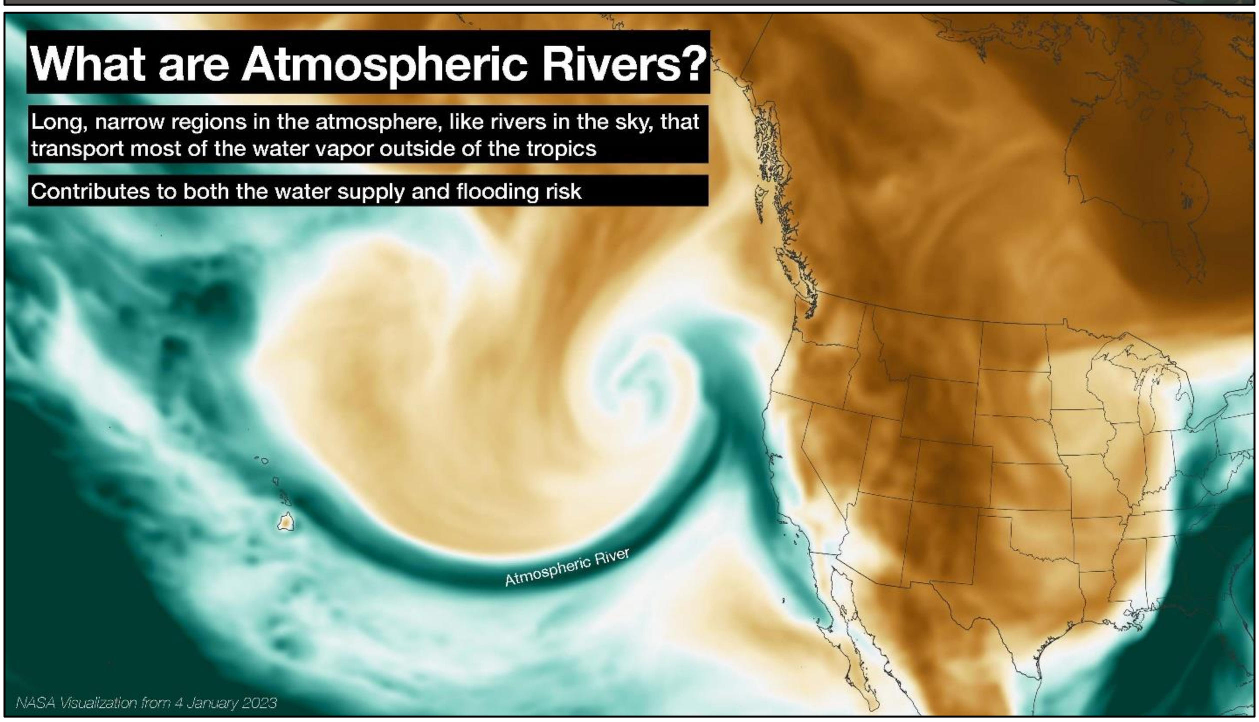
3.2.4.1 Abstract

Accurate precipitation and hydrologic forecasts are crucial for mitigating natural disasters such as floods or droughts and optimizing reservoir operations for diverse and sometimes competing user needs. This presentation will describe the heavy precipitation and flooding impacts from a sequence of 9 atmospheric rivers into the state of California in approximately 3 weeks from late December 2022 to mid-January 2023. In that time frame, the state of California received an average of over 11 inches of precipitation. The presentation will describe how the National Weather Service (NWS) forecasts these atmospheric rivers, the challenges of forecasting and communicating the expected precipitation and associated impacts, and new frontiers in forecasting these events.

The NWS has also developed the Hydrologic Ensemble Forecast Service (HEFS). The HEFS uses "raw" precipitation and temperature forecasts from weather and climate forecast models and provides bias-corrected ensemble forcing and streamflow forecasts at forecast locations across the US. Streamflow forecasts from the HEFS have shown consistently better quality than those from the climatologically based Ensemble Streamflow Prediction (ESP), which is being replaced by the HEFS. This presentation explains HEFS, shows validation results for HEFS, including from January 2023 atmospheric river events, and describes future enhancements for the HEFS.

3.2.4.2 Presentation (ADAMS Accession Nos. ML23177A159 and ML23177A160)



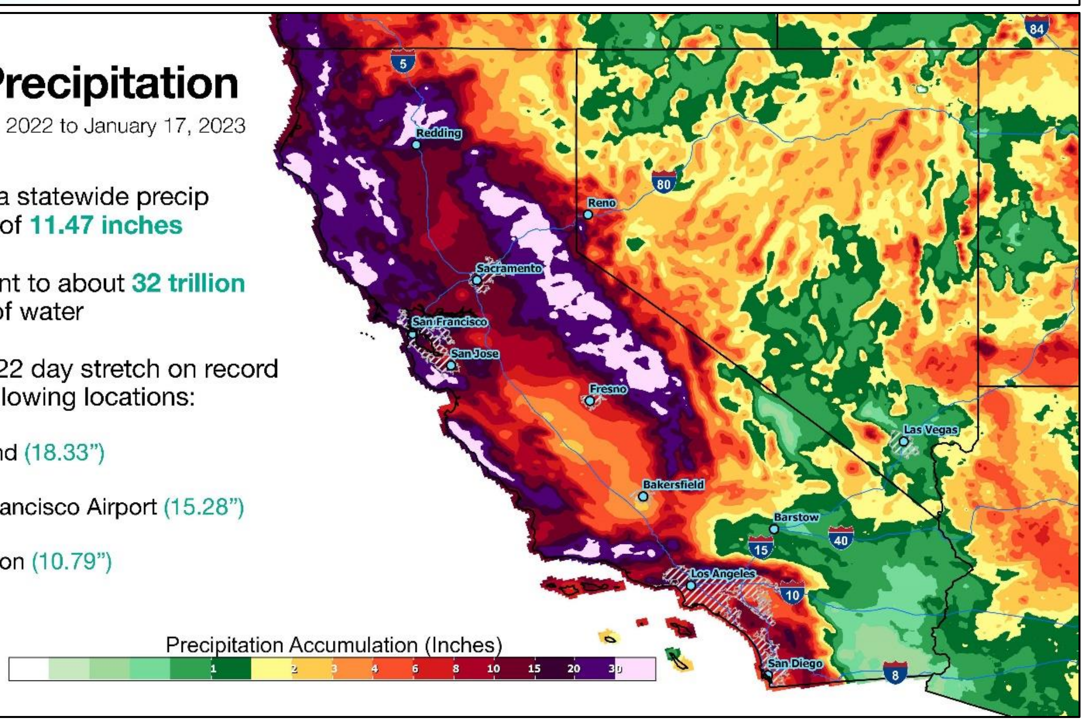


What Happened in January 2023?

Total Precipitation

December 26, 2022 to January 17, 2023

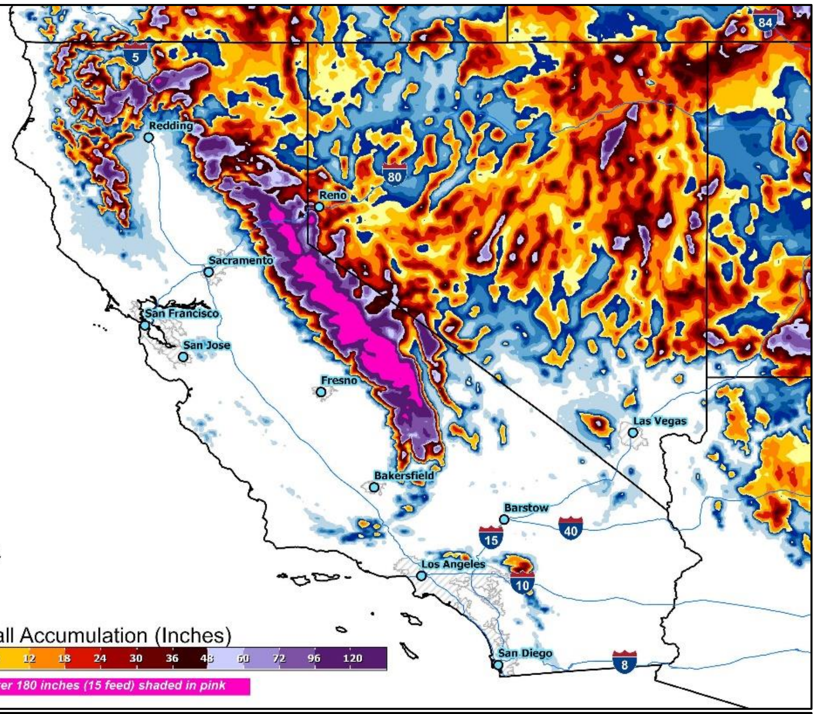
- California statewide precip average of **11.47 inches**
- Equivalent to about **32 trillion** gallons of water
- Wettest 22 day stretch on record at the following locations:
  - Oakland (18.33”)
  - San Francisco Airport (15.28”)
  - Stockton (10.79”)



Total Snowfall

December 26, 2022 to January 17, 2023

- **Over 15 feet of snow** in about 3 weeks in the highest elevations of the Sierra Nevada
- Sierra snowpack as of Jan 17:
  - 251% of normal for the date
  - 124% of April 1st average
- **240 inches** (20') at Mammoth Mountain Main Lodge
- **182 inches** (15') at Donner Pass



Snowfall Accumulation (Inches)

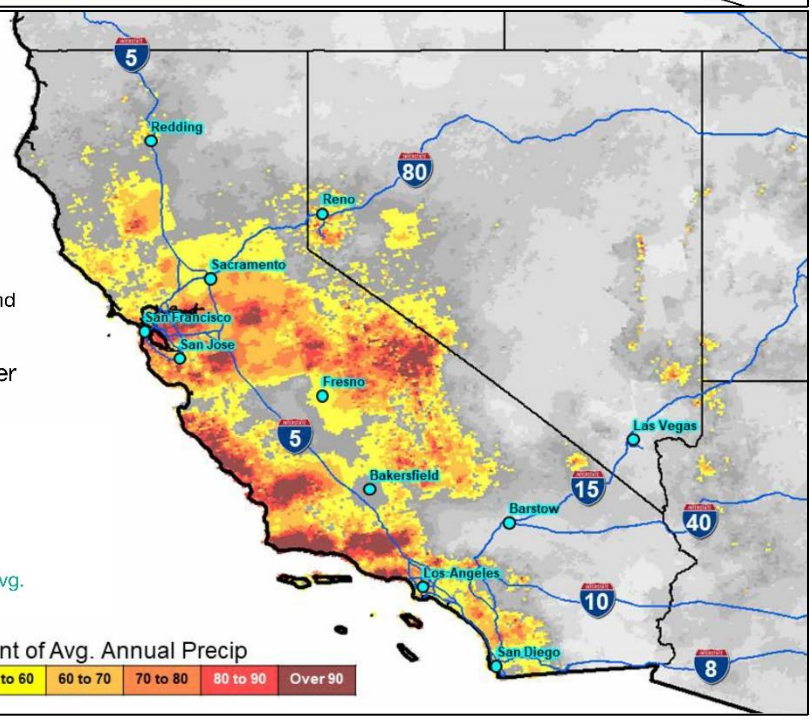
2 4 6 8 12 18 24 30 36 48 60 72 96 120

Totals over 180 inches (15 feed) shaded in pink

Percent of Annual Average Precipitation

December 26, 2022 to January 17, 2023

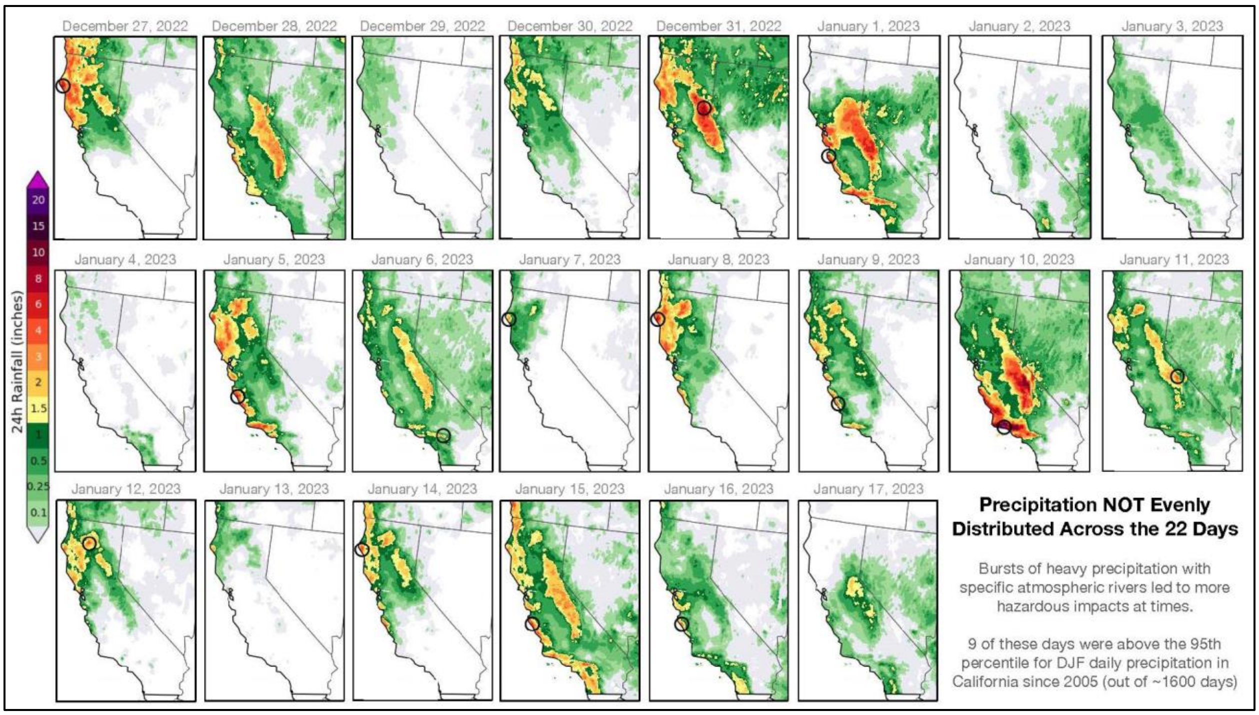
- Not exactly an apples-to-apples comparison, but close.
  - Stage IV observed precip from NWS and PRISM annual averages
- Much of central California saw over half their annual average precipitation in about 3 weeks
- Observed Bay Area comparisons:
  - Oakland: 88% of annual avg.
  - Downtown San Fran.: 77% of annual avg.

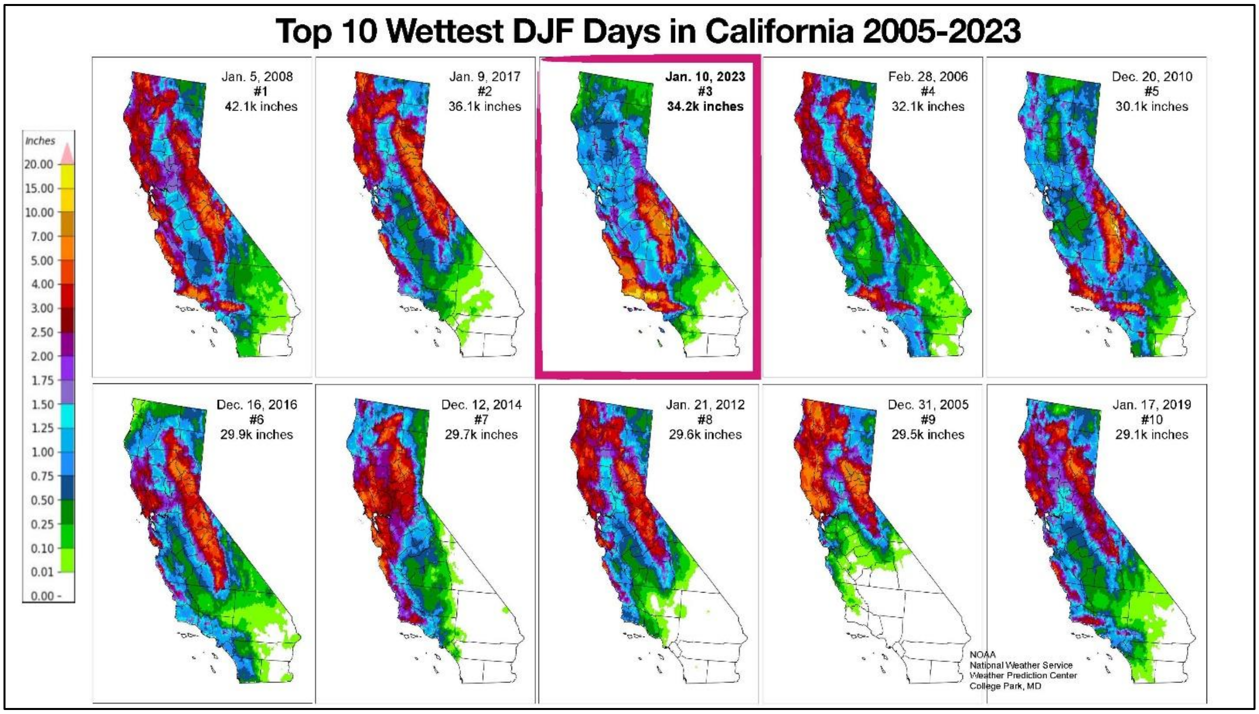


22-Day Precipitation as Percent of Avg. Annual Precip

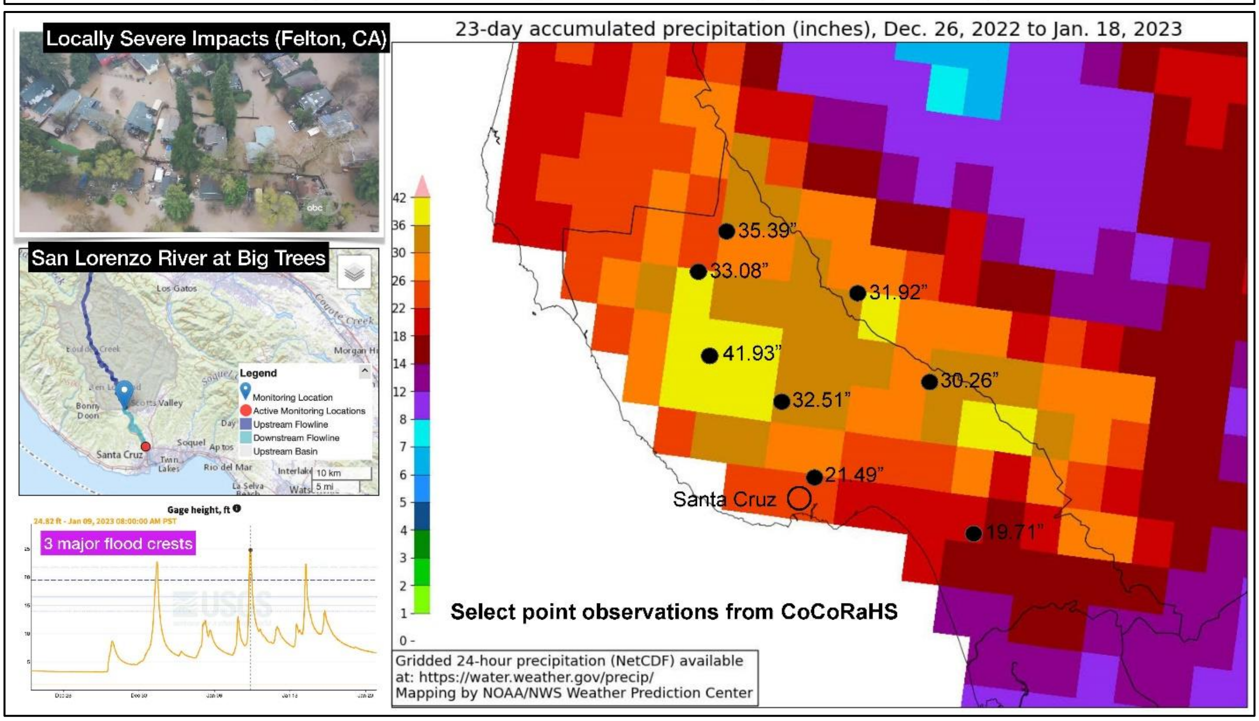
0 to 10	10 to 20	20 to 30	30 to 40	40 to 50	50 to 60	60 to 70	70 to 80	80 to 90	Over 90

Details Mattered Too





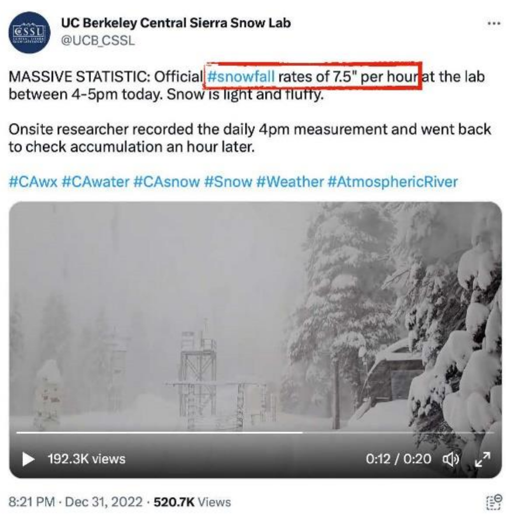
Top 10 Wettest DJF Days in California 2005-2023
Inches
20.00
15.00
10.00
7.00
5.00
4.00
3.00
2.50
2.00
1.75
1.50
1.25
1.00
0.75
0.50
0.25
0.10
0.01
0.00
Jan. 5, 2008 #1 42.1k inches
Jan. 9, 2017 #2 36.1k inches
Jan. 10, 2023 #3 34.2k inches
Feb. 28, 2006 #4 32.1k inches
Dec. 20, 2010 #5 30.1k inches
Dec. 16, 2016 #6 29.9k inches
Dec. 12, 2014 #7 29.7k inches
Jan. 21, 2012 #8 29.6k inches
Dec. 31, 2005 #9 29.5k inches
Jan. 17, 2019 #10 29.1k inches
NOAA
National Weather Service
Weather Prediction Center
College Park, MD



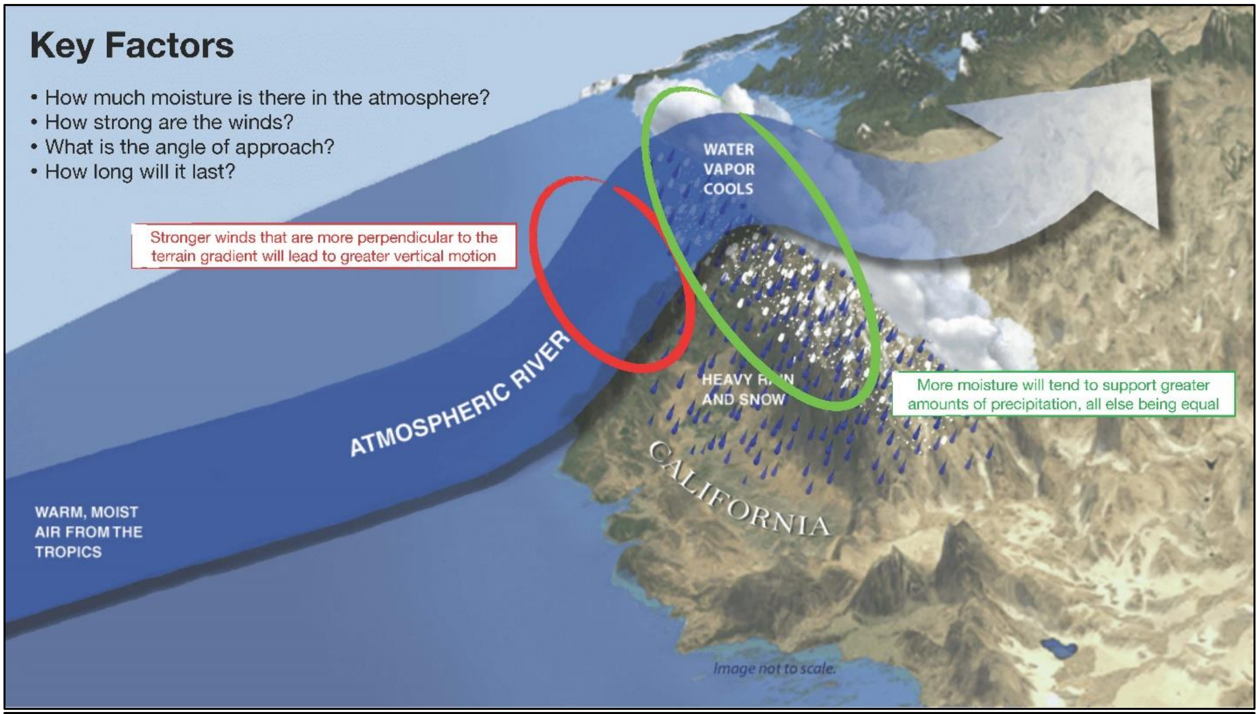
Locally Severe Impacts (Felton, CA)
San Lorenzo River at Big Trees
Legend
Monitoring Location
Active Monitoring Locations
Upstream Flowline
Downstream Flowline
Upstream Basin
Santa Cruz
Gage height, ft
3 major flood crests
23-day accumulated precipitation (inches), Dec. 26, 2022 to Jan. 18, 2023
35.39"
33.08"
31.92"
41.93"
30.26"
32.51"
21.49"
Santa Cruz
19.71"
Select point observations from CoCoRaHS
Gridded 24-hour precipitation (NetCDF) available
at: https://water.weather.gov/precip/
Mapping by NOAA/NWS Weather Prediction Center

Extreme Precipitation Rates

Occasional instances of extreme precipitation rates embedded in the multi-week event led to significant impacts



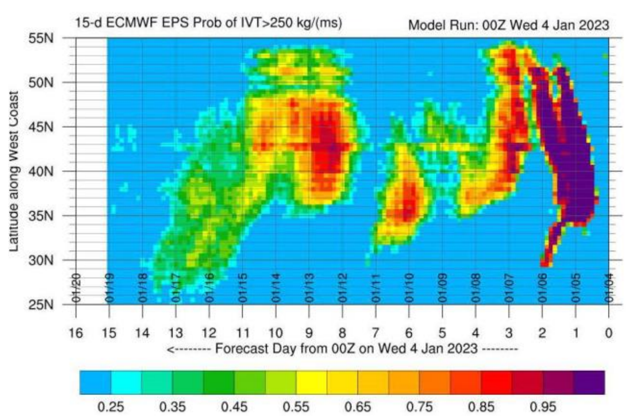
Forecasting Atmospheric Rivers

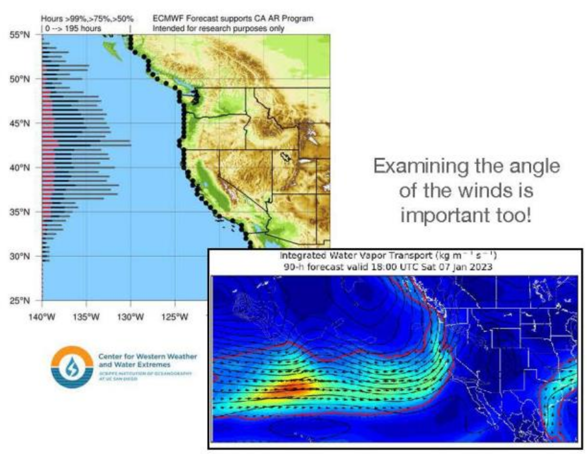


Integrated Vapor Transport

IVT is a combination of the atmospheric moisture content and the wind speeds, integrated through the troposphere. A good metric that corresponds to a lot of the key factors for forecasting atmospheric rivers.

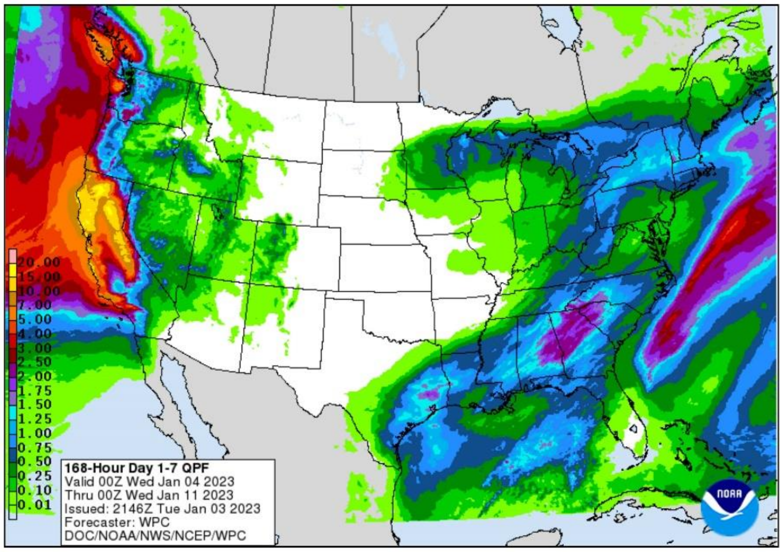
Forecasters can examine probabilistic data to get at the most likely timing and placement.





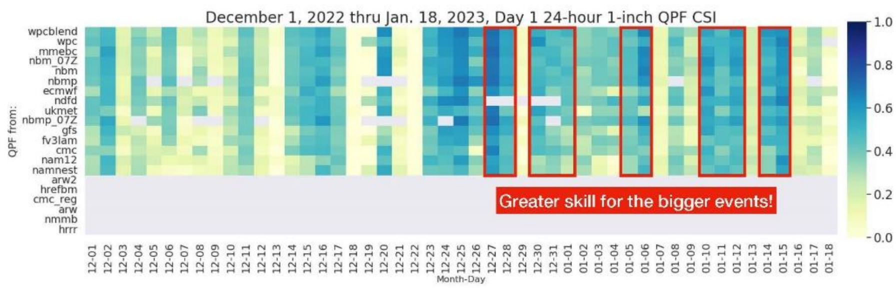
Examining the angle of the winds is important too!

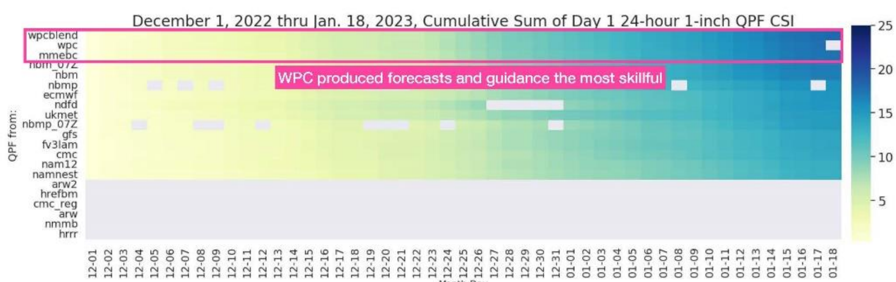
QPF Serves as the Foundation

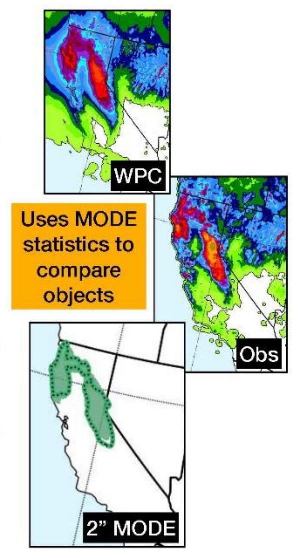


- **QPF** is the **Q**uantitative **P**recipitation **F**orecast
- Collaborated with the entire NWS field structure
- Our "best guess" for liquid equivalent precipitation over the next week
- Going to represent larger scale average amounts, not every local minimum and maximum
- Forecast extends out 7 days
- QPF can be, and is, fed into hydrologic models and river forecast models

QPF Verification for the Western U.S. in this Period







What Does a Forecast of Rain Actually Mean?

Something very common…

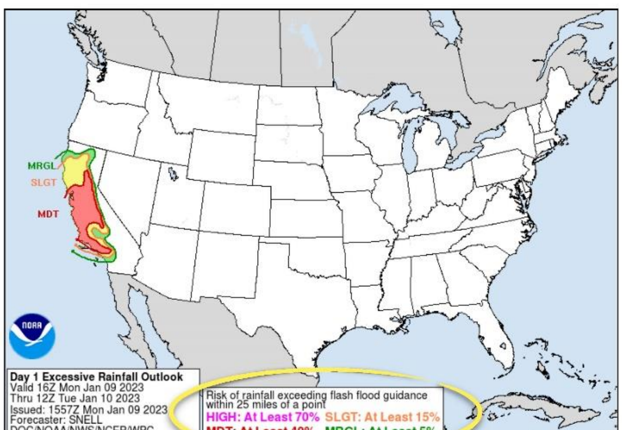
The average American will experience thousands of rainy days in their lifetime

…can have uncommon results

However, some people will never experience a true flooding catastrophe

<u>The context is crucial!</u> If we're forecasting an inch of rain it matters where that's falling, and how fast it's falling. Is it all arriving in an hour, or evenly spread through the day?

We "Translate" with the Excessive Rainfall Outlook



Answers the Question:

What are the chances of rainfall intense enough that it would be expected to cause flash flooding?

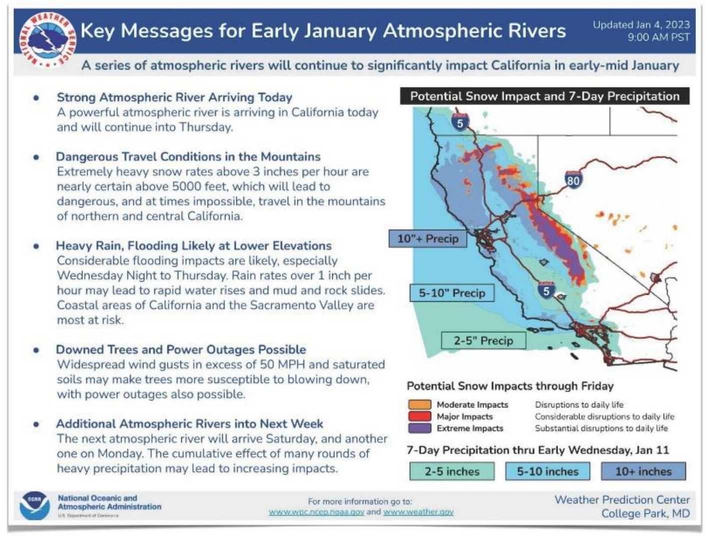
Other Things to Know:

- ✓ A situational awareness and planning tool that "gets your head in the game"
- ✗ Not an explicit forecast of flash flooding at a specific location
- ✓ Accounts for uncertainty in placement, timing of intense rainfall, and summarizes the larger scale risk factors such as wet soils

Verification shows these probabilities are reliable. That is, when we say there is a 40-70% chance of rainfall-induced flash flooding within 25 miles of a point, it really does happen about 50% of the time.

Key Messages

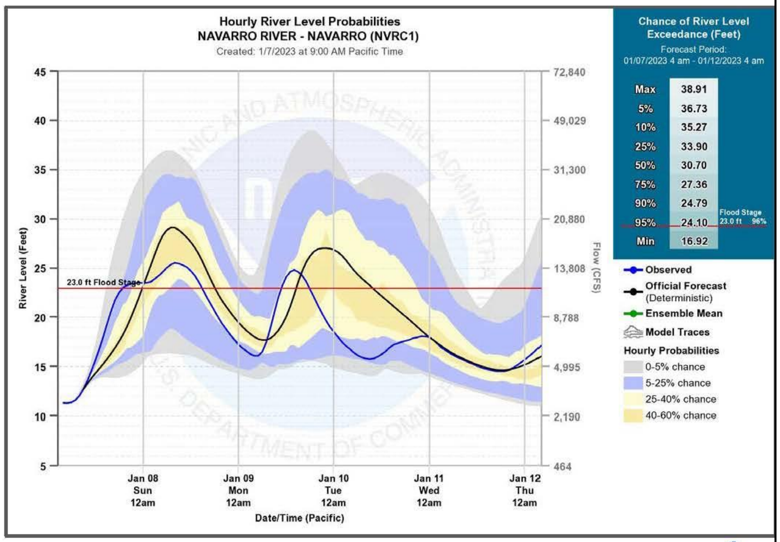
- WPC has been producing plain language Key Messages for winter storm events for several years
- Goal: an easily-understood summary of the most important weather information over a larger region, combining insights from WPC forecasters at the national level, and local level NWS forecasters
- Took the unusual step in this case of emphasizing the entire sequence of atmospheric rivers and the cumulative accumulation instead of focusing on each individual event in isolation
- Developed novel map graphics to combine the snow and rain forecast information on a single map



Key Messages graphic issued by WPC on January 4th for the California atmospheric rivers

Hydrologic ensemble forecasts

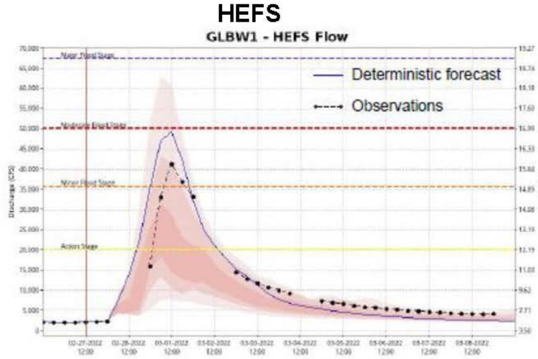
- A collection of streamflow (e.g. rivers) forecasts
- Drives probabilistic forecasting needed for risk-based decision making
- Becoming the standard, over single value (deterministic) forecasts
- Provides guidance to human forecasters



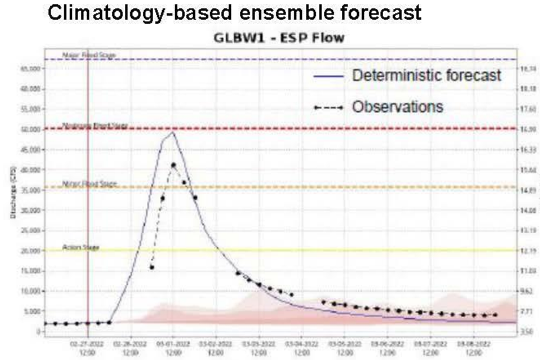
Hydrological Ensemble Forecast Service (HEFS) - Introduction

HEFS incorporates forecasts of precipitation and temperature into the forecast, an improvement over traditional hydrologic ensemble forecasts, which are based on climatology

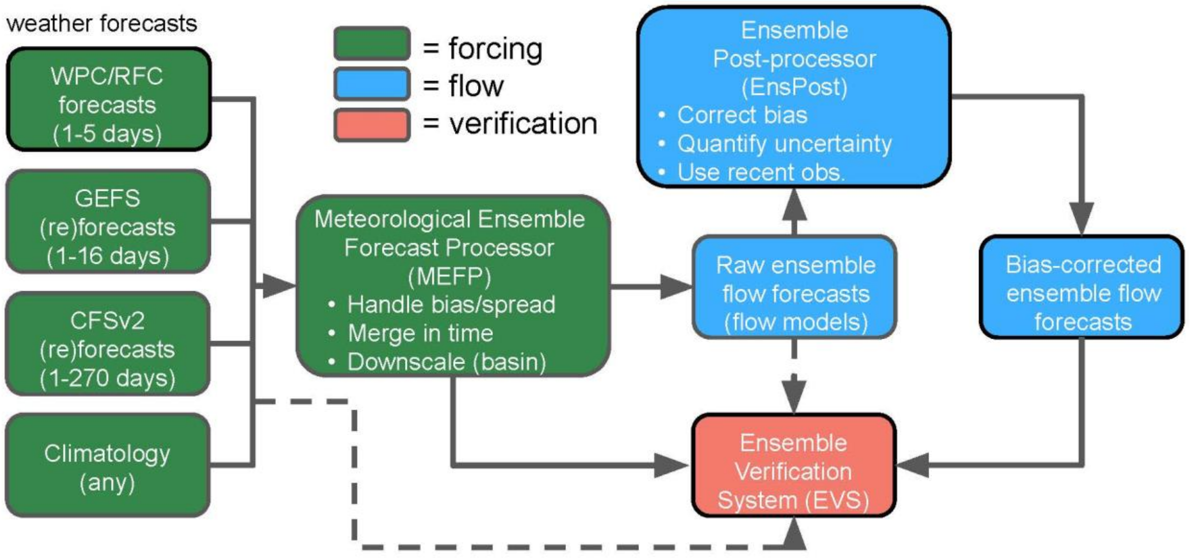
HEFS



Climatology-based ensemble forecast



HEFS structure



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New York City - Early HEFS user

NYC Water Supply

- Croton; Catskill; and Delaware watersheds
- Includes 19 reservoirs, 3 lakes; 2000 square miles
- Serves 9 million people
- Delivers 1.1 billion gallons/day
- Uses HEFS forecasts in a decision support system
- Avoids (**$10B+**) water filtration costs

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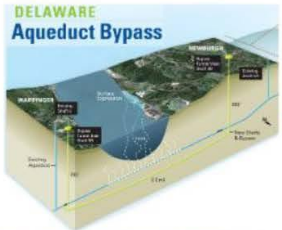
New York City Reservoir Management Decisions

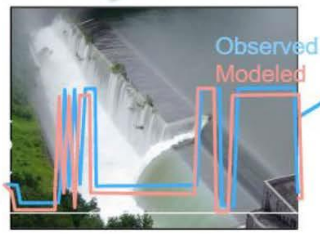


“Mission critical decision to manage shutdown of RBWT Tunnel based on HEFS forecasts”

Ashokan Reservoir

“HEFS forecasts critical to protecting NYC drinking water quality during high turbidity events”

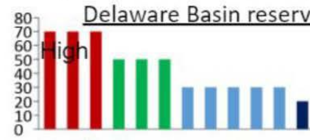
HEFS streamflow forecasts are used to optimize and validate the NYC OST for million/billion dollar applications



(Cannonsville Reservoir Spillway)

“HEFS forecasts help optimize rule curves for seasonal storage objectives in NYC reservoirs”

Risk to water availability from Delaware Basin reservoirs

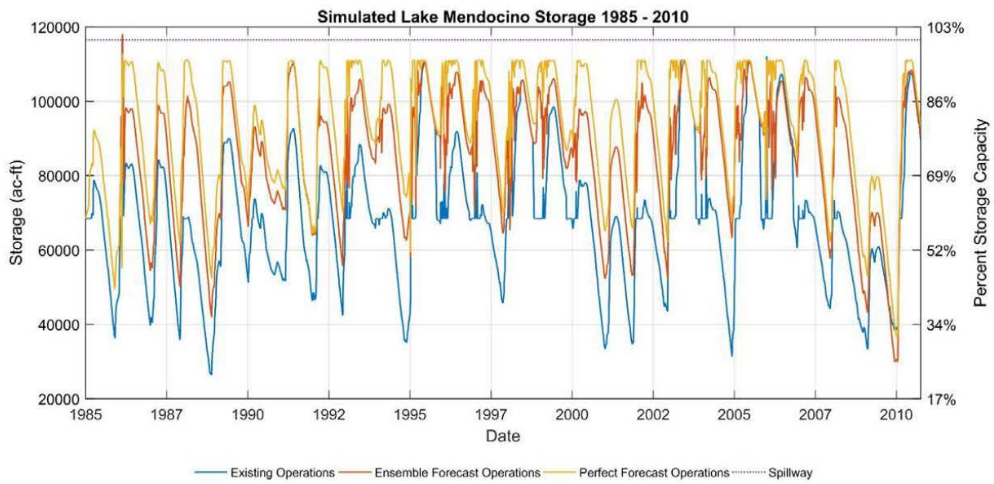


“HEFS forecasts used to determine risks to conservation releases”

Russian River/Lake Mendocino, CA

- Based on a multi-agency study on Lake Mendocino, reservoir operations were changed to use HEFS forecasts to inform decisions about releasing or storing water
- The study used 25 yrs of HEFS hindcasts
- Process can be replicated in other watersheds

Russian River/Lake Mendocino FIRO



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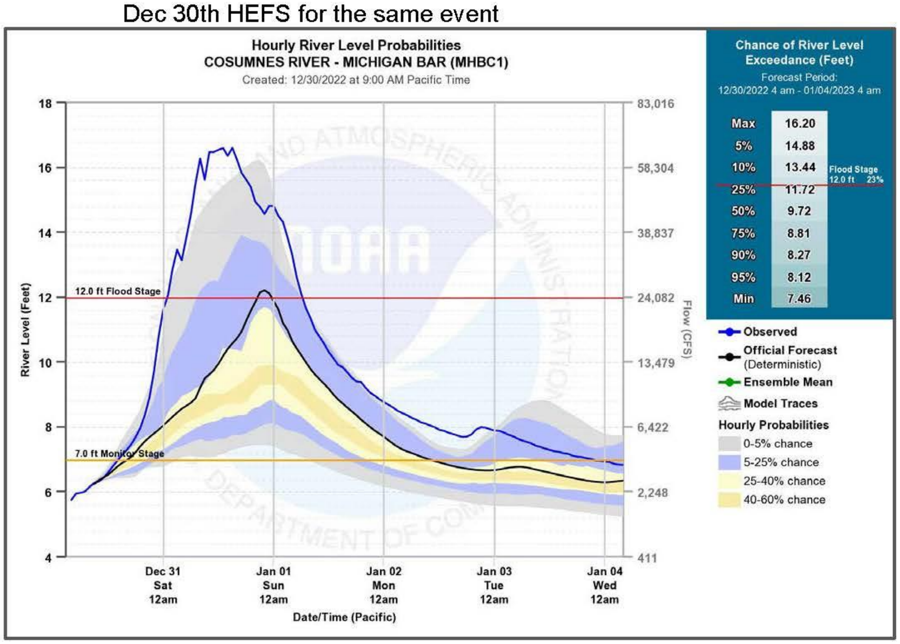
Dec 30th HEFS for the same event



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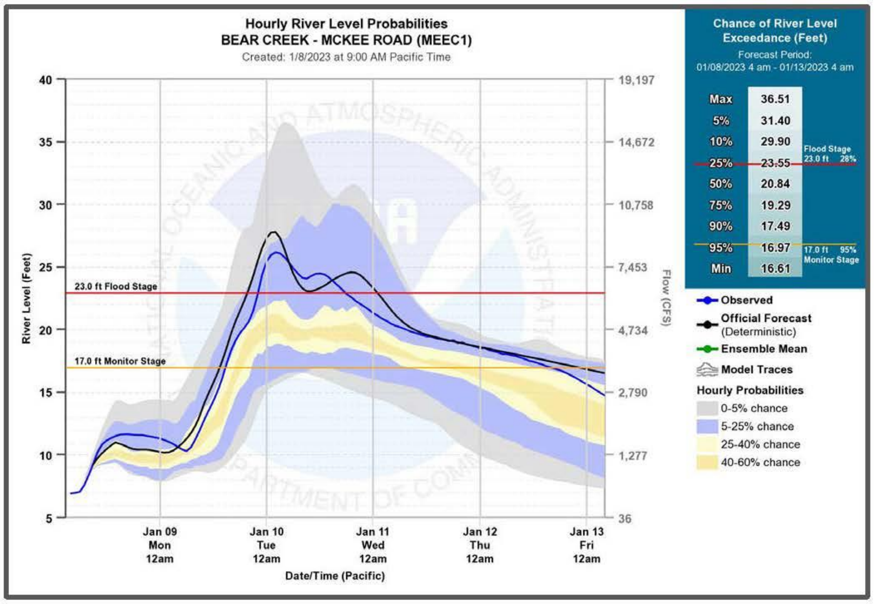
January 8th forecast that resulted in major flooding



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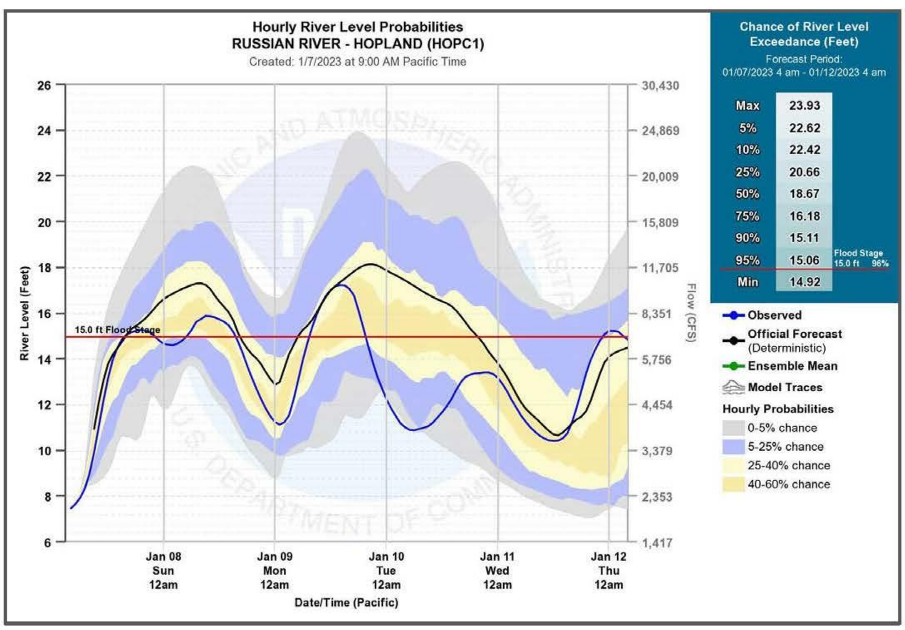

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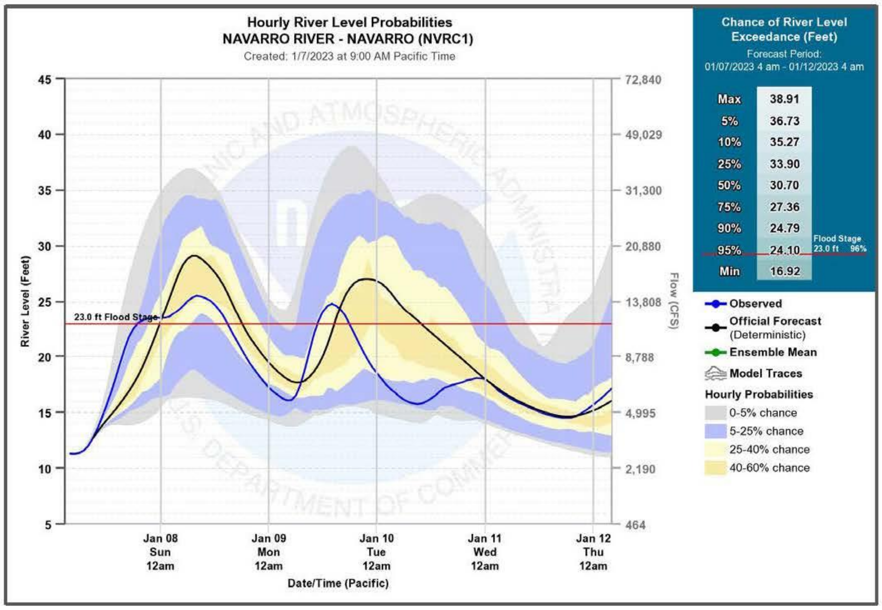

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Summary - HEFS Advantages

- Provides probabilistic streamflow forecasts
- Incorporates the latest weather forecasts
- Allows for risk-based decision making
- Guidance to human streamflow forecasters
- Completing US roll-out in May 2023 - 95% done
- Future: address limitations, especially large precip events

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3.2.4.3 Questions and Answers

Question:

Broadly, how does the recent December-January, and I guess maybe continuing, atmospheric river events in California, compare to the ARkStorm scenario[6] that was developed in a 2011 USGS report? It's obviously less than that but broadly how does it compare? Is it 20%, 50%, 60%?.

Answer:

David Novak[7]: In terms of peaks, the ARkStorm event was towards 100". I think this event peaked at about 40".

Joseph Kanney: This is about 40%.

Question:

In Alex's presentation, he made some comments about the skill of the quantitative precipitation forecast (QPF) and it being better for the bigger events. I recall a report from the 2010 time-frame by Marty Ralph, Mark Dettinger and other folks in the Journal of Hyrdometeorology that compared about 20 years' worth of QPF, not just for atmospheric rivers, but more broadly for other storms as well. They had the exact opposite conclusion, that is, the more intense the precipitation event, the worse the skill was in terms of timing and location. So, my question is, has the forecasting improved that much broadly, over all types of storms, or is this improvement

[6] A modeled scenario of U.S. West Coast winter storm events induced by the formation of Atmospheric Rivers (AR) and capable of causing massive and devastating flooding. https://www.usgs.gov/programs/science-application-for-risk-reduction/science/arkstorm-scenario

[7] Provided this response in the meeting chat.

that you've noted there something that is more pertaining to the atmospheric river events, that our forecasting has gotten much better for them.

Answer:

Zack Taylor: In general, the QPF forecasting has improved, just with the improvements in numerical weather prediction, maybe not necessarily tied to the specific atmospheric river forecasting. On average, we've seen ~15% improvement in QPF over the decade. This improvement lags other elements. Atmospheric rivers are some of the better forecast phenomena, but there is certainly room for improvement. Summer-time isolated thunderstorms are poorly resolved.

Mark Fresch: I can't speak to pulling out the data from atmospheric rivers only and comparing it to overall performance.

Question:

How will climate change affect atmospheric river strength and frequency?

Answer:

Zack Taylor: In terms of climate change and how it impacts these weather events, like all impacts across all weather events, we would expect to see potentially stronger systems and maybe perhaps more frequent systems. For atmospheric rivers specifically you might see a greater frequency within a season perhaps or maybe the strength of them could be stronger. I think that's what we would expect in a changing climate, that the intensity and frequency would be amplified, whether that means more frequent of them or that the strength of them specifically. But the direct ties there are a little bit more loose in terms of one particular event to climate change.

Mark Fresch: Also, on Day 2, there's a talk by some of my colleagues on precipitation frequency. They are better to speak towards precipitation frequency than I am.

Question:

Are atmospheric rivers associated with exceedance probabilities?

Answer:

Mark Fresch: We provide exceedance probabilities for any event, including atmospheric rivers. For the different thresholds of flooding, those are available, and atmospheric rivers are no different than any other flooding event in that regard, as far as the products available.

Question:

How can atmospheric river events affect the probable maximum precipitation used in riverine flood or LIP assessments?

Answer:

Mark Fresch: The Hydrologic Ensemble Forecast System (HEFS) is calibrated using past data. We like to use at least 10 years of data, and the most recent data is the data that we favor, although it's a bit lagging. It's not predictive in as far as calibrating the hydrologic models or HEFS ensembles. Again, those atmospheric rivers aren't labelled as special events, but they are in the period of record. So those values of observed precipitation are used to calibrate HEFS, but they are just part of the record.

3.2.5 Presentation 1B-5: Sharpening of cold-season storms over the western United States

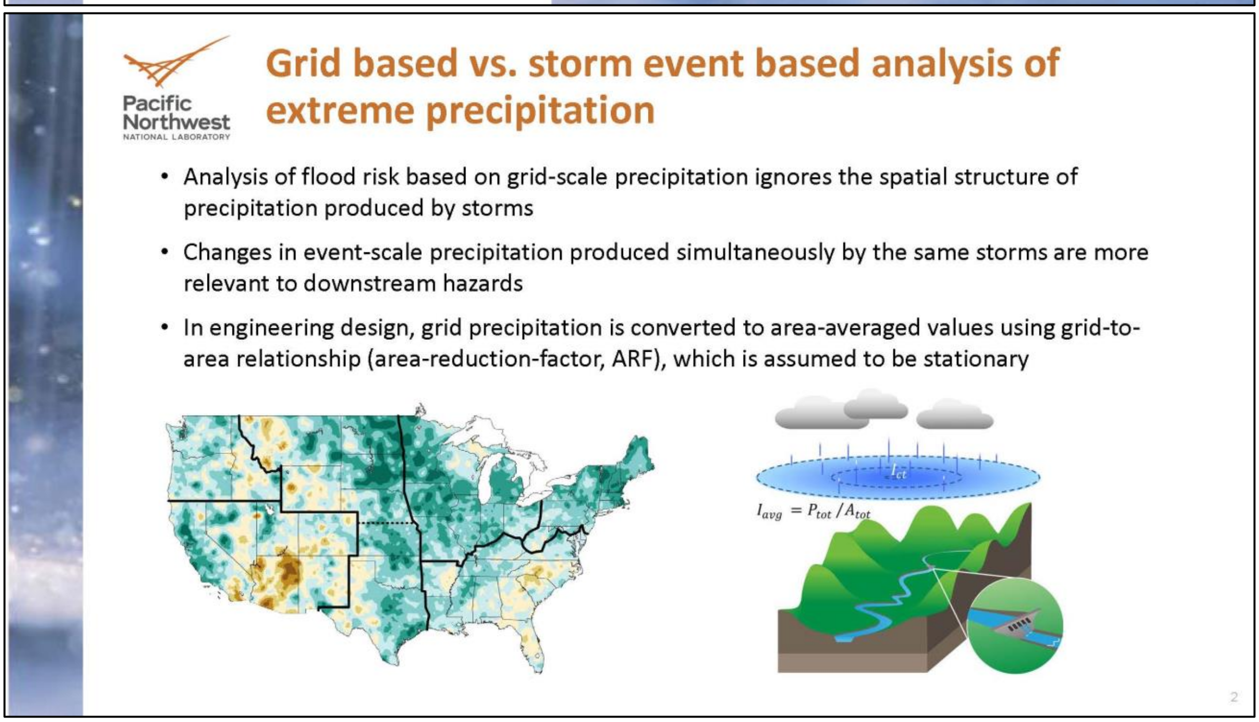
Authors: Xiaodong Chen, L. Ruby Leung, Yang Gao, Ying Liu, Mark Wigmosta; Pacific Northwest National Laboratory

Speaker: L. Ruby Leung

3.2.5.1 Abstract

Winter storms are responsible for billion-dollar economic losses in the western United States. Because storm structures are not well resolved by global climate models, it is not well established how single events and their structures change with warming. Here we use regional storm-resolving simulations to investigate climate change impact on western U.S. winter storms. Under a high-emissions scenario, precipitation volume from the top 20% of winter storms is projected to increase by up to 40% across the region by mid-century. The average increase in precipitation volume (31%) is contributed by 22% from increasing area coverage and 19% from increasing storm intensity, while a robust storm sharpening with larger increase in storm centre precipitation compared with increase in storm area reduces precipitation volume by 10%. Ignoring storm sharpening could result in overestimation of the changes in design storms currently used in infrastructure planning in the region.

3.2.5.2 Presentation (ADAMS Accession No. ML23177A161)

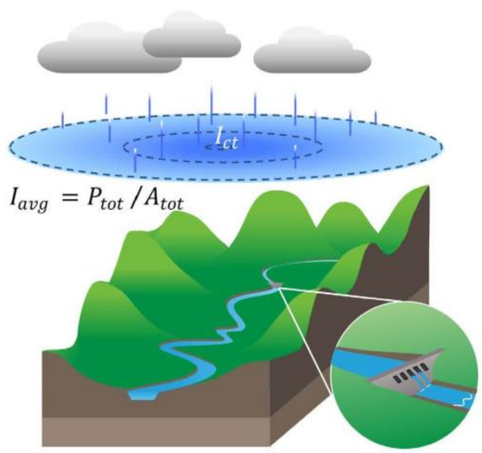


Approach

- Storm-resolving simulations performed using WRF for 1981-2010 and 2041-2070 using pseudo-global warming (PGW) over the western US at 6 km grid spacing
- PGW experiments were performed using climate perturbations simulated by 5 GCMs in CMIP5
- Identified a total of 8843 daily storm events in 1981-2010
- Storms are analyzed using 4 storm metrics

3

Storm metrics



$$I_{avg} = P_{tot}/A_{tot}$$

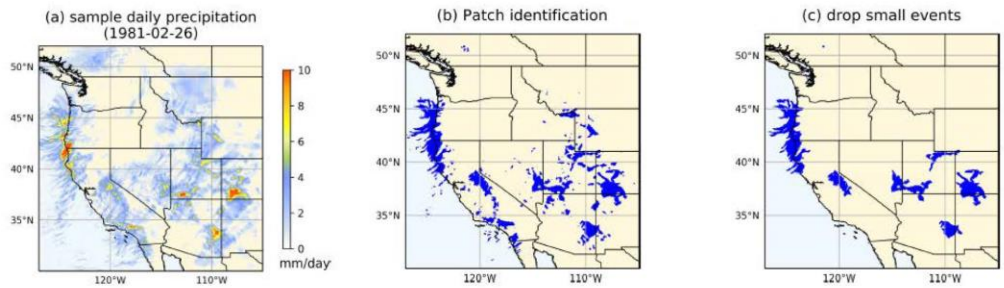
$$P_{tot} = A_{tot} \times I_{ct} \times SC$$

$$SC = I_{avg}/ I_{ct}$$

$$SC < 1 \ if \ I_{avg} < I_{ct}$$

4

Identifying storms



- Precipitation threshold: 5 mm/day
- Area threshold: top 10% by precipitation area (200–1000 grid cells for PNW, CA, and SW)

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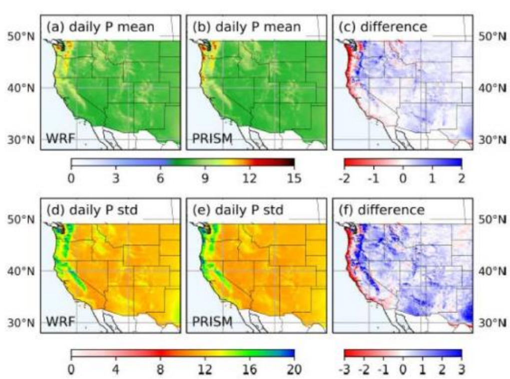
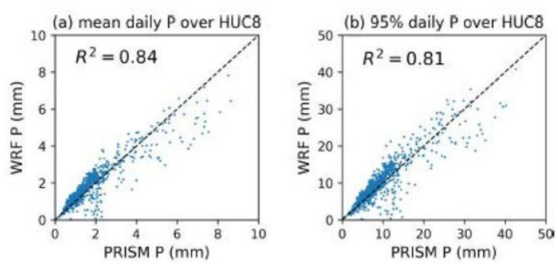
Mean and extreme precipitation are well simulated by WRF for the historical period





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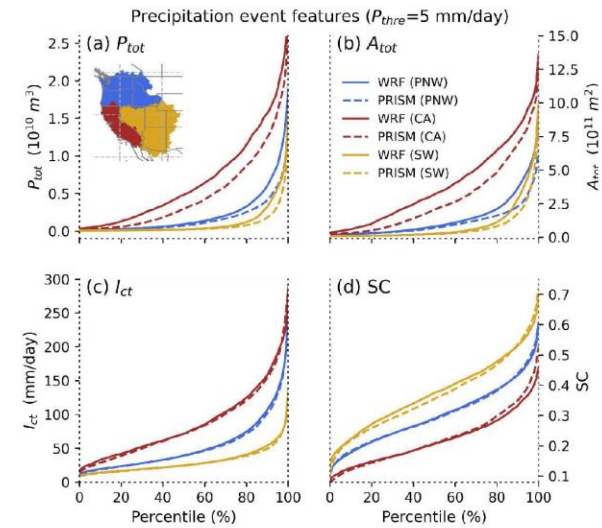
Pacific Northwest
NATIONAL LABORATORY

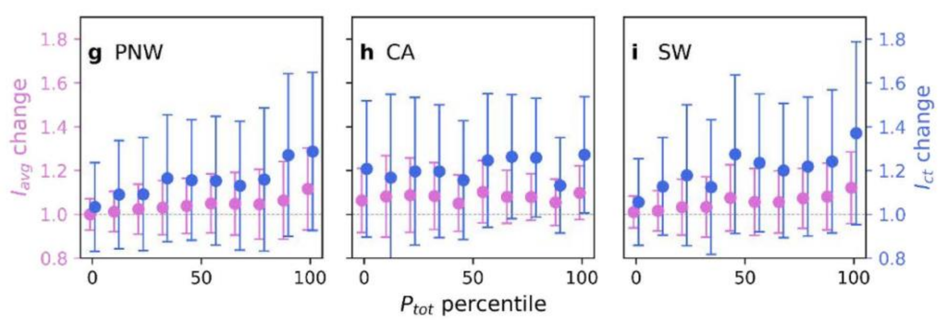
Storm-resolving simulations well capture the storm metrics from observations



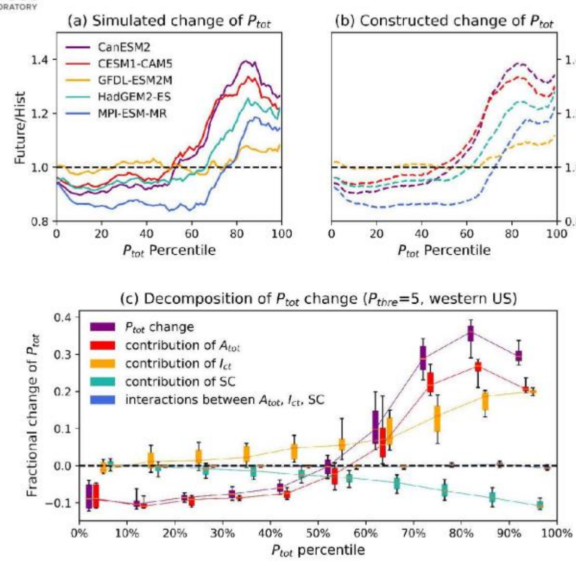
Pacific Northwest
NATIONAL LABORATORY

Storm-resolving simulations well capture the storm metrics from observations

Larger increases in peak intensity than mean intensity, particularly for storms with higher precipitation percentiles (typically AR storms)



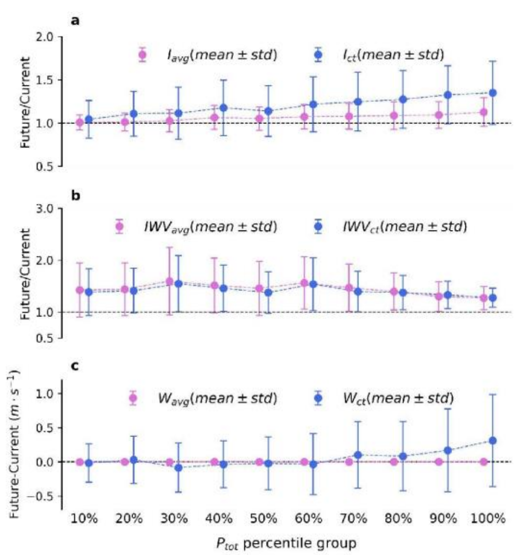
Decomposition of precipitation volume changes



$$P_{tot} = A_{tot} \times I_{ct} \times SC$$

- For the top 20% extreme storms, P_{tot} increases by 32% - 40%, which is contributed by increased A_{tot} (69% contribution) and I_{ct} (60% contribution), with the robust sharpening of the spatial structure (*SC*) of future storms considerably offsetting their impacts (-31% contribution).

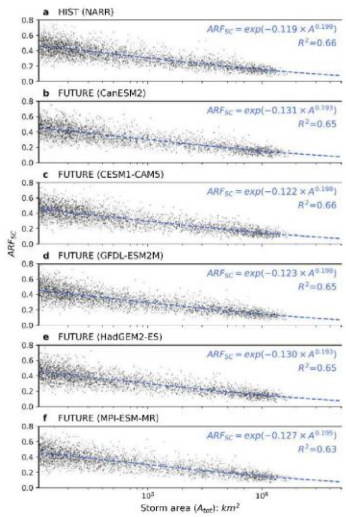
Storm sharpening contributed by sharpening of storm upward motion

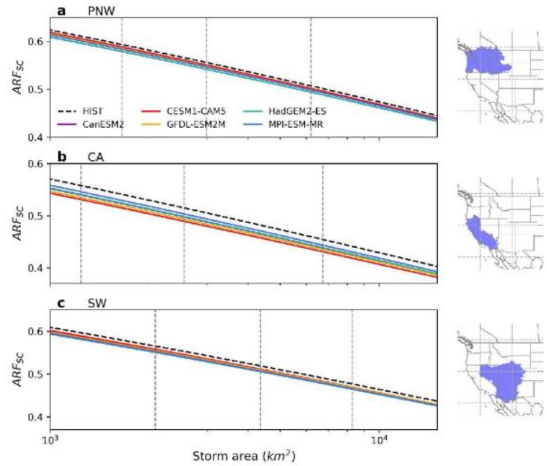


Larger increase in latent heat increase at storm center due to increase in moisture with warming drives larger increase in upward motion and amplifies storm center peak intensity

Area-reduction-factor (ARF)

Regional precipitation = Point precipitation × ARF



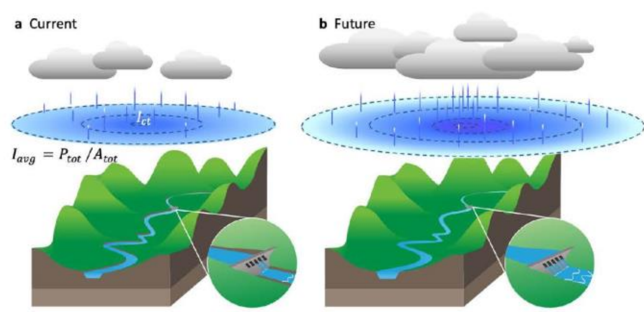


Failure to account for the reduced ARF biases the regional precipitation by up to 10% too high

Sharpening of cold season storms in the western US

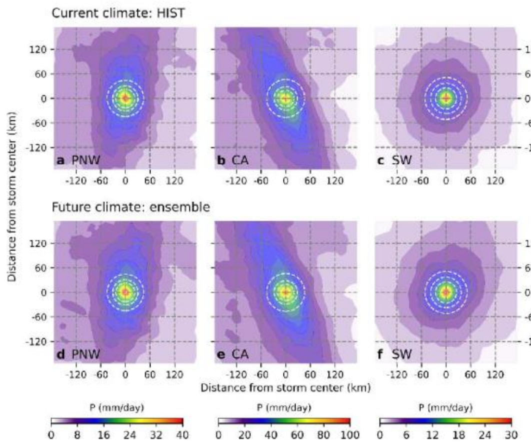
- Failure to account for climate change significantly underestimates flood risk due to increasing precipitation volume (**slow rising flood**) and increasing peak intensity (**flash flood**).
- Accounting for climate change, grid scale precipitation analysis overestimates flood risk by ignoring storm sharpening or decreasing area reduction factor (spatial concentration).


AP
Warming to make California downpours even wetter, study says



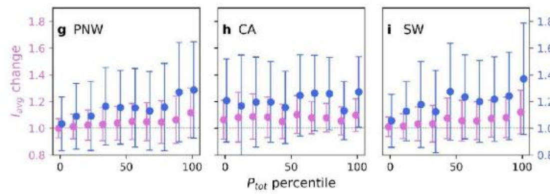
Chen, X., Leung, L. R., Gao, Y., Liu, Y. & Wigmosta, M. "Sharpening of cold-season storms over the western United States," *Nature Climate Change* **13**, 167–173 (2023). [DOI: 10.1038/s41558-022-01578-0]

Changes in storm metrics in the future

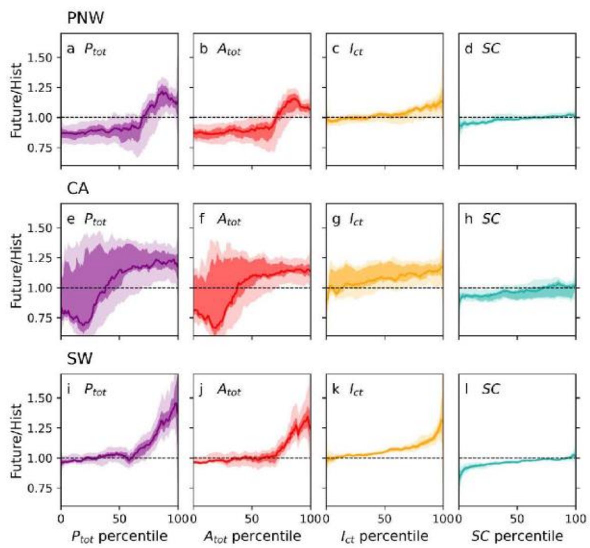


White circles approximate the 10th, 50th and 90th percentile of the size of the watersheds in each region

Peak intensity increases more than area-averaged intensity



Changes in storm metrics in the future



- AR storms with larger P_{tot}, larger A_{tot}, higher I_{ct}, and smaller *SC* have larger increase in P_{tot}, A_{tot}, and I_{ct}, as well as more sharpening (reduced *SC*)

Background

- Increasing extreme precipitation with warming may amplify flood risk
- Analysis of flood risk based on grid-scale precipitation ignores the spatial structure of precipitation produced by storms
- Changes in event-scale precipitation produced simultaneously by the same storms are more relevant to downstream hazards than grid-scale precipitation associated with different precipitation events
- In engineering design, grid precipitation is converted to area-averaged values using grid-to-area relationship (area-reduction-factor, ARF), which is assumed to be stationary
- Event-scale analysis is needed to determine potential changes in ARF, but GCMs are too coarse to support event-scale analysis of storms

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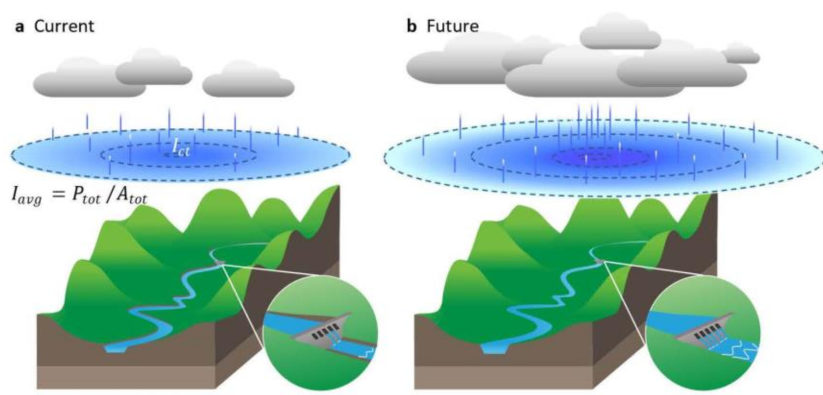
Response of extreme precipitation events to climate change



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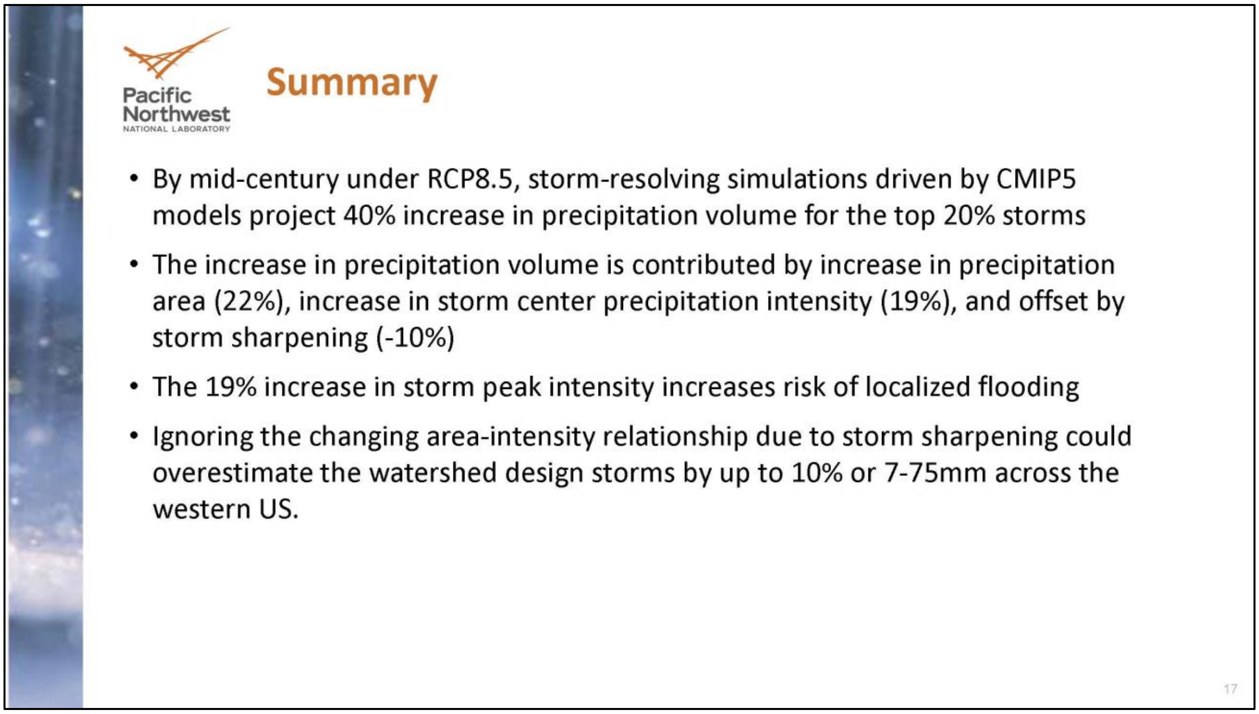


3.2.5.3 Questions and Answers

Question:

Have you applied this to the East Coast or Alaska?

Answer:

After seeing these results for the western United States, and because these are cold season storms, I would imagine that warm season storms, such as those convective storms that happen over the central and eastern United States, could potentially behave in a similar way. As I mentioned before, the reason we get this special concentration is because the of the increased moisture in the future and therefore releasing more latent energy that causes the vertical motion to become stronger. Because of this, I would expect that perhaps for convective storms, this kind of spatial concentration may become even larger. We have started analyzing similar kinds of simulations produced by other storms across the United States and then we can look at how warm season storms might behave, similarly or not, for a comparison.

Question:

Your description of how the vertical motion plays into this makes a lot of sense for mesoscale convective systems in terms of the enhanced updraft but also the downdraft of cold air. But I had a bit of a problem wrapping my head around that explanation when you are talking about these cold season storms on the west coast, which are large-scale or synoptic-scale systems. Can you maybe explain that a little bit more. What is the mechanism for how those vertical motions play out in these synoptic systems?

Answer:

In my view, regardless of whether you are talking about storms that are associated with synoptic systems or storms that might be related to convection or things like that, essentially all storms have vertical motion. You have to have some kind of convergence, whether the convergence is brought about by temperature gradients or by some other mechanisms like convective available potential energy. So, you always need to have vertical motion. So regardless then, in the future when you have more moisture, so you can consider then the moisture will be converged by the vertical motion and then producing a large amount of precipitation and therefore releasing more latent energy. The latent energy then becomes a feedback to the vertical motion to make the vertical motion even stronger. So, in fact, I think the mechanism would be very similar except like how big would the storms be: like frontal storms versus mesoscale convective systems as well as how strong the vertical motion is. I think that this would really distinguish between the behavior of the two types of storms in terms of their changes in the future. But overall, I think the picture remains similar in that you need to have vertical motion, and vertical motion can induce downward motion towards the edges of the storm and that would actually suppress the precipitation to cause lighter precipitation near the edge.

3.2.6 Presentation 1B-6: 2022 U.S. Billion-dollar Weather and Climate Disasters Analysis and Tools

Author: Adam Smith, NOAA National Centers for Environmental Information (NCEI)

Speaker: Adam Smith

3.2.6.1 Abstract

The NOAA National Centers for Environmental Information (NCEI) has released the final update to its 2022 Billion-dollar disaster report (www.ncei.noaa.gov/access/billions), confirming another intense year of costly disasters and extremes throughout much of the country.
In 2022, the U.S. experienced 18 separate weather and climate disasters costing at least 1 billion dollars. That number puts 2022 into a three-way tie with 2017 and 2011 for the third-highest number of billion-dollar disasters in a calendar year, behind the 22 events in 2020 and the 20 events in 2021. It was another year with a high diversity of destructive disasters:

- 1 winter storm/cold wave event (across the central and eastern U.S.).
- 1 wildfire event (wildfires across the western U.S. including Alaska).
- 1 drought and heat wave event (across the western and central U.S.).
- 1 flooding event (in Missouri and Kentucky).
- 2 tornado outbreaks (across the southern and southeastern U.S.).
- 3 tropical cyclones (Fiona, Ian and Nicole).
- 9 severe weather/hail events (across many parts of the country, including a derecho in the central U.S).

2022 was also third highest in total costs (behind 2017 and 2005), with a price tag of at least $165.0 billion. Over the last seven years (2016-2022), 122 separate billion-dollar disasters have killed at least 5,000 people and cost >$1 trillion in damage. In addition, the $100 billion cost figure has been eclipsed in 5 of the last six years (2017-2022 with 2019 being the exception). One of the drivers of this cost is that the U.S. has been impacted by landfalling Category 4 or 5 hurricanes in five of the last six years, including Hurricanes Harvey, Irma, Maria, Michael, Laura, Ida, and Ian.

The increase in population and material wealth over the last several decades are an important cause for the rising costs. These trends are further complicated by the fact that much of the growth has taken place in vulnerable areas like coasts, the wildland-urban interface, and river floodplains. Vulnerability is especially high where building codes are insufficient for reducing damage from extreme events. Climate change is also supercharging the increasing frequency

and intensity of certain types of extreme weather that lead to billion-dollar disasters—most notably the rise in vulnerability to drought, lengthening wildfire seasons in the Western states, and the potential for extremely heavy rainfall becoming more common in the eastern states. Sea level rise is worsening hurricane storm surge flooding. Given all of these compounding hazard risks, there is an increased need to focus on where we build, how we build, and investing in infrastructure updates that are designed for a 21st-century climate.

3.2.6.2 Presentation (ADAMS Accession No. ML23177A162)

U.S Billion-dollar Weather and Climate Disasters

Outline:

- Context for Measuring Disaster Impact
- Data Sources / What we are Measuring
- 2022 U.S. Disasters in Historical Context
- Data, Tools, Hazard & Socioeconomic Vulnerability Mapping

U.S. Billion-dollar Weather and Climate Disasters – 2022 in Context 2

NOAA's National Centers for Environmental Information (NCEI) –

Climate Science and Service Division

Statutory mission to describe the climate of the United States and act as the **"Nation's Scorekeeper" regarding the trends and anomalies** of weather and climate.

- As part of this responsibility we also analyze extreme weather and climate events in the U.S. that have **great economic and societal impacts** known as "**U.S. Billion-dollar Weather & Climate Disasters**"
- NCEI's U.S. billion-dollar disaster analysis seeks to bring the best public and private disaster loss data together in a systematic approach. To that end, we maintain a consistent record of weather and climate disasters with costs equaling or exceeding $1 billion in damages (adjusting for inflation) using high-quality data sources and peer-reviewed methods.
- **Period of record: 1980-2022 (Quarterly updates)**
- The U.S. has sustained **341** separate weather and climate disasters since 1980 where overall damages/costs reached or exceeded $1 billion.
- **Total, direct costs exceed $2.475 trillion (CPI-adjusted to 2022).**

U.S. Billion-dollar Weather and Climate Disasters – 2022 in Context 3

To capture losses requires a broad array of **public** and **private** data

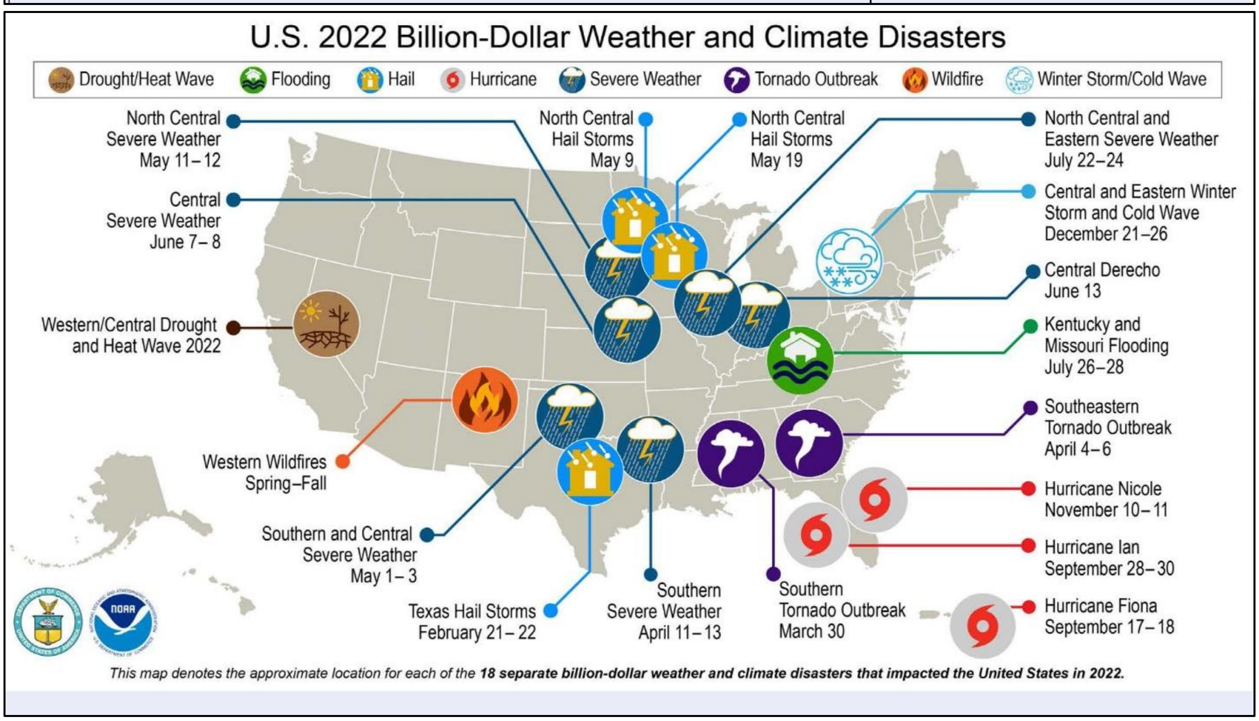
	Hurricanes/ Tropical Storms	Severe Local Storms	Winter Storms	Crop Freeze	Wildfire	Drought / Heat Wave	Inland / Riverine Flooding
Insurance & Reinsurance	x	x	x		x		x
FEMA – Presidential Disaster Declarations	x	x	x	x	x		x
FEMA – National Flood Insurance Program	x						x
USDA – Risk Management Agency	x	x	x	x	x	x	x
National Interagency Fire Center					x		
Energy Information Administration	x	x	x		x	x	
US Army Corps of Engineers							x
State Agencies / Storm Events Database	x	x	x	x	x	x	x

Account for total, direct losses (i.e., **insured** and **uninsured**) for assets including:

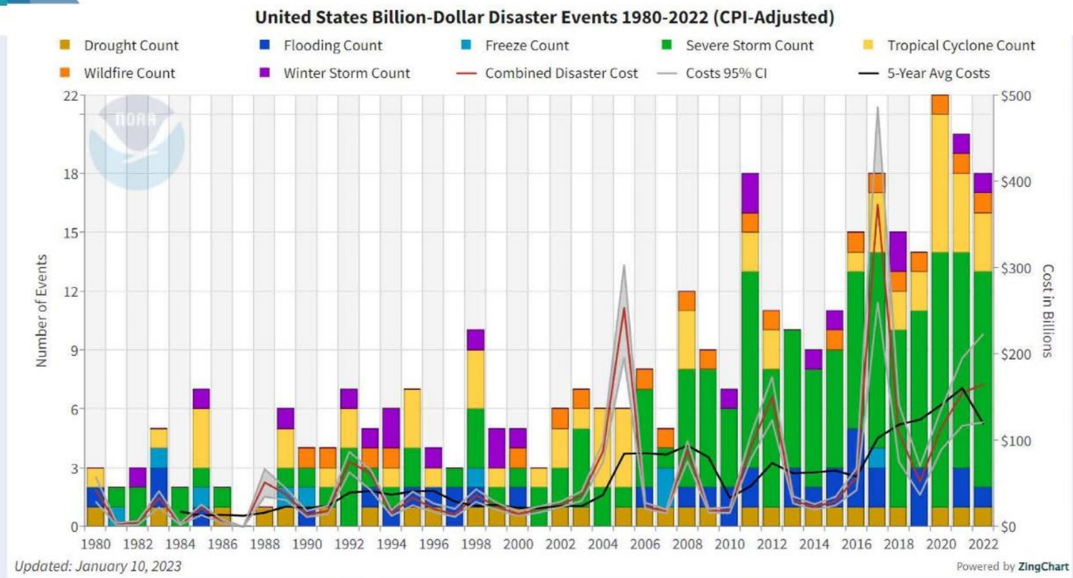
- **physical damage** to residential, commercial, and government buildings
- **material assets** (content) within a building
- **time element losses** (i.e., time costs for businesses; hotel costs for loss of living quarters)
- **vehicles, boats, offshore energy platforms, military bases**
- **public infrastructure** (i.e., roads, bridges, levees, electrical systems, hydropower)
- **Agricultural / forestry assets** (i.e., crops, livestock, commercial timber, wildfire fighting)

We do not account for:

- natural capital/envn. degradation;
- mental or physical healthcare-related costs;
- all downstream (indirect) costs

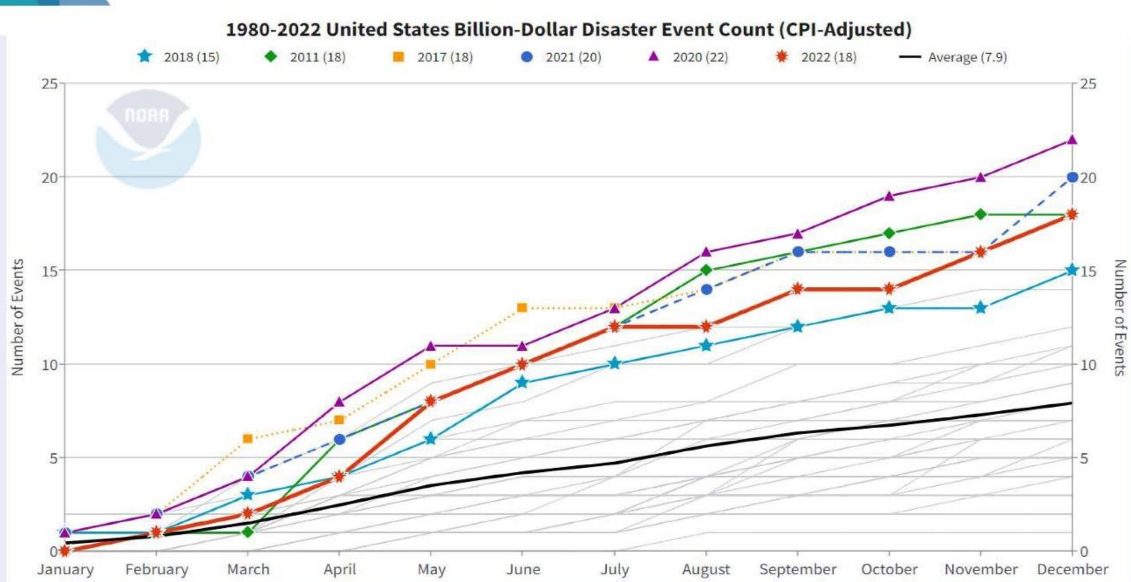


U.S. Billion-dollar event frequency (1980–2022), annual cost, 5-year cost avg.



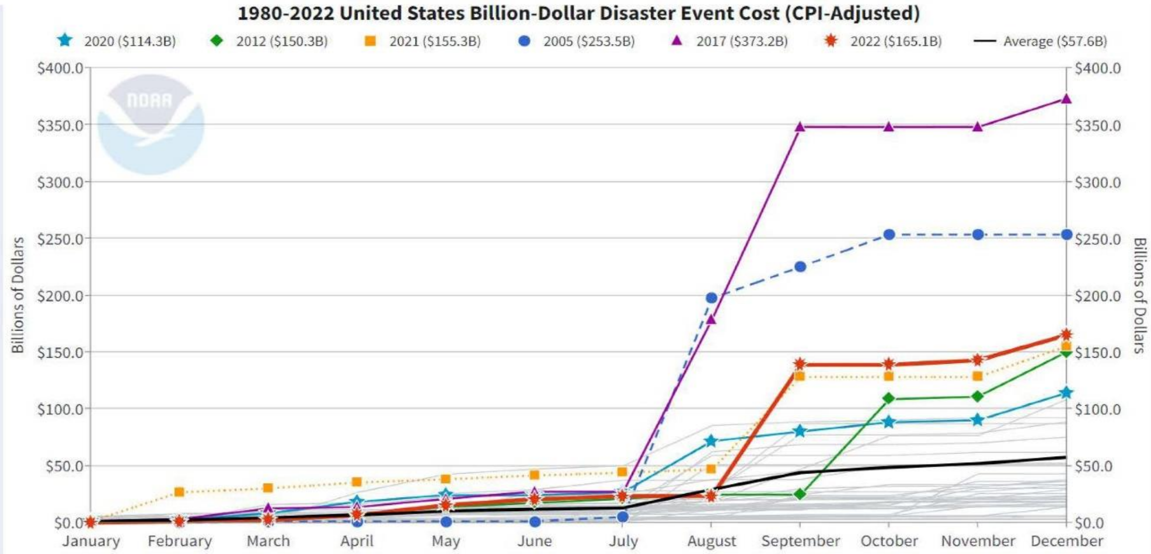
- Western wildfires, severe storms, inland flooding and hurricane costs all on the rise
- **5-year annual cost average** >**$119.1 billion;** disaster costs over the last **7 years** (2016-2022) = **$1.026 trillion**

Cumulative U.S. billion-dollar disaster frequency (year-to-date) for years 1980-2022



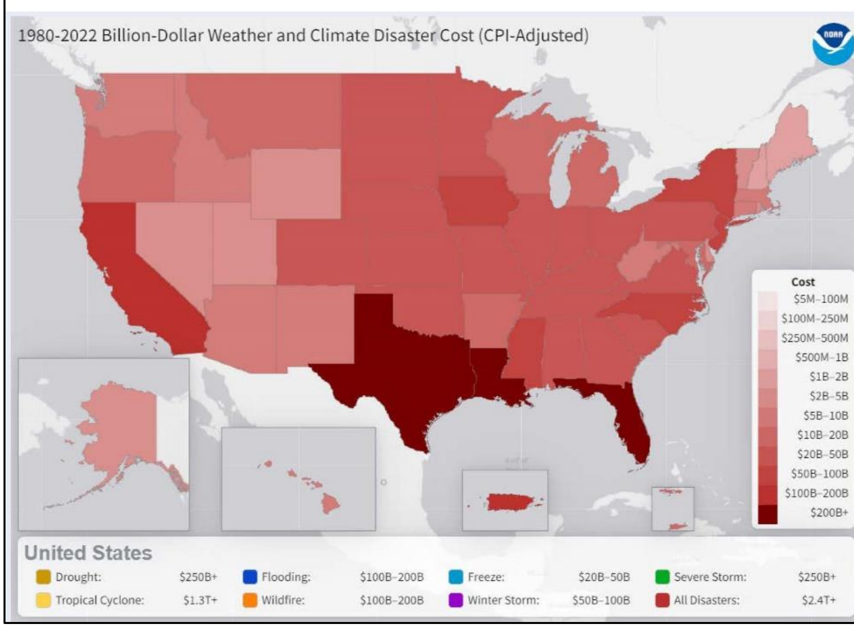
- **1980 – 2022:** annual average: **7.9 events** (CPI-adjusted). **2018–2022** (5-year average): **17.8 events** (CPI-adjusted)
- **2022 - 18 events** [11 severe storm events, 3 tropical cyclones, 1 floods, 1 winter storm, drought & wildfire]

Cumulative U.S. billion-dollar disaster cost (year-to-date) for years 1980-2022



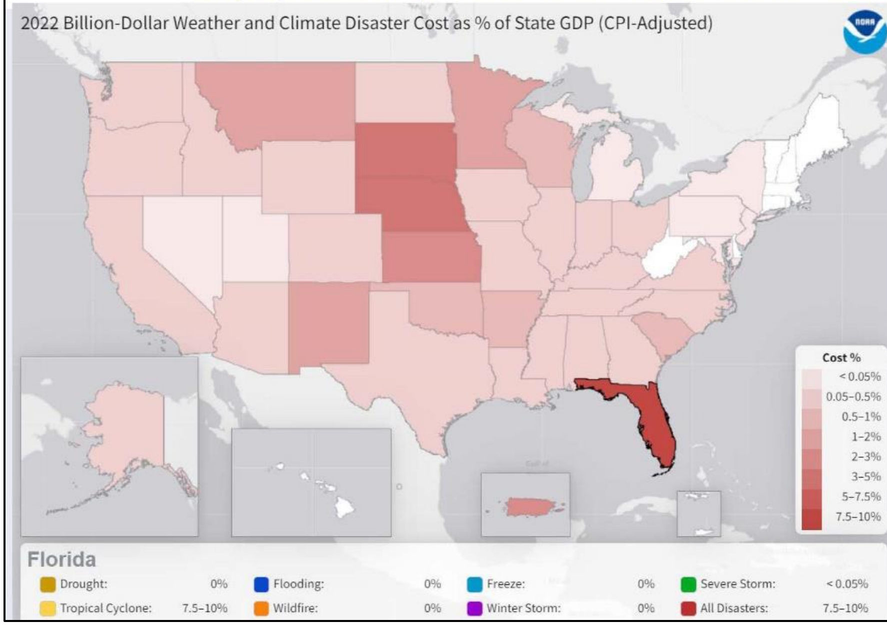
- **2022** cost total (**$165.0 billion – 3rd highest**) vs. the 43-year period of record at **$57.5 billion**
- The **top 3 most costly years** for U.S. - **2017** ($373.2 billion); **2005** ($253.5 billion); **2022** ($165.0 billion)

From 1980–2022, the U.S. **South, Central** and **Southeast** regions experienced a higher cost from billion-dollar disaster events. CA, NY, NJ, PR and V.I. as well.



- Reflects the **severity, vulnerability and exposure** of weather and climate events impacting different regions
- The **top 3 most impacted states:**
  - **Texas** ($376 billion)
  - **Florida** ($373 billion)
  - **Louisiana** ($293 billion)
- The **relative costs are more acute in Louisiana**, as its population and economic size is much smaller than Texas or Florida.
- Louisiana also has a high frequency of disaster events, which can leads to compounding, cascading socioeconomic impacts.

The **2022 disaster costs** for each state as a **% of that state's 2022 GDP** (economic output)... clear impact from billion-dollar disaster events.



- Compound hazards and cascading impacts slow down recovery and increase the cost
- Disasters can have strong effects on economic growth (GDP) post-disaster.

From **1980-2022**, the U.S. has experienced **341** distinct billion-dollar weather & climate events - each causing at least $1 billion in direct losses

- **Total, direct losses** from these **341 events** exceeds **$2.475 trillion** (CPI-adjusted, 2022)

Disaster Type	Events	Events/ Year	Percent Frequency	Total Costs	Percent of Total Costs	Cost/ Event	Cost/ Year	Deaths	Deaths/ Year
Drought	30	0.7	8.8%	$327.7B	13.2%	$10.9B	$7.6B	4,275†	99†
Flooding	37	0.9	10.9%	$177.9B	7.2%	$4.8B	$4.1B	676	16
Freeze	9	0.2	2.6%	$35.3B	1.4%	$3.9B	$0.8B	162	4
Severe Storm	163	3.8	47.8%	$383.7B	15.5%	$2.4B	$8.9B	1,982	46
Tropical Cyclone	60	1.4	17.6%	$1,333.6B	53.9%	$22.2B	$31.0B	6,890	160
Wildfire	21	0.5	6.2%	$133.1B	5.4%	$6.3B	$3.1B	435	10
Winter Storm	21	0.5	6.2%	$84.9B‡	3.4%‡	$4.2B‡	$2.0B‡	1,401	33
All Disasters	**341**	**7.9**	**100.0%**	**$2,476.2B‡**	**100.0%‡**	**$7.3B‡**	**$57.6B‡**	**15,821**	**368**

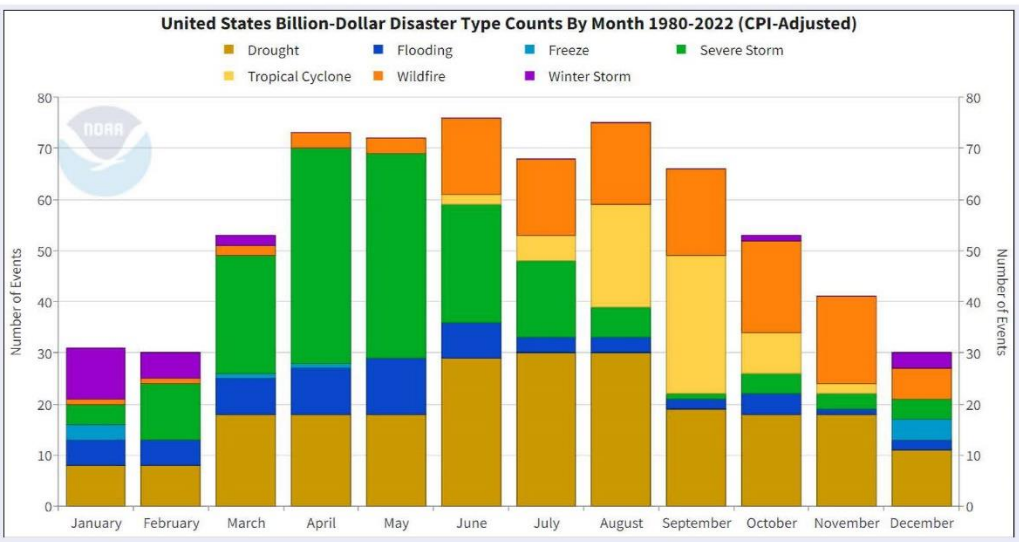
†Deaths associated with drought are the result of heat waves. (Not all droughts are accompanied by extreme heat waves.)
Flooding events (river basin or urban flooding from excessive rainfall) are separate from inland flood damage caused by tropical cyclone events.

Comparison of U.S. Billion-dollar disaster stats over time

Time Period	Billion-Dollar Disasters	Events/Year	Cost	Percent of Total Cost	Cost/Year	Deaths	Deaths/Year
1980s (1980-1989)	31	3.1	$204.9B	8.3%	$20.5B	2,970	297
1990s (1990-1999)	55	5.5	$313.6B	12.7%	$31.4B	3,062	306
2000s (2000-2009)	67	6.7	$586.8B	23.7%	$58.7B	3,102	310
2010s (2010-2019)	128	12.8	$936.3B	37.8%	$93.6B	5,227	523
Last 5 Years (2018-2022)	89	17.8	$595.5B‡	24.0%‡	$119.1B‡	1,751	350
Last 3 Years (2020-2022)	60	20.0	$434.6B‡	17.6%‡	$144.9B‡	1,460	487
Last Year (2022)	18	18.0	$165.0B‡	6.7%‡	$165.0B‡	474	474
All Years (1980-2022)	**341**	**7.9**	**$2,476.2B‡**	**100.0%‡**	**$57.6B‡**	**15,821**	**368**

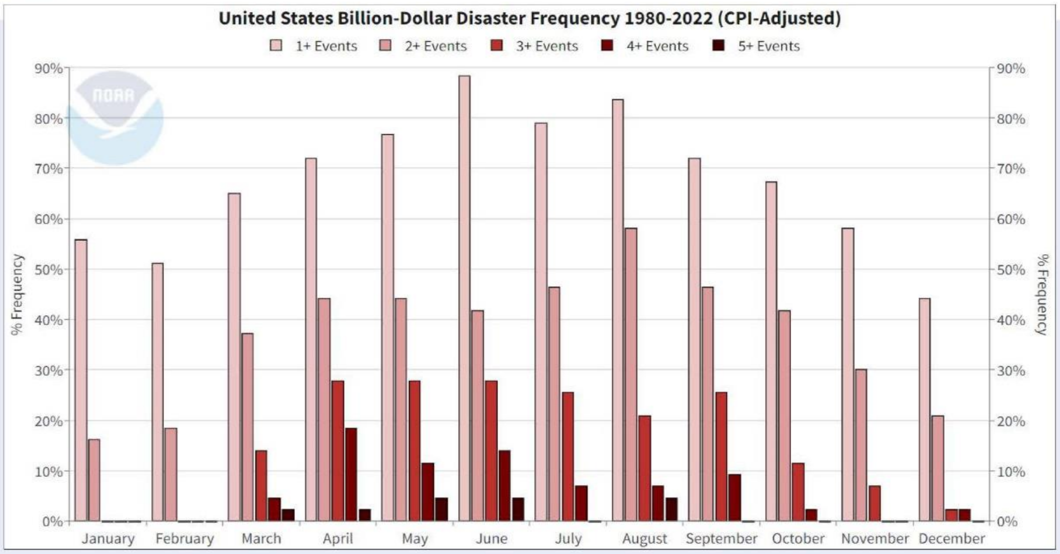
The **number and cost of disasters are increasing over time** due to a **combination of** increased exposure (i.e., values at risk of possible loss), vulnerability (i.e., where we build; how we build) and that climate change is increasing the frequency of some types of extremes that lead to billion-dollar disasters (NCA 2018, Chapter 2)

Severe storm and **inland flooding events** frequent during **Spring** and **Summer** **Wildfires** and **hurricanes** most frequent during **Fall** months.

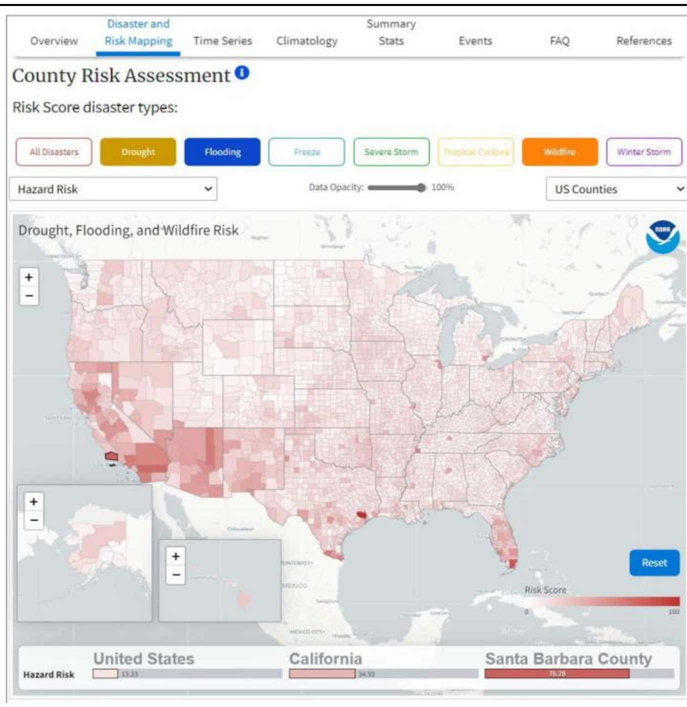


- Visualizing the 43-year **frequency of climatology of extreme**, damaging events across the Nation.
- A way for decision-makers to understand which types of large events typically occur at what times of year, by region.

Historic record for multiple, billion-dollar events, by month



- In recent years (2017-2022), there **were just 18 days** on average between billion-dollar disasters **compared to 82 days in the 1980s**.
- Shorter time intervals between disasters often mean less time and resources available to respond, recover and prepare for future events.
- This increased frequency of events produces cascading impacts that are particularly challenging to vulnerable socioeconomic populations.



Compound hazard county risk (Drought, Wildfire and Flooding)

Each region faces **unique hazard combinations, which are useful in a new era of more likely cascading hazard impacts** (i.e., drought-enhanced wildfires produce mountain-side burn scars, which often enhance debris flows from flooding.

As noted in National Climate Assessment (2017) **"the physical and socioeconomic impacts of compound extreme events (such as simultaneous heat and drought, wildfires associated with hot and dry conditions, or flooding associated with high precipitation on top of snow or waterlogged ground) can be greater than the sum of the parts."**

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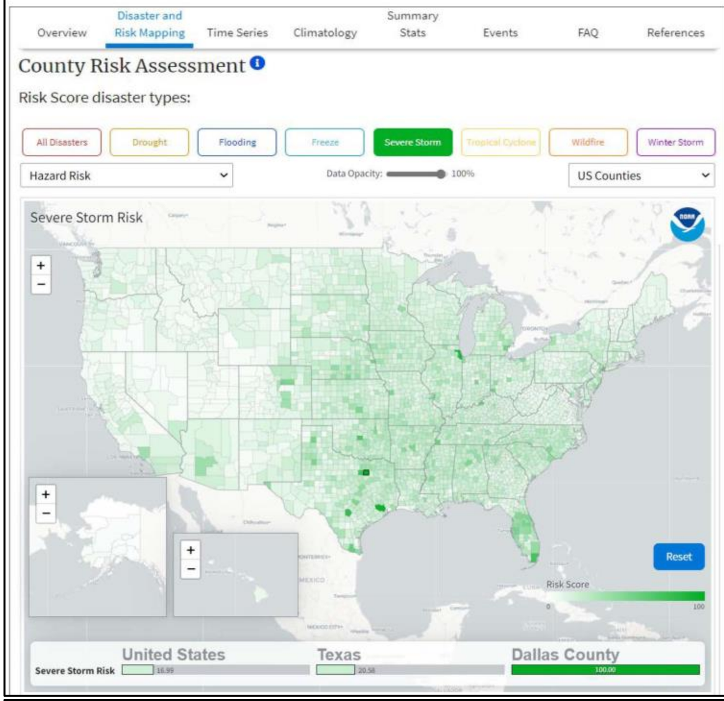

This map provides county risk scores for combined **severe storm events (i.e., tornado, hail, high wind damage)** reflecting a county's annualized hazard frequency; its potential hazard cost related to building value, crop value and population exposure; and its social vulnerability and resilience to recover from hazard impacts based on dozens of socioeconomic variables.

The map highlights that **Dallas County, Texas has a very high score for severe storm risk** due to its historic frequency of being impacted by these events in addition to having a large urban population and valuable exposure, which further increases the damage potential for severe storm impacts and costs.

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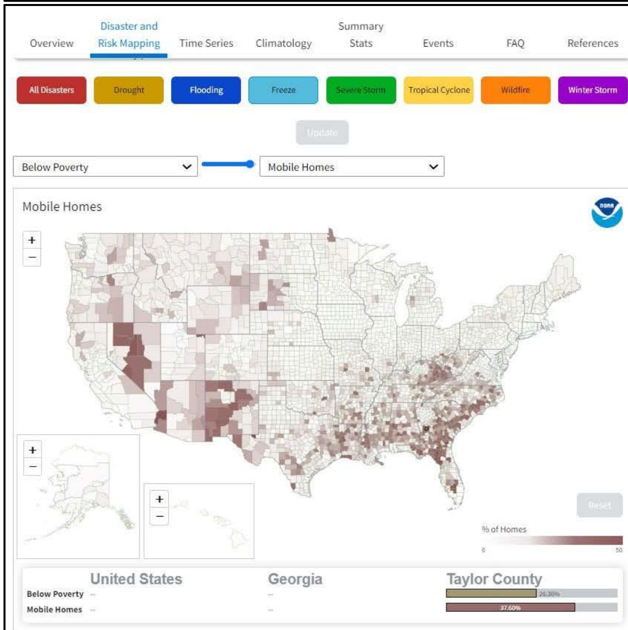
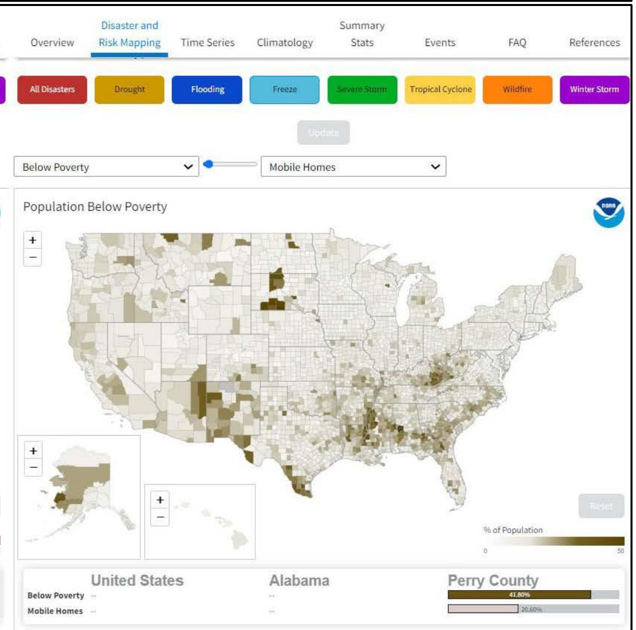
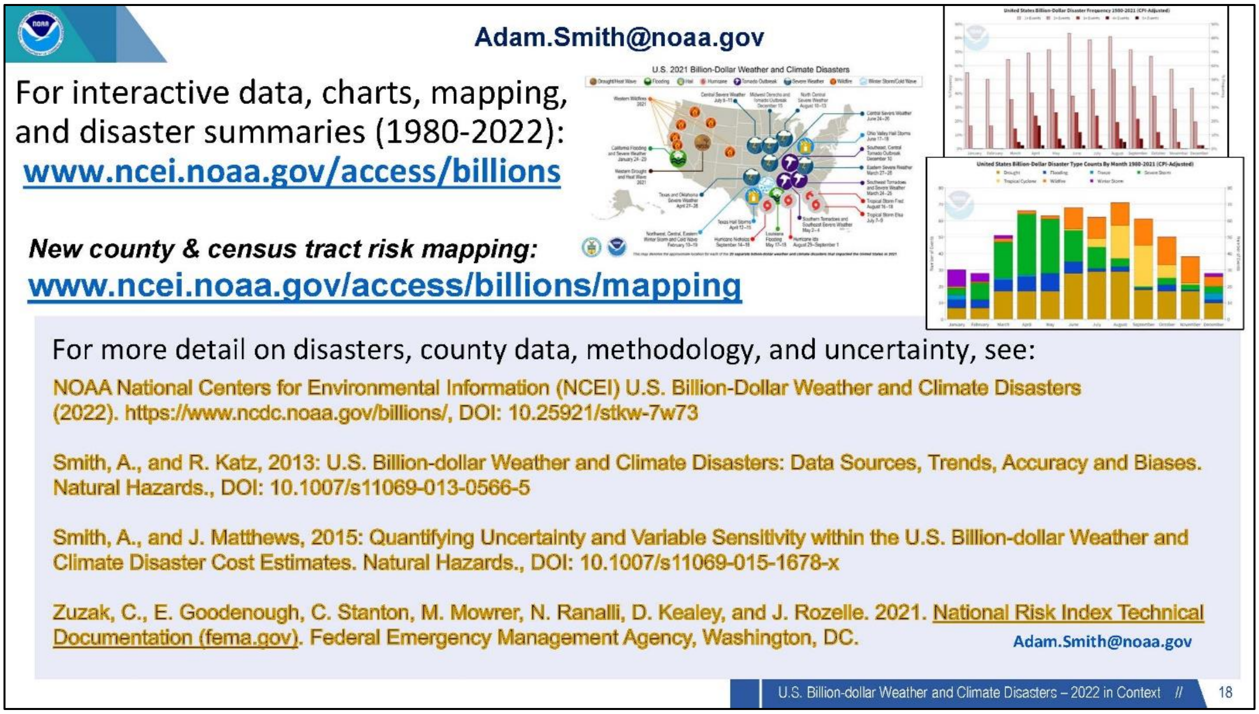






2A-1

3.2.6.3 *Questions and Answers*

Question:

How do you account for overlap in the data, for example, severe storms and flooding?

Answer:

Joseph Kanney[8]: In what Adam presented, there isn't overlap. The flooding impacts are separate from the severe storms. Severe storm in this context means high wind events. The criterion for high winds is over 58 mph or something like that. So, it's high wind phenomena like tornadoes, straight-line winds, etc. Also hail is included in the severe storm category. So those sorts of damages would be in severe storms. If the same storm had flooding, then that would be counted under flooding. So, there's no an overlap in that.

Question:

Are costs for prior years adjusted to 2022 dollars before determining the number of billion-dollar events?

Answer:

Joseph Kanney: Slide 6 shows that the costs are CPI (Consumer Price Index) adjusted..

3.2.7 1B-7: Climate and Weather Panel Discussion

Moderator: Elena Yegorova, NRC/RES

[8] Adam Smith was not available for questions during the workshop.

Participants:

- Michael Kuperberg, Executive Director, U.S. Global Research Program
- William Sweet, NOAA National Ocean Service
- Benjamin Hamlington, NASA Jet Propulsion Laboratory
- Mark Fresch, NOAA National Weather Service Office of Water Prediction
- L. Ruby Leung, Pacific Northwest National Laboratory

Question:

Regarding PFHA for nuclear power plants, which one is more effective, PFHA based on past meteorological or hydrological data or PFHA based on forecast results considering climate change?

Answer:

Michael Kuperberg: I don't know, this is not my area. I do think that it is dangerous to assume stationarity when we know that is not the case and will not be the case going forward.

Question:

Nuclear facility site characterization activities are carried out within a quality assurance plan. What is the quality assurance plan for climate change assessment activities?

Answer:

Michael Kuperberg: It seems to me that the world has changed its view very recently from "I don't believe it" to "OK, I believe it, what do I do?" The research enterprise is struggling to move quickly enough to answer those questions. And in the absence of authoritative data, what we are seeing is a wild west of people using what they find (e.g., Google online). We are well aware of the need and the challenge, and we are working very hard on coming up with a resolution to it. But right this second, authoritatively across the government, I can't tell you that there is a single place. There is a lot of good information. I don't mean to downplay that. Unfortunately it is very siloed. Where you ought to go and whether you'll find exactly what you need within the government depends on what you are looking for. Maybe you'll find what you are looking for outside the government.

Question:

What do you see as the most exciting new science emerging out of the USGCRP program?

Answer:

Michael Kuperberg: It has to do with extremes. When you are worried about really important infrastructure, you have to be concerned about those extremely high-impact, low probability events. They are very difficult for us to tease out of our understanding because they happen so infrequently and it's very hard to model them. But there is a lot of work going on. What you heard from Ruby earlier today and the work of Billy Sweet and a lot of their colleagues around the federally funded research enterprises focused on dealing with extreme events and those tail risks.

Question:

What are some of the measures that can be taken to prepare for the coastal flood regime shifts that you discussed in your presentation?

Answer:

William Sweet: For built infrastructure, it seems like some of the first things that communities are doing are stormwater upgrades, whether it's inflow preventors and outflows (i.e., active pump systems). Charleston and Miami are looking at moving water downhill, down gradient in storm water systems that are gone. Green infrastructure. Also, raising sea walls. Use the maps to get a sense of what's getting wet now and what's likely to start getting wet more often. Can you move infrastructure? It's hard because right now a lot of it is at a local level and communities are asked to adapt, change, deal with it. Collectively, if we could keep emissions in check, perhaps there wouldn't be that much mitigation needed moving forward. But that doesn't really bode well at a municipal level when you are saying "I have a problem and what do I need to do?" Storm barriers work, but they come at a cost for ecosystems. Storm and waste-water systems are the ones that are at the front edge of the impacts right now. Combined systems and septic systems are starting to fail.

Question:

What are the limitations of current methods used to measure sea level rise; we have satellite altimetry and tide gages. How can these limitations be addressed to improve the accuracy and precision of sea level rise measurements?

Answer:

Benjamin Hamlington: We have known for a long time that our satellite observations don't get us very close to the coast. Tide gages certainly do get us up to the coast, but there are gaps between them so there's big spatial gaps between our tide gage observations. While the two can work together nicely (the tide gages can help get our open ocean information from satellites ultimately to the coast), both of them still have these limitations that really prevent us providing information everywhere along the coastlines. I think there are necessary developments on the satellite side to fill some of those gaps. One in particular is the Surface Water and Ocean Topography (SWOT) Mission, , which we launched in December 2022 here at NASA. It's going to get us closer to the coast and start measuring some of those higher-resolution, smaller-scale features that we know are happening along the coastline. Right now, we are limited somewhat by the data directly at the coast, but I think there are these opportunities to do better and to start to fill some of those gaps, including with technologies that we are just launching now. The next decade or so is going to be a big evolution in our ability to deliver information at the coast.

Question:

When you work with the tide gages, especially when you are doing the regionalization, I assume that you define some sort of a homogenous region and within that region, you can use those collective tide gages to improve the at-site results. As a practical matter, how big are the homogenous regions when you are talking about the tide gages? Is it like you are going from at-site to three or at-site to ten? How much power do you get from the regionalization?

Answer:

Benjamin Hamlington: In terms of what the ice sheets are contributing, these are very large-scale patterns; you aren't getting much variability along the coast. As you start to think about other processes, that's where you start to get more and more local and regional, like ocean dynamics. Those changes often drive how we group regionally. The groupings we had for that technical report were really driven by considerations of ocean dynamics. Where you have common ocean signals you can then group. To get even more local, the big issue then is subsidence. It can be very localized along the coastlines of the world and indeed of the U.S. As you start to group regionally, you are going to miss some of those vertical land motion signals that could be quite local. There are definitely utilities in starting to group, and reasons to do that, and simplifications that can be made, but you have to be aware of the information that you are losing when you are doing that regionalization.

William Sweet: In terms of extreme water levels, previous regional frequency-type analysis oftentimes try to make very large homogenous regions. That has been done and we've found it useful for, say, the Pacific Islands where you just don't have enough gages. You need very big physically defined regions that the statistics work out, so it is homogenous. Although in the gridded for the United States, we did a 500-mile diameter and you typically had plenty of tide gages except along certain areas of the Florida coast. Statistically it tends to get sort of bogged down after greater than 10 gages. That is something we are going to continue to work with and get improvement of the results. I think that it's important to recognize the storms that are missed, in general. Without including past storms or synthetic storms. For instance, the tide gage at Virginia Key has had periodic gaps in it. When hurricane Andrew came across Haulover Key it didn't pick up the big surge that occurred away from it. Reanalysis is a step in the right direction, but ultimately, I think you need the dynamical model simulated historical storms as well as unknown storms, with the regionalization approach to really get at a robust solution.

Question:

I've got a question for Ruby, and its relation to the impact of the storm sharpening on the larger basins in the Pacific Northwest, in particular the Columbia River basin. Given that we will be expecting snow on the higher elevations, with rainfall at the foothills. But then that snow field melts during the spring runoff, so it must be a very complicated pattern you're going to be building up in relation to the Columbia River Basin given how vast it is and how complicated the various mechanisms are. Can you possibly comment on that?

Answer:

Ruby Leung: I think you brought up a very important point about storm analysis. In what I have been showing in my presentation, we did not separate the precipitation into rainfall versus snowfall, but we know that this separation is very important. We know that under global warming, more of the precipitation would be falling in the form of rain, rather than snow and therefore contribute more immediately or directly to flooding. In fact, the next step for this type of analysis would be to separate out the rainfall versus the snowfall. One speculation is that the storm sharpening normally happens in areas where the mountain has very large effects. But that would also mean that perhaps the sharpening happens in a region of high elevation such that even under global warming, maybe the change from rainfall to snowfall is not that significant, meaning that the increased intensity of the precipitation would still be in the form of snow. But this is just a speculation. I think that this is an important point that we need to continue to look into.

Question:

Where do you see modeling going in the next 5 to 10 years? Can we quit worrying about downscaling? Are we going to be able to take care of this with regional models and high-resolution earth system models?

Answer:

Michael Kuperberg: So, we are seeing a real demand for downscaled climate data and sort of an argument over which is the right downscaling approach to use. Earth system models run at 100 km. I can't make decisions at that scale, so we downscale and then you derive things from that. Then you've got regional climate models and you've got the modelers saying don't worry, we will be at 5 km in a few years with exascale computing, etc.

Ruby Leung: This is interesting because we just achieved a milestone for the DOE Energy Exascale Earth System Model project. We now have a graphical processing unit (GPU) enabled global cloud-resolving model at 3 km resolution that we can run on the fastest machine in the world. This is the first exascale computer. We got our first benchmark running this global scale 3 km resolution model on the first exascale computer: you can simulate 1 year running on the whole machine in 1 day. As you can imagine, this is not fast enough for any useful simulations. If we need to provide information for decision-making, we need to provide a lot of simulations to capture the uncertainty and we also need all kinds of simulations like different scenarios and things like that. So, I would say that, even in the next ten years will we not be able to run this kind of global cloud resolving model to provide the type of information needed for supporting decisions. But it doesn't mean that this type of model would not be useful because there are other types of simulations besides running one thousand years of simulations. I mentioned an approach that we use called pseudo global warming (PGW) where you can select a specific storm that happened in the past and simulate how it looks in the future. For that type of simulation, you want high resolution so you can actually resolve the storm, but you don't need to run it for thousands of years. You only need to run the storm for a few days and perturb the conditions to see how it would look. So, I would say that we need to think along the line of what are the different uses of these different types of approaches and how can we combine them together. In the future, regional model is one way of doing dynamical downscaling. But even for global models we now have the capability to zoom in to a specific region of interest to do high-resolution only over a region, but still within a global context. So there are multiple approaches that we can and should take advantage of in thinking about how we can provide higher resolution information to support decisions.

Question:

You mentioned the pseudo global warming (PGW) modeling again. Do you have to downscale the reanalysis before doing the pseudo global warming or do we have enough fine scale reanalysis model results out there at this point in time.

Answer:

Ruby Leung: It depends on whether you already have simulations driven by some trustworthy boundary condition such as reanalysis. Different groups have done that kind of simulation, so you can build on that and take those as your control simulations and run the future projection by perturbing the boundary conditions corresponding to some projected mean changes provided by global models. This is one way you can take advantage of some existing simulations and data. Also, as I mentioned, for PGW simulations in the past, we refer to that type of simulation as continuously running for let's say 10 years or 30 years. But now you can also take the storyline approach, which is a very similar kind of approach, but you only run it for a collection of storms, or a collection of extreme events. You don't have to run it continuously for decades. That would be much more do-able.

Question:

Everyone wants answers, data and modeling, at local scales. By downscaling and regional modeling, we have some ability to do that. To what extent is the National Climate Assessment going to move to more local scales. Right now, it's like the northeast, the southeast. I'm sure that you get questions coming back like: "Where in the south? Can you give me more local information?" So, what is the NCA thinking about in that regard?

Answer:

Michael Kuperberg: The national climate assessment is 32 chapters, 1700 pages now and I think that everybody recognizes that it can't keep getting bigger. It keeps getting bigger because we continue to try to cover more and more information. Regions were an addition, I think, in NCA3. National wasn't good enough. Regions went from 8 to 10, I believe, in NCA4. We are still with 10 regions and yes, we are getting questions like that: "I can't make any decisions until you tell me in my building, on my city block what the temperature is going to be in 2050." Personally, I think that's a red herring. It's going to be hotter, plan for it, or wetter or drier, we can tell you what those trends are. That aside, human nature says that we won't want to make decisions until we can get sufficiently resolved information until we feel comfortable making those decisions. I hope what happens with the NCA is that it has an associated information resource that's more of what you are talking about. We can't just keep making the thing bigger and bigger until you find there's a chapter for each zip code. But the information exists and I think that instead of us just pulling out and cherry picking examples to share with people, I think we can provide that information as a resource that you can dive further into when you want to go beyond the level of detail that we can provide in the document.

Question:

What are the challenges in forecasting atmospheric rivers (ARs) and what key improvements to forecasting models are planned by the National Weather Service?

Answer:

Zack Taylor: The things that we're looking at in terms of forecasting atmospheric rivers are: how much moisture we're dealing with and, within that, how strong are the winds that transport within the AR, and then in terms of more on the mesoscale or local level, what is the angle of the approach against the terrain and how that might impact the vertical lift and the precipitation. Finally, how long it's going to last. The duration obviously is a big component in terms of the precipitation forecasting within the AR. The key ingredients are moisture, angle of the AR, and then the duration are the key factors that forecasters generally look for in terms of forecasting the severity of the atmospheric rivers.

Question:

You had satellites and gages working in parallel to be able to collect data, so does that mean if you for example got partial data from a tide gage, does the satellite complete the rest of it? For example, if the flood is too high for the gage to really understand the actual data going on, did the satellite finish that data?

Answer:

Benjamin Hamlington: I wish that was possible. It's not really a one-to-one match. We can find ways to combine with consideration of the different time and space scales, but they are not exactly exchangeable. But there is a lot of research to go into how we can leverage the two together.

Question:

The second part of my question was how do you deal with partial data? It gives you a lot of information but doesn't take you all the way to the actual realistic scenarios that's happening. Like in the example I gave if the flood is too high for the gage to actually measure.

Answer:

Benjamin Hamlington: Within the sea level research community, we're increasingly viewing it as a network of observations and observational platforms. So, a lot of the most interesting research, and I think most important research, is finding ways to leverage a diverse range of observations to get at what you are ultimately looking for.

William Sweet: If a gage gets destroyed, they'll come in and re-survey afterwards and get like a high-water mark around where the tide gage was. As in anything it has to be surveyed, it has to fit into a reference frame. We have benchmarks that have elevations on them, like terrestrial elevations that you can make measurements to, so it can match the other types of measurements that are there. That's fairly standard practice after a big event. There will also be high water marks that will eventually be used by FEMA to help calibrate the flooding models that go into FEMA for instance.

Question:

I think having the moderate and the major flooding categories are good because they include impacts and, as I understand it, they're defined by local folks on ground who know what's going to get flooded at different water levels. To what extent does that definition include the economic value of the infrastructure? If it does, that's good in one way. But on the other hand it might have to be adjusted over time. How is that taken into account?

Answer:

William Sweet: Right now we are working with FEMA on their next update for the National Risk Index. They take these levels (minor, moderate, and major) and the associated elevations, and do an exposure on the ground. They get the building footprints within that to come up with what would be impacted. I think they have a damage curve that they have used previously. So we do flood frequencies exposure, let's say moving forward to 2050. How is that likely to change? Those are the kind of things that they are looking to incorporate. But you're right, the damage is key. It would be great to talk sea level rise in money. Don't even talk about sea level rise, just talk about changes in money. That would get people's attention. But the minor, moderate, major at least is a communication starting point that people hearing the weather service issue coastal flood warning, can take these measures. So, it means something. People can relate to it. It makes it very personal. What tide gage means something to folks? Getting that money aspect is key. So, the best thing I've seen is the National Risk Index. I know there's other vendor groups out there, private industry groups that do a lot more of the insurance-type secrets that's harder for some of us to get our hands on to really do these types of assessments.

3.3 Day 2: Session 2A – Precipitation

Session Chair: Joseph Kanney, NRC/RES

3.3.1 Presentation 2A-1: NOAA's Exploration of Future Probable Maximum Precipitation Datasets and Methods

Authors: Kelly Mahoney[1], Janice Bytheway[2], Diana Stovern[2], James Correia[3], Sarah Trojniak[3], Ben Moore[1]; [1]NOAA Physical Sciences Laboratory (PSL), [2]NOAA PSL/University of Colorado Boulder & Cooperative Institute for Earth System Research and Data Science (CIESRDS), [3]University of Colorado Boulder & CIESRDS, NOAA/NWS/Weather Prediction Center

Speaker: Kelly Mahoney

3.3.1.1 Abstract

Under recent Congressional support, NOAA has renewed ability to study, develop, and operationalize updated probable maximum precipitation (PMP) estimates. One of the first steps in this process is NOAA's support of a National Academies of Science, Engineering, and Medicine (NASEM) study to examine the pressing questions, needs, and modern scientific capabilities to inform the process. This study is now underway, and we will provide information about its objectives, process, and intended outcomes.

NOAA is also actively performing research to optimize for extreme precipitation estimation analyses of existing, experimental, and possible future operational datasets. These include quantitative precipitation estimation (QPE), quantitative precipitation forecast (QPF), and numerical weather prediction (NWP) based datasets, as well as exploration of approaches to generate new datasets. This talk will highlight early results focusing on the assessment of the strengths and weaknesses of NOAA's operational QPE products, particularly in areas of complex terrain and limited observations. We will also highlight emerging results from characterization of the QPF skill and error characteristics of NOAA's operational high-resolution forecast models, including the High-Resolution Rapid Refresh (HRRR) and High-Resolution Ensemble Forecast (HREF) model datasets. We will detail next steps for further exploration and will welcome feedback and discussion from the audience of these research plans, as well as invite potential stakeholder partnerships for testing and evaluation.

3.3.1.2 Presentation (ADAMS Accession No. ML23177A163)

How hard can it possibly rain?
NOAA's exploration of future probable maximum precipitation datasets and methods

Johnstown Flood of May 31, 1889 (2,200 lives lost)

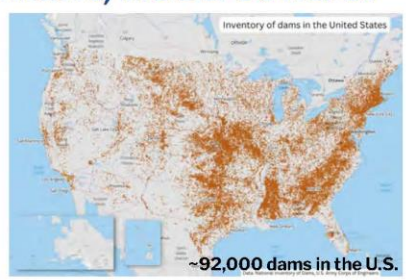
Hurricane Harvey flooding August 29, 2017 (107 lives lost)

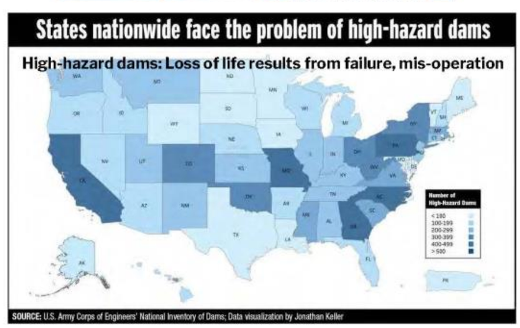
Kelly Mahoney, Janice Bytheway, Diana Stovern, James Correia, Sarah Trojniak, Ben Moore

NOAA | OAR | Physical Sciences Laboratory & NOAA | NWS | Weather Prediction Center & Univ of CO/CIESRDS

8th Annual NRC Probabilistic Flood Hazard Assessment (PFHA) Research Workshop 03/22/23

Dams are critical for water management, flood control





Dams are critical for water management, flood control

Why do dams fail?

- **Overtopping (48%)**
- Piping/Internal Erosion (46%)
- Foundation (4%)
- Seismic (2%)

Dams overtopping due to excessive rainfall

Probable Maximum Precipitation (PMP)

- Probable Maximum Precipitation (PMP) is the maximum depth of precipitation over a given area and duration that is meteorologically possible
- A conceptual "upper bound" of physically-possible precipitation
- Used to ensure that structures like high-hazard dams are safely designed, operated, and maintained

4

How does PMP relate to Precipitation Frequency?

Example:
High hazard
dams vs.
levees

OWP | OFFICE OF WATER PREDICTION

Probable Maximum Precipitation (PMP) and Atlas 14 Precipitation Frequency (PF) Comparison

Purpose: Describe differentiation between Probable Maximum Precipitation (PMP) and Atlas 14 Precipitation Frequency (PF) estimation information.

Comparison	PMP	Precipitation Frequency (Atlas 14)
Definition	Defined as the greatest depth of precipitation for a given duration meteorologically possible for a design watershed or a given storm area at a particular location at a particular time of year (World Meteorological Organization, WMO-No. 1045, 2009) Defined for areas such as watersheds; can cover up to 10,000 square miles.	Defined as the precipitation depth, at a particular location and for a given duration that has a statistically-expected 1-in-YY chance of being exceeded in any given year, where YY is the annual recurrence interval. Defined for finite points on the earth surface.
Development	Storm-based approach that uses archived and projected storms to assess extreme rainfall events that can be geographically transposed to the study area. Incorporates meteorologic and statistical methods. Future PMP studies should account for climate change. Method summary in ESEWG recommendations report, Section 4.2.2.	Point-based approach that uses observed point precipitation (e.g., rain gages) without regard to causative storm events. Incorporates statistical methods. Current methods assume stationary climate. Future methods under development are expected to consider non-stationary climate impact on point locations. Method details in Atlas 14, Volume 11, Section 4
Use	Used for design of large-scale, critical facilities and assets (e.g. dams, nuclear power plants) to address high-hazard risks for events involving catastrophic failure. Considered to represent the "worst case" maximum rainfall to be able to occur.	Used for design of engineering projects and planning and development (e.g. transportation, stormwater management, small-scale infrastructure, flood risk) to design at acceptable risk level. Not intended for use beyond 1000-year average recurrence interval, or 1/1000 annual exceedance probability.

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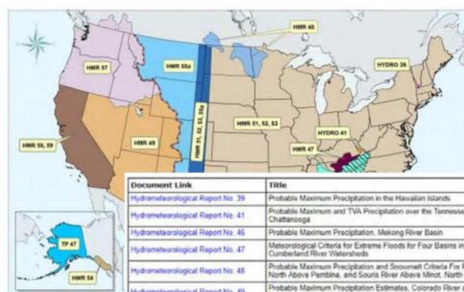
PMP suffers from outdated data, methods, lack of sustained support

- Science of extreme precipitation has advanced since federally-produced estimates created.
- Some recent events have exceeded the PMP (e.g., Hurricane Harvey 2017), but PMP more often criticized for being far too high (and deterministic) → expensive engineering to meet requirements
- Climate change is not accounted for
- **Dams are aging. Climate is changing. Infrastructure risk assessment is becoming higher-stakes. Newer science and tools offer untapped potential.**



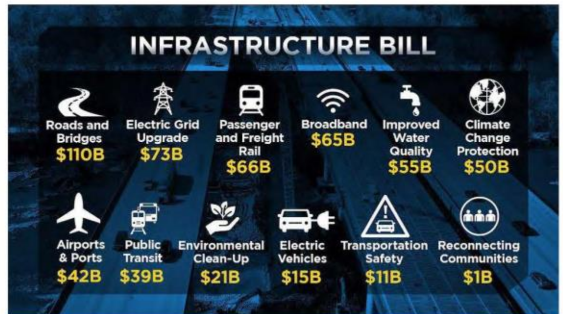
Document Link	Title	Year
Hydrometeorological Report No. 39	Probable Maximum Precipitation in the Hawaiian Islands	1963
Hydrometeorological Report No. 41	Probable Maximum and TVA Precipitation over the Tennessee River Basin abo[ve] Chattanooga	1965
Hydrometeorological Report No. 46	Probable Maximum Precipitation, Mekong River Basin	1970
Hydrometeorological Report No. 47	Meteorological Criteria for Extreme Floods for Four Basins in the Tennessee a[nd] Cumberland River Watersheds	1973
Hydrometeorological Report No. 48	Probable Maximum Precipitation and Snowmelt Criteria For Red River of the North Above Pembina, and Souris River Above Minot, North Dakota	1973
Hydrometeorological Report No. 49	Probable Maximum Precipitation Estimates, Colorado River and Great Basin Drainages	1977
Hydrometeorological Report No. 51 (Digitized maps)	Probable Maximum Precipitation Estimates, United States East of the 105th Meridian	1978
Hydrometeorological Report No. 52	Application of Probable Maximum Precipitation Estimates - United States East [of] the 105th Meridian	1982
Hydrometeorological Report No. 53	Seasonal Variation of 10-Square-Mile Probable Maximum Precipitation Estima[tes], United States East of the 105th Meridian	1980
Hydrometeorological Report No. 54	Probable Maximum Precipitation and Snowmelt Criteria for Southeast Alaska	1983
Hydrometeorological Report No. 55A	Probable Maximum Precipitation Estimates - United States Between the Continental Divide and the 103rd Meridian	1988
Hydrometeorological Report No. 56	Probable Maximum and TVA Precipitation Estimates With Areal Distribution for Tennessee River Drainages Less Than 3,000 Mi^2 in Area	1986
Hydrometeorological Report No. 57	Probable Maximum Precipitation - Pacific Northwest States, Columbia River (including portions of Canada), Snake River and Pacific Coastal Drainages	1994
Hydrometeorological Report No. 58	Probable Maximum Precipitation for California - Calculation Procedures	1998
Hydrometeorological Report No. 59 (HMR58 and HMR59 shapefiles)	Probable Maximum Precipitation for California	1999

Summary of NOAA's Hydrometeorological Reports ("HMRs")

New federal support for PMP modernization

- **Infrastructure Investment and Jobs Act /Bipartisan Infrastructure Law (**FY 2022–2026) and **PRECIP Act** (passed Dec 2022)
- Provide support to **NOAA to modernize PMP**
- Fund NOAA to work with the **National Academies of Science, Engineering, and Medicine** to:

    "… convene an ad hoc committee to consider approaches for estimating probable maximum precipitation (PMP) in a changing climate, with the goal of recommending an updated approach, appropriate for decision-maker needs…that can serve as a national standard."



PUBLIC LAW 117–58—NOV. 15, 2021

(3) $492,000,000 shall be for coastal and inland flood and inundation mapping and forecasting, and next-generation water modeling activities, including modernized precipitation frequency and probable maximum studies;

7

National Academies Study on PMP: When and how?

- Study kicked off in October 2022. It will take two years to complete.
- Committee of 12 volunteer experts
- Public information gatherings coming up to broadly engage public- and private-sector users and stakeholders of PMP estimates

  Sign up for announcements: https://www.nationalacademies.org/our-work/modernizing-probable-maximum-precipitation-estimation
- Culminate in recommendations/report published on publicly available website

NATIONAL ACADEMIES Sciences Engineering Medicine

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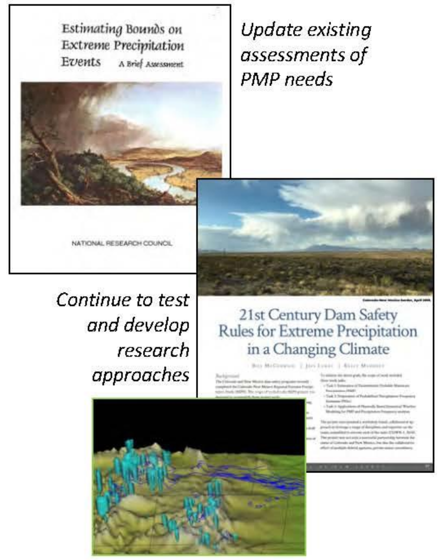
NOAA's next steps for PMP under BIL and PRECIP Act

- Work with National Academies Study
- Pursue research to develop and prototype innovative science, tools
  - Consider, develop key dynamical model capabilities
  - Balance scientific possibilities with user appetite/needs/capabilities
  - Test possible approaches with relevant stakeholder groups
- Ultimate goal: Federally-endorsed, state-of-the-science-informed design values for safe infrastructure engineering and operations



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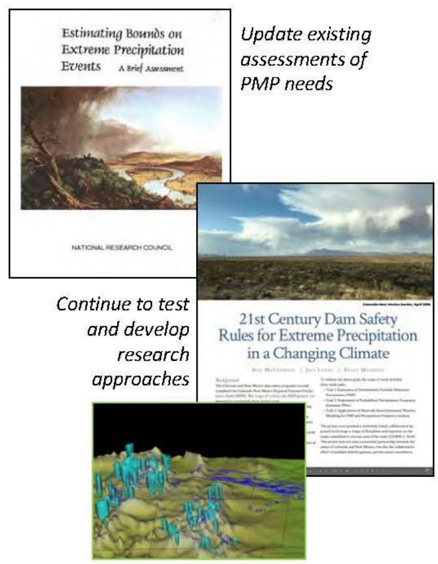
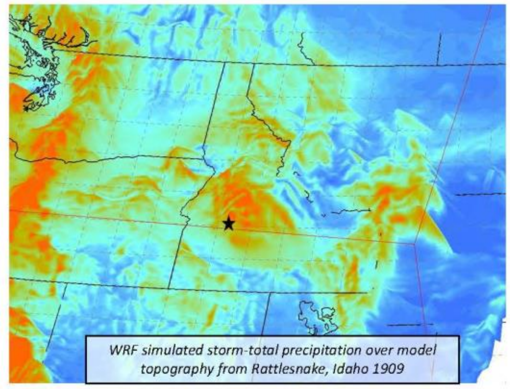


10

Why emphasize dynamical modeling?

Dynamical model benefits to dam safety applications, updated PMP estimation:

- Continuous in space and time
- Reduce need for many spatial, temporal, physical assumptions
- Huge benefit in data-sparse regions of complex & high-elevation topography
- Quantification of uncertainty, incorporation of climate change scenarios
- Physical integration with newer dynamical hydrologic models



Mahoney, Kelly M., Chesley McColl), Doug Hultstrand, Bill Kappel, Bill McCormick, Gilbert P. Compo (2021): Blasts from the past: Reimagining historical storms with model simulations to modernize dam safety and flood risk assessment. *Bull. Am. Meteor. Soc.*

New capabilities, increasing computational resources offer promise for dynamical model-driven, "PMP-like" product

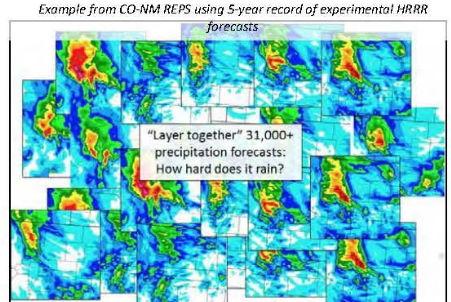
Design, tractability, support, applications to be explored...

Opportunities: Use numerical models more comprehensively

Mining available model-based datasets

- ➢ "Ensemble" of all HRRR forecasts (prototyped for CO-NM PMP project)
- ➢ What else can be mined? National precipitation (obs, forecast) datasets

Example from CO-NM REPS using 5-year record of experimental HRRR forecasts



How to generate a suite of model representations of physically-possible, internally consistent, precipitation states?

Opportunities: Use numerical models more comprehensively

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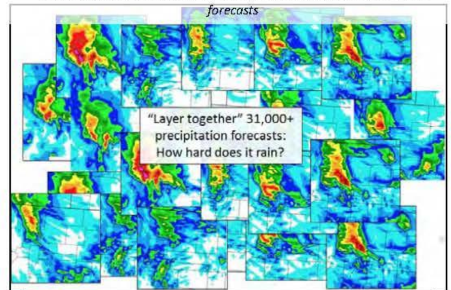

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An extreme precipitation-optimized ensemble

- High-resolution ("convection-permitting")
- Go beyond selected historical events
- Maximize spatial, temporal continuity

A super-ensemble suited to a "PMP-like" problem?

- Increase period of record using historical reanalyses from 1800s
- Take advantage of state-of-the-art ensemble design methods (e.g., adjoint methods, initial state perturbation optimization), stochastic physics
- Perturbations to maximize dynamically-derived sensitivities toward maximizing precipitation

State-of-the-art perturbation strategies, moisture-maximizing 'butterflies'?

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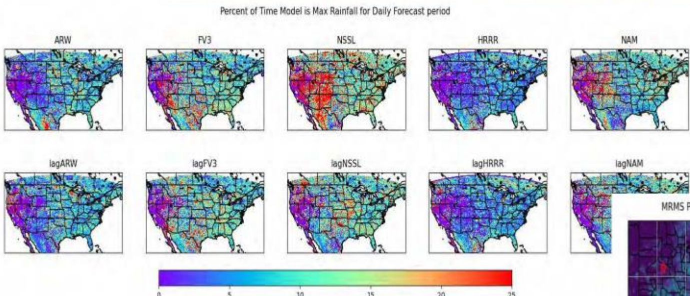
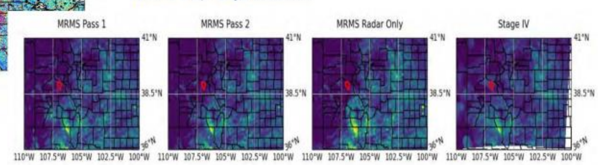
Characterize representation of extreme precip in NOAA's existing QPE, QPF datasets



NOAA High-Res QPF products

NOAA QPE products



Opportunities: Use numerical models more comprehensively

NOAA has multiple convection-allowing models and ensemble modeling systems

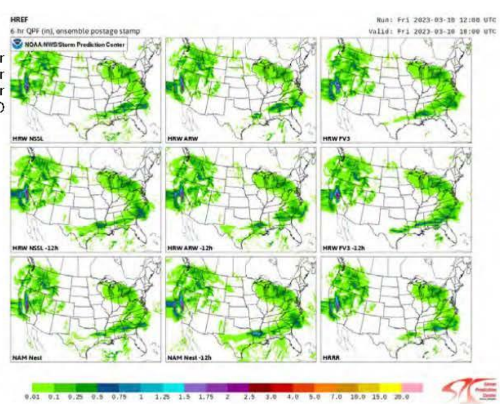
- ➢ Are they useful?
- ➢ Are their forecasts physically consistent, and do they produce extremes to help with PMP modernization?
- ➢ What are the relative strengths, weaknesses, general error characteristics of different models?
- ➢ Are there regions of the CONUS where these models are less adequate for purpose?

Opportunities: Use numerical models more comprehensively

NOAA has multiple convection-allowing models (CAMs) and ensemble modeling systems

- ➢ **The High Resolution Ensemble Forecast System (HREF)**
- ➢ Set of different high resolution forecast models at varied initialization times cobbled into an “ensemble of opportunity”
- ➢ The “ensemble to beat” when it comes high impact forecasts for severe and hazardous weather events
- ➢ The developmental “sandbox” for a new, formal ensemble: the next generation Rapid Refresh Forecast System (RRFS)

HREF member by member forecast for 2023-03-10



- ➢ Caveats
  - ○ Not a formally designed ensemble system - all members not equally likely - but adequate for spread at certain scales.
  - ○ Minimal use of advanced data assimilation and thus current observations.
  - ○ Individual members have slightly different grid spacing and thus representation of physical processes.

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Analysis approaches

1. **Ensemble analysis**

+ What can we learn from means, maxima, and advanced probabilistic diagnostics?
- Ensemble means reduce data volume, compute requirements; limit ability to understand, interpret, explain individual member contribution, physical process fidelity

2. **Individual member analysis**

+ Members have different cores, physics, initial conditions...outputs (forecast skill, biases, etc.) will vary; value in preserving and understanding sources of ensemble spread
- Multiple high-resolution members makes for very large datasets, and computationally expensive analysis calculations

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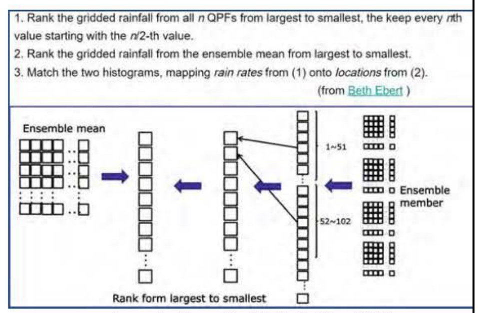
When using an ensemble mean, peak values are smoothed out and too low; extremes are removed.

Probability Matched Mean (PMM) and Local Probability Matched Mean (LPMM) are useful diagnostics that maintain the spatial distribution of the ensemble mean, but retain peak values of individual members

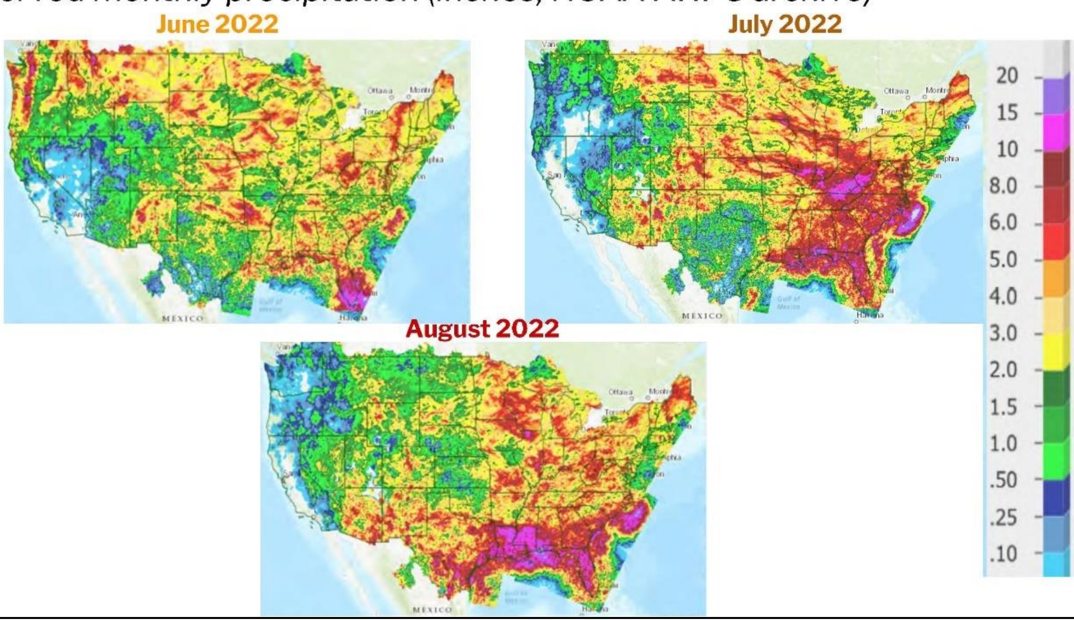
- PMM uses entire domain
- LPMM looks over smaller areas to keep coherent precip areas separate



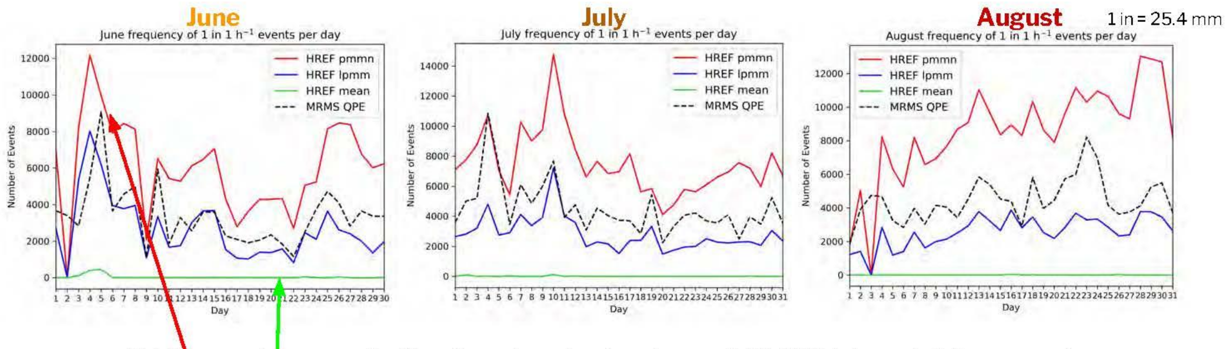
Improving Ensemble QPF Dr. Dai Kan (NMC)

HREF Analysis of 2022 Summer Convective Season

Observed monthly precipitation (inches; NOAA AHPS archive)



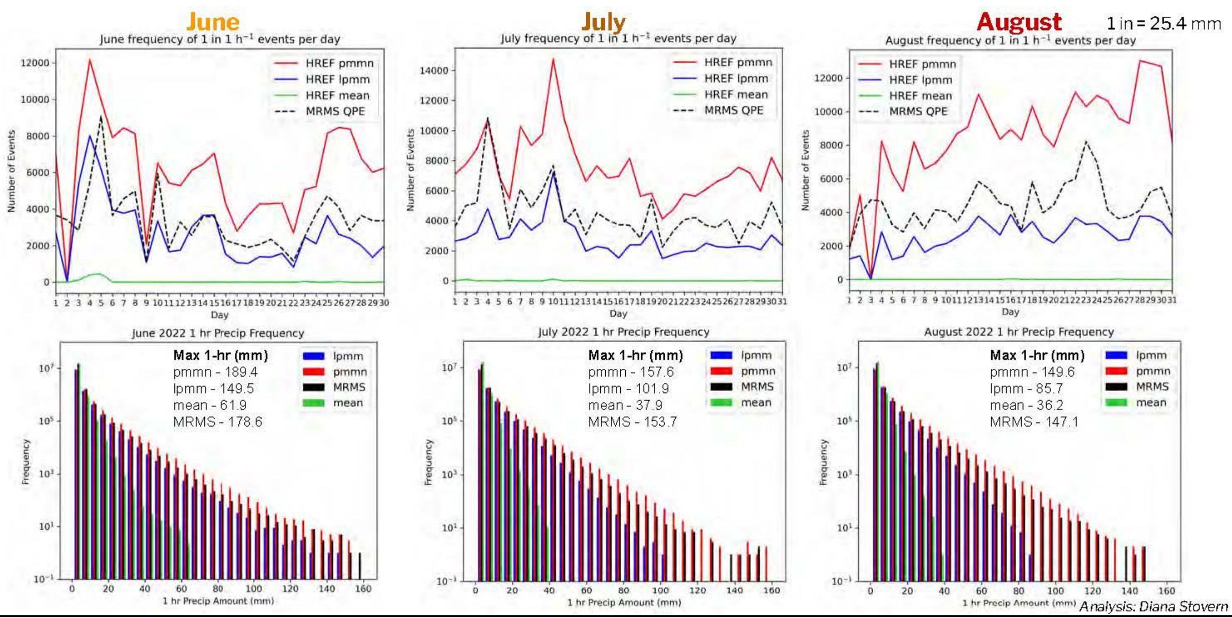
HREF Analysis of 2022 Summer Convective Season - Preliminary Results from the Day 1 - 00 UTC Forecast over CONUS: Ensemble Mean Analysis



- HREF ensemble mean significantly underestimates observed (MRMS) 1-h precipitation amounts
- The PMM highlights precipitation forecast maxima most clearly relative to other means

Analysis: Diana Stovern

HREF Analysis of 2022 Summer Convective Season - Preliminary Results from the Day 1 - 00 UTC Forecast over CONUS: Ensemble Mean Analysis



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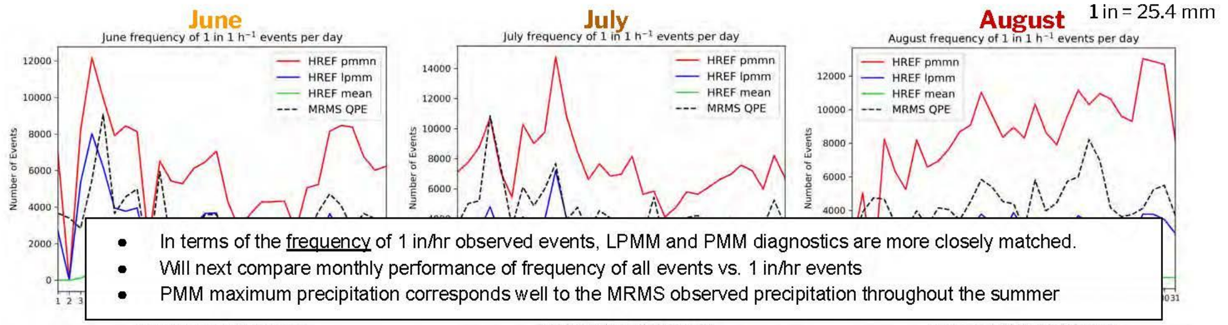
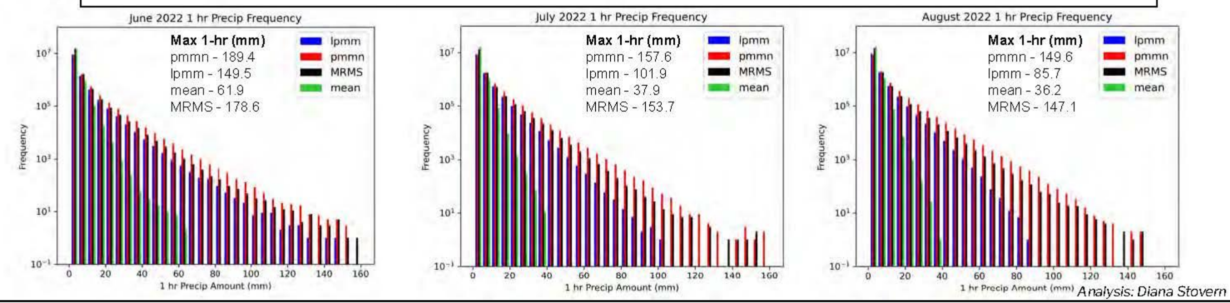


- In terms of the <u>frequency</u> of 1 in/hr observed events, LPMM and PMM diagnostics are more closely matched.
- Will next compare monthly performance of frequency of all events vs. 1 in/hr events
- PMM maximum precipitation corresponds well to the MRMS observed precipitation throughout the summer



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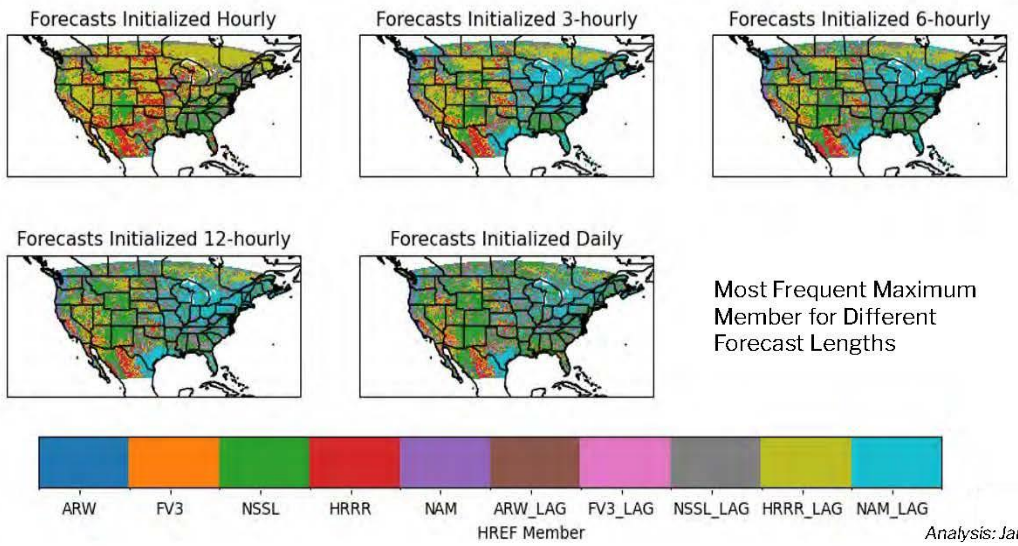
HREF Analysis of 2022 Summer Convective Season - Preliminary Results from the Day 1 - 00 UTC Forecast over CONUS: Individual Member Analysis

Which of the HREF members provides the maximum daily rainfall?



Analysis: Janice Bytheway

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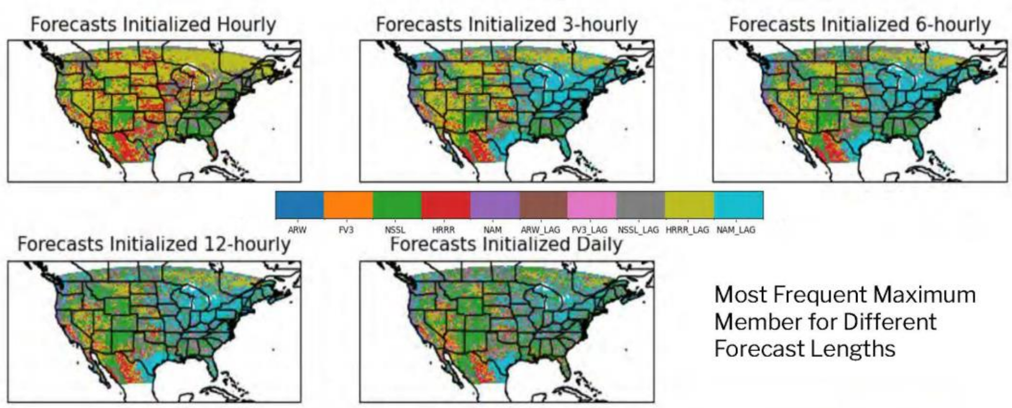
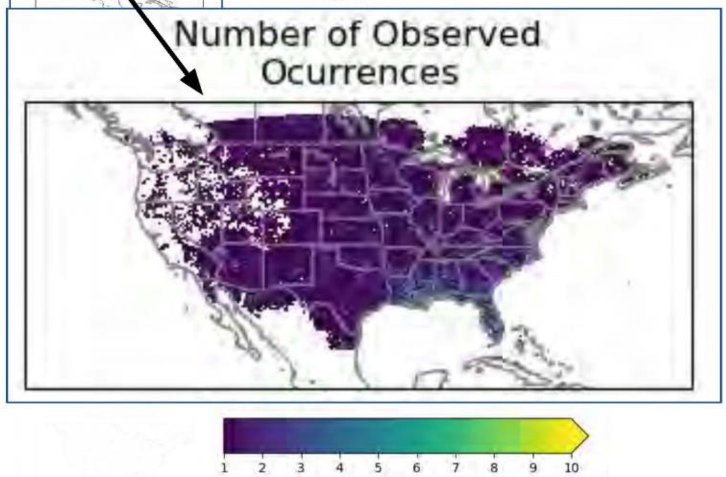


- Depends on how often we consider a new model run
- For hourly-updated forecasts each hour, HRRR and lag-HRRR generally provide maximum daily accumulation over most of the US; NSSL dominates in southeast and North American Monsoon
- Daily rainfall calculated from daily-initialized forecasts highlights NSSL model in western US and lag-NAM east of Rockies

HREF Analysis of 2022 Summer Convective Season - Preliminary Results from the Day 1 - 00 UTC Forecast over CONUS: Individual Member Analysis

How much do individual members agree with exceedances of 1 in/hour?

- In observations, most occurrences of 1"/hour along the Gulf Coast, into the Great Plains and North American Monsoon region



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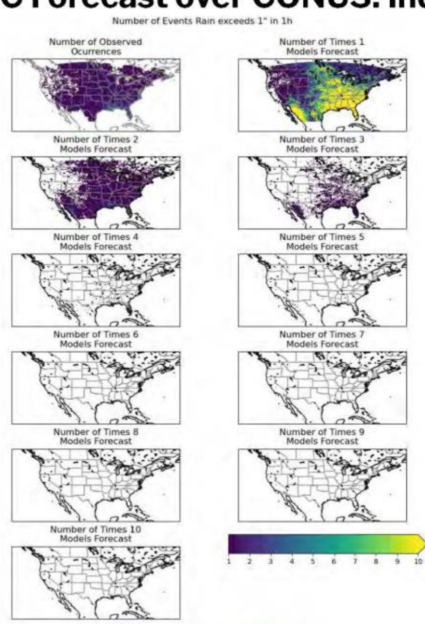

- In observations, most occurrences of 1" in 1 hour along the Gulf Coast, into the Great Plains and North American Monsoon region.
- In the HREF forecasts, fairly common to have one member predict 1"/h.
- Frequency with which 2 models predict 1"/h fairly similar to frequency of observations of 1"/h
- Increasingly unlikely to have additional models agree on a prediction of 1"/h

Analysis: Janice Bytheway

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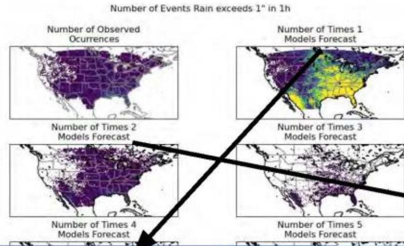

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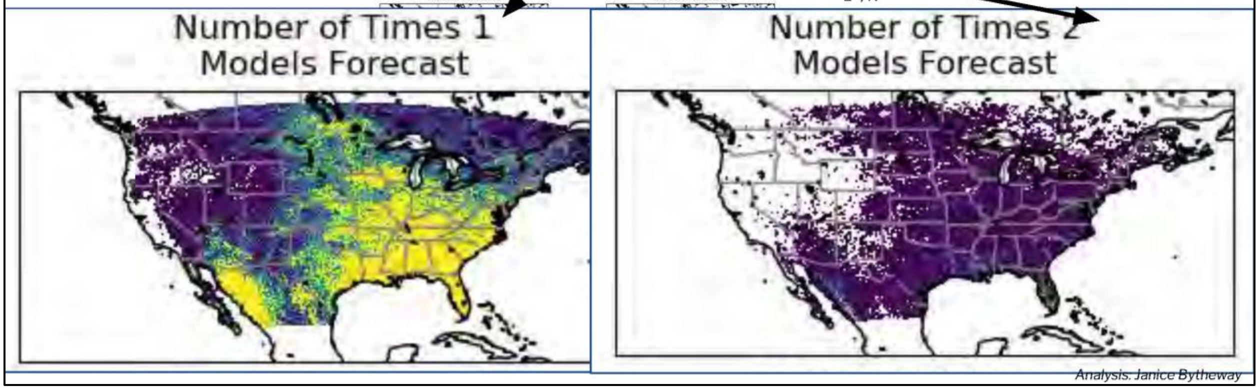

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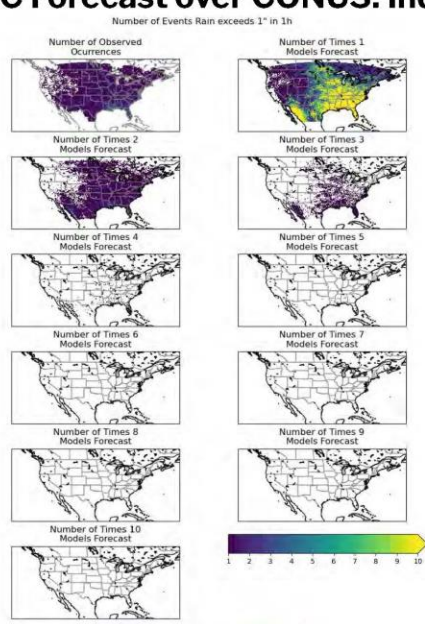

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Analysis: Janice Bytheway

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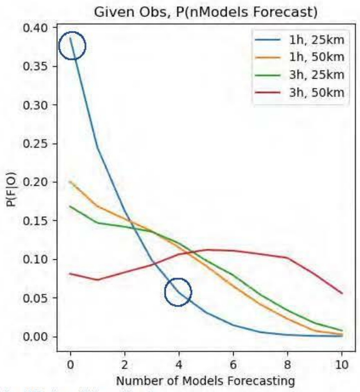
Given an observation of 1" of rainfall has fallen (in 1 or 3h), what is the probability that N model members will have predicted 1" in the same time period, and within a given radius?



Example: 1 h, 25-km (blue line)

- If 1"/hour is observed, ~38% chance *none* of the members will predict 1"/hour within 25 km
- *But* a 5% chance that 4 members *will* have extreme rainfall (1"/hour) within a 25-km radius)

Analysis: Janice Bytheway

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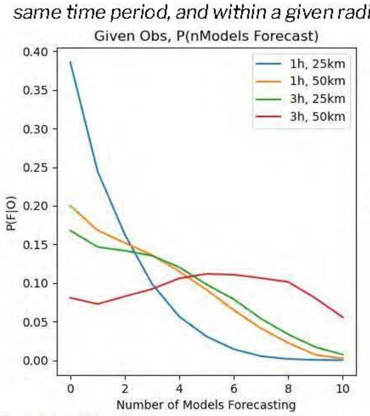
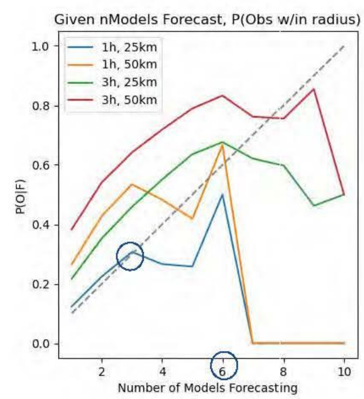


Example: 1 h, 24-km (blue line)

- If 1"/hour is observed, ~38% chance *none* of the members will predict 1"/hour within 25 km
- *But* a 5% chance that 4 members *will* have extreme rainfall (1"/hour) within a 25-km radius)

Given N model members predict extreme rainfall, what is the probability that it will be observed within a given radius?



- Never more than 6 models predicting 1"/hour (in this period)
- For 1"/hour within 25 km, HREF useful for highlighting extreme rainfall: when up to 3 members agree: i.e., if 3/10 models predict, there's a 30% chance it was observed)
- For larger radius or longer period, HREF underpredicts somewhat

Analysis: Janice Bytheway

Summary: Preliminary characterization of extreme precipitation in NOAA's high-resolution datasets

- Initial analysis of HREF for summer 2022: reinforces that convection-allowing ensemble of sufficient size increases the ability to capture extreme rainfall and/or environments capable of supporting extreme rainfall
- Ensemble mean not useful for PMP, but diagnostics (PMM) helpful as reasonable skill, likelihood demonstrated for at least one HREF member indicating extreme rainfall
- Complementary analysis approaches: couple ensemble means, diagnostics with individual model framework to understand forecast confidence, ability of modeling systems to capture extremes
- Ensembles provide wiggle room for expected individual member failure from cascading errors and challenging compound environments (e.g., convective outflow as trigger to extreme rainfall)
- Future work: focus on optimization of ensemble design; analyses to investigate regional signals, weather regime relationships (relevant for different steps, ingredients in existing PMP methods)

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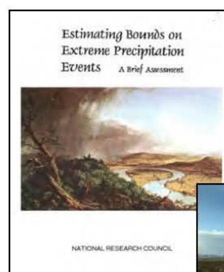
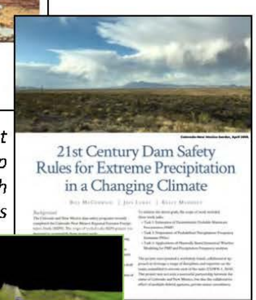
Summary: NOAA's upcoming plans for PMP

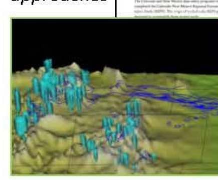
- Continue to work with National Academies Study
- Continue research to develop and prototype innovative analysis, model development, climate science
- **Ultimate goal: Federally-endorsed, state-of-the-science-informed design values for safe infrastructure engineering and operations**
- **Timeline**
  - October 2022 - October 2024 National Academies Study, NOAA prototyping research
  - 2024 - 2026 NOAA responds to, implements study recommendations
  - By 2030: New PMP estimates produced, publicly available



Update existing assessments of PMP needs



Continue to test and develop research approaches



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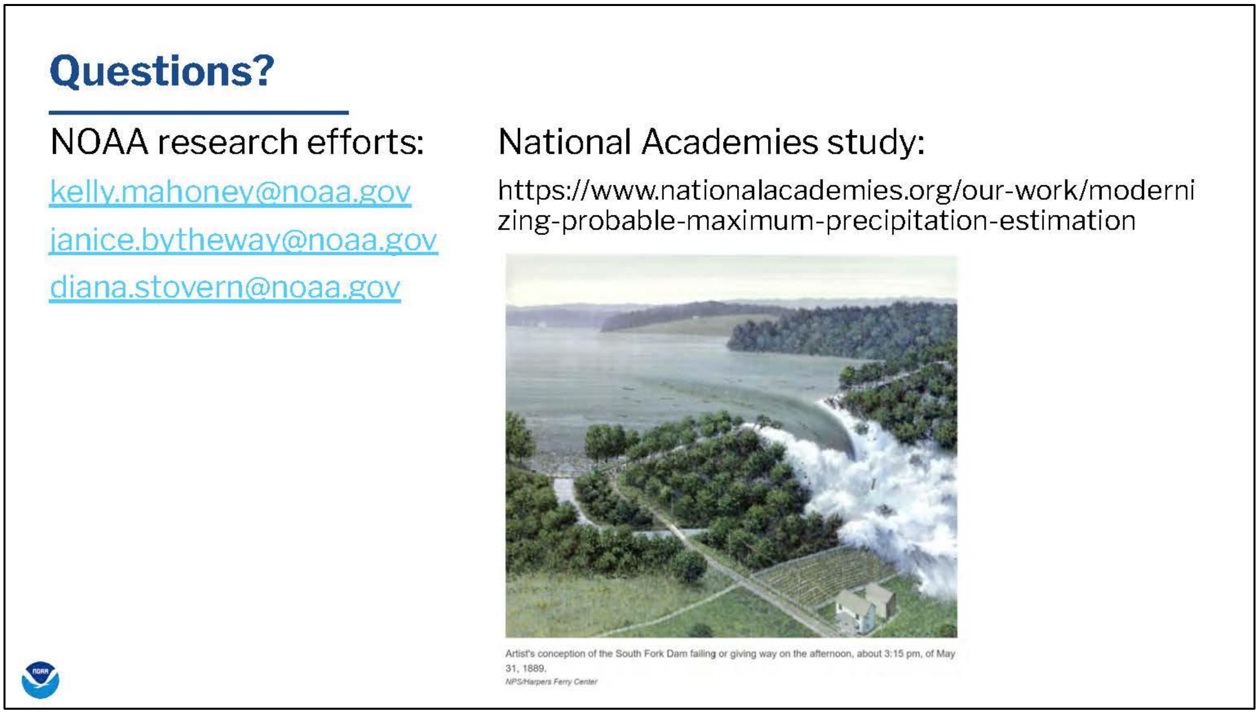


3.3.1.3 Questions and Answers

Question:

When we look at our risk analysis models for our [nuclear] plants, we have to choose a mission time and it's typically around 24 hours, but it could be shorter, it could be longer. So, with regard to the tools you are going to be developing for PMP, is it going to be able to use a different timescale or a selectable timescale, for example, a PMP on a 24-hour period, a 12-hour period, or maybe even longer that 24? Can you select the timescale that you are interested in when you are focusing in on a plant or a region?

Answer:

The caveat is, in terms of what results NOAA puts forth, it's going to depend on the recommendation of the National Academies study. But in terms of the actual research we're developing, all of NOAA's high resolution dynamical models are well beyond an hourly time cycle and increasingly sub-hourly information is available. I think that that is very possible to have things that are scalable in duration and have near-continuity in the temporal resolution. So, I think those options will be certainly available in terms of the research and it's really useful to hear from the community what those needs are and that they should be prioritized in terms of how we decide to put out the official new guidance. So thank you for that.

Question:

Usually with the information that we've used from NOAA for the PMP or other estimates. I think they have been capped at 24 hours, maybe I'm wrong. Will this go out beyond 24 hours?

Answer:

It could. For other regions they do go out beyond that, to 72 hours and so on. It depends on the region and the weather phenomenon of interest. I think, once again, that's an open question.

They can go out longer, and whether or not they will go out longer in discrete chunks or in a spectrum that you could cater to your own needs, I think it's possible.

Comment:

Joseph Kanney: I think the dam safety community would certainly want much longer durations for many of their applications.

Question:

Will the annual excess probability for the PMP will be presented when the improved PMPs are announced?

Answer:

We explored that idea through the Colorado-New Mexico extreme precipitation study that I mentioned, and I see a number of folks online who were part of trying to make that happen. It was an interesting exploration. I do not know if or how it will happen here, but I think the conversation is one to keep having. I completely understand that is how most of the user community is going to be brought to the table here, by at least addressing each of those approaches.

3.3.2 Presentation 2A-2: The "Perfect Storm": Can Atmospheric Models Improve Confidence in Probable Maximum Precipitation (PMP)?

Author: Emilie Tarouilly, University of California, Los Angeles

Speaker: Emilie Tarouilly

3.3.2.1 Abstract

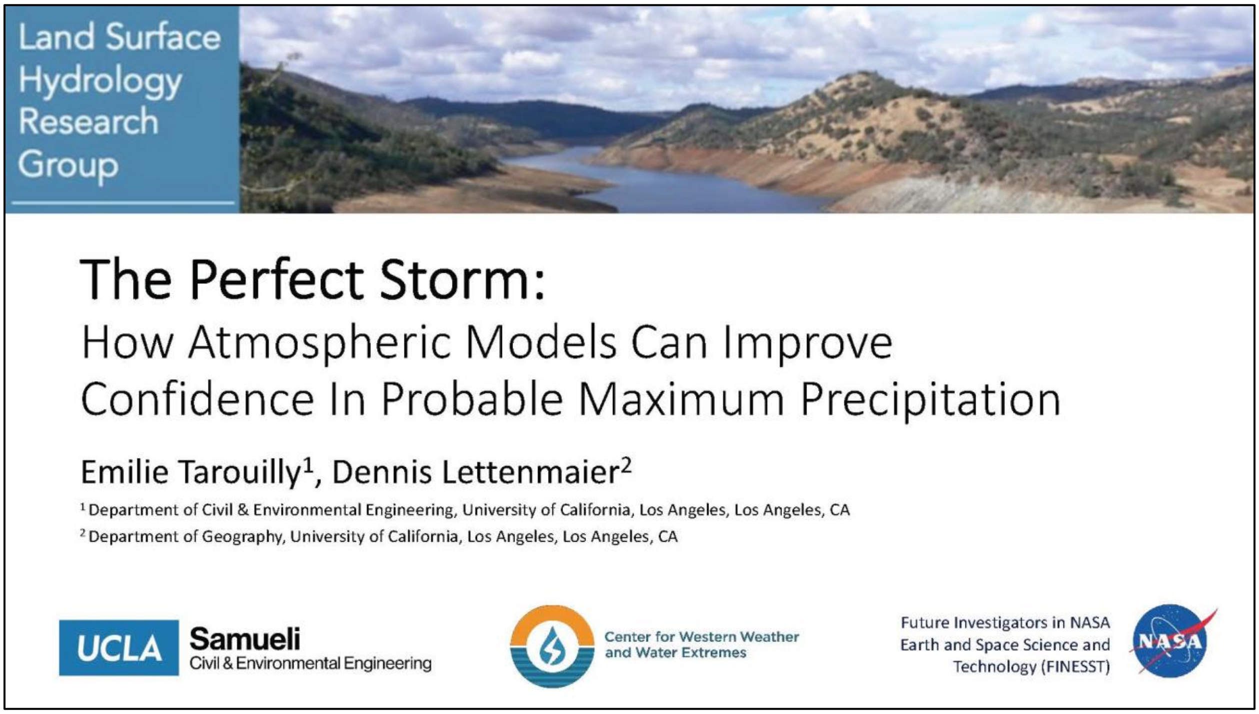
The flood that would result from the greatest depth of precipitation "meteorologically possible", or Probable Maximum Precipitation (PMP) is used to ensure the safety of nuclear power plants, among other high-risk structures. Historically, PMP has been estimated by scaling (extrapolating) depth-area-duration relationships obtained from severe historical storms, following guidelines from the so-called Hydrometeorological Reports (HMRs). Over the last decade, frameworks that leverage numerical weather prediction models to predict precipitation resulting from the addition of moisture (called relative humidity maximization, or RHM) have been developed. Incorporating current understanding of precipitation processes in those model-based methods represents an important advance.

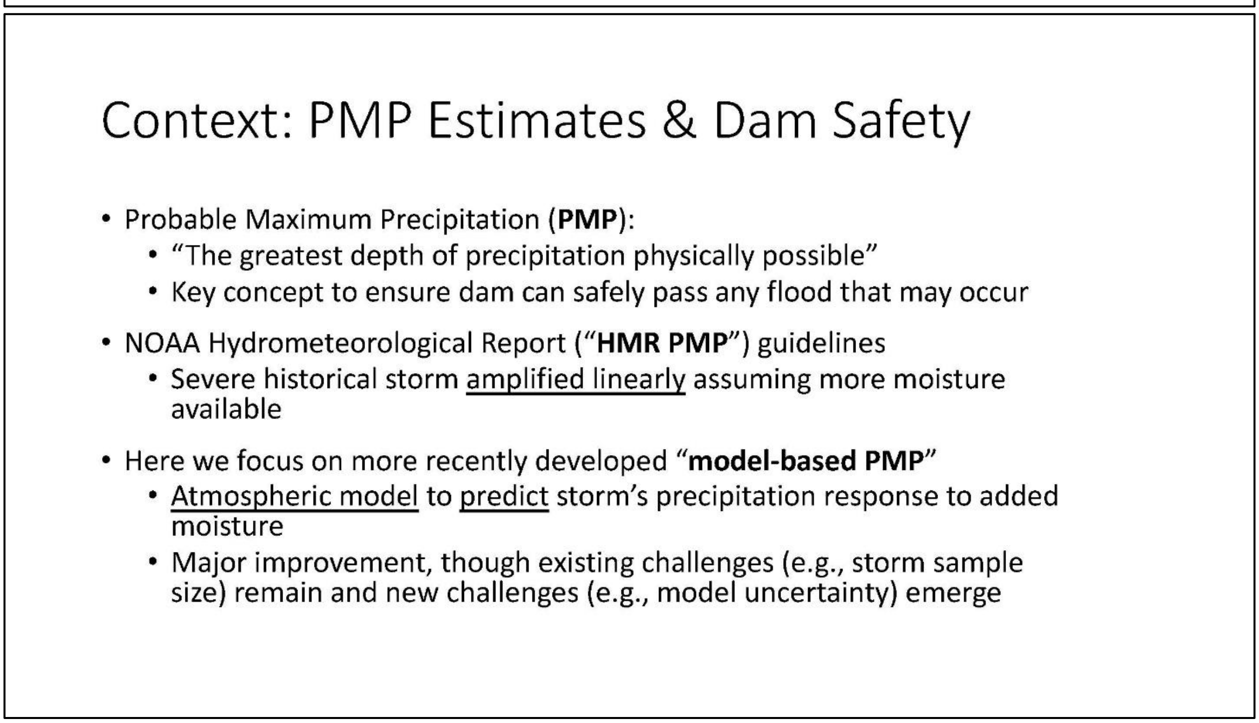
Nonetheless, model-based PMP still relies on key assumptions: (1) that severe historical storms achieved maximum efficiency (moisture conversion to precipitation), such that only moisture needs to be maximized and (2) that maximizing moisture (i.e., saturating the atmosphere) near the target basin is realistic and consistently maximizes precipitation. Numerical weather prediction models allow us to re-evaluate those assumptions and perform scenario analyses to develop physically-based guidelines on how to reliably maximize storms. Additionally, as the use of model-based tools introduces new challenges such as model uncertainty, our scenarios include different model setups and parametrizations that aim to characterize the magnitude of this uncertainty.

Focusing on the Feather River basin in California, we downscale the most severe historical storms from ERA5 reanalysis using the WRF model. Using this ensemble of high-resolution simulations, we seek to identify key attributes of these storms (storm orientation, convection and

large-scale convergence) that control precipitation efficiency and we characterize the nonlinear precipitation response to the addition of moisture in our simulations. In so doing, we highlight that PMP would be better presented as an ensemble of values, such that uncertainty can be communicated, rather than a single estimate, and develop guidance for the engineering community on how to consistently maximize storms.

3.3.2.2 Presentation (ADAMS Accession No. ML23177A164)





Research Questions

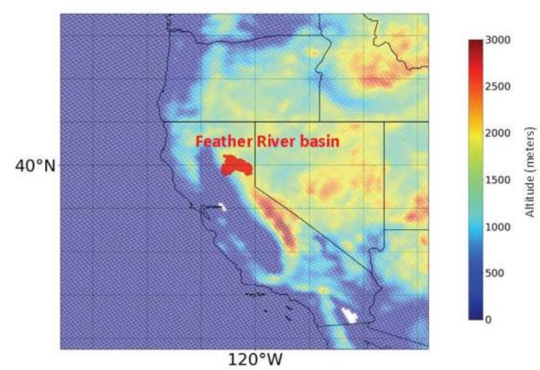
How is the model-based PMP estimate affected by the following sources of uncertainty:

1. Model uncertainty (e.g., initial conditions, choice of parametrization)?
2. Storm efficiency uncertainty due to small sample of historical storms?
3. Moisture maximization uncertainty (how much moisture to add, when and where?)

Goals: Improve the **robustness** of model-based **PMP estimates** by better representing uncertainty and providing the engineering community with more **physically-based guidelines** on how to reliably maximize storms

Study Domain

Feather River basin (3600 sq mi) above Oroville dam, California



Model-based PMP Procedure
(Common To All Experiments)

(1) Storm Selection from Forcing Dataset
Storm with the largest 3-day precipitation totals are selected from ERA5 reanalysis

(2) Storm Reconstruction
Reconstruct (i.e., downscale) selected storms using regional climate model (WRF)

(3) Storm Amplification
Amplification of the storms using the Relative Humidity Maximization (RHM) method (100% relative humidity at model boundaries)

Model-based PMP Procedure
(Sensitivity Analysis)

(Q1) Identify a larger sample of storms to evaluate importance of storm efficiency

(1) Storm Selection from Forcing Dataset
Storm with the largest 3-day precipitation totals are selected from ERA5 reanalysis

(2) Storm Reconstruction
Reconstruct (i.e., downscale) selected storms using regional climate model (WRF)

(Q2) Vary modeling setup to evaluate importance of modeling choices

(3) Storm Amplification
Amplification of the storms using the Relative Humidity Maximization (RHM) method (100% relative humidity at model boundaries)

(Q3) Vary moisture perturbations to evaluate importance of implementation

Q1: Model Uncertainty

Problem: Model creates new sources of uncertainty, which limits confidence in the resulting model-based PMP estimate

Solution: Design an ensemble of PMP simulations that samples these known sources of uncertainty + Assess the resulting range of possible PMP estimates

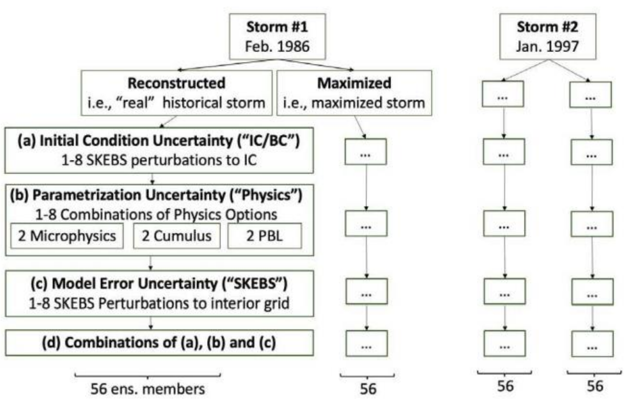
Published in J. Hydromet. (2023)

Improving Confidence in Model-Based Probable Maximum Precipitation: How Important is Model Uncertainty in Storm Reconstruction and Maximization?

Emilie Tarouilly, Forest Cannon, Dennis P. Lettenmaier

Model Uncertainty

Methods: Ensemble Design



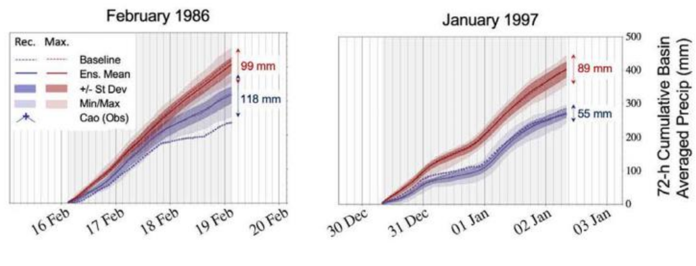
Sampling known sources of uncertainty e.g., impact of:

- Different physics parametrizations
- Error ("SKEBS" perturbations) in initial conditions and model simulations

56 ensemble members for each version (reconstructed and maximized) of each storm (Feb. 1986 and Jan. 1997)

Model Uncertainty

Results: Uncertainty estimates



Reconstructed storms differ:

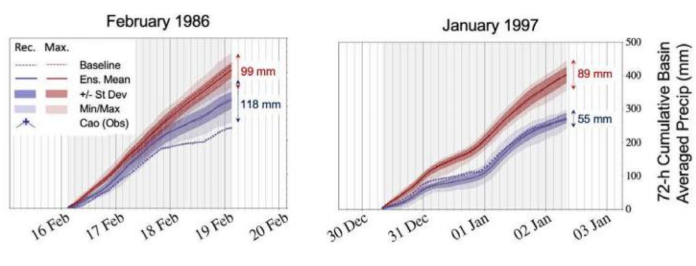
- Magnitude differs
- Quality of reconstruction and spread differ

Yet **maximized storms** have similar behavior

- 3-day totals roughly 400 mm
- Ensemble spread ~100 mm

Model Uncertainty

Results: Uncertainty estimates



Reconstructed storms differ:

- Magnitude differs
- Quality of reconstruction and spread differ

Yet **maximized storms** have similar behavior

- 3-day totals roughly 400 mm
- Ensemble spread ~100 mm

⇒ Ensemble 90th perc is ~110% of the ensemble mean i.e., uncertainty would not cause maximized totals to be much greater than existing single-value estimates

Key Points

- Wider assessment of model uncertainty needs to be conducted:
  - Impact of different forcing datasets?
  - Does uncertainty depend on storm type?
  - Further assessment of model error (”SPPT” in addition to “SKEBS” perturbations)
- Model uncertainty is not large enough to be a barrier to the further development of model-based PMP
- Nevertheless, an ensemble of PMP estimates rather than a single value should be reported in order to represent the uncertainty

Q2: Storm Sample Size & Storm Efficiency Uncertainty

Problem:
Much work has been done on moisture, but not on storm efficiency*

1. Efficiency assumed to be already maximized in historical storms
2. Assumed not to change as a result of maximization

Solution:

- Identify storm efficiency historical maxima (i.e., approximate the upper bounds)
- Search a large sample of artificial storms and identify how extreme efficiency and precipitation are

*Efficiency defined as precipitation/precipitable water

Storm Sample Uncertainty

Methods: Storm Selection before Downscaling

In addition to ERA5 (historical) storms, use CESM2-LE (a GCM large ensemble) to provide additional ~1200 years of artificial storms with same characteristics (equally plausible) as ERA5

Top 10 storms by 3-day total precipitation (Feather basin average) before downscaling:

ERA5*

Storm	3-day Precip (mm)
13-Oct-62	293.15
18-Feb-86	246.95
23-Dec-64	240.80
1-Jan-97	229.15
9-Jan-95	208.70
9-Jan-17	196.46
1-Dec-12	185.80
10-Mar-95	184.24
31-Jan-63	181.22
11-Nov-73	171.00

From 1950-2020 i.e., ~70 years

CESM2*

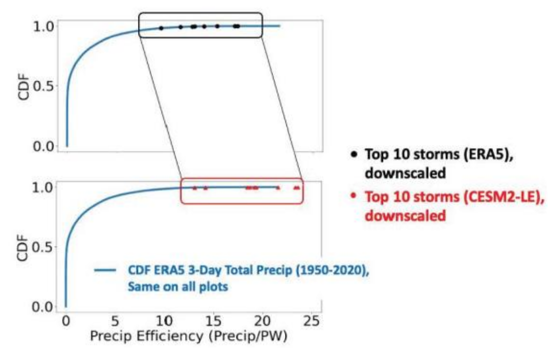
Ens. Mem.	Storm	3-day Precip (mm)
009	18-Jan-2011	291.83
003	13-Jan-1924	257.87
009	17-Dec-1985	249.63
007	26-Jan-1946	248.82
010	29-Dec-1979	247.23
001	29-Dec-1979	247.23
008	30-Dec-1906	246.68
003	16-Jan-1973	242.26
005	16-Nov-1908	235.5
005	4-Jan-1924	228.86

x10 from 1900-2020 i.e., ~1200 years

Storm Sample Uncertainty

Results: Storm Efficiency in Model Reconstructions

CESM2-LE storms have **efficiency up to 30% higher than historical storms from ERA5** (HMRs assumed historical storms reached maximum)

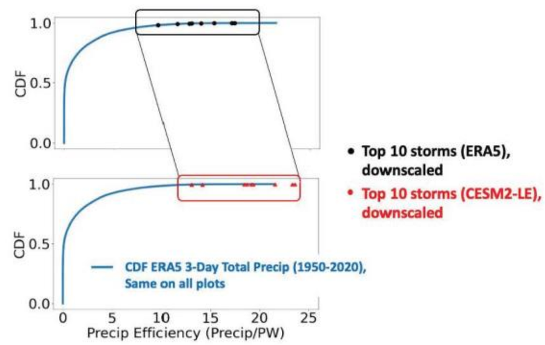


Storm Sample Uncertainty

Results: Storm Efficiency in Model Reconstructions

CESM2-LE storms have **efficiency up to 30% higher than historical storms from ERA5** (HMRs assumed historical storms reached maximum)

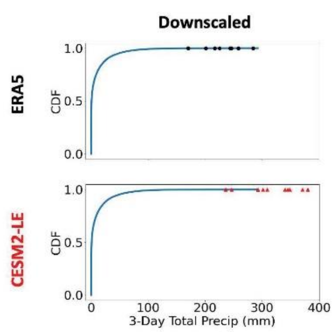
⇒ **HMR assumptions not verified**
⇒ **Could PMP estimates be larger if storms with maximum theoretical efficiency were found?**



Storm Sample Uncertainty

Results: Impact of storm efficiency on PMP estimate

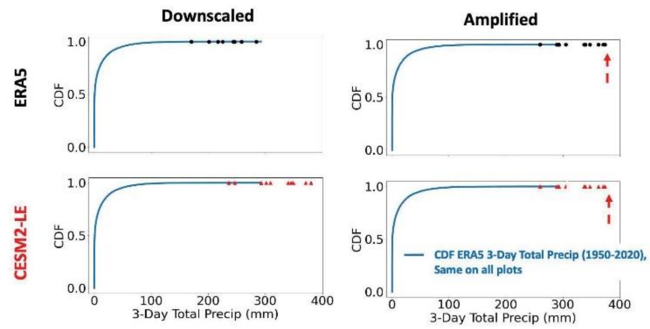
- Owing to higher storm efficiency, CESM2-LE storms have higher precipitation than ERA5 storms



Storm Sample Uncertainty

Results: Impact of storm efficiency on PMP estimate

- Owing to higher storm efficiency, CESM2-LE storms have higher precipitation than ERA5 storms
- Yet once amplified, CESM2-LE storms do not produce much larger totals than ERA5 storms



Storm Sample Uncertainty

Results: Impact of storm efficiency on PMP estimate

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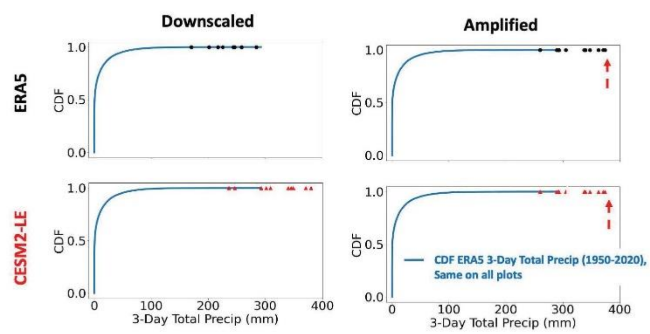
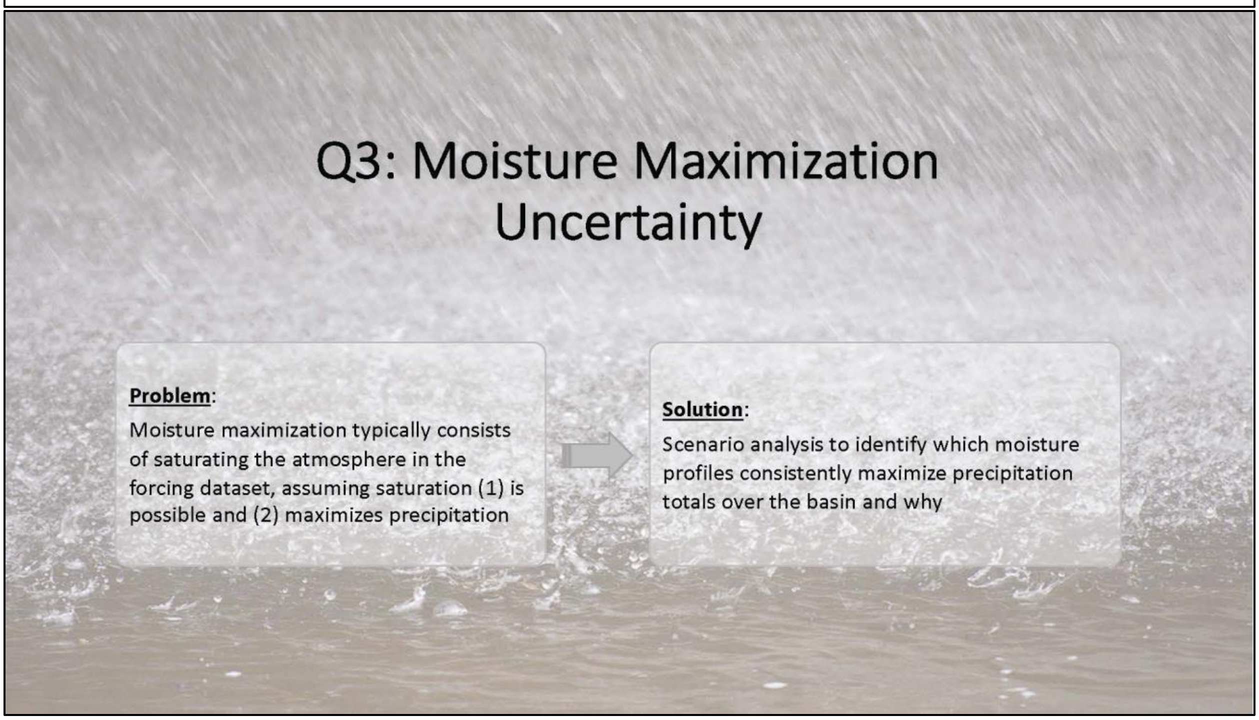


⇒ **Impacts of higher efficiencies on the resulting precipitation, hence PMP estimate, appear to be minimal**

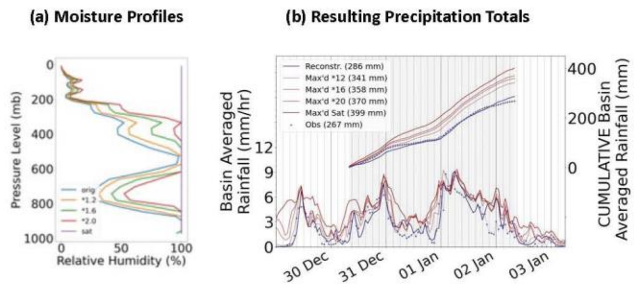
Key Points

- Storms with up to 30% higher efficiency than historical storms exist, but do not appear to produce larger maximized precipitation totals
- Nevertheless, the extended sample of storms examined here is only an approximation to the theoretical upper bound of storm efficiency
- Storms from much larger samples should be assessed, which could come from other GCM ensembles



Results 1: Choice of Moisture Amounts

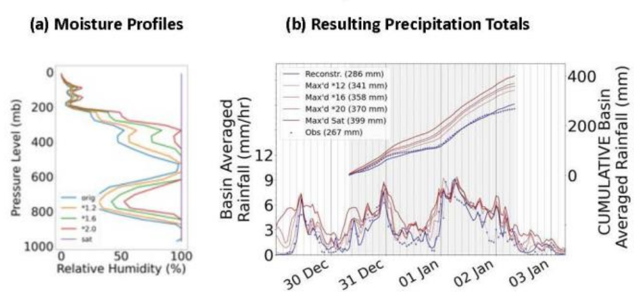
Jan. 1997 storm example



- Relative Humidity Maximization (RHM) consists of saturating the entire column
  - Most commonly used
- Alternatively, multiply moisture amounts in order to preserve the atmospheric profile
  - Called Relative Humidity Perturbation (RHP)
  - Arguably more realistic

Results 1: Choice of Moisture Amounts

Jan. 1997 storm example



- Relative Humidity Maximization (RHM) consists of saturating the entire column
  - Most commonly used
- Alternatively, multiply moisture amounts in order to preserve the atmospheric profile
  - Called Relative Humidity Perturbation (RHP)
  - Arguably more realistic

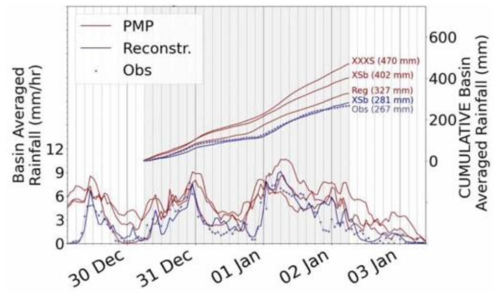
⇒ RHP results in lower precipitation totals than RHM but may be more defensible

⇒ **Frequency analysis to decide how much moisture?**

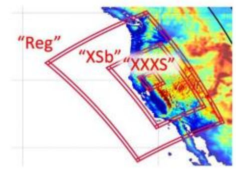
Moisture Maximization Uncertainty

Results 2: Choice of Domain Size

Jan. 1997 storm example



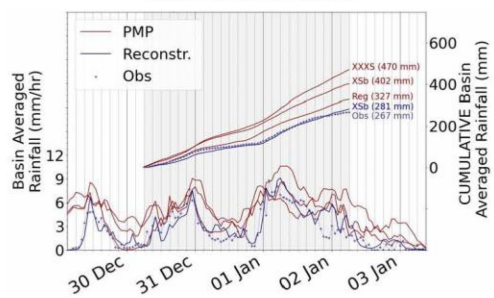
- Moisture added in forcing dataset, i.e., at domain boundary
  - Domain size controls how close to study basin moisture is added
- Distance from study basin is a key factor in determining how much precipitation increase results from the added moisture



Moisture Maximization Uncertainty

Results 2: Choice of Domain Size

Jan. 1997 storm example



- Moisture added in forcing dataset, i.e., at domain boundary
  - Domain size controls how close to study basin moisture is added
- Distance from study basin is a key factor in determining how much precipitation increase results from the added moisture

⇒ Smaller domain has a big impact on precipitation
⇒ **How to decide? Closest that is over the ocean?**

Moisture Maximization Uncertainty

Key Points

- Moisture maximization (moisture amounts, distance from study basin) exerts a strong influence on maximized precipitation totals, hence PMP (more so than any other source of uncertainty)

- Next step towards producing guidelines will be to determine how to decide on the appropriate implementation
  - Choices should not produce unrealistically severe storms
  - But also need to ensure storm is severe enough that it cannot be exceeded
- This will also depend on risk tolerance i.e., regulator/dam owner and is not purely a science question

Conclusions

- This study is the first to quantify the impact of various sources of uncertainty on model-based PMP estimates
  - Uncertainty needs to be described and communicated
  - But findings do not question the viability of model-based approaches
- Additional sources of uncertainty will need to be evaluated
- Most important for operational purposes will be to evaluate where model-based PMP estimates differ from HMR PMP and why
- The atmospheric modeling tools used here will allow to:
  - Force a hydrologic model to convert PMP to PMF
  - Assess the impact of climate change on both PMP and PMF

3.3.2.3 Questions and Answers

Due to technical issues, there was no Q&A for this presentation.

3.3.3 Presentation 2A-3: Improving the Reliability of Stochastic Modeling of Short-Duration Precipitation by Characterizing Spatiotemporal Correlation Structure and Marginal Distribution

Authors: Giuseppe Mascaro[1], Simon Papalexio[2], Daniel Wright[3]; [1]Arizona State University, [2]University of Calgary, [3]University of Wisconsin-Madison

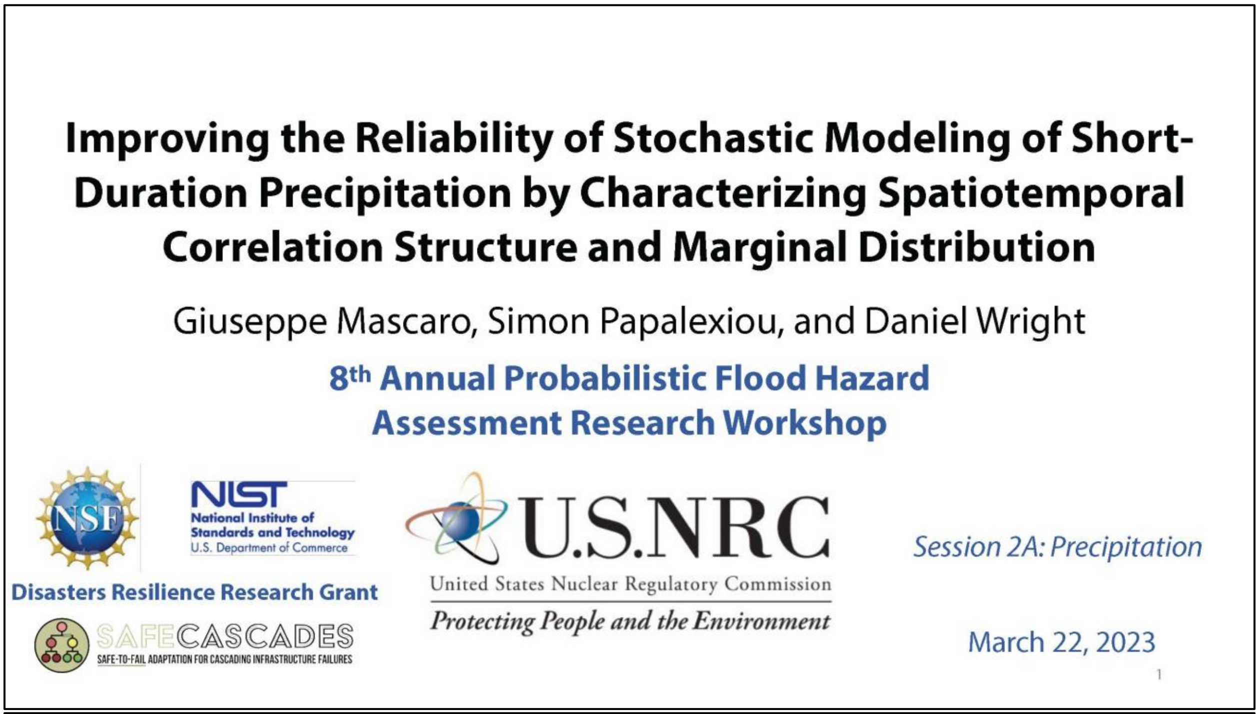
Speaker: Giuseppe Mascaro

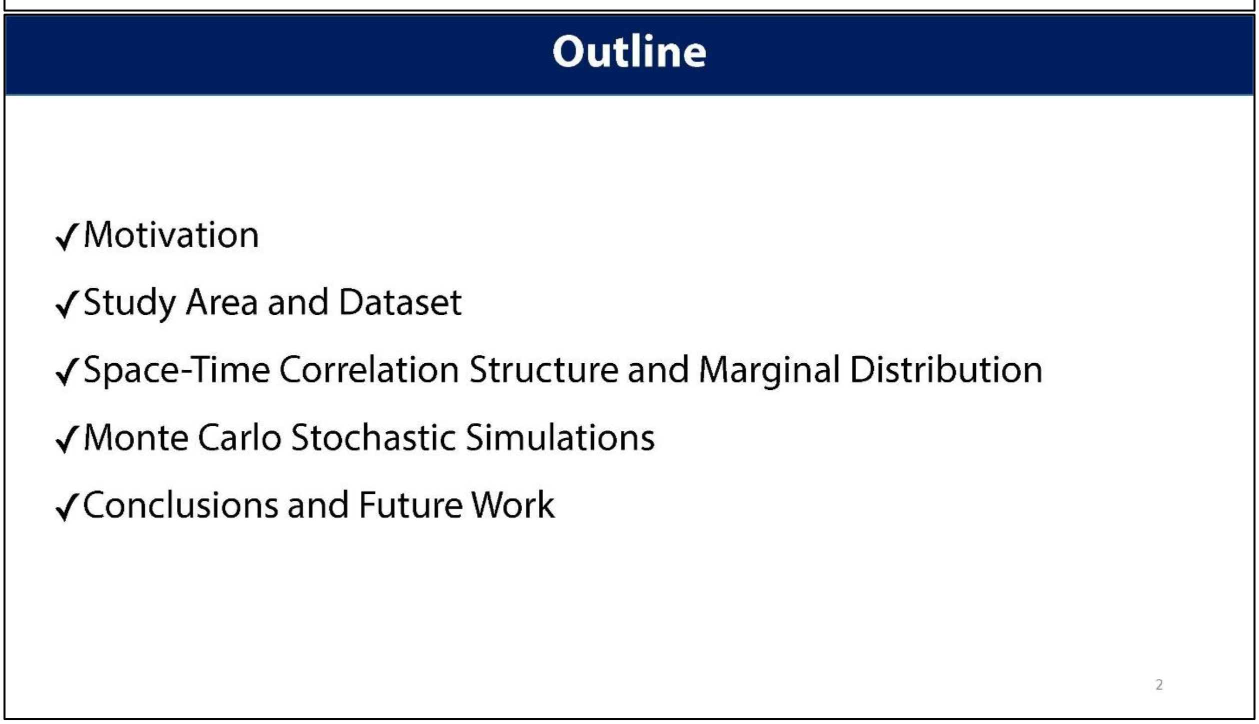
3.3.3.1 Abstract

Realistic space-time stochastic simulations of short duration (≤24 h) precipitation (P) provide critical support for flood hazard assessment. In this talk, we improve the accuracy of space-time simulations by increasing the ability to characterize and model the spatiotemporal correlation structure (STCS) and the marginal distribution of short-duration P. We design a framework that relies on multisite Monte Carlo simulations with the Complete Stochastic Modeling Solution (CoSMoS) which we test with a dense network of 223 high-resolution (30 min) rain gages in central Arizona. We first show that an analytical model and a three-parameter probability distribution capture the empirical STCS and marginal distribution of P, respectively, across Δt's from 0.5 to 24 h in both the summer and winter seasons. We then carry out Monte Carlo multisite stochastic simulations of P time series with CoSMoS which reveal significant seasonal differences in the statistical properties of short-duration P, especially at low Δt: summer P exhibits weaker STCS and heavy-tailed distributions because of the dominance of localized convective thunderstorms, whereas winter P has stronger STCS and distributions with lighter tails as a result of more widespread and longer frontal systems. Moreover, P is largely

characterized by a homogeneous and isotropic STCS across the region, and by marginal distributions with constant shape parameters and scale parameters and P occurrence dependent on elevation. The only exception is winter P at $\Delta t \geq 3$ h, where the motion of frontal storms could introduce anisotropy, and additional factors are required to explain the variability of the scale parameter. The findings of this work are useful to generate more realistic stochastic P models and validate convection-permitting atmospheric models.

3.3.3.2 Presentation (ADAMS Accession No. ML23177A165)





Outline

✓Motivation

✓Study Area and Dataset

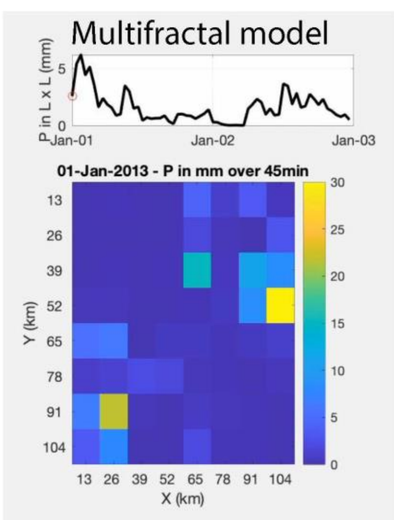
✓Space-Time Correlation Structure and Marginal Distribution

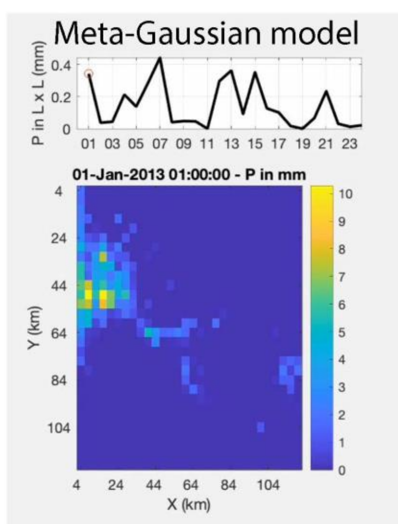
✓Monte Carlo Stochastic Simulations

✓Conclusions and Future Work

Motivation

What are stochastic models of short-duration (≤24 h) precipitation (P)?





Categories of Paschalis et al. (2013):

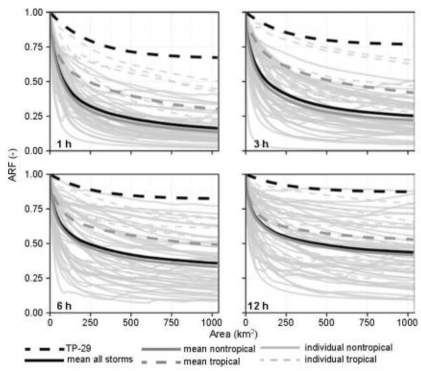
1. Multisite temporal simulations (e.g., Bardossy and Pelgram, 2009)
2. Superposition of two-dimensional pulses (e.g., Cowpertwait et al., 2002)
3. Theory of random fields (e.g., Papalexiou et al., 2021)
4. Scale invariance and multifractality (e.g., Deidda et al., 2004)

Motivation

Stochastic models of short-duration P are useful for several scientific and practical applications

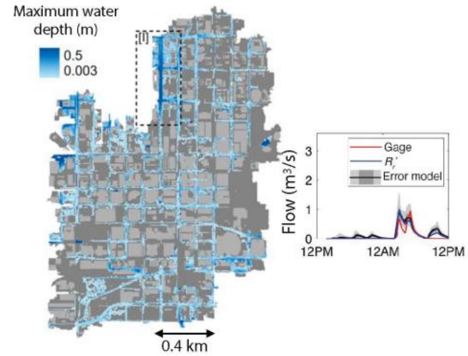
Design storms for stormwater infrastructure

Improve estimates of areal reduction factors



Wright et al. (2013)

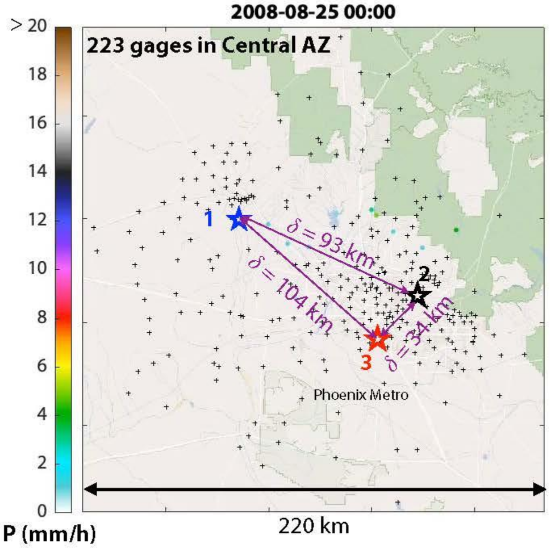
Increase accuracy of hydrologic simulations (e.g. flash-flood forecasting)

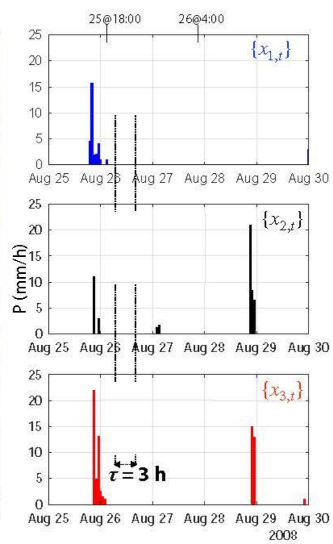


Hjelmstad et al. (2021)
Shreshta et al. (2022)

Motivation

What should these models be able to simulate?





Space-time correlation structure (STCS):

X: random variable P at time resolution Δt

$\{x_{j,t}\} = x_{j,1}, x_{j,2}, \ldots, x_{j,T}$ realization at *j*-th site

Spatial correlation at distance δ:

$r(\{x_{1,t}\}, \{x_{2,t}\}) \rightarrow \rho_X(\delta = 93\text{ km})$

$r(\{x_{2,t}\}, \{x_{3,t}\}) \rightarrow \rho_X(\delta = 34\text{ km})$

Temporal correlation at lag τ:

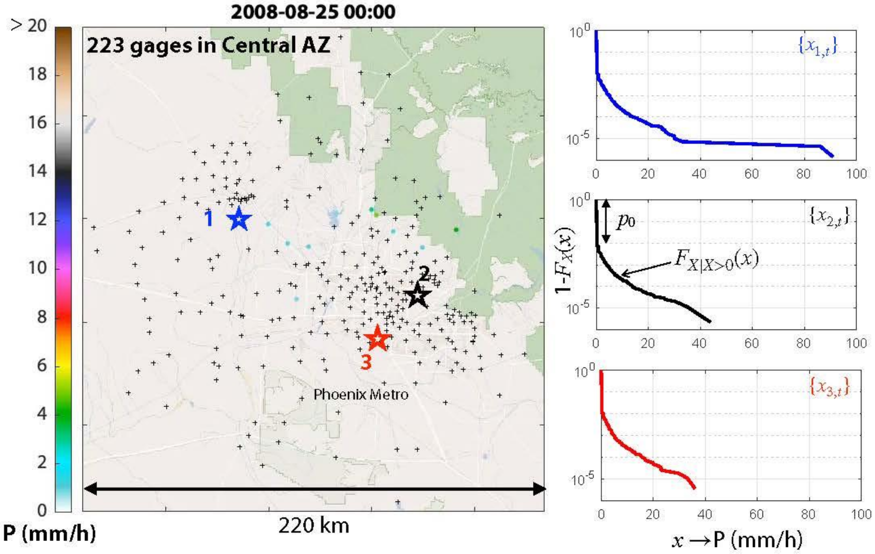
$r(\{x_{1,t}\}, \{x_{1,t+3\text{h}}\}) \rightarrow \rho_X(\tau = 3\text{h})$

Spatiotemporal correlation:

$r(\{x_{1,t}\}, \{x_{2,t+3\text{h}}\}) \rightarrow \rho_X(\delta = 93\text{km}, \tau = 3\text{h})$

Motivation

What should these models be able to simulate?



Distribution of zero and nonzero P

X: random variable P at time resolution Δt

CDF of intermittent process:

$$F_X(x) = p_0 + (1 - p_0)F_{X|X>0}(x)$$

Probability of zero P — Marginal distribution of nonzero P

In this talk, we will characterize and model STCS and marginal distribution, which have received limited attention

Outline

- ✓Motivation
- ✓**Study Area and Dataset**
- ✓Space-Time Correlation Structure and Marginal Distribution
- ✓Monte Carlo Stochastic Simulations
- ✓Conclusions and Future Work

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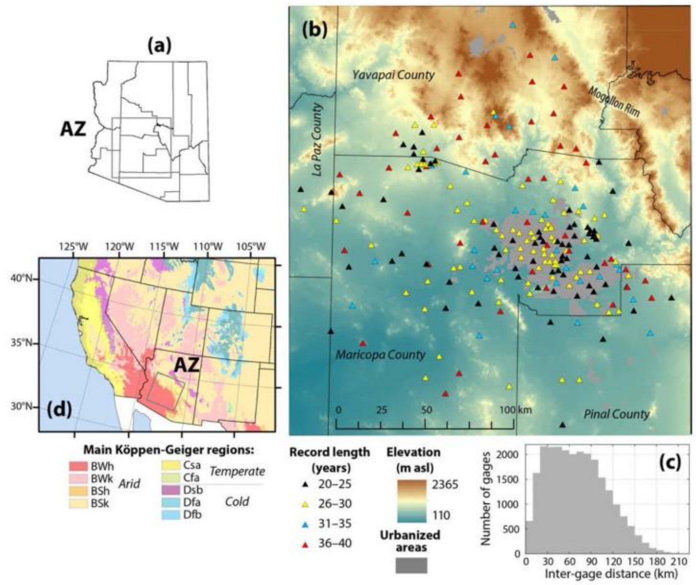
Study Area and Dataset



High-resolution and high-density rain gage network from Flood Control District of Maricopa County (FCDMC):

- 365 gages (223 with >20 years)
- Δt = 0.5, 1, 2, 3, 6, 12, 24 h
- 1 gage every 95 km^2 in 29,600 km^2
- 1 gage every 23 km^2 in Phoenix Metro (2037 km^2)

Precipitation regime with **two seasons**:

- Summer (Jul-Sep): short (<1 h) and localized convective thunderstorms during the North American monsoon
- Winter (Nov-Mar): widespread storms caused by cold fronts mainly originated in the Pacific

Outline

✓Motivation

✓Study Area and Dataset

✓Space-Time Correlation Structure and Marginal Distribution

✓Monte Carlo Stochastic Simulations

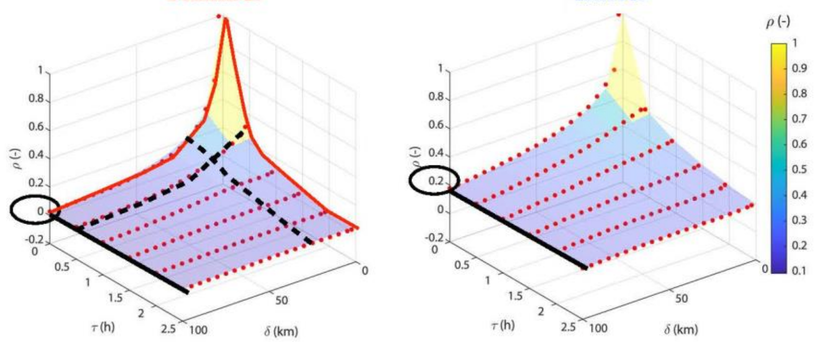
✓Conclusions and Future Work

Space-Time Correlation Structure

Clayton-Weibull model for stationary, isotropic, and homogeneous STCS:

$$\rho_X(\tau, \delta; \theta) = \left\{ \exp\left[\theta\left(\frac{\delta}{b_S}\right)^{c_S}\right] + \exp\left[\theta\left(\frac{\tau}{b_T}\right)^{c_T}\right] - 1 \right\}^{-\frac{1}{\theta}}$$

← Papalexiou et al. (2021)



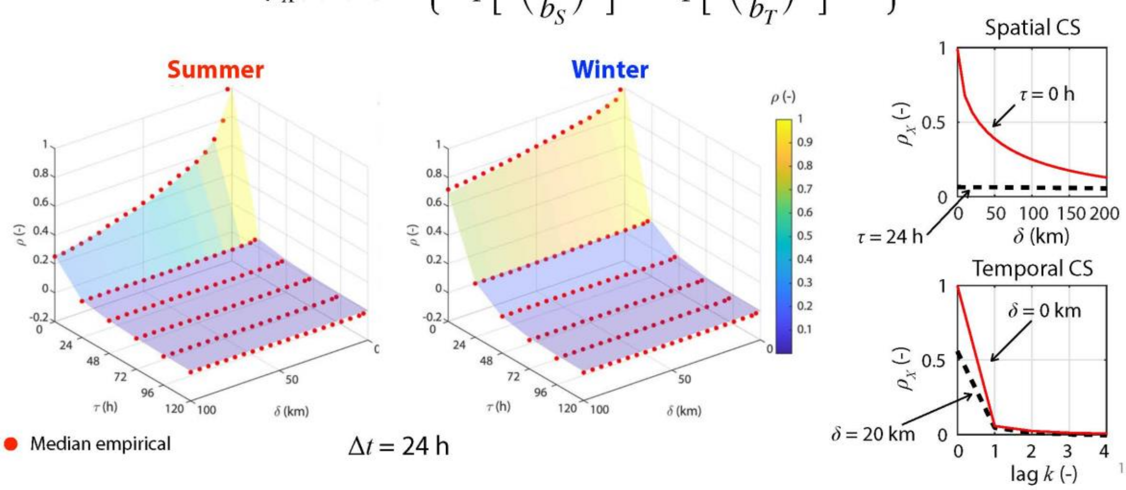
● Median empirical $\Delta t = 0.5$ h

1

Space-Time Correlation Structure

Clayton-Weibull model for stationary, isotropic, and homogeneous STCS:

$$\rho_X(\tau, \delta; \theta) = \left\{ \exp\left[\theta\left(\frac{\delta}{b_S}\right)^{c_S}\right] + \exp\left[\theta\left(\frac{\tau}{b_T}\right)^{c_T}\right] - 1 \right\}^{-\frac{1}{\theta}}$$



● Median empirical $\Delta t = 24$ h

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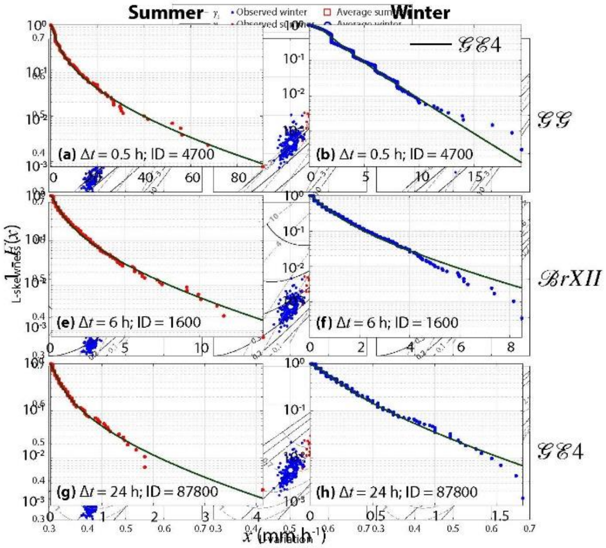
Marginal Distribution

L-moment ratio diagrams to identify good parametric distribution for $F_{X|X>0}(x) \equiv F_X(x)$



- Distributions capturing low, moderate, and heavy P rates with two shape, γ_1 and γ_2, and one scale β parameters:
  - Generalized Gamma ($\mathscr{GG}$),
  - Burr Type XII ($\mathscr{B}rXII$)
  - Generalized Extreme Type 4 ($\mathscr{GE}4$)
- $\mathscr{B}rXII$ most flexible, but infinite variance for $\gamma_2 \geq 0.5$
- $\mathscr{GE}4$ was selected:

$$F_{X|X>0}(x) = F_{\mathscr{GE}4} = 1 - \left\{ \left[\exp\left(\left(\frac{x}{\beta} \right)^{\gamma_1} \right) - 1 \right]^{\gamma_2} + 1 \right\}^{-1/\gamma_2}$$

- Very good fit across seasons and Δt

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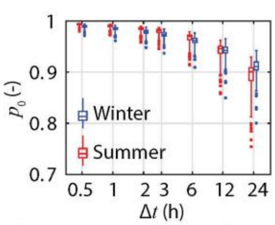
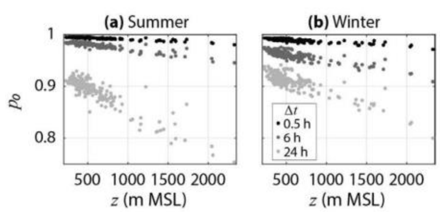
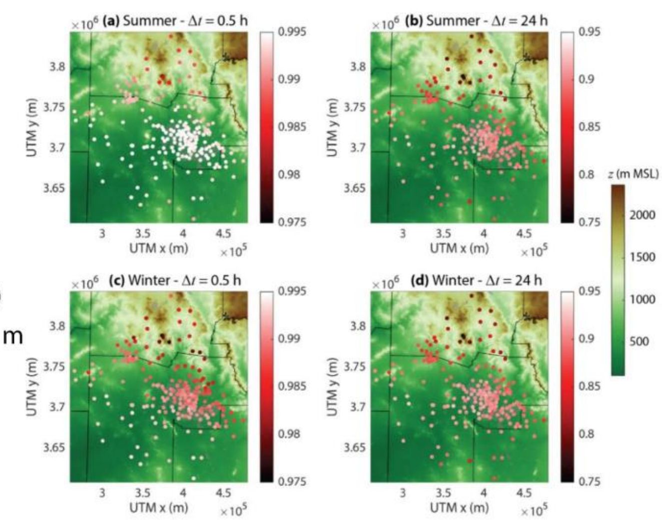
Marginal Distribution

Seasonal and spatial variability of p_0



- Linear decreasing relation between p_0 and Δt
- Higher p_0 in summer (winter) for $\Delta t \leq 6$ h (> 6 h)
- Strong linear relation with elevation for $z \geq 400$ m





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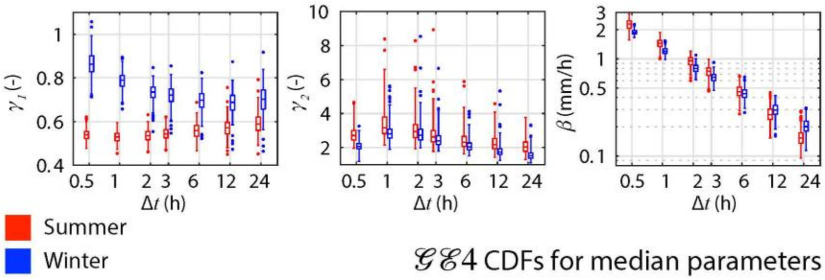
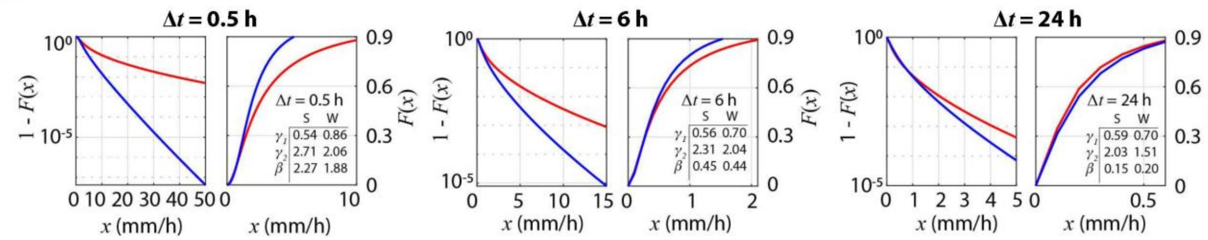
Marginal Distribution

Seasonal and spatial variability of $\mathscr{GE}4$ parameters



- γ_1 is higher for winter P
- γ_2 is slightly higher for summer P
- No apparent spatial control on γ_1 and γ_2
- β exhibits "scaling" with Δt; moderate control of elevation

$\mathscr{GE}4$ CDFs for median parameters

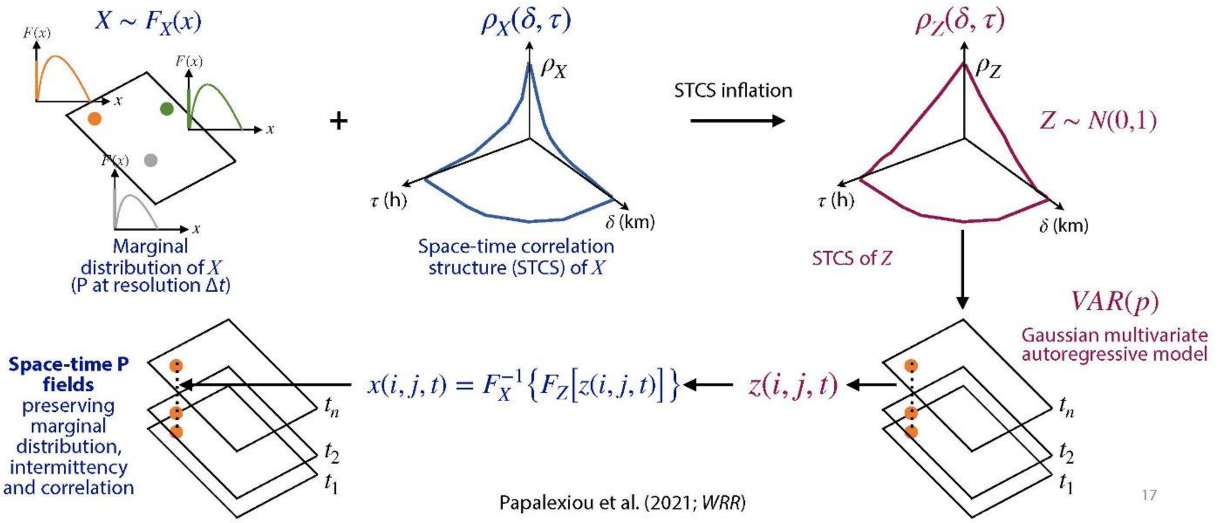


Outline

- ✓ Motivation
- ✓ Study Area and Dataset
- ✓ Space-Time Correlation Structure and Marginal Distribution
- ✓ Monte Carlo Stochastic Simulations
- ✓ Conclusions and Future Work

Multisite Stochastic Simulations with CoSMoS

We performed **Monte Carlo simulations** with the Complete Stochastic Modeling Solution (**CoSMoS**) framework



Papalexiou et al. (2021; *WRR*)

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Multisite Stochastic Simulations with CoSMoS

Monte Carlo simulations with CoSMoS to test **two hypotheses**:

1. ***Can the STCS be considered homogeneous and isotropic in each season?***
2. ***Is the spatial variability of the marginal distribution captured by regional*** $\mathscr{GG}4$ ***shape parameters and by linking*** β ***and*** p_0 ***to elevation (z)?***

For each Δt, 100 multisite time series for summer and winter P with same observed record lengths:

Regional: CoSMoS → Clayton-Weibull STCS + $\begin{cases} p_0 = a + b \cdot z \\ \beta = \beta_\infty + (\beta - \beta_\infty) \cdot e^{-\alpha \cdot z} \\ \text{mean value for } \gamma_1 \text{ and } \gamma_2 \end{cases}$

homogeneous and isotropic

Hypotheses testing → empirical observed VS. 90% confidence intervals of synthetically generated

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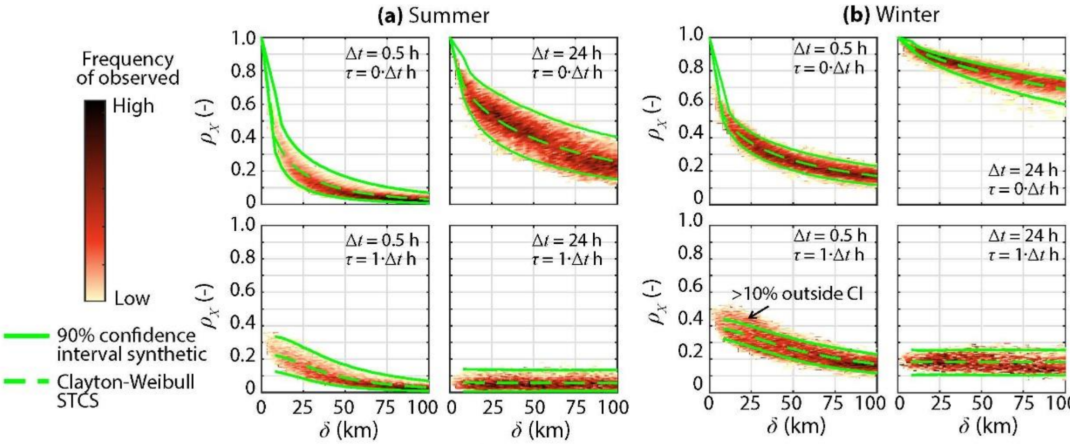
Multisite Stochastic Simulations with CoSMoS

1. Can the STCS be considered homogeneous and isotropic in each season?

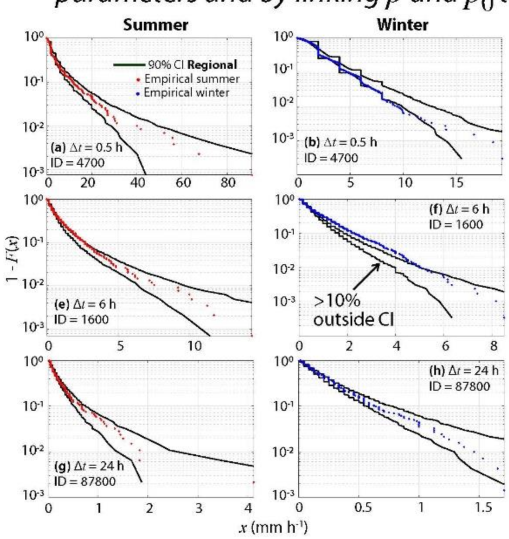


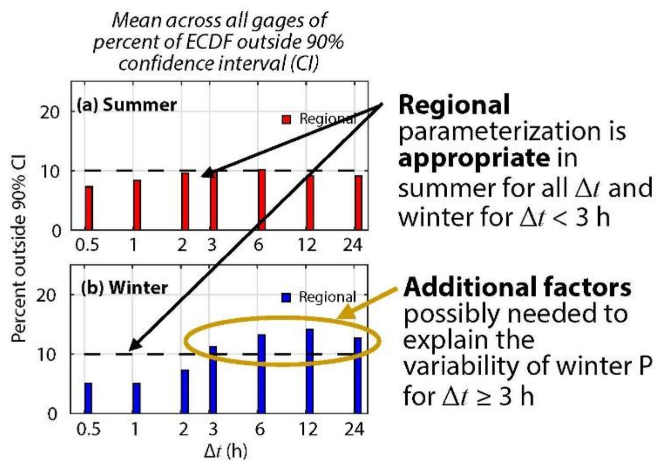
With very high confidence in summer

In most cases in winter

Multisite Stochastic Simulations with CoSMoS

2. Is the spatial variability of the marginal distribution captured by regional $\mathcal{GE}4$ shape parameters and by linking β and p_0 to z?





Outline

✓Motivation

✓Study Area and Dataset

✓Space-Time Correlation Structure and Marginal Distribution

✓Monte Carlo Stochastic Simulations

✓Conclusions and Future Work

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Conclusions and Future Work

1. High-resolution, long-term, dense rain gage networks are a precious resource to characterize and model key statistical properties of P
2. Clayton-Weibull STCS and $\mathscr{G}\mathscr{E}4$ are flexible models for STCS and $F_X(x)$ of P across scales and seasons
3. Significant seasonal differences in STCS and $F_X(x)$ in Central Arizona
4. Monte Carlo experiments with CoSMoS show that:
   - In most cases: homogeneous and isotropic STCS; regional, elevation-dependent parameterization of $F_X(x)$
   - Exception in winter for $\Delta t \geq 3$ h
5. Future work: apply CoSMoS while accounting for storm advection and anisotropy

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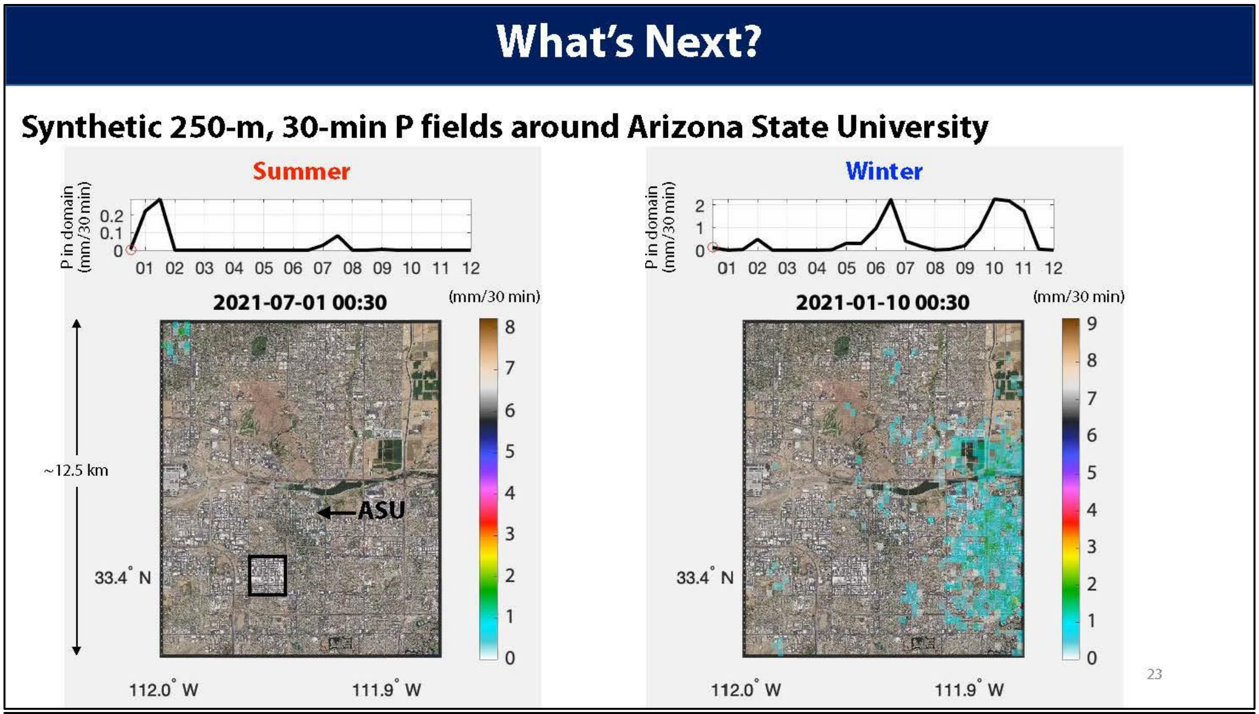

Thanks!

Questions?

Giuseppe Mascaro: gmascaro@asu.edu

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3.3.3.3 Questions and Answers

Question:

With respect to the copula used for the spatio-temporal correlation, why did you choose the Clayton-Weibull copula? Did you compare it with other copulas?

Answer:

This was part work reported in a couple of papers that my colleague, Professor Simon Papalexio from the University of Calgary published in 2021 and 2022. They proposed a number of combinations of correlation functions mixed with different copulas, but they did not test them against the data. They proposed them, the equations are there in the papers. This is the first time that these have been actually applied on such a large data set. So yes, there are other copulas that have been proposed. We tried this one, and this was the one that worked the best in this study region. It doesn't mean that it's the best everywhere and this has to be still demonstrated.

Question:

Could two different copulas be chosen, one for time, the other for the space correlation?

Answer:

The idea of the copula is to essentially link two different marginal distributions, which in this case are not really distributions but they are the decay of the correlation in space and the decay of the correlation in time. They are mixed together to form the surface, so I think you should use one copula at a time. You can choose different distributions of the decay, the marginal distribution. We are actually improperly using the term distribution because this is a correlation function. You can choose a different correlation function for space or time, but then the copula that mixes them, that combines them, has to be one.

3.3.4 Presentation 2A-4: Stochastic Design Storm Sequence in the Lower Mississippi River Basin

Authors: Yuan Liu, Daniel Wright; University of Wisconsin-Madison

Speaker: Yuan Liu

3.3.4.1 Abstract

This study aims to address major limitations of conventional univariate rainfall frequency analysis, which includes the difficulty of incorporating information from relevant atmospheric variables and representing the frequency of areal extremes that is relevant for flooding. Here we proposed a new method of estimating extreme rainfall frequency based on rainstorm tracking and atmospheric water balance. A rainstorm tracking algorithm STARCH was developed to identify two-dimensional precipitation systems over the Mississippi Basin based on ERA5 hourly precipitation data from 1951 to 2020. The 70-year annual maximum rainstorm precipitation was extracted and fitted to a multivariate distribution of atmospheric water balance components using vine copulas. We used this approach to estimate precipitation frequency for rainstorm areas from 5,000 to 100,000 km^2 and duration from 2 to 72 hours in the Mississippi Basin and its five major subbasins. The estimated precipitation distribution fits well with the reference data and is close to the conventional GEV distribution. The approach can estimate precipitation frequency at arbitrary rainstorm duration and area and provides an alternative way to characterize the depth-area-duration relationships of major storms in a basin. Our approach explicitly modeled the contribution of atmospheric water balance components to extreme precipitation. Of these, the water vapor flux convergence is the major contributor, while the water vapor storage and a mass residual term can also be important, especially for rainstorms with short durations and small areas. The approach can utilize additional atmospheric variables to inform precipitation frequency analysis and benefits from advancements in reanalysis products and storm tracking techniques. In the end, some recent work on developing stochastic design storms for the Lower Mississippi River Basin will also be covered.

3.3.4.2 Presentation (ADAMS Accession No. ML23177A166)

Stochastic Design Storm Sequence
in the Lower Mississippi River Basin

Yuan Liu, Daniel Wright
University of Wisconsin-Madison

Large-scale atmospheric variables Simulated storm ensembles

Flood risk in the Lower Mississippi Basin

Economic damage

- 1927 Mississippi Flood **$350** million
- 1973 Mississippi Flood **$250** million
- 2011 Mississippi Flood **$2.8** billion
- 2019 Mississippi Flood **$20** billion

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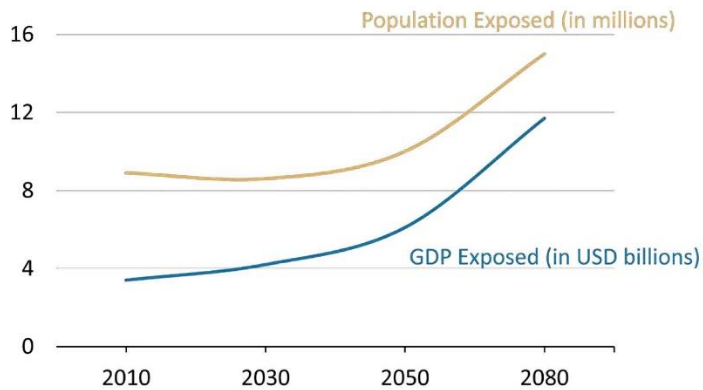
Flood risk in the Lower Mississippi Basin

Flood damage will increase in the Mississippi Basin



Source: World Research Institute

Economic damage

- 1927 Mississippi Flood **$350** million
- 1973 Mississippi Flood **$250** million
- 2011 Mississippi Flood **$2.8** billion
- 2019 Mississippi Flood **$20** billion

Design storm sequence HYPO-58A (Myers, 1955)

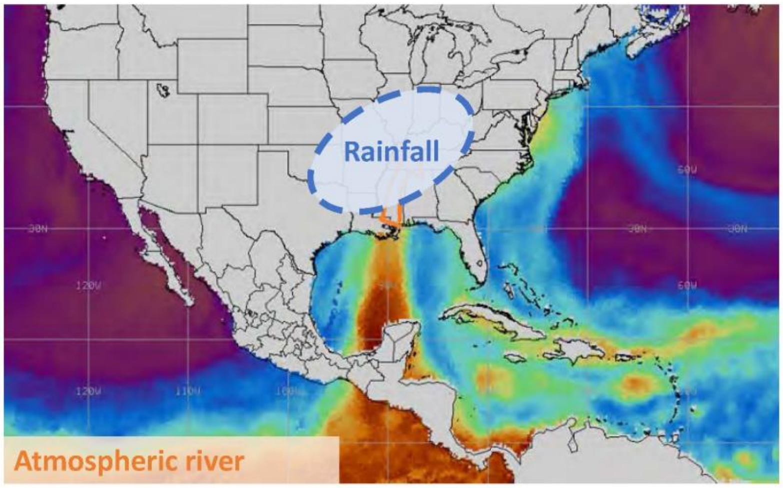
Used for all flood protection structures!

- Highlights: **Storm sequencing** in Mississippi flood
- Limitations:
  - **Single** hypothetical event
  - Lack of **probability**
  - Lack of **future climate impact**

Source: USACE. The Mississippi River & Tributaries Project: Controlling the Project Flood. 2007.

Key rainfall generating mechanism:

(Su & Smith, 2022; Nayak & Villarini, 2017; Moore et al., 2012)

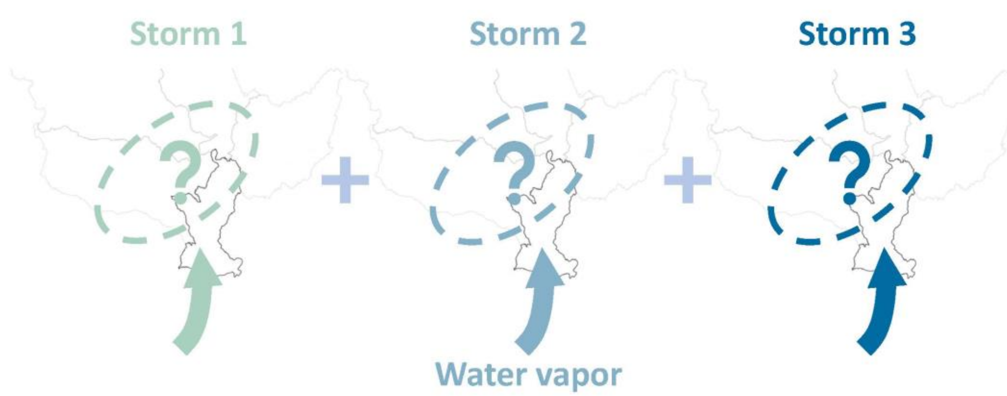


Long, narrow corridor of water vapor transport

Source: Nayak and Villarini (2017), National Weather Services

University of Wisconsin-Madison

Research objective:
Develop a **stochastic storm sequence generator** based on **atmospheric rivers** and **large-scale atmospheric variables**

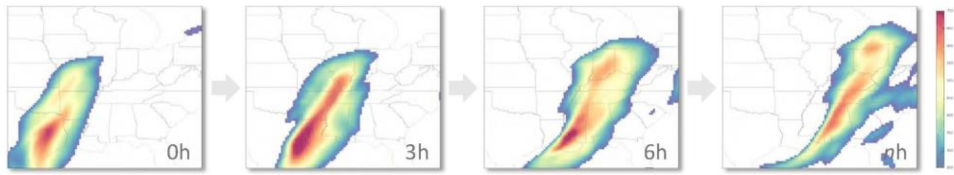


Method | **AR-storm identification** | Rainfall distribution fitting | Noise field generation

Storm Tracking and Regional Characterization (STARCH, Liu & Wright, 2022)

1. AR event tracking:

1979-2021 AR-storm database



ERA5 3-hour integrated water vapor transport

2. Extract associated atmospheric variables:

Observed precipitation
AORC 0.03° grid

Large-scale precipitation | Precipitable water | 500 mb vertical velocity
ERA5 reanalysis 0.25° grid

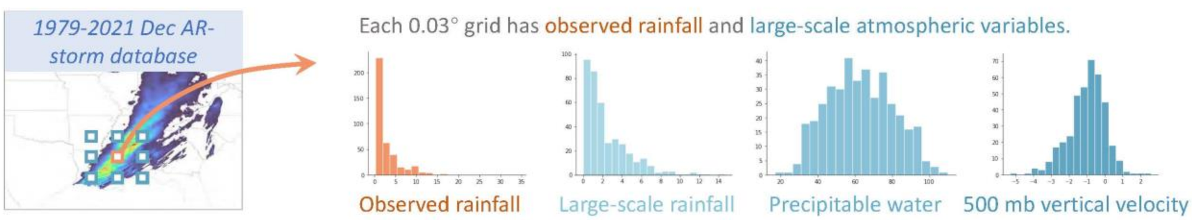
STARCH repository: https://github.com/lorenliu13/starch

Method | AR-storm identification | **Rainfall distribution fitting** | Noise field generation

UW-Madison Probabilistic Downscaling (UWPD, Dave Lorenz)

1979-2021 Dec AR-storm database

Each 0.03° grid has observed rainfall and large-scale atmospheric variables.



Observed rainfall y | Large-scale rainfall R | Precipitable water W | 500 mb vertical velocity ω

1. Rainfall occurrence

$$y\{0, 1\} \sim \text{Logistic}(P_{\text{rain}}(t))$$

$$P_{\text{rain}}(t) = \alpha_0 + \alpha_1 R + \alpha_2 W + \alpha_3 \omega$$

2. Rainfall mangitude

$$y \sim \text{Generalized Gamma}(\mu(t), a(t), c)$$

$$\mu(t) = \beta_0 + \beta_1 R + \beta_2 W + \beta_3 \omega$$
$$a(t) = \gamma_0 + \gamma_1 R + \gamma_2 W + \gamma_3 \omega$$
$$c = \text{constant}$$

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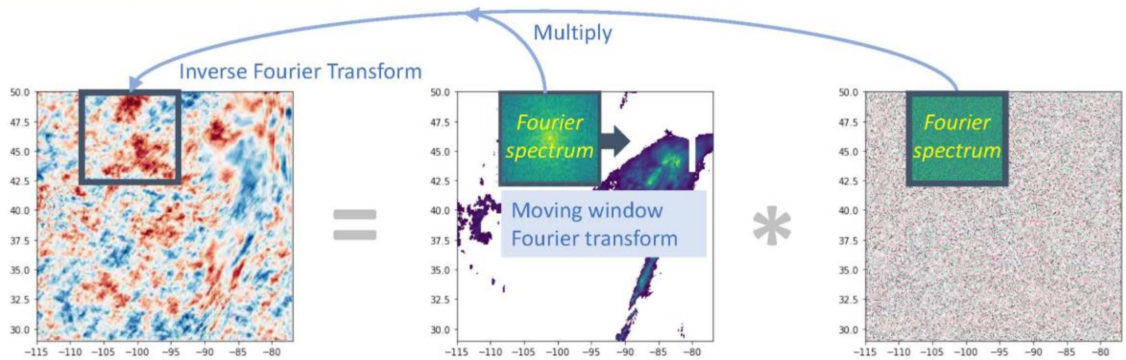
UWPD: https://djlorenz.github.io/downscaling2/main.html

STREAM (Hartke, et al., 2021) and pySTEPs (Pulkkinen et al., 2019)

1. Spatially correlated random noise



Correlated Gaussian noise
0.03° resolution

Observed rainfall field
0.03° resolution

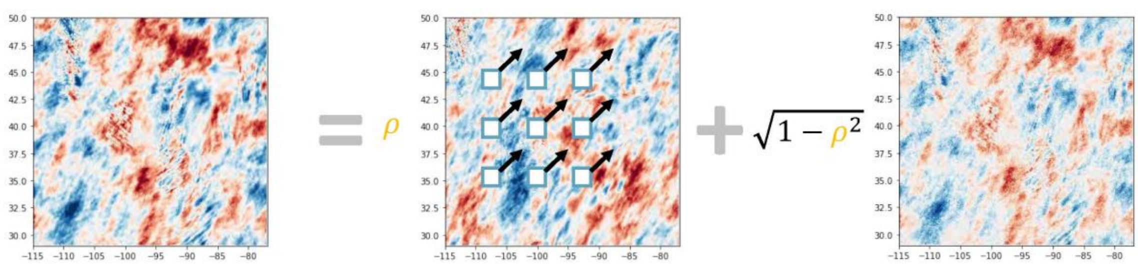
White Gaussian noise
0.03° resolution

STREAM: https://zenodo.org/record/6564982#.ZAZt8B_MI2w; pySTEPs: https://pysteps.readthedocs.io/en/stable/

University of Wisconsin-Madison

Method | AR-storm identification | Rainfall distribution fitting | **Noise field generation**

2. Temporally correlated random noise

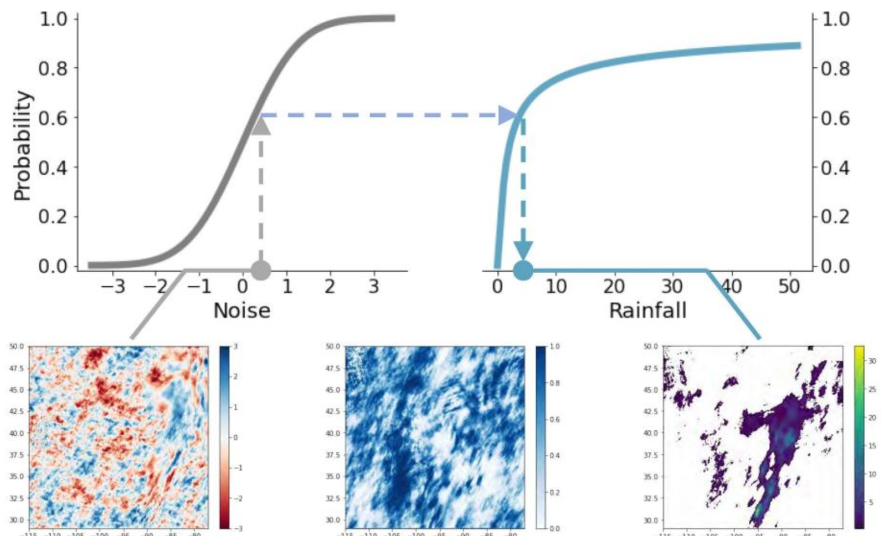


Final noise at *t*+1

Noise at *t*
Transported by ERA5 wind velocity
ρ: lag 1 autocorrelation of rainfall field

New noise at *t*+1

3. Transform noise to rainfall



Correlated noise field

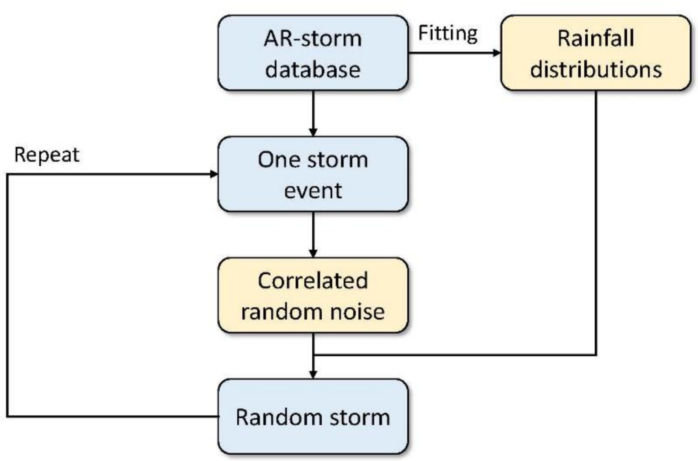
Probability field

Rainfall field

Figure idea: Simon, 2022.

Method	AR-storm identification	Rainfall distribution fitting	**Noise field generation**

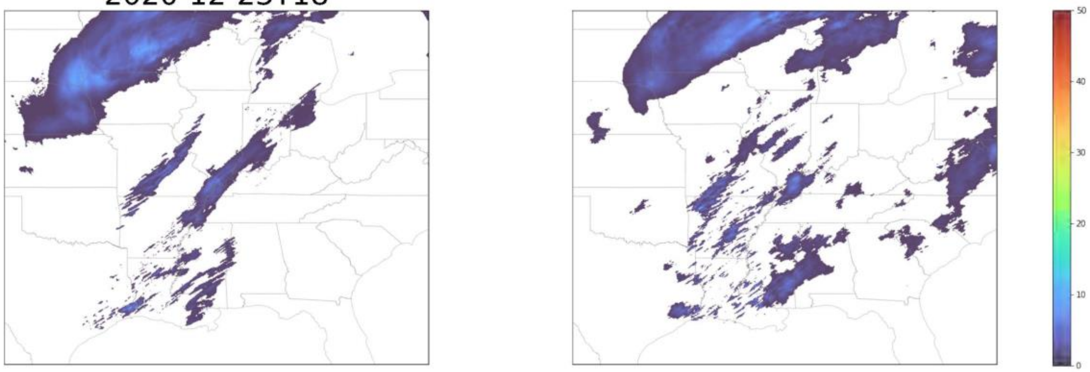
Overview:



166 AR-storms → *166,000 random storms*

Results Random storm examples

2020-12-23T18



Observed Simulation

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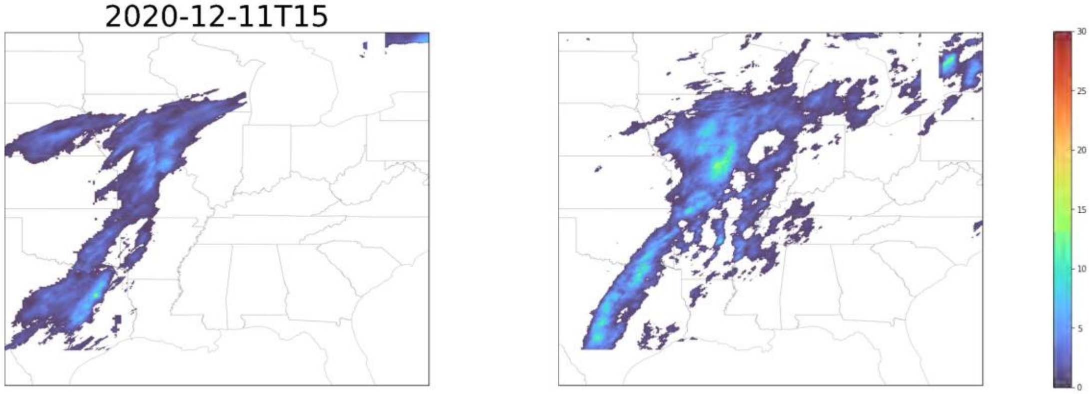
Results Random storm examples

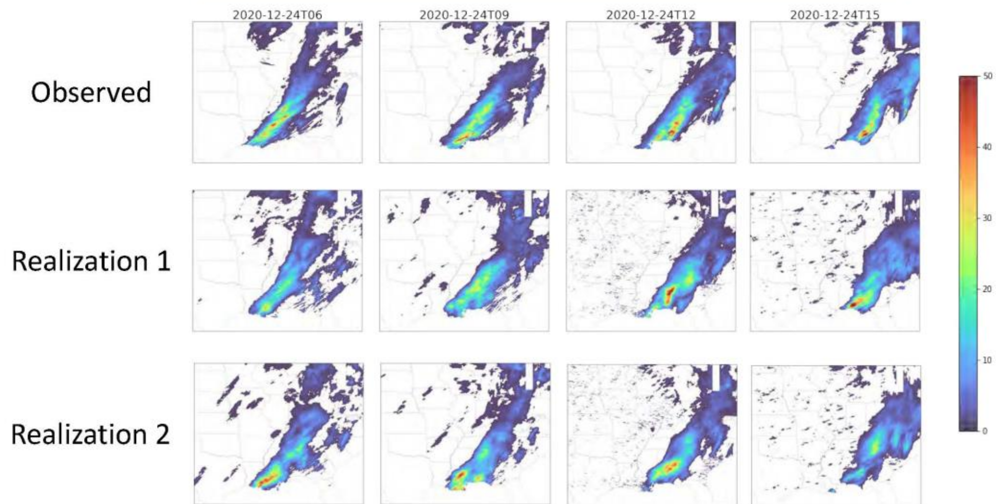
2020-12-11T15



Observed Simulation

14

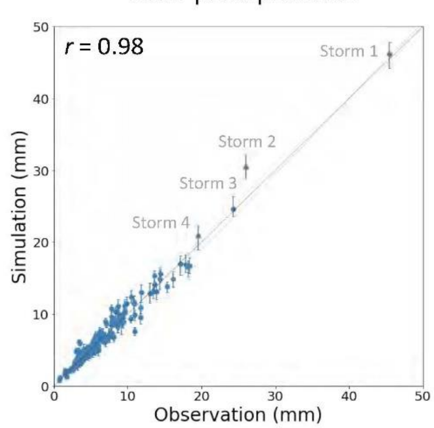
Results Random storm examples



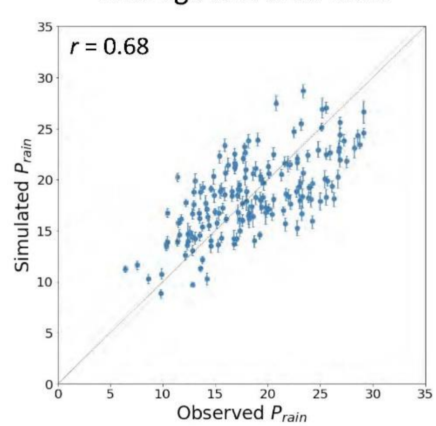
Source: Missouri DNR

Results Random storm evaluation

Total precipitation



Average wet area ratio



Discussion

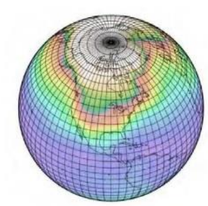
Model features:

- Wide range of **hypothetical storms**
- **Storm sequencing** (future work)
- Support **probability**
- Incorporate **climate change impact**

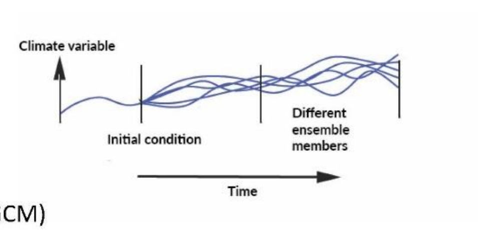
Limitation of HYPO-58A:

- **Single** hypothetical event
- Lack of **probability**
- Lack of **future climate impact**

Discussion GCM-based storm sequencing (future work)



Global Climate Model (GCM)



CGM storm temporal sequence
(1900-2100, *n* ensembles)

Deep neural network

Random storm sequence 1

Random storm sequence 2

⋮

Random storm sequence *n*

Source: Earth Exploration Toolbook, Verisk

Summary

- **A stochastic storm sequence generator in the Lower Mississippi Basin**
  - Based on atmospheric rivers
  - Informed by large-scale atmospheric variables
  - Generate random storms (sequences) with realistic statistical properties
- **Design rainfall in a changing climate**
  - *GCM-informed* stochastic weather generator
  - *Storm sequencing*

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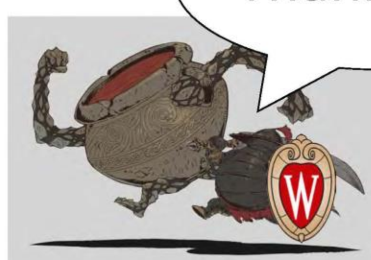
ACKNOWLEDGEMENTS

National Science Foundation (funding source), Daniel Wright (my advisor), Dave Lorenz (Center for Climatic Research, UW-Madison), Aaron Alexander, Ruihai Wu, and members in Hydroclimatie Extremes Research Group at UW-Madison.

Thank you!



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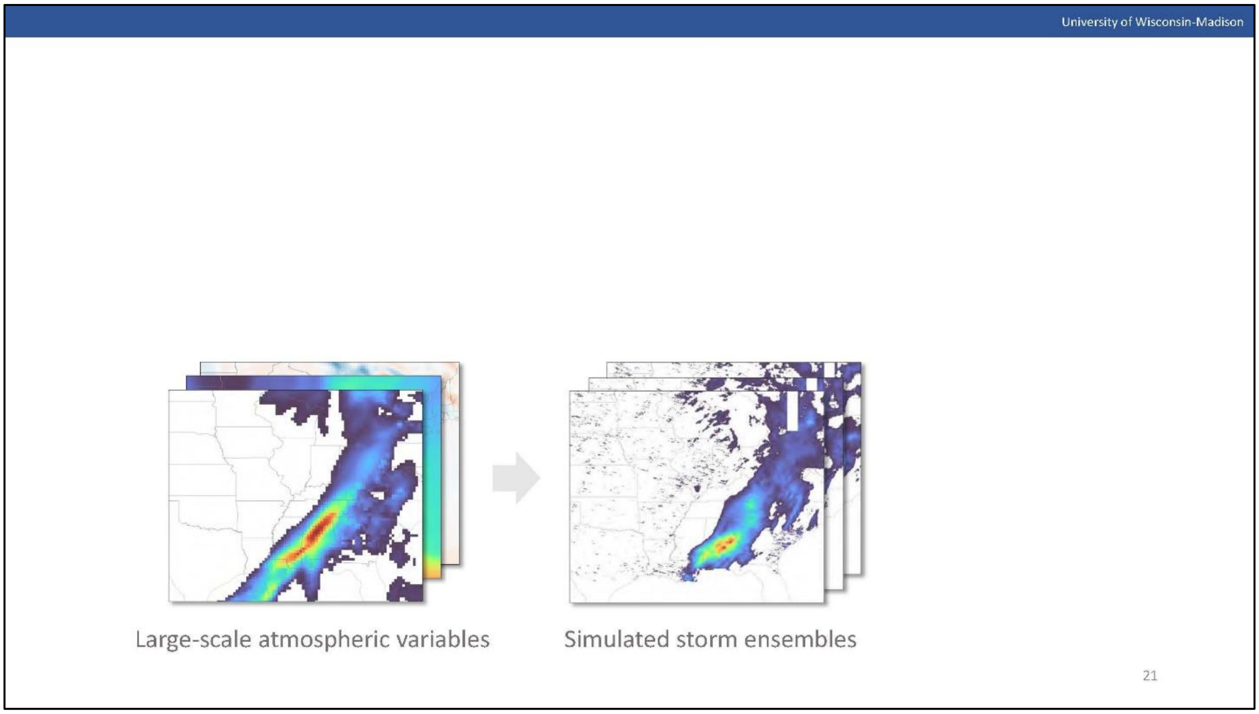


3.3.4.3 Questions and Answers

Question:

What are the durations of the storms that you are focusing on here?

Answer:

The duration is variable because once we selected the storm from the dataset, it just tracks storms from start to the end. Generally, we focus on storm durations longer than 24 hours, like an average of 72 hours, but it varies.

3.3.5 Presentation 2A-5: An Update to the NOAA Atlas 14 National Precipitation Frequency Standard

Authors: Michael St Laurent, Sandra Palovic, Carl Trypaluk, Dale Unruh, Fernando Salas; NOAA National Weather Service Office of Water Prediction

Speaker: Michael St Laurent

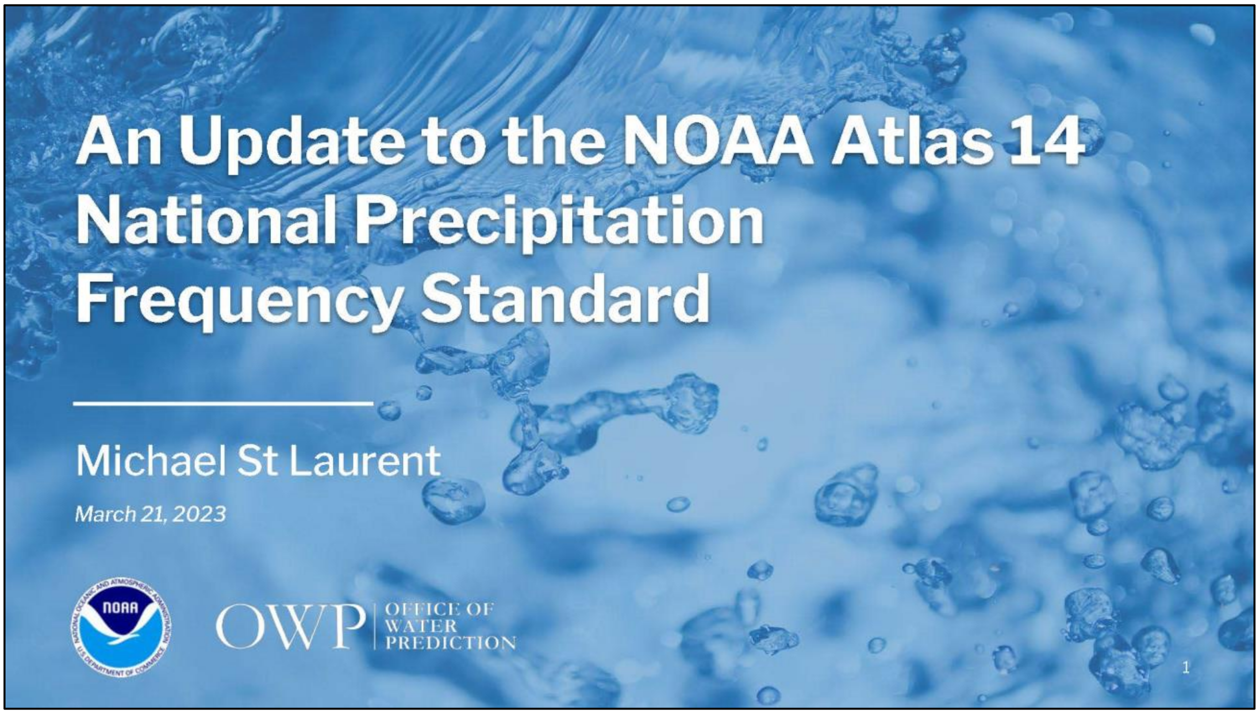
3.3.5.1 Abstract

The National Weather Service's Office of Water Prediction (OWP) has produced an authoritative atlas of precipitation frequency estimates as volumes of the NOAA Atlas 14 "Precipitation-Frequency Atlas of the United States", and these estimates are published on a Precipitation Frequency Data Server with an interactive map interface. The Atlas 14 estimates are the de-facto standard for a wide variety of design and planning activities under federal, state, and local regulations, and are used to design stormwater management and transportation infrastructure, develop design considerations for floodplain and watershed management, and perform hydrologic studies for reservoir and flood protection projects.

With support from the 2022 Bipartisan Infrastructure Law, OWP has received funding to update the precipitation frequency standard. These updated precipitation frequency estimates will be referred to as NOAA Atlas 15 and will be presented in two volumes. The first volume would apply a consistent methodology that accounts for temporal trends in historical observations, and the second volume would use future climate projections to generate adjustment factors for the first volume. This new update is anticipated to (1) develop a seamless spatial national analysis, (2) replace current Atlas 14 estimates based on historical data (historical estimates), (3) add new product features to account for future precipitation information (future estimates), and (4) enhance service delivery via new Web visualizations and data services.

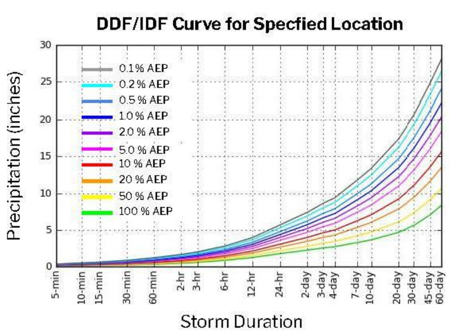
This presentation will review the planning, and development efforts on the proposed NOAA Atlas 15 update, and will discuss in detail the proposed methodology as well as additional research that is anticipated to complete product development. The Atlas 15 estimates, once completed, will provide critical information for the design of national infrastructure under a changing climate.

3.3.5.2 Presentation (ADAMS Accession No. ML23177A167)



What are Precipitation Frequency Estimates?

- Precipitation amounts for a specified storm duration and an annual exceedance probability (or average annual recurrence interval).
- Precipitation **D**epth (or **I**ntensity) for a specified **D**uration and **F**requency (ARI or AEP).



Depth-**D**uration-**F**requency (DDF) curves

Intensity-**D**uration-**F**requency (IDF) curves

How much precipitation would be expected for a storm event that is 10 days in duration and has a 1% chance of being observed?

How rare is it to observe 5 inches of precipitation over 2 days?

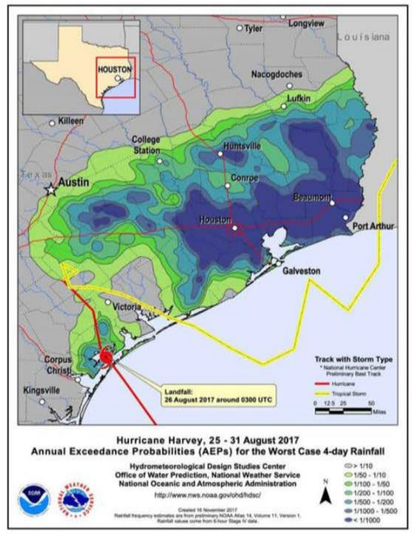
2

Precipitation Frequency Data Serve as a Foundation for Built Infrastructure Nationwide and Supports Prediction Mission

Type of structure	Return period (years)
Highway culverts	
Low traffic	5–10
Intermediate traffic	10–25
High traffic	50–100
Highway bridges	
Secondary system	10–50
Primary system	50–100
Farm drainage	
Culverts	5–50
Ditches	5–50
Urban drainage	
Storm sewers in small cities	2–25
Storm sewers in large cities	25–50
Airfields	5–10

- **Majority of built infrastructure leverages precipitation frequency data for design and planning under federal, state and local regulations**
  - Transportation
  - Development and building code
- FEMA National Flood Insurance Program
- Risk management and Reinsurance Industry

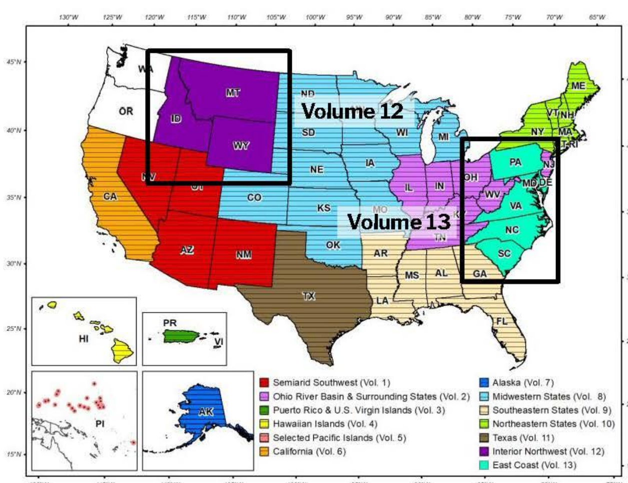
Hurricane Harvey Example



Precipitation Frequency Data **facilitates the comparison of observed and forecast precipitation** with threshold precipitation to **quantify the severity and spatiotemporal nature** of extreme events and their impacts.

3

NOAA Atlas 14 Product Suite



https://www.weather.gov/owp/hdsc

Hydrometeorological Design Studies Center (HDSC)

- Since 2003, develops and updates precipitation frequency estimates for the United States and territories
- Part of Office of Water Prediction (NWS, NOAA)

Funding Approach

- Performed at request of and funded by states through FHWA - not from NWS appropriation
- Discontinuities at volumes' boundaries, and irregular update cycle creates issues for users

Volumes

- Volume 1 (2004): Semi arid Southwest

....

- Volume 11 (2018): Texas
- **Volume 12 (2024) :** Montana, Idaho, and Wyoming
- **Volume 13 (2025):** Mid-Atlantic

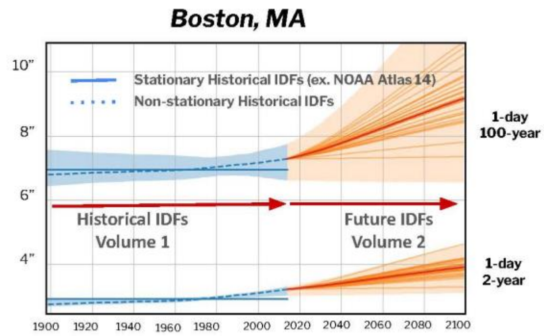
4

Atlas 15 Methodology Developed: Accounting for the Impact of Nonstationarity

"Analysis Of Impact Of Nonstationary Climate On NOAA Atlas 14 Estimates : Assessment Report"

Objective 1: Assess the suitability of state-of-the-science methodologies for nonstationary precipitation frequency analysis.

Objective 2: Evaluate downscaled global projections' ability to mimic extreme precipitation at the temporal and spatial scales needed for the engineering application.

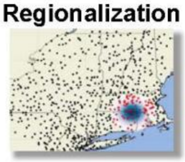


- Result of extensive, multi-year study conducted with Penn State University, University of Illinois Urbana-Champaign and University of Wisconsin-Madison
- Testing done for Atlas 14 Volume 10 project area (Northeastern States)
- Development of methodology conducted in coordination with, and funded by, DOT FHWA

#Preliminary Results

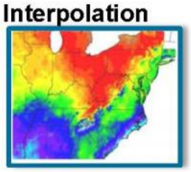
Major Methodology Enhancements

Regionalization



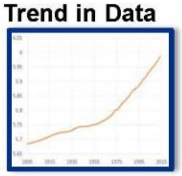
Regional observation ***weighting*** *(eg. triweight kernel)*

Interpolation



Spatial *covariate (eg. PRISM)*

Trend in Data



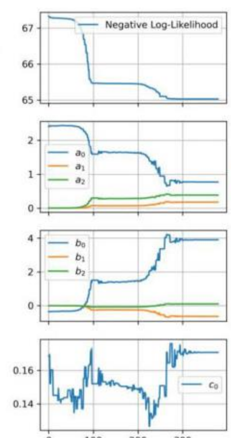
Temporal *Global covariate (eg. ln(CO_2) RCP8.5)*

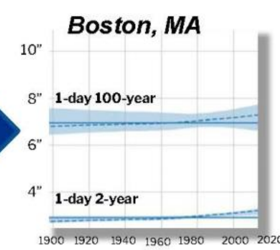
Parametrization @ grid cell

$$loc = a_0 + a_1 * \sqrt{PRISM} + a_2 * RCP$$
$$scale = \exp(b_1 + b_1 * \sqrt{PRISM} + b_2 * RCP)$$
$$shape = c_0$$

Final iteration parameters						
a_0	a_1	a_2	b_0	b_1	b_2	c_0
0.768	0.174	0.383	3.90	-0.632	0.105	0.171

Station	Year	AMS	PRISM	RCP8.5	Weight
4	1955	7.70	45.9	0.584	6.78e-03
4	1956	1.60	45.9	0.592	6.78e-03
4	1957	1.54	45.9	0.599	6.78e-03
4	1958	2.42	45.9	0.607	6.78e-03
4	1959	4.31	45.9	0.614	6.78e-03
...	...	...	...	...	...
1136	2009	2.13	47.75	2.104	7.21e-03
1136	2010	5.32	47.75	2.154	7.21e-03
1136	2011	2.25	47.75	2.205	7.21e-03
1136	2012	1.97	47.75	2.256	7.21e-03
1136	2013	3.23	47.75	2.307	7.21e-03
Weighted Negative Log-likelihood					65.0269





Major Methodology Enhancements

Methodologies

- Quasi Stationary (QS) and Nonstationary (NS)

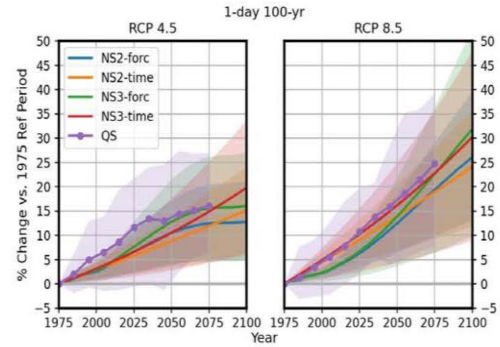
NS – regional maximum likelihood approach.

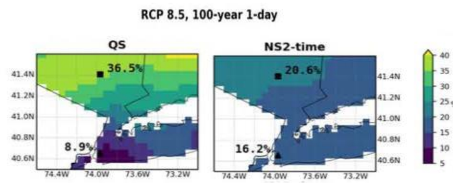
Method	Emission	Covariates
QS	RCP 4.5/8.5	None
NS2-year	RCP 4.5/8.5	'year'
NS2-forc	RCP 4.5/8.5	RCP delta radiative forcing
NS3-year	RCP 4.5/8.5	'year'
NS3-forc	RCP 4.5/8.5	RCP delta radiative forcing

*1950-2099 LOCA AMS data used

Findings

- NS model directly integrates nonstationary assumptions in the model development, and provides greater flexibility with modeling the shape parameter, and is faster to implement.





7

Evaluation

Datasets

- CMIP5 LOCA, UWPD, BCCAv2, and NA-CORDEX

UWPD: https://registry.opendata.aws/noaa-uwpd-cmip5/

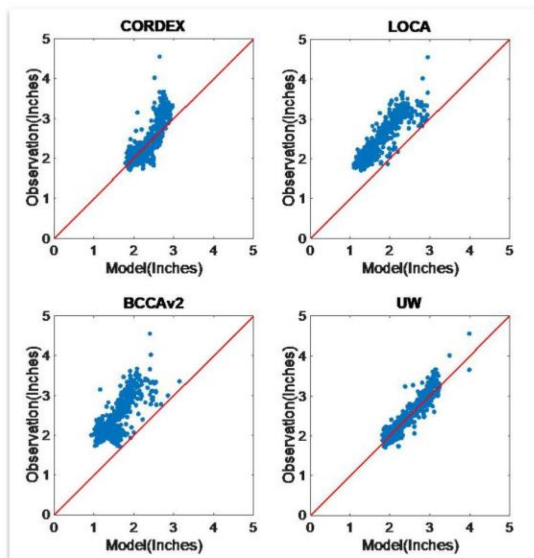
Climate model scenarios

- RCP4.5 and RCP8.5

Evaluation based on the historical period:

- Goodness of fit statistics
- Observation vs Model comparisons
  - Mean AMS, return periods, etc.
  - Q-Q plots
- Performance of downscaled products at stations not used in downscaling
- Represented spatial patterns
  - Mean annual maxima, return periods, etc.

Volume 10 - Mean AMS Observation vs Models



Evaluation

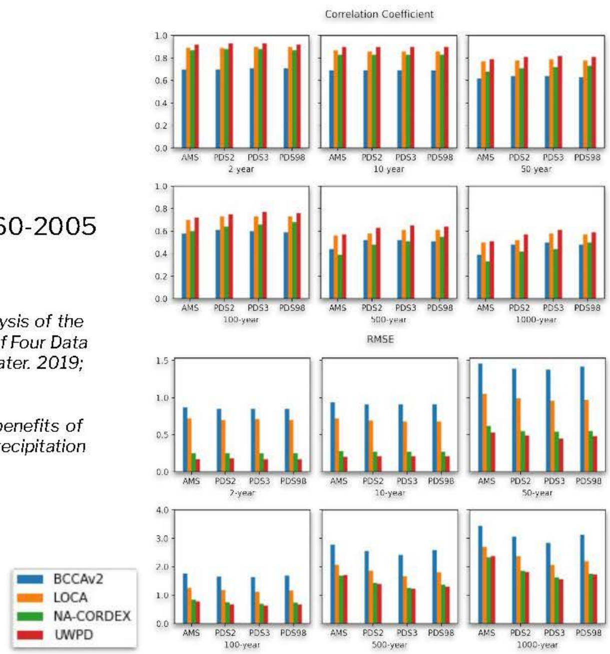
Datasets retained

- CMIP5 LOCA, UWPD, and NA-CORDEX

Performance based on observed vs models in 1960-2005 “historical” period.

Wu S, Markus M, Lorenz D, Angel JR, Grady K. A Comparative Analysis of the Historical Accuracy of the Point Precipitation Frequency Estimates of Four Data Sets and Their Projections for the Northeastern United States. Water. 2019; 11(6):1279. https://doi.org/10.3390/w11061279

Grady K, Markus M, Shu W, Wang F, Koric S. Assessment of the benefits of climate model weights for ensemble analysis in three urban precipitation frequency studies. JAWRA. 2022; DOI: 10.1111/1752-1688.13065

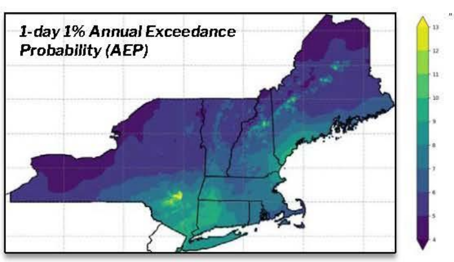


The NOAA Atlas 15 Product

Volume 1: Based on historical gages and observed trends

- First-ever, nationally-consistent, precip frequency data that serves as the basis for Volume 2
- Integrated terrain information
- Accounts for trends in historical observations (when it exists)
  - Non-stationary trends represents a major enhancement from Atlas 14

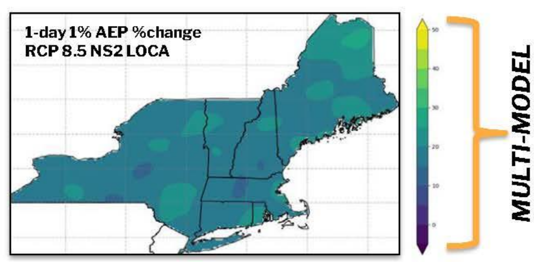
1930 › 1940 › 1950 › 1960 › 1970 › 1980 › 1990 › 2000 › 2010 › 2020



Volume 2: Incorporates climate projection adjustment factors

- Future precipitation informed by global climate models, modeled non-stationary temporal changes
- Provides adjustment factors to Volume 1 to calculate future estimates

2030 › 2040 › 2050 › 2060 › 2070 › 2080 › 2090 › 2100 › 2110 › 2120



Summary

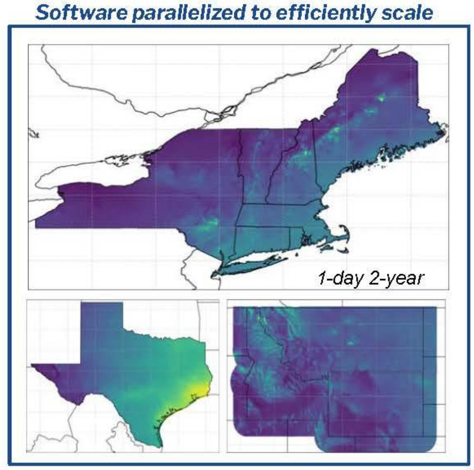
Updating the statistical methodology to account for temporal nonstationarity as follows:

1. changing parameterization estimation technique
2. adding covariates to the estimation of the distribution parameters
3. altering regional technique
4. altering the spatial interpolation technique
5. altering confidence interval technique

Adding new product features to account for future precipitation information:

1. providing future estimates as adjustment factors to Volume 1
2. multi-model approach to account for the uncertainties
3. apply methodology in part A to calculate the precipitation adjustment factors to methods that rely on extreme time series from downscaled climate models

Software parallelized to efficiently scale



Projected NOAA Atlas 15 Timeline

2022/2023

- **Sept. 2022** - Distribute Public Notification Statement (PNS) and collect public feedback.
- **Jan. 2023** - Host technical workshop with federal partners.
- **Apr. 2023** - Award contracts and grants and initiate product development.

2024

- **Pilot** - Deliver Atlas 15 Vol. 1 and Vol. 2 pilot over Montana. Collect feedback on preliminary estimates and Web dissemination strategies.

*   *Evolve Atlas framework*
*   *Create quality controlled national precipitation repository*
*   *Evaluate climate model projections*
*   *Develop Web dissemination solutions*

2025

- **CONUS** - Initiate 60-day peer review for Atlas 15 Vol. 1 and Vol. 2 for CONUS (lower 48 states). Collect feedback on product.

2026

- **CONUS** - Complete Atlas 15 Vol. 1 and Vol. 2 and deliver estimates, documentation and supplementary products to stakeholders.
- **oCONUS** - Initiate peer review for oCONUS (e.g. Hawaii, Alaska, Puerto Rico, U.S. Virgin Islands, Guam). Collect feedback.

2027

- **oCONUS** - Complete Atlas 15 Vol. 1 and Vol. 2 and deliver estimates, documentation and supplementary products to stakeholders.

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3.3.5.3 Questions and Answers

Question:

Are the confidence intervals are going to take into account uncertainty that comes from sources that were not addressed in NOAA Atlas 14, such as uncertainty that comes from statistical modeling choices (choice of distribution or parameter estimation methods). Is it going to be considered in the confidence intervals?

Answer:

Currently we do not have that included in our method, but we'd like to have more feedback on that.

Question:

Later, when you consider climate models, will the uncertainty due to that be considered?

Answer:

Currently, we are handling uncertainty in the climate models by including the spread of the individual ensemble members. A lot of what you saw in those slides were the median and then the spread of the median. There's also the spread of the individual ensemble members that weren't really shown in those slides. A big part of this is also how we are going to show the final information. If we show every single ensemble member, all the spread of information and so forth, it can be kind of overwhelming of how to present that to the public. I think a lot of this will also have to be solved during our web dissemination, in what we present as sort of the final argument. If we show the true spread of everything, of every single ensemble member, you could get pretty much any value, to be honest.

Question:

Can you elaborate more on the point grid-based region? Are you looking for a homogeneous region that includes the closest gages to each grid point?

Answer:

For the first part of that question (the grid-based regions), we did that so that we'd have smooth transitions as you go from different areas. We're not, for instance, doing a project for the northeast or doing county by county, grouping together clusters of stations, we have sort of have a rolling window. And then for the homogenous region, it's kind of a tradeoff between getting enough stations to have enough independent data (a big enough region to get sort of how things are changing with time or with respect to a covariate) versus having a region that's just small enough to get local information. We don't expect climate change to affect areas that are 100 miles apart differently. They are probably going to be correlated. So, we need to make the region size big enough to account for that.

Question:

How does your method validate estimates of future precipitation for the more extreme recurrence intervals (ARI > 100) when using future projected data that is limited in length and quality since GCMs are limited in their skill to simulate such extreme events (e.g., 1000-year return period)

Answer:

One way we've done a sanity check is to compare to results from the National Climate Assessment. So, for example in the Northeast, comparing the late century region average percent changes to the ones we derived.

Question:

Will NA15 include future conditions up to 1000-year return periods like NA14 shows?

Answer:

We intend to provide up to the 1000-year, though the adjustment factors above 100-year are not set in stone. It is very possible that adjustment factors above 100-year (% changes) are fixed to the 100-year adjustment factors due to the reasons you mentioned.

Precipitation Panel Discussion (Session 2A-6)

Moderator: Joseph Kanney, NRC/RES

Participants:

- Kelly Mahoney, NOAA Physical Sciences Laboratory
- Emilie Tarouilly, University of California, Los Angeles
- Giuseppe Mascaro, Arizona State University
- Yuan Liu, University of Wisconsin-Madison
- Michael St Laurent, NOAA National Weather Service, Office of Water Prediction

Question:

I was wondering if Kelly and Emilie could talk a little bit about the relationship between their two studies because they were hitting on similar topics but maybe from a little bit different perspective. Just help us understand how they relate.

Answer:

Emilie Tarouilly: They were planned completely separately, but they do touch on very similar problems. I think maybe Kelly, you can talk about what went into planning the Arizona-New Mexico study as that happened first. That happened before I started the work that I'm doing now.

Kelly Mahoney: I used to do things more like what Emilie's working on, but as we've been given this opportunity to do things more holistically for the nation, we're kind of having a shift. So, I view Emilie's study as a really useful deep-dive demonstration of a method or a type of method that we might want to consider going forward for NOAA. It is one of many really interesting regional, phenomena-specific demonstrations that are being done right now. So when we're talking about doing something that works for the whole country, we will ultimately need to look at a lot of different research approaches and methods and, again, leading back to the opportunity that we've had as NOAA to put a lot of these sort of methodological and stakeholder-fit questions in the hands of the National Academies study. Part of their job will be to integrate the meaning of studies like Emilie's in the context of what we can use that's suitable for the country. That's the NOAA answer in terms of the research and the intersection there. We have long had dynamical models and such derived products at our disposal, they just haven't been brought to bear on the PMP problem. They're very different worlds, the way PMP has been done versus what could be done going forward. So, there's a ton of open questions and I really appreciate Emilie's study trying to actually address some of the big pieces of that: the issues of uncertainty and what it represents for an atmospheric river and so on.

Emilie Tarouilly: The way my work fits into what you are doing at the moment is that my approach to this has been to look at PMP, and given that we're most likely going to need numerical models to improve PMP, what's the biggest obstacle, what's are the biggest issues that we have with the numerical models and what can we do to address those questions. That's why I've been looking at model uncertainty and trying to use an ensemble and artificial storms because that's one of the main questions that seems to be the biggest barrier to developing model-based PMP further.

Question:

We've seen different approaches this morning. The spectrum ranges from hard-core statistical approaches to mechanistic modeling approaches, and then there's also bringing in the climate models. In each of these particular approaches, I keep coming back to this question of how well do we know that we are capturing the possible extremes? In regard to the dynamic modeling, do we have the right physics in there to really capture the most extreme precipitation that we think we might see? We also know that climate models have a problem with precipitation extremes and I think that most people feel that the stochastic weather generation statistical approaches sometimes we don't capture the extremes either. What do you think is a way forward in that regard?

Answer:

Giuseppe Mascaro: From a statistical perspective, an extreme is a rare event that you don't know exists until it happens. If that event has been recorded and it's part of your statistical analysis, then that gives you some robustness and some trust on shape parameter that captures the most intense extremes of a statistical distribution that you use, is actually perhaps correct. Doing PMP is a way of setting a little bit of a limit to that. What Emilie is doing, for example, through physics and numerical models can give an idea to help understand what the shape of the statistical distribution that we use, in NOAA 14 for example, should be. Is there a limit to that? Is it a bounded distribution? The distributions that we use statistically, have a domain goes from zero to infinity. Is it really infinite? So, these are all questions that are open.

It's a matter of increasing the sample size to give an answer and use physics and numerical models to help narrow the range, I would say.

Kelly Mahoney: I appreciate that response, especially coming from the more dynamical side, and so I think the power of the complement and the need for both approaches this is a natural point. I think nowadays there's an important third question or third party in the room too, which is the stakeholder need and whether we are asking the right questions. Should we be spending all of our time and resources chasing this one upper bound versus looking at decision points and using a dynamical approach for part of that and supplementing space and time with statistical approaches to get at what the true decision point is. With that I would just add that we've never had more options than we do now and with that comes a huge responsibility. To the point about climate models, you can mis-apply these things so easily. Even just looking at trends, if you are using the wrong data set and you're applying that even as one ingredient in a process we can be misled. We have a lot of options in front of us and collectively we all have responsibility to understand the limitations and strengths of each one

Emilie Tarouilly: I think a lot of the limitations of the numerical weather models that we've had issues with for predicting future climates don't necessarily apply to what we are doing with PMP, for example issues with representing frequency properly and biases and so on. Because what we're doing with PMP is worst case scenario, we don't have a lot of those issues with PMP so that's good. It doesn't mean that there aren't other issues, but there's fewer than what people typically have in mind with those models.

Yuan Liu: I was thinking about the perspective of integrating both the statistics and the current model together. The statistical model can describe the extreme values using the shape parameter but also the statistics distribution parameter can be informed externally by climate models or large-scale atmospheric models to incorporate non- stationarity. Also, our current model can provide many ensembles and that can give you more data and more objects that you can use instead of just using historical record which is pretty limited, with few extreme events. But the integration would be a very nice thing to do in the future.

Michael St Laurent: I was just going to relate it to Bill's question[9] here about using RCP8.5[10]:

> *You noted RCP8.5 as the % adjustment factor for climate change. Given that this RCP is the most unlikely scenario and shown to already be incorrect, wouldn't utilizing RCP 4.5 (or CMIP6[11] SSP4.5[12]) be a more realistic application? And how does this process plan to utilize CMIP updates going forward and adjust for updated climate change outputs going forward?*

It's unrealistic, so we use all the ensembles to get a wide range of what can happen. One thing we've experimented with is to weight the models. One way is to weight them based on the historical period and we've gone over a little bit of weighting the different climate models in our assessment report of. Another thing is to look at different external assessment reports. I know that for CMIP6 specifically there are deemed hot models (unrealistic models), so we exclude those from our analysis based on those recommendations. So, we use assessments that aren't just from us. We look at the literature too for that type of narrowing down.

Question:

Will NOAA Atlas15 include areal reduction factors for application of the data to catchments?

---

[9] Referring to a question from the meeting chat.

[10] Representative Concentration Pathway (RCP) scenario 8.5.

[11] Coupled Model Intercomparison Projects (CMIP) generation 6.

[12] Shared Socioeconomic Pathway (SSP) scenario 4.5

Answer:

Michael St Laurent: We've gotten a lot of questions about that. So, there's definitely works for the grantee process, that I'm not involved in, but there's definitely talk about that.

Question:

Any possibilities to obtain NOAA draft data (for NY) for a statewide hydrologic study for the State?

Answer:

Michael St Laurent: I'm not sure about that, but I wrote it down and I'll ask the correct people for that and get back to you.

3.4 Day 2: Session 2B – Riverine Flooding

Session Chair: Joseph Kanney, NRC/RES

3.4.1 Presentation 2B-1: Lowering the Barriers to Process-Based Probabilistic Flood Frequency Analysis using the NextGen Water Modeling Framework

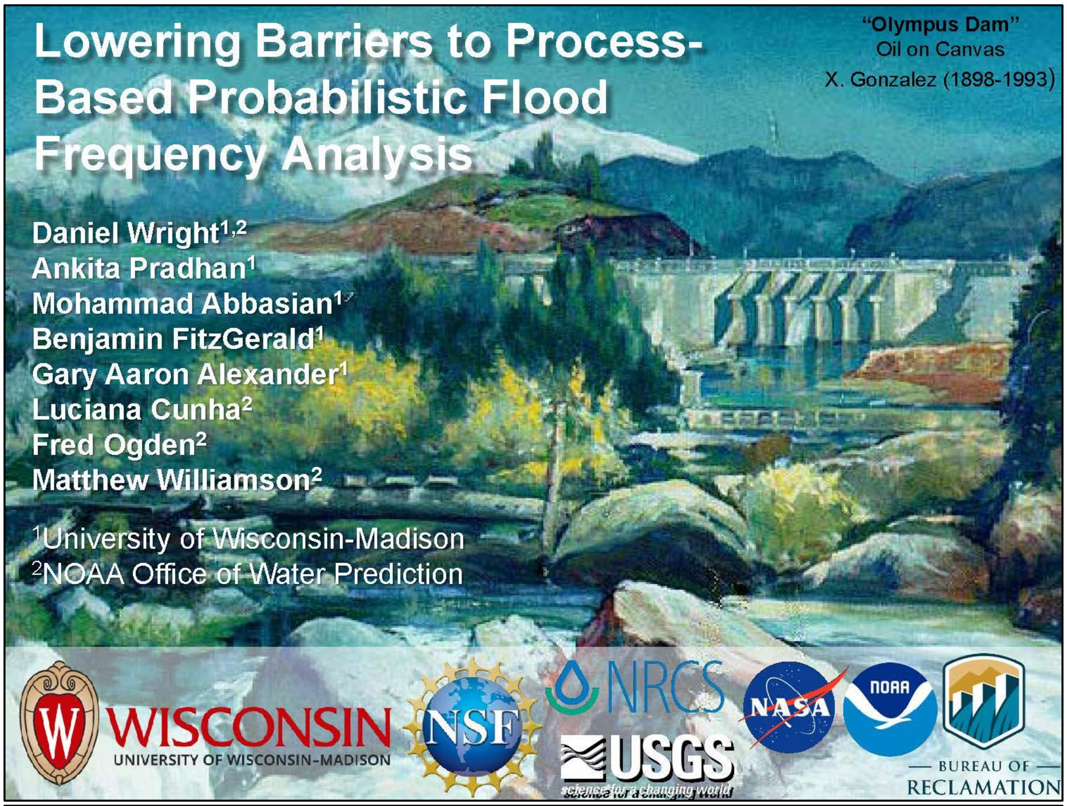
Authors: Daniel, Wright[1], Ankita Pradhan[1], Mohammad Sadegh Abbasian[1], Benjamin Fitzgerald[1], Gary Aaron[1], Fred Ogdan[2], Mathew Williamson[2]; [1]University of Wisconsin-Madison, [2]NOAA National Water Service Office of Water Prediction

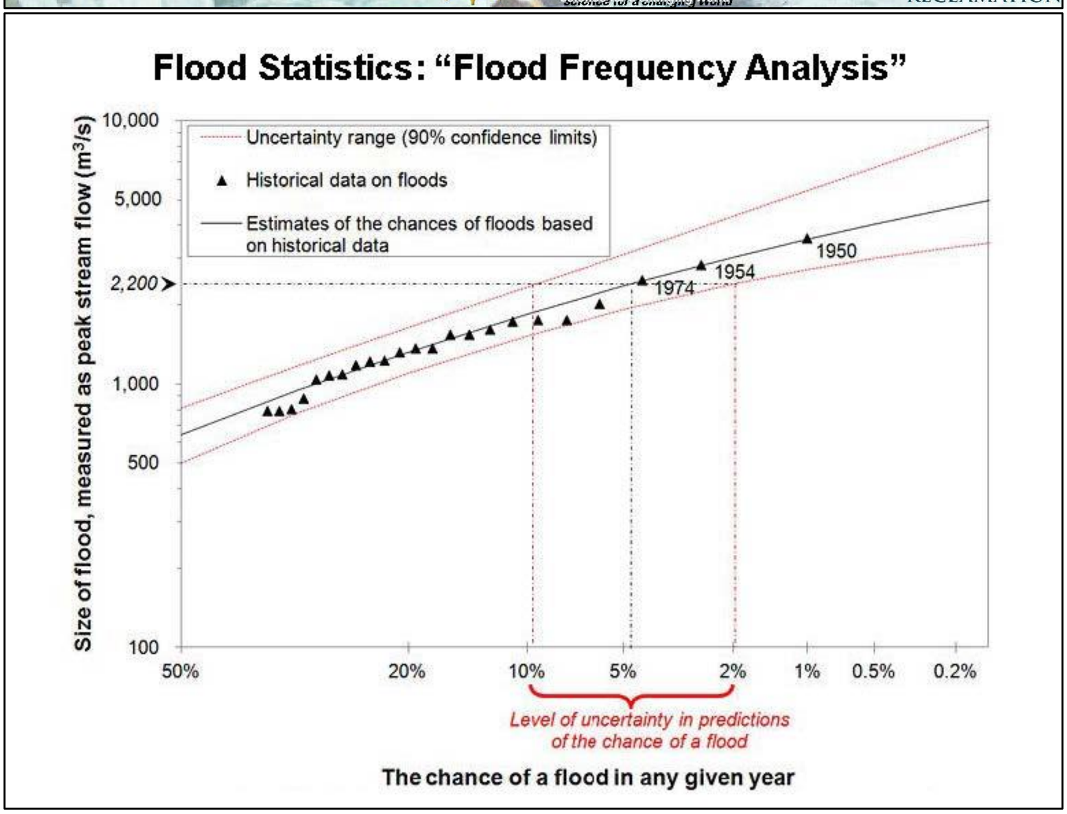
Speaker: Daniel, Wright

3.4.1.1 Abstract

Explicit modeling of the joint roles of rainfall, soil moisture, snowpack, and other hydrologic processes can improve estimates of flood frequency metrics such as the 100-year flood—as well as provide insights into the combinations of physical hydrologic processes that control such floods. These capabilities are particularly relevant for nonstationary climatic and land use conditions, where conventional flood frequency analysis techniques, which ignore or oversimplify flood physics, tend to suffer. This complexity of process-based approaches to flood frequency analysis, however, place them beyond the expertise and resources of many users. Under this project, we are developing an open-source workflow and Monte Carlo simulation system that combines the NextGen Water Modeling Framework from NOAA's National Water Center with the RainyDay rainfall analysis system from the University of Wisconsin-Madison. It will leverage NextGen's hydrofabric, model selection, calibration, and intercomparison tools, as well as unique high-performance computing resources at University of Wisconsin. Project goals include expanding the usability, reliability, and reproducibility of process-based hydrologic modeling for flood frequency research and practice.

3.4.1.2 Presentation (ADAMS Accession No. ML23177A168)





Pitfalls of “statistics-only” flood frequency

INVITED COMMENTARY

HP TODAY

HYDROLOGICAL PROCESSES
Hydrol. Process. **23**, 1671–1675 (2009)
Published online 17 March 2009 in Wiley InterScience (www.interscience.wiley.com). DOI: 10.1002/hyp.7292

Transcending limitations of stationarity and the return period: process-based approach to flood estimation and risk assessment

Murugesu Sivapalan[1,2,3]*
and Jos M. Samuel[4]

Geophysical Research Letters

RESEARCH LETTER
10.1029/2022GL098855

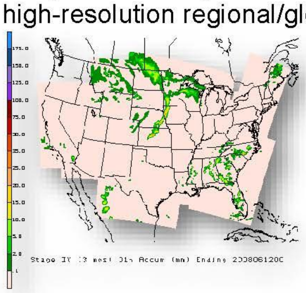
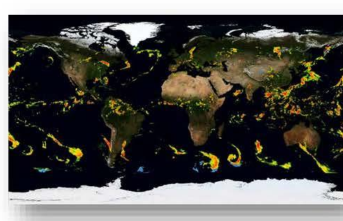
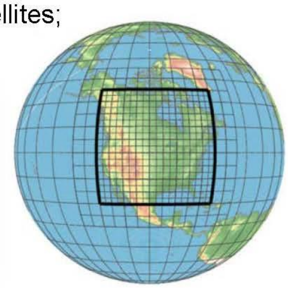
Diverse Physical Processes Drive Upper-Tail Flood Quantiles in the US Mountain West

Guo Yu[1,2], Daniel B. Wright[1], and Frances V. Davenport[3,4]

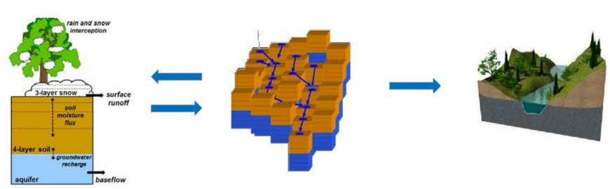
[1]Department of Civil and Environmental Engineering, University of Wisconsin-Madison, Madison, WI, USA, [2]Division of Hydrologic Sciences, Desert Research Institute, Las Vegas, NV, USA, [3]Department of Earth System Science, Stanford University, Stanford, CA, USA, [4]Department of Atmospheric Science, Colorado State University, Fort Collins, CO, USA

How can we use observational and modeling advances to improve flood frequency analysis?

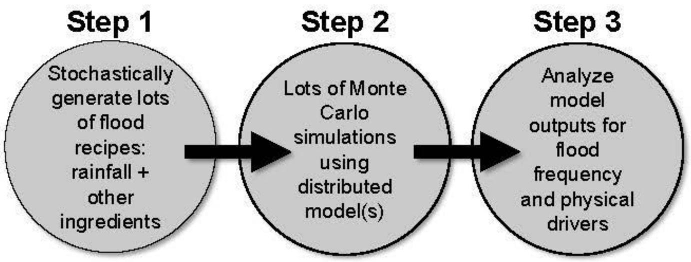
Observational Advances: gridded precipitation & other met datasets
Merged radar/gage/etc. datasets (e.g. AORC, Stage IV); satellites; high-resolution regional/global climate models

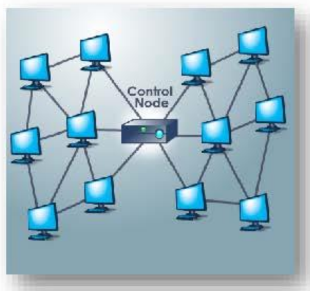
Modeling Advances: HPC-based distributed, physics-based models
(GSSHA, HLM, WRF-Hydro, NGEN, etc.)



One solution: Process-Based Flood Frequency Analysis



Combination of both long-term and event-scale simulations



HTCondor
High Throughput Computing

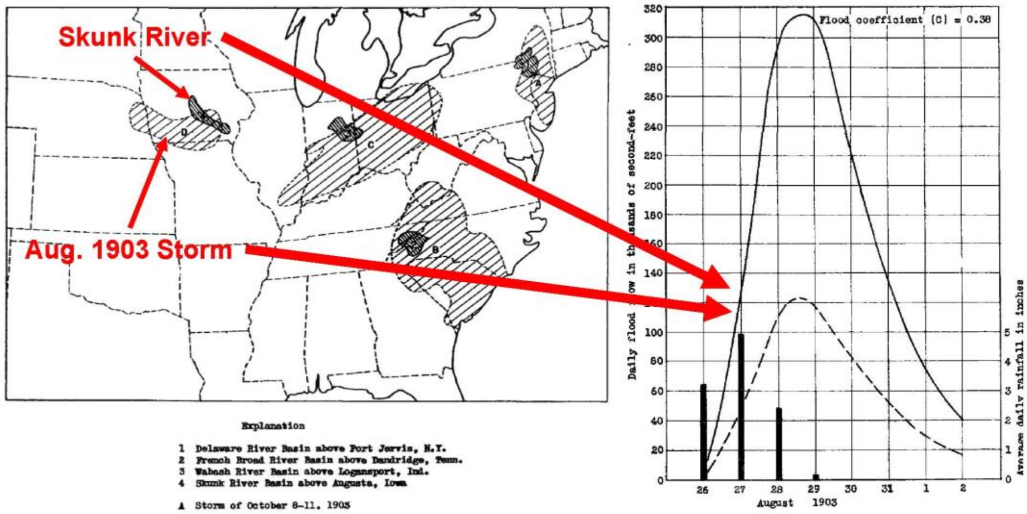
HOW DO WE GET "LOTS" OF RAINFALL SCENARIOS?

Open-source, Python-based RainyDay software

RAINY DAY

- Stochastic Storm Transposition to generate large numbers (100k+) of rainfall scenarios
- Uses archives of gridded precipitation data (e.g. radar, climate models, satellites)
- Can provides reasonable estimates to 1,000+ year recurrence intervals for rainfall and floods with 1-2 decades of data
- ~10 years old; currently refactoring to support xarray and dask libraries

Storm Transposition



Bernard, M.M., 1936, The unit hydrograph method and storm transposition of flood problems relating to great storms in the Eastern United States, USGS Water Supply Paper 772

Gives "what-if" rainfall or flood scenarios—but not their probability

Stochastic Storm Transposition

Journal of Hydrology **1** (1963) *46-57*;

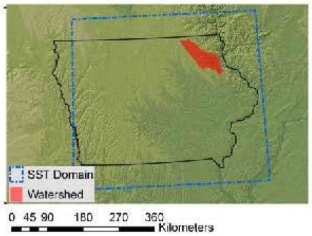
USING THE PROBABILITY OF STORM TRANSPOSITION FOR ESTIMATING THE FREQUENCY OF RARE FLOODS

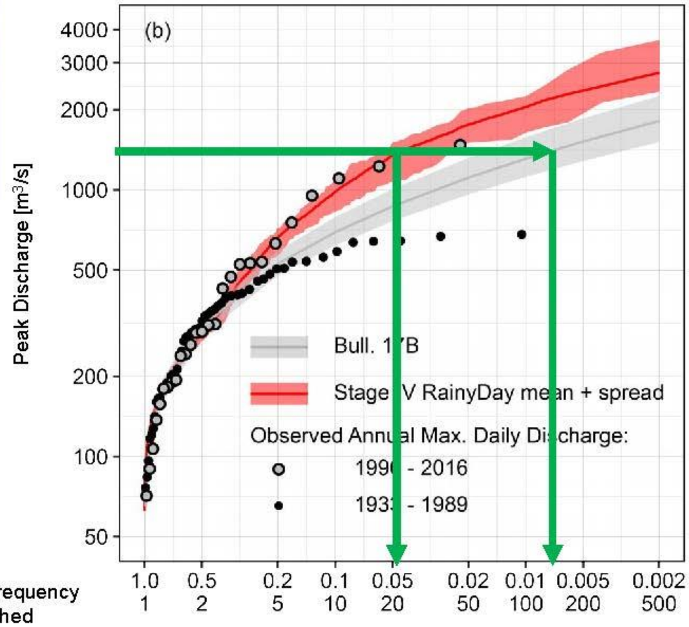
G. N. ALEXANDER

State Rivers and Water Supply Commission, Armadale, Victoria, Australia

When estimating the frequency of rare floods from a given catchment using storm rainfall data, the pertinent question is: "What is the probability of a rainfall averaging more than d inches (in a specified duration) occurring *over the catchment in question* within a long period such as the life of the dam?"

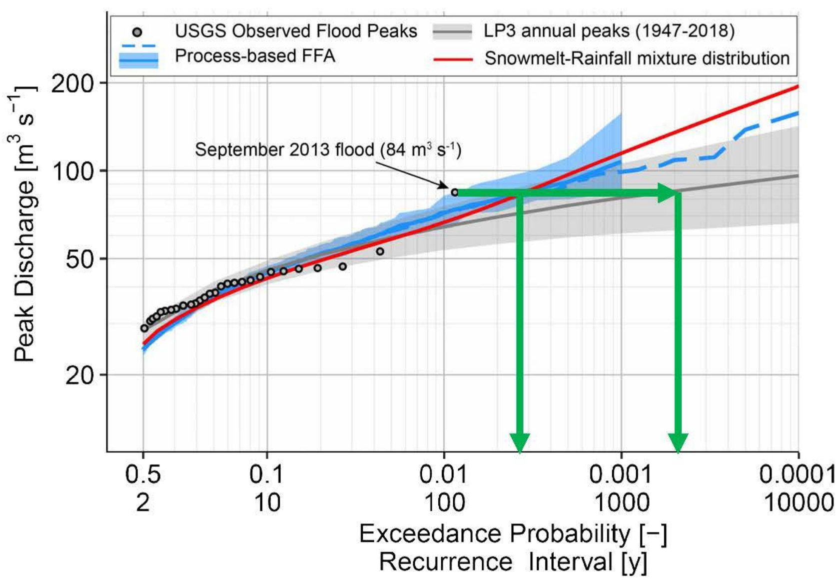
Example 1: Turkey River, IA





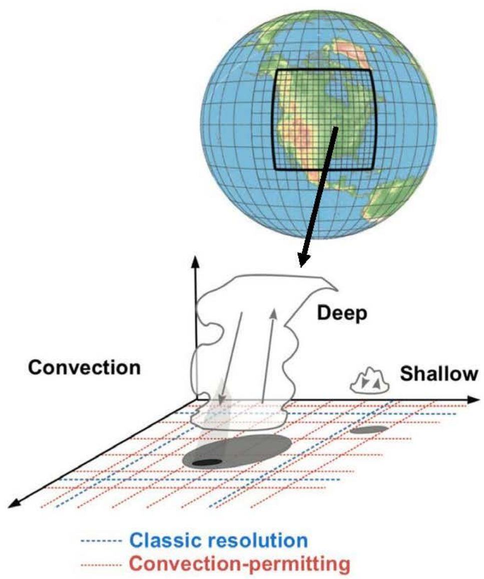
Yu et al., Process-Based Flood Frequency Analysis in an Agricultural Watershed Exhibiting Nonstationary Flood Seasonality, *HESS*, 2019.

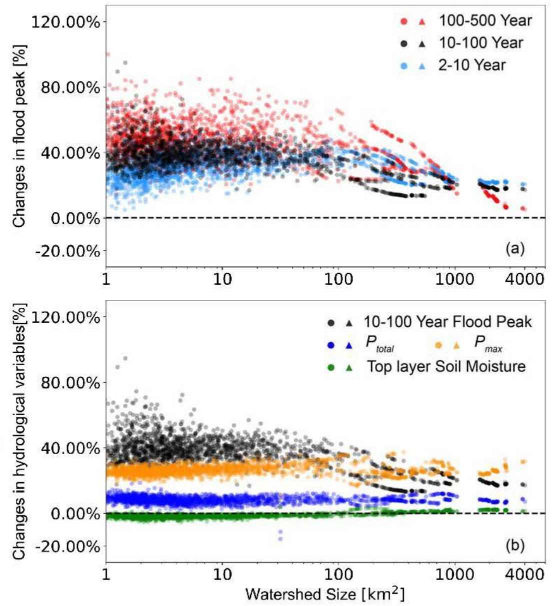
Example 2: Big Thompson River, CO



Yu et al., Connecting Hydrometeorological Processes to Low-Probability Floods in the Mountainous Colorado Front Range, *WRR*, 2021

Example 3: Future Flood Frequency

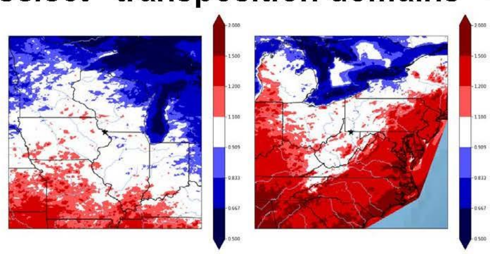




Yu et al., The Upper Tail of Precipitation in Convection-Permitting Regional Climate Models and Their Utility in Nonstationary Rainfall and Flood Frequency Analysis, *Earth's Future*, 2020

Unresolved questions with our approach

1. **How do we select "transposition domains" objectively?**



2. **How can we account for model structural and parameter uncertainty?**


Environmental Modelling & Software
Volume 109, November 2018, Pages 191-201

A model-independent iterative ensemble smoother for efficient history-matching and uncertainty quantification in very high dimensions

Jeremy T. White

3. **How can we lower the high "skill barriers"—meteorology, coding, HPC, hydrologic modeling, calibration, etc.?**
   - **NGEN solves these issues:** Varied model formulations and calibration approaches, hydrofabric and model-as-a-service simplify workflows

Process-based flood frequency is coming to HEC-HMS and NextGen!

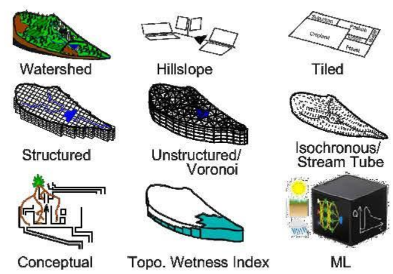
US Army Corps of Engineers®

Check out poster 3A-1!

RISK RATING 2.0

FEMA

OWP | OFFICE OF WATER PREDICTION

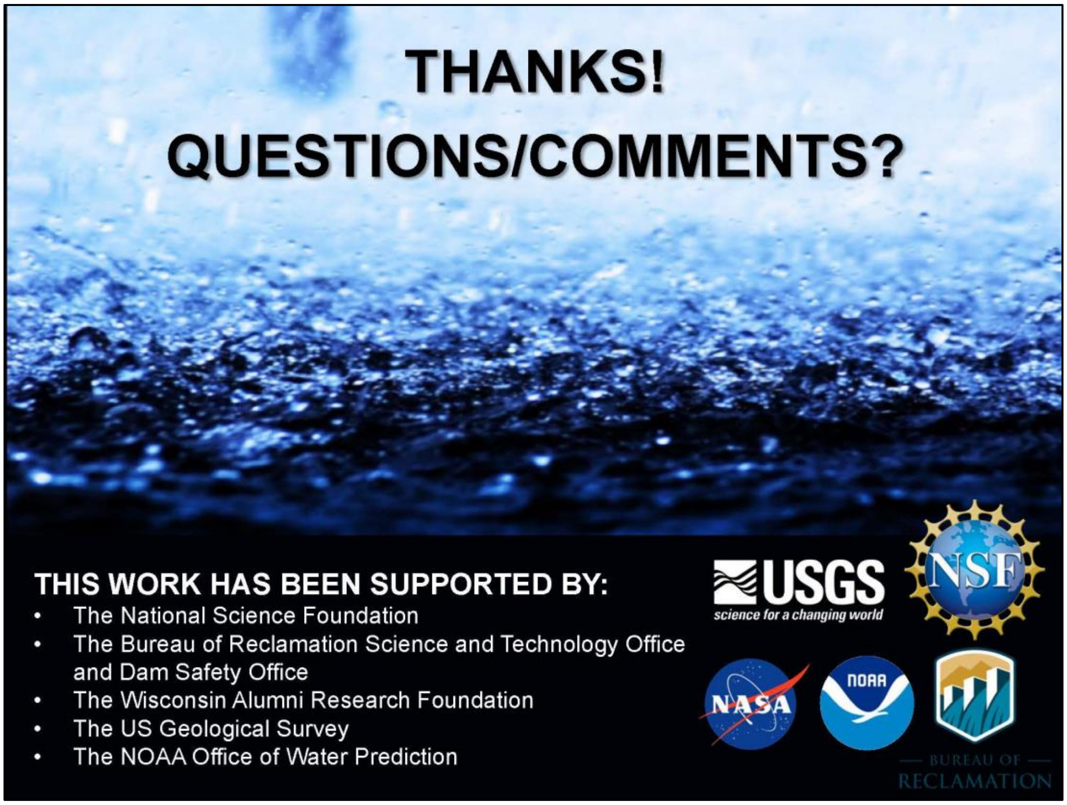


SUMMARY

- Complex hydroclimatic regimes and trends mean that we need more physical methods to estimate flood frequency
- Process-based methods give us an alternative way to estimate flood frequency, and to understand what drives it
- Coming to flood modeling software near you!
  - Soon: HEC-HMS; later: NGEN

Acknowledgements/Collaborators

Jim Smith & Mary Lynn Baeck (Princeton University), Witold Krajewski & Nicolas Velasquez (University of Iowa), Ricardo Mantilla (University of Manitoba), Christa Peters-Lidard (NASA), Amanda Stone & Kathleen Holman (Bureau of Reclamation), Eric Booth (University of Wisconsin-Madison); Zhe Li & Frances Davenport (Colorado State University), Guo Yu (Desert Research Institute), Mike Fienen & Jeremy White (USGS), Zhengzheng Zhou & Qi Zhuang (Tongji University), Zhihua Zhu (Sun-Yat Sen University), Soren Thorndahl & Christoffer Andersen (Aalborg University), Nadav Peleg (University of Laussane), Gabriel Perez Mesa (Oak Ridge National Lab)



3.4.1.3 Questions and Answers

Question:

I'm a big fan of the probabilistic modeling over pure statistics, but I was wondering, have you looked at the answers you're getting out of the process-based probabilistic models and how those compare to the suite of models one would get with alternate statistical modeling approaches beyond just the Bulletin 17B, Bulletin 17C type of approaches and seeing sort of how that process-based model compares to that range of uncertainties?

Answer:

One of those examples that I gave hinted at what you're asking about. We published a paper, I guess it was 2 years back in Water Resources Research where we were applying the method to Big Thompson watershed in Colorado, which has had the attention of flood hydrologists for a while now for reasons related to Big Thompson flood in the 70s and more recently during the big storm in 2013. In that process we did compare against a mixture distribution statistical approach. I blew through it in this presentation, but basically, the point here was that both the mixture distribution and our hydrologic process-based approach gave very similar answers. So, considering the physical processes that make up floods, the fact that a statistics-based method and our method gave very similar answers suggests that those physical processes and being able to explicitly account for them in one way or another is really important. If you don't do that, i.e., if you use a 17B or 17C sort of approach, you might get yourself into some trouble.

Question:

What parameters might be available within HEC-HMS for calibration that the user could toggle when applying this new feature for stochastic storm transposition?

Answer:

That's a great question, but one that I'm not able to answer very well. The HMS development team is currently implementing the stochastic storm transposition within the HEC-HMS software. If what you mean by calibration is literally calibrating your HMS model, then I suspect the answer is going to be everything that you can do now in HMS. But when it comes to parameters more related to the storm transposition piece, I'm not entirely sure what all is going to be there. I do know that you'll be able to not only capture the issues related to the storm transposition itself. but also be able to pair those transposed storms with seasonally appropriate randomly selected initial conditions using centrally batched processing tools within the HMS software.

Question:

Have you experimented with drawing transposition regions based on precipitation ingredients in combination with precipitation characteristics?

Answer:

We haven't. I think it's a really good idea and one that I'd be interested in exploring. I kind of pretend that I'm a meteorologist, but that's not really true based on my background. So, working with Kelly, who asked the question here, and with others, I think would be the right way forward on that. Our initial goal is, let's say, a rainfall-only approach, so that everything's kind of self-contained. You'd be transposing the same storms that you're using to define these transposition domains. But I think, in the longer run, it's going to be useful to pull in additional characteristics, or ingredients as you say.

Question:

Is there a method to group and bin weights for SST events to reduce the total sample size and computational demand? I'm familiar with approaches to do this in fixed distributions (convolution and stratified importance sampling), but don't know whether this is possible with storm movement.

Answer:

We haven't done a lot of work that does exactly what you're describing. But we are in some of the changes that we're currently making to RainyDay, some of those things would end up being easier than they are right now. In general, computational demand hasn't been a huge problem with RainyDay, so you can run it on a laptop. The computational problems come in if you are really trying to push to some of these very high-resolution radar datasets like 1-square kilometer, 5-minute rainfall data. Then we are running into some memory problems. But we're going to able to work around those by re-writing the code and using some more modern Python libraries.

Question:

What might be good ways to validate the process-based modeling? Can the modeling use past extreme floods to test the validity of the model and its parameter inputs?

Answer:

When we do our hydrologic model calibration and validation, we take a very holistic view. Even though we're really focused on modeling peak flows (that's our end goal), to do this process-based approach, you really need to be able to simulate the entire hydrologic regime from low flows to high flows and everything in between, as well as soil moisture and ET and everything like that. You need to be able to simulate all those things well. So, we end up pulling in data, in some cases for calibration and in other cases for validation, from different sources including looking at seasonal water balances and annual ET amounts and things like that to try to make sure that we're doing all the processes as best as we can.

Question:

Can you incorporate a longer-term temporal window from preconditional factors. I'm thinking of a brand-new paper that came out in Environmental Research Letters that groundwater-contributed baseflow is better for predicting extremeness than precipitation on longer time scales.

Answer:

We do draw from a seasonal climatology of watershed initial conditions (soil moisture, snowpack, baseflow) to initialize each simulated flood. Not sure that is exactly answering your question though.

Question:

I am wondering about the time window that you are using for the simulations and are there limits on that window? For example, a six-month span or a 3 -day span?

Answer:

In the past we've used a +/-14-day window, so roughly a month. It would probably be ok to use a shorter window. A longer window would likely get into trouble with snowpack occurring unrealistically early or late in the season.

3.4.2 Presentation 2B-2: Towards the Development of a High-Resolution Historical Flood Inundation Reanalysis Dataset for the Conterminous United States

Authors: Sudershan Gangrade[1], Ganesh Ghimire[1], Shih-Chieh Kao[1], Mario Morales-Hernandez[2], Michael Kelleher[1], Alfred Kalyanapu[3]; [1]Oak Ridge National Laboratory, [2]University of Zaragoza (Spain), [3]Tennessee Technological University

Speaker: Sudershan Gangrade

3.4.2.1 Abstract

To evaluate regional flood risks and develop long-term flood mitigation and resilience measures, a high-resolution historical flood inundation dataset covering the entire conterminous United States (CONUS) can be very valuable. The accurate representation of flood dynamics at a large scale necessitates the solution of full 2D shallow water equations at a locally relevant spatial resolution. We introduce a CONUS-wide implementation of a GPU-accelerated 2D hydrodynamic model – TRITON (https://triton.ornl.gov/) to reconstruct major historic flood events for all HUC04 subregions. TRITON is driven by historic runoff and streamflow simulated by a calibrated VIC-RAPID hydrologic modeling framework forced with National Center for Environmental Prediction Stage IV hourly Quantitative Precipitation Estimates from 2002 to 2018. The baseline terrain information for the TRITON inundation model is provided by a 10m National Elevation Dataset. The default TRITON implementation is driven by long-term climatic mean runoff and streamflow to obtain steady-state channel flow conditions, which serve as

initial water depths and velocity information for event-based TRITON simulation. The performance of simulated flood inundation maps is evaluated using various temporally static benchmark information, including high-water marks, remote sensing-derived inundation maps, and local high-fidelity simulation maps. The temporal evolution of flood simulations is evaluated using U.S. Geological Survey stage data. Finally, we discuss the challenges and barriers in national/continental scale high-resolution inundation modeling, calibration and validation, and future developments targeted to improve the representation of flood regimes, and their implications for real-time flood forecasting.

3.4.2.2 Presentation (ADAMS Accession No. ML23177A169)

Oak Ridge National Laboratory

Towards the development of a high-resolution historical flood inundation reanalysis dataset for the conterminous United States

8th Annual Probabilistic Flood Hazard Assessment Research Workshop
U.S. Nuclear Regulatory Commission's Office of Nuclear Regulatory Research

March 21-24, 2023

Sudershan Gangrade[1], Ganesh R. Ghimire[1], Shih-Chieh Kao[1], Mario Morales-Hernández[2], Michael E Kelleher[1], and Alfred J. Kalyanapu[3]

1 Oak Ridge National Laboratory, Oak Ridge, TN, USA
2 I3A-University of Zaragoza, Spain
3 Tennessee Technological University, Cookeville, TN, USA.

ORNL is managed by UT-Battelle, LLC for the US Department of Energy

U.S. DEPARTMENT OF ENERGY

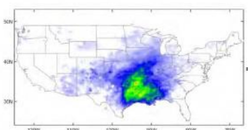
High-Resolution Flood Inundation Reanalysis Dataset

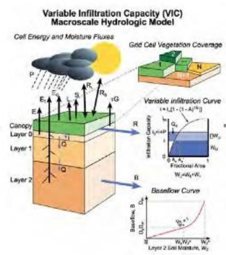
- **Development of a historical inundation reanalysis dataset**
  - Accurately represent flood dynamics and help evaluate flood risks
  - Support develop long-term flood mitigation and resilience measures
- **Objectives**
  - Develop a hierarchical modeling framework to generate high resolution flood inundation maps
  - Reconstruct major historic flood events and develop an inundation reanalysis dataset
  - Evaluate flood inundation maps using various benchmark information

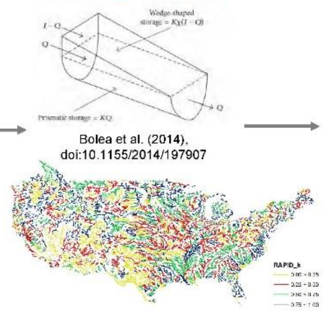
Oak Ridge National Laboratory

Hierarchical modeling framework for high-resolution flood inundation mapping

Precipitation	Hydrologic Modeling	Streamflow Routing	Hydrodynamic Modeling
Radar-QPE Stage IV (ST4) Hourly, 4km	Variable Infiltration Capacity (VIC)	Routing Application for Parallel computation of Discharge (RAPID)	Two-dimensional Runoff and Inundation Toolkit for Operational Needs (TRITON)



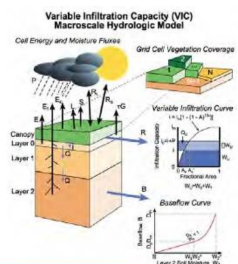


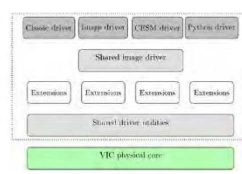


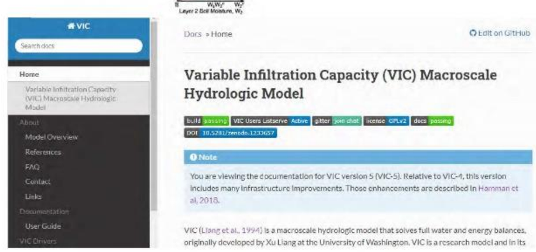
Bolea et al. (2014), doi:10.1155/2014/197907

Variable Infiltration Capacity (VIC) Model

- **VIC Version 5 (Hamman et al., 2018)**
  - Macroscale, distributed hydrologic model
  - Reconfiguration of the legacy VIC source code
- **ORNL Setup and Calibration**
  - Based on the initial parameters from 9505V2 (Oubeidillah et al., 2014; Naz et al., 2016)
  - Spatial Resolution = 1/24° (~4 km)
  - Driven by latest DaymetV4
  - Comparison with the monthly USGS WaterWatch runoff dataset
  - Model Evaluation – 1982-2000



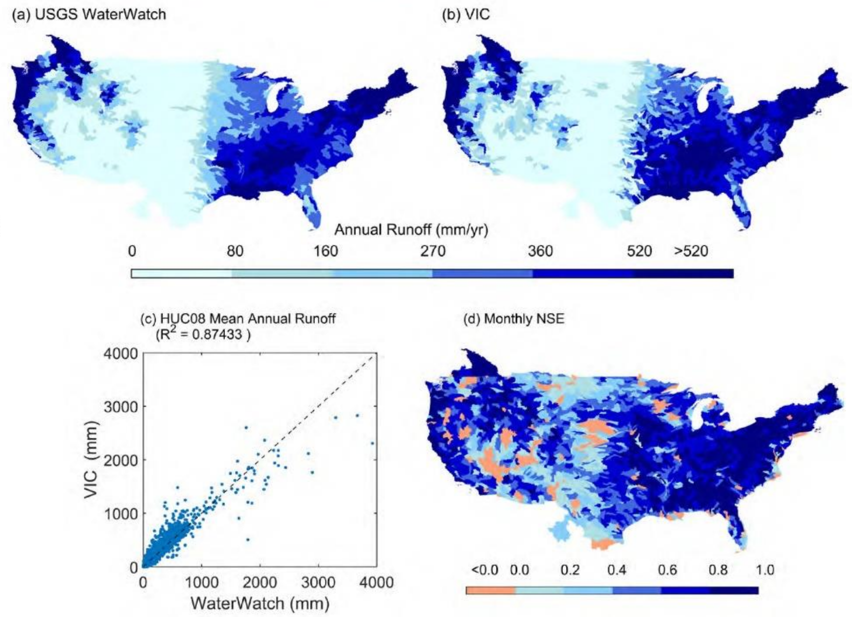




Hamman et al. (2018)

VIC Performance

- **VIC5 (DaymetV4)**
  - Calibration results presented at aggregated HUC08 scale.
  - Calibration period :1982–2000
  - Comparison with the monthly USGS WaterWatch runoff dataset



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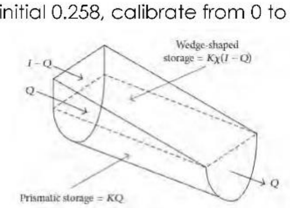
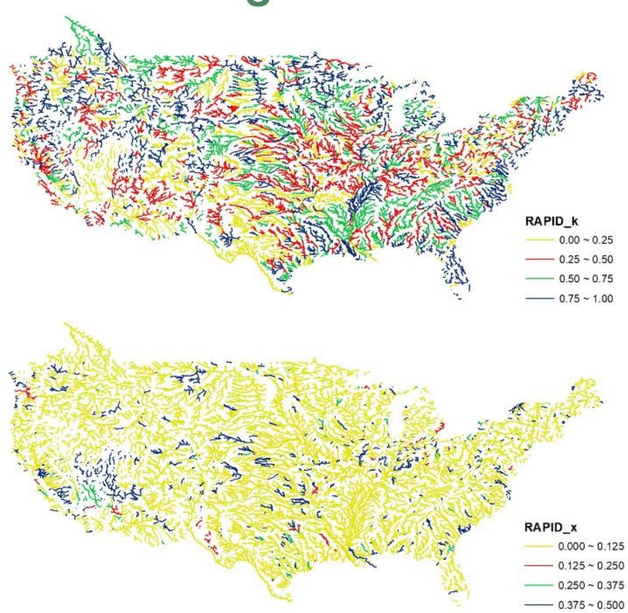
RAPID Streamflow Routing

- **Routing Application for Parallel computation of Discharge (RAPID)**
- **Muskingum parameters**
  - K: storage constant in time
  - x: relative influence of inflow on storage
- **Calibration (David et al., 2011)**
  - K = k * L / c
    - L: River segment length (m)
    - c: celerity (0.28 m/s)
    - k: initial 0.131, calibrate from 0 to 1
  - x
    - initial 0.258, calibrate from 0 to 0.5

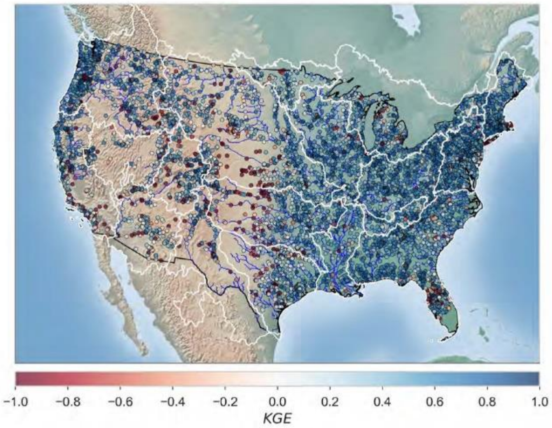


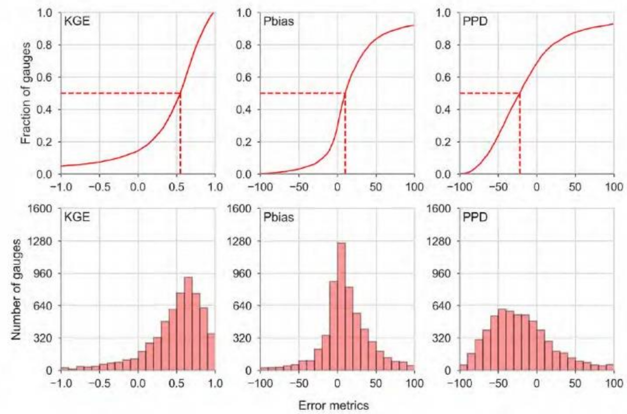
Bolea et al. (2014), doi:10.1155/2014/197907



OAK RIDGE National Laboratory

Performance of VIC-RAPID Streamflow driven by ST4





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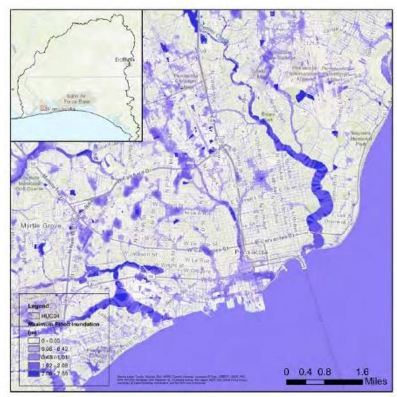
TRITON Hydrodynamic Model

- **Two-dimensional Runoff and Inundation Toolkit for Operational Needs (TRITON)**
  - Developed by ORNL and TTU, supported by USAF Numerical Weather Modeling Program (Morales-Hernández et al., 2021)
  - https://code.ornl.gov/hydro/triton
- **Physics-based hydrodynamic flood model**
  - Resolution of the 2D shallow water equations
  - Can simulate the backwater effects
  - Allow flash (pluvial) flood simulation
- **Support multiple platforms**
  - Single GPU (CUDA)
  - Multiple CPUs (OpenMP+MPI)
  - Multiple GPUs (CUDA+MPI)



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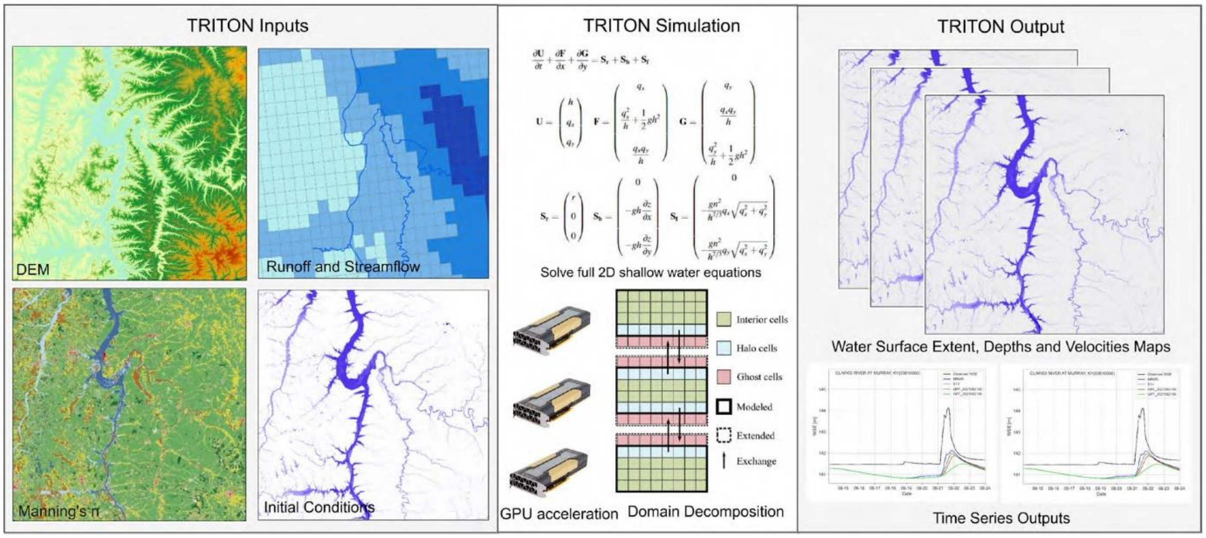
TRITON Hydrodynamic Model



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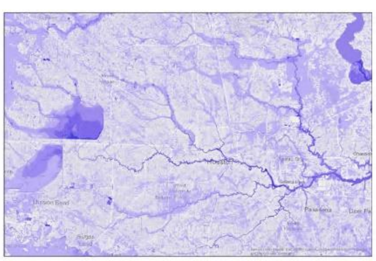
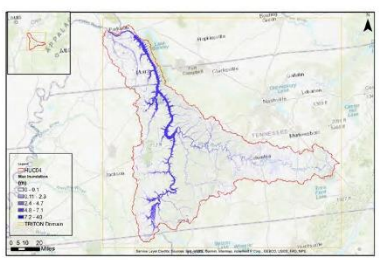
TRITON Applications

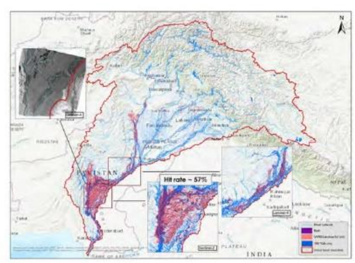
- **VIC-RAPID-TRITON has been successfully applied to simulate several flood events in the CONUS**
  - Hurricane Harvey, Laura, Sally
  - Central Tennessee Floods
  - Midwestern Flood 2019 (Missouri River Basin)
- **Hydrodynamic modeling in global watersheds using NASA LIS runoff outputs**
  - La Plata River Basin in South America
  - Indus River Basin in Asia



Hurricane Harvey, 2017



Central Tennessee Flood, 2021



Pakistan Floods, 2022
Indus River Basin

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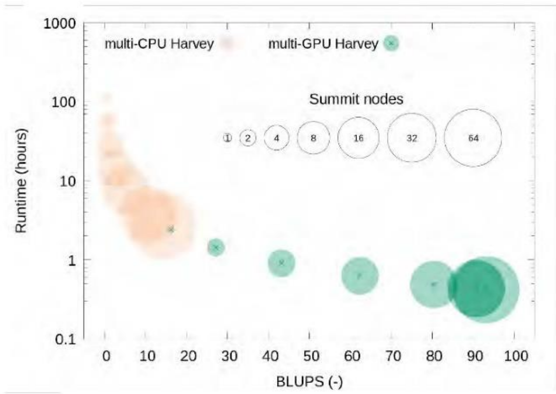
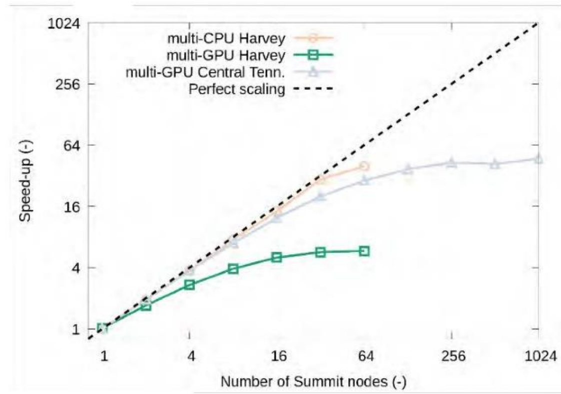
Multi-GPU architecture shows reasonable scaling performance for large-scale modeling





- **Hurricane Harvey, 2017 (68 million cells @ 10m, 10-day simulation)**
- **Central Tennessee floods, 2021 (700 million cells @ 10m, 10-day simulation)**

Hindcast Flood Simulations

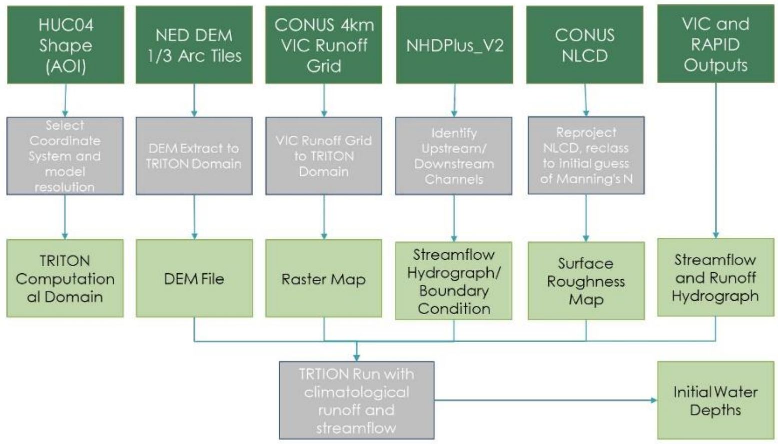
- **Generate a CONUS-scale TRITON implementation**
  - TRITON setup for 202 HUC04s at 10 m resolution
  - Average TRITON domain size of ~1 billion grid cells
  - Default TRITON inputs for any place within CONUS
  - Event based modeling using VIC-RAPID driven by ST4 precipitation, 18 largest events based on 3-day runoff at each HUC04

Rainfall → Runoff → Streamflow → Inundation

- Rainfall
  - **Radar-QPE Stage IV (ST4)**
  - Hourly, 4km
- Runoff
  - **VIC**
  - Hourly, 4km
- Streamflow
  - **RAPID**
  - Hourly, NHDPlus v2 river network
- Inundation
  - **TRITON**

TRITON Implementation Workflow

1. Area of Interest > Bounding Box
2. Extract NED DEM > DEM map
3. Extract NLCD > Manning's n map
4. VIC Runoff Grids > Runoff map
5. RAPID streamflow > Upstream flow (Stream Order >5)
6. NHDPlus_v2 Slope > Downstream Boundary Condition
7. TRITON run with climatological runoff and streamflow > initial conditions (stop criterion, change in flooded area/volume <= 1%)
8. Event based modeling using VIC-RAPID driven by ST4 precipitation, 18 largest events based on 3-day runoff at each HUC04



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Strategies for TRITON Evaluation

- **Static and remote sensing based datasets**
  - USGS High water marks, Dartmouth Observatory
  - RAPID NRT Flood Maps https://rapid-nrt-flood-maps.s3.amazonaws.com/index.html
- **Temporal (USGS stage data)**
  - Event based sub-daily stage data comparisons where available

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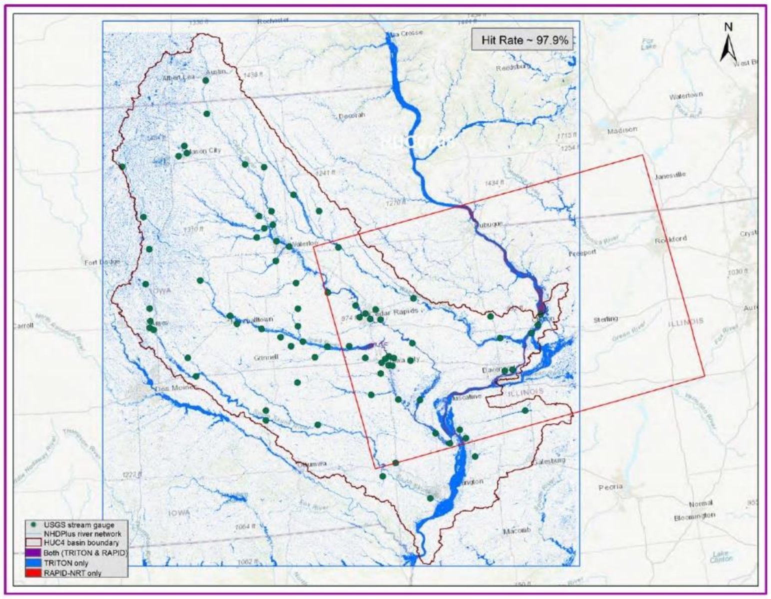
Example – HUC0708 in Iowa

- Binary comparison of the spatial pattern of flooding.
- Benchmark flood map - RAPID NRT [Shen et al. (2019)]
- Near Real-time High-resolution (10 m) flood inundation dataset over the Contiguous United States.
- Based on the Sentinel-1 SAR imagery (2016-current) archive using an automated Radar Produced Inundation Diary (RAPID) algorithm.



Shen, Xinyi, Emmanouil N. Anagnostou, George H. Allen, G. Robert Brakenridge, and Albert J. Kettner. "Near-real-time non-obstructed flood inundation mapping using synthetic aperture radar." *Remote Sensing of Environment* 221 (2019): 302-315.

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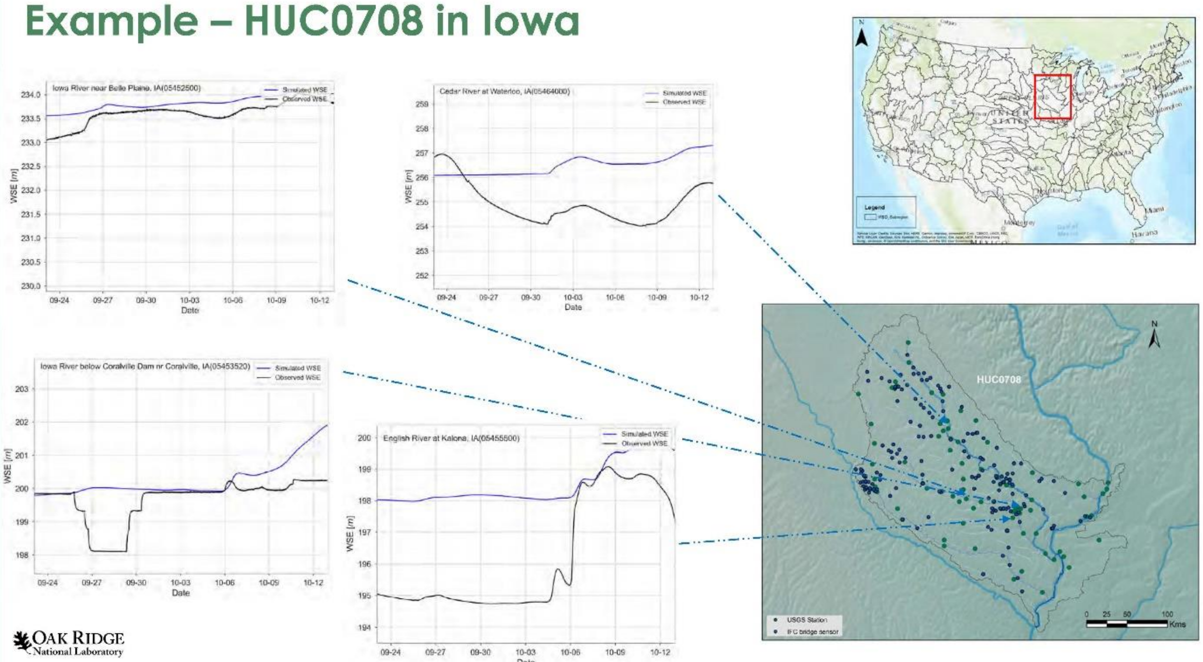
Example – HUC0708 in Iowa



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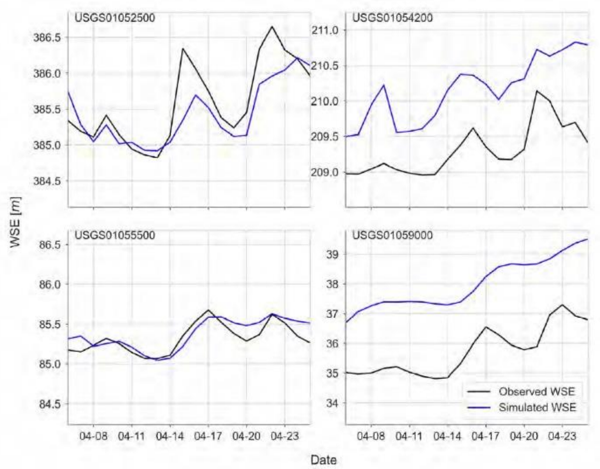
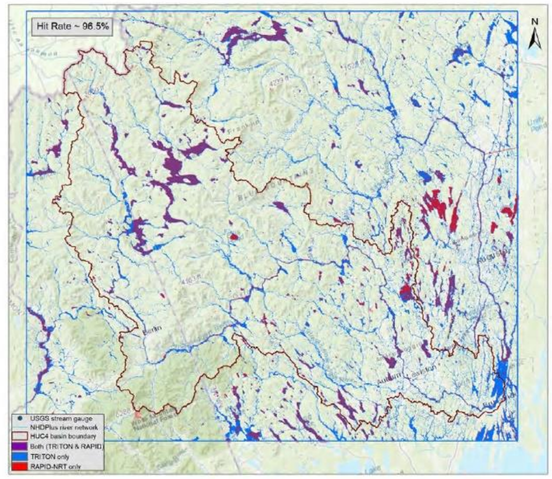
Example – HUC0104

- HUC04 based simulations in the CONUS reasonably represent observed inundations





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Challenges and Future Opportunities

- **Lack of adequate large-scale benchmarking datasets for validation of inundation predictions**
- **DEM Related**
  - DEM needs additional hydro-conditioning; bridges and other road intersections can act as local dams
  - Lack of proper channel conveyance and reservoir bathymetry
  - Lack of representation of levees/ flood defenses
- **Lack of reservoir operation representation**
- **TRITON related**
  - Developing appropriate initial conditions prior to flood event
  - Long-term disk space for file storage

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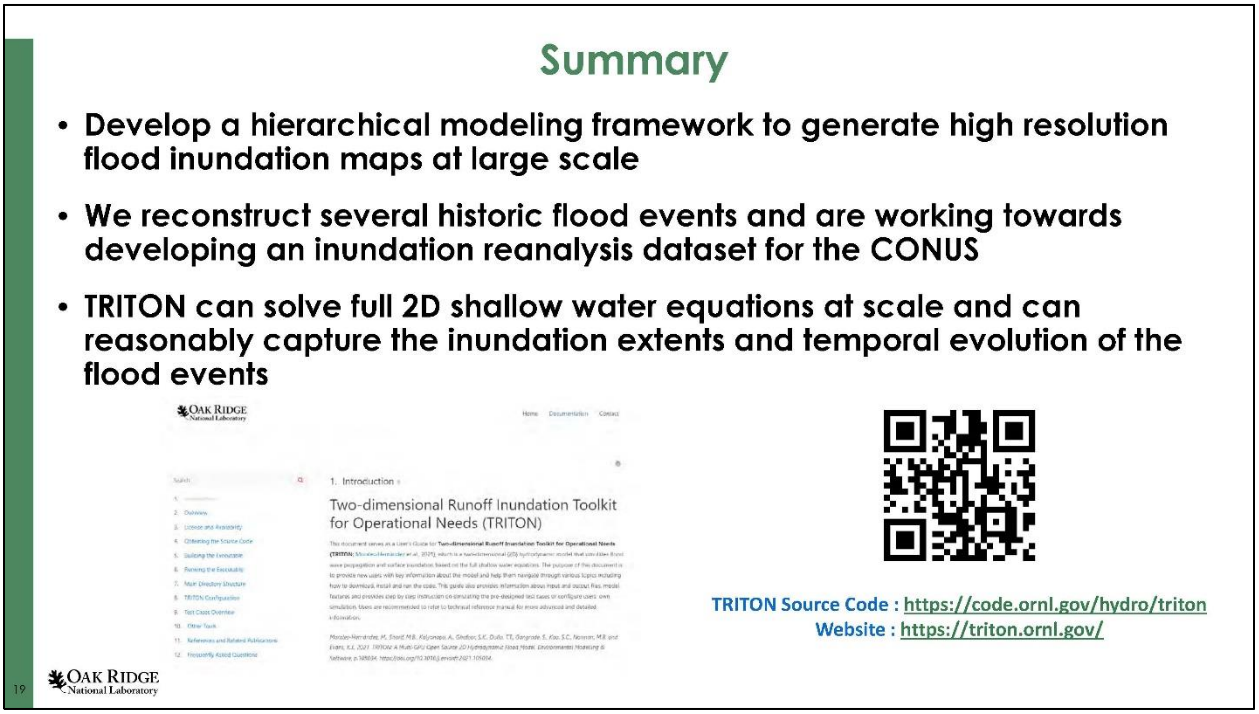
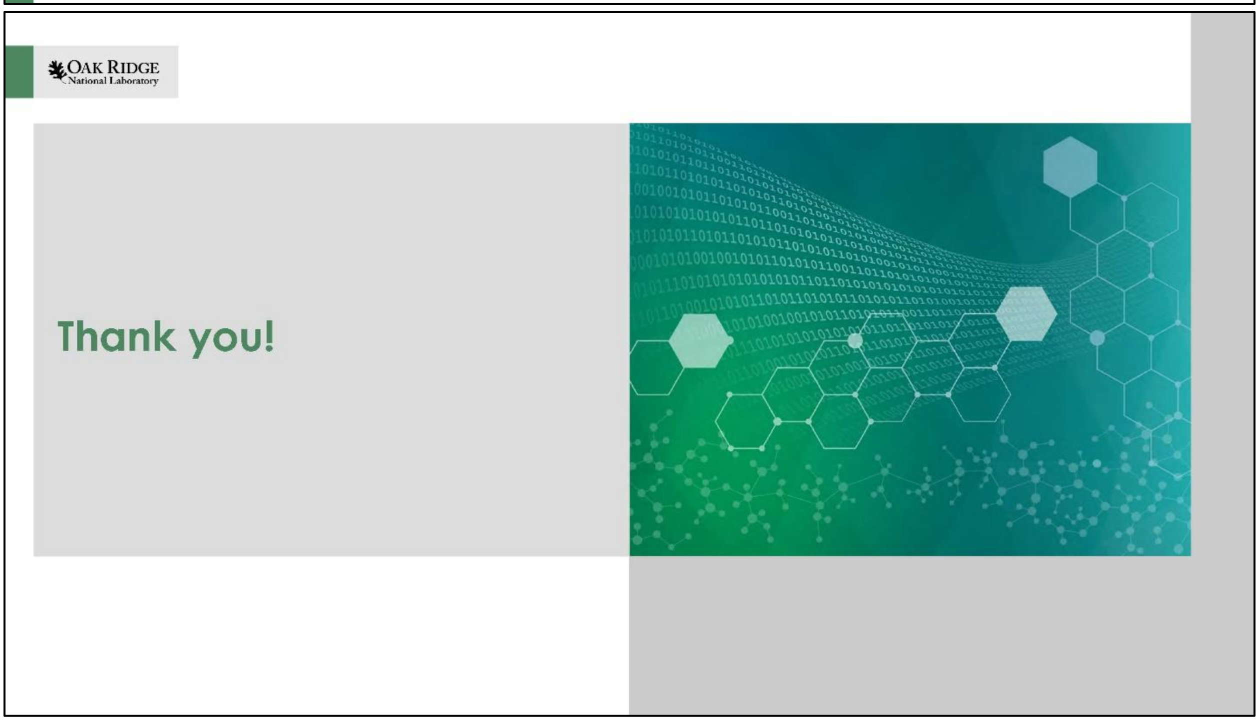




3.4.2.3 Questions and Answers

Question:

With respect to TRITON, what was the resolution of the cells used for a HUC-4 watershed? What are the simulation times?

Answer:

We used a 10-meter DEM for every HUC-4, and that becomes the base resolution for the model. But it doesn't have to be 10 meters. If there is finer resolution data available from lidar we can use that. In terms of running the simulation, we simulate a 20-day flood event. We have done 10-day flood events too, so it just depends. But to be consistent across all the HUC-4s, we are sticking to a 20-day flood event simulation.

Question:

How does TRITON compare to HEC-RAS 2D which is widely used in the industry?

Answer:

In terms of similarities, we are also solving shallow water equations. The major difference is TRITON's ability to run on GPUs. It can efficiently utilize multiple GPUs to run on a very large scale and solve a lot of cells within the domain. That becomes the main point in this case so that we can efficiently conduct a large-scale simulation. For instance, we simulated a Hurricane Harvey flood event that was around 70 million grid cells in the Houston area and we were able to conduct that entire simulation, a 10-day simulation, in less than 30 minutes of wall time. I believe that is currently not possible with HEC-RAS 2D.

Question:

When you are simulating these flooding events, how are you defining the events (the beginning and end of the events) and how are you picking up the antecedent conditions such as soil moisture, the preceding flows, or maybe if you are in a cold region, things like snowpack? How are you acquiring that information?

Answer:

To come up with the antecedent conditions, we are using a framework. In terms of the hydrologic modeling, VIC is there, and then the RAPID[13] model is there to do the stream routing. Some of those hydrologic processes are captured by VIC. When it comes to the initial conditions in the channels, the way we are approaching the problem currently is that we run the TRITON long enough using some climatological mean run off and streamflow as an input to the domain and let it run until it achieves a steady-state condition in the domain. That becomes our starting point for these flood events. In terms of selecting the flood event itself, the way we are doing it is at HUC-4 by HUC-4, so we look at the streamflow and the runoff for every HUC-4 and select the annual maximum flood events for each of those HUC-4s and we try to keep the peak towards the end of the simulation because that gives us the maximum inundation extent through TRITON.

3.4.3 Presentation 2B-3: Quantifying Uncertainty for Local Intense Precipitation and Riverine Flooding PFHA at Critical Structures on the Idaho National Labs Property

Authors: Ryan Johnson[1], Shaun Carney[1], Paul Micheletty[1], Debbie Martin[1], Bruce Barker[2]; [1]RTI International, [2]MGS Engineering

Speaker: Ryan Johnson

[13] Routing Application for Parallel computatIon of Discharge

3.4.3.1 *Abstract*

Research Triangle Institute (RTI) International is performing Probabilistic Flood Hazards Analyses (PFHA) for critical structures on the Idaho National Lab (INL) property to satisfy requirements outlined in Department of Energy (DOE) STD-1020-2016, “Natural Phenomena Hazards Analysis and Design Criteria for DOE Facilities”. Flooding hazards are separated into two classifications in the DOE STD-1020-2016 standard—riverine flooding hazards and flooding due to local intense precipitation (LIP). Depending on the location of a structure within the INL property, both of these flood mechanisms and their associated aleatory variability and epistemic uncertainty are considered. All structures regardless of location are evaluated for flooding from LIP events. Structures located next to rivers are also evaluated for riverine flooding. Sources of uncertainty evaluated for LIP and riverine flooding include precipitation frequency characteristics, breaches of upstream embankments, hydrologic model parameters, Manning’s surface roughness and culvert blockage. The Stochastic Event Flood Model (SEFM is used in combination with U.S. Corps of Engineers (USACE) Hydrologic Engineering Center (HEC) Hydrologic Modeling System (HEC-HMS) and River Analysis System (HEC-RAS) models to conduct stochastic simulations, generate hydrologic hazard curves, and characterize uncertainty in flood frequency estimates for specific buildings of interest. This presentation will discuss the methods used to characterize uncertainties and propagate these through to uncertainties in key flood metrics for critical infrastructure, as well as discussing methods employed to address computational challenges with employing detailed structure-level hydraulic modeling in a stochastic framework.

3.4.3.2 Presentation (ADAMS Accession No. ML23177A170)

Quantifying Uncertainty for LIP and Riverine Flooding PFHA at Critical Structures on the INL Property

RTI International | Center for Water Resources

Idaho National Laboratory

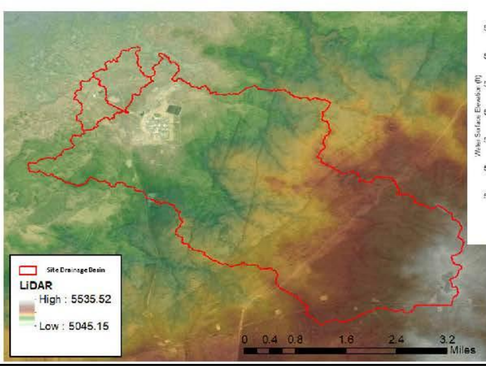
MGS Engineering Consultants, Inc.

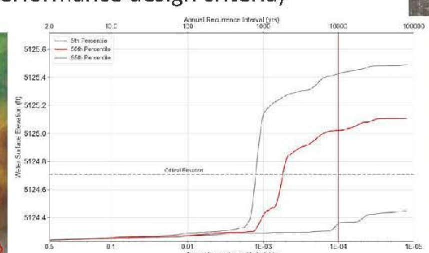
DTN

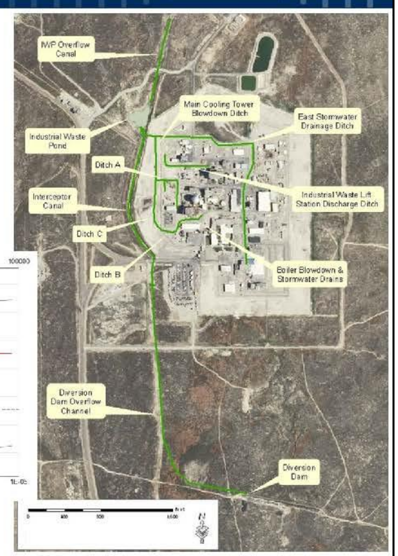
1

Background

- Purpose:
  - PFHA analysis to satisfy Department of Energy (DOE) STD-1020-2016, "Natural Phenomena Hazards Analysis and Design Criteria for DOE Facilities".
- Objective:
  - Develop hazard curves for each structure to show range of inundation for required AEP levels (based on performance design criteria)







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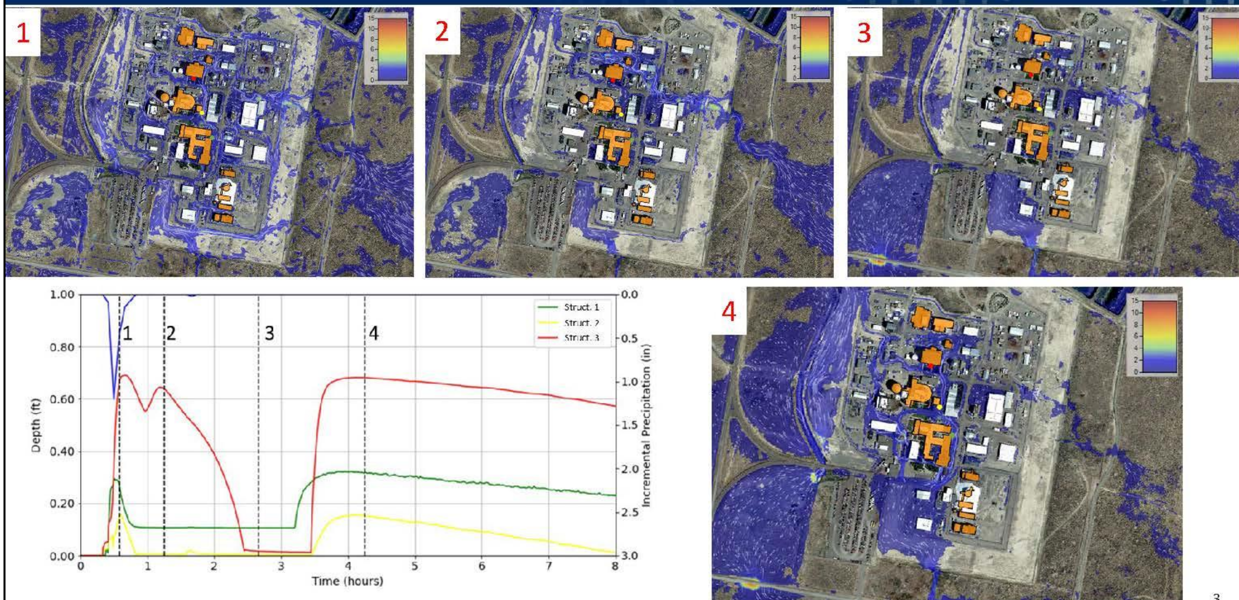
Site Hydraulics



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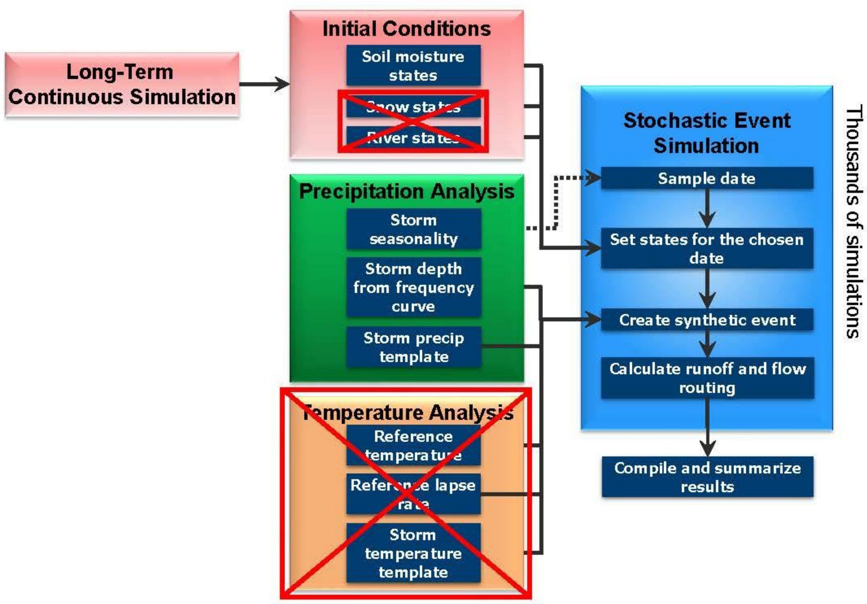
PFHA Framework



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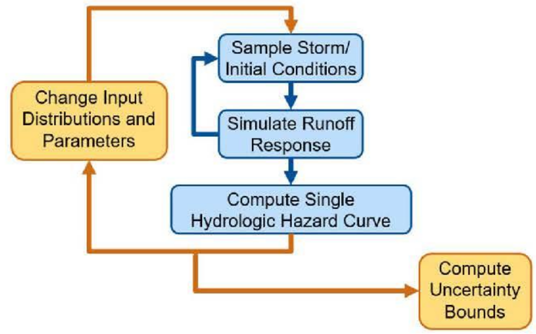
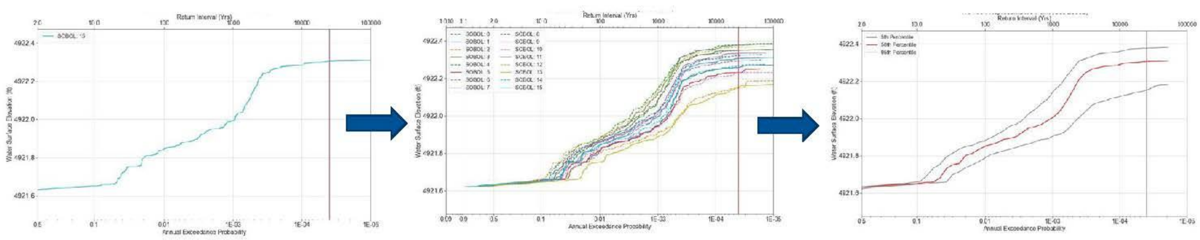
PFHA Framework

- Two looped, nested Monte Carlo Simulation:
  - Inner loop uncertainty; natural variability
    - Precipitation seasonality/template/depth
  - Outer loop uncertainty: knowledge
    - Precipitation frequency
    - Soils loss parameters
    - Surface roughness
    - Long-term precip/temp
    - Dam failures





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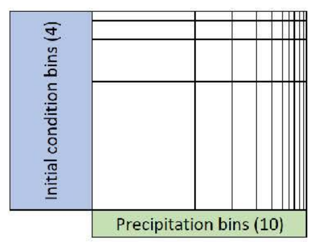
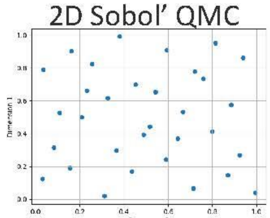
SEFM Input Sampling

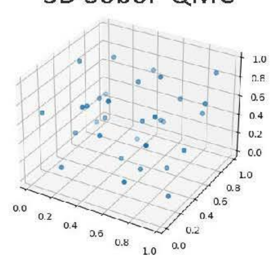
- Inner loop uncertainty; natural variability
  - Stratified sampling of precipitation depth and initial condition
- Outer loop uncertainty: knowledge
  - Scrambled Sobol' Quasi Monte Carlo sampling method
  - Need to get all dimensions ranked



2D Sobol' QMC



3D Sobol' QMC



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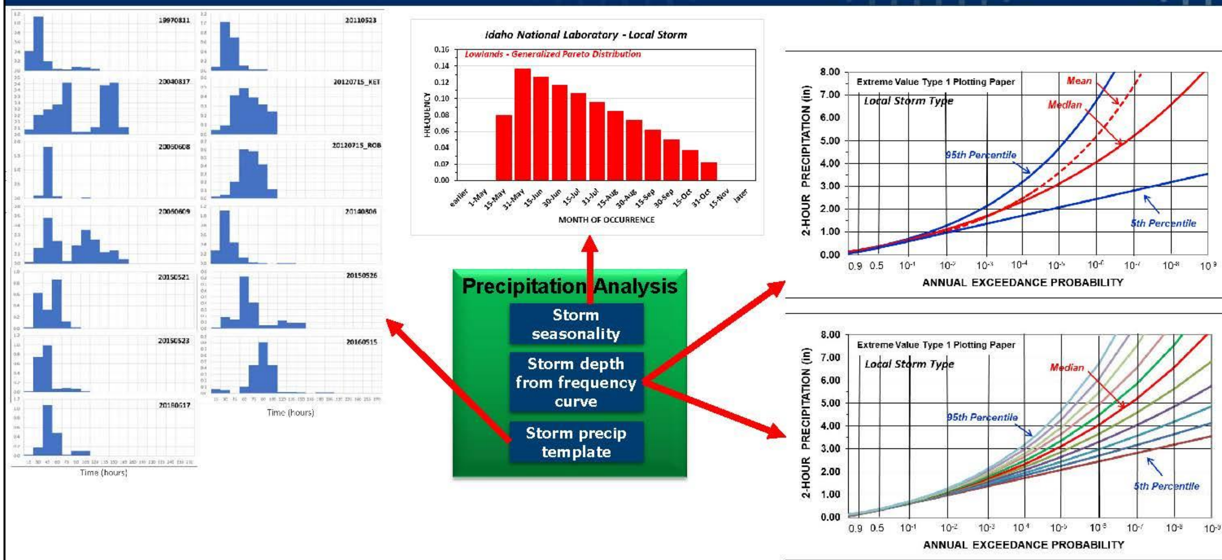
Precipitation



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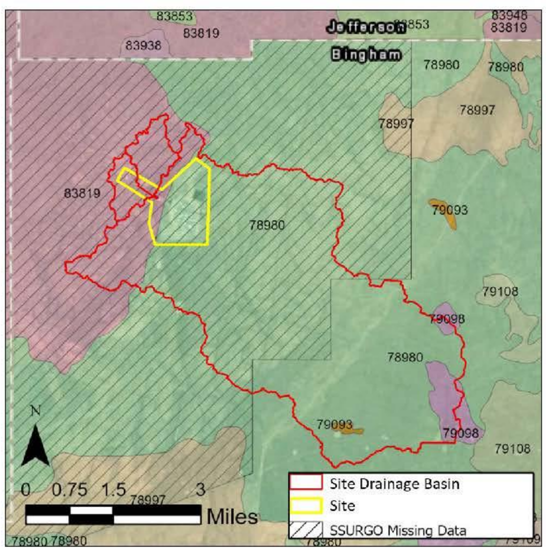
Soils Uncertainty

Soil Types ✖ # Parameters ✖ Range of Parameter Values = **Lots of Uncertainty!**



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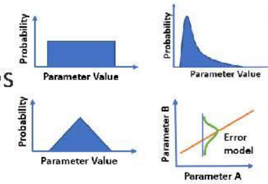
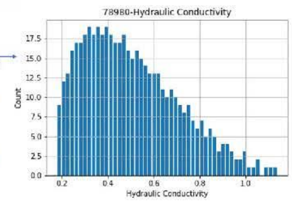
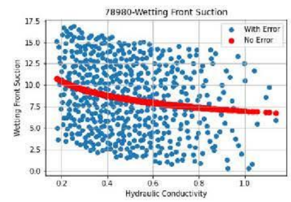
Soils Uncertainty

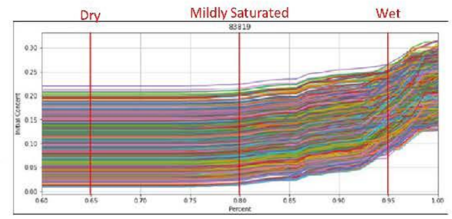
1. Range of Parameter Values



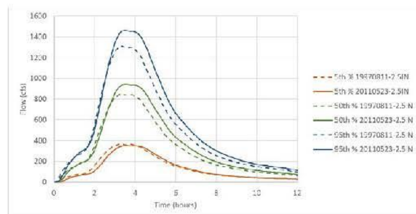




2. Run long-term/event simulations with all parameters sets

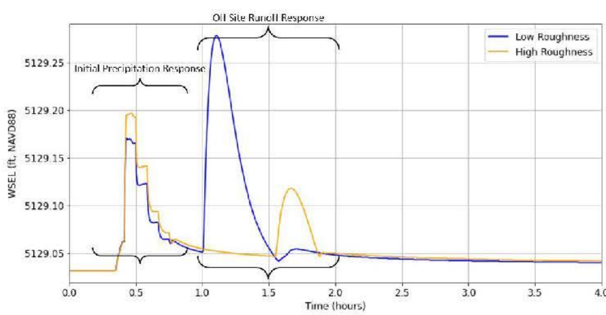


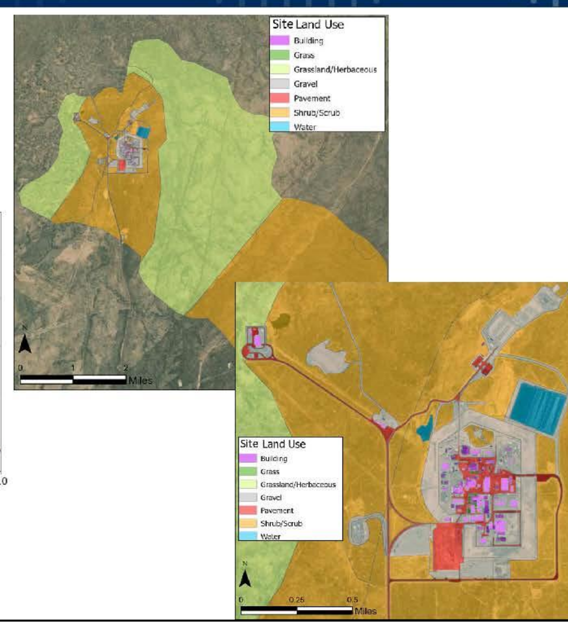
3. Compute combined rank



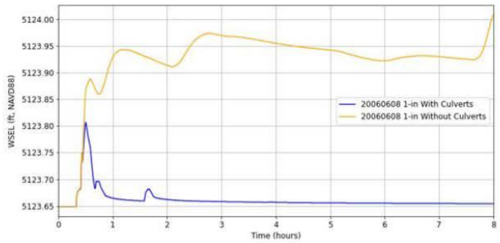
Manning's Roughness

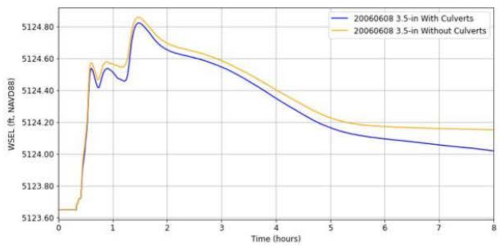
- Changes in roughness impact the timing of off-site runoff and peak WSEL

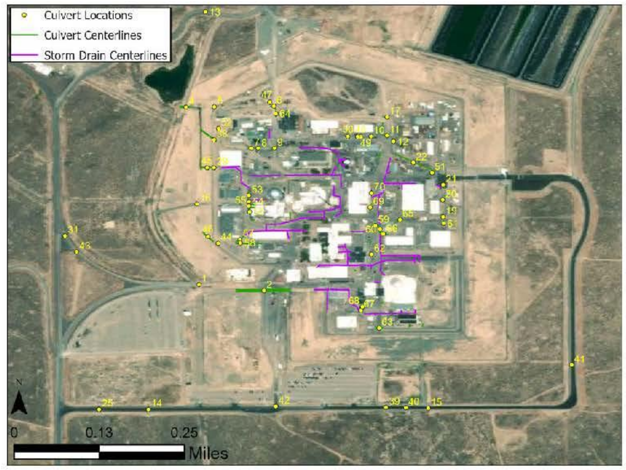




Culvert Blockage







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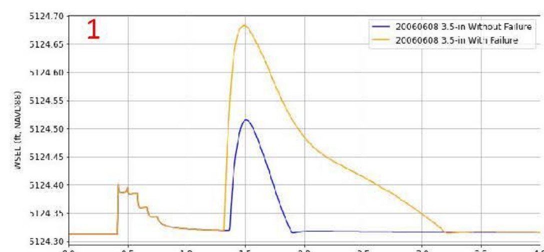
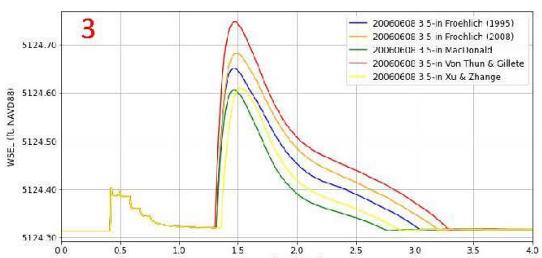
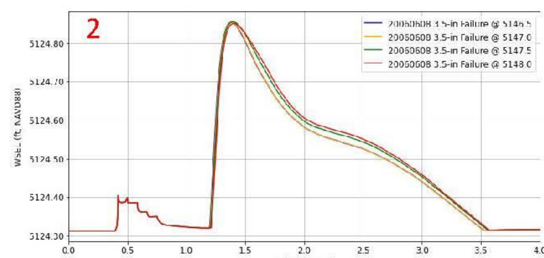
Diversion Dam Sensitivity

1. Ran simulations with and without breach (sensitive)
2. Ran simulations with constant breach parameters but different failure elevations (not sensitive)
3. Ran simulations with constant elevation but different breach configurations (sensitive)







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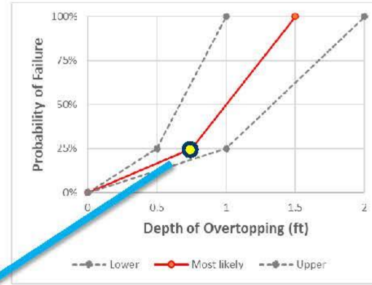
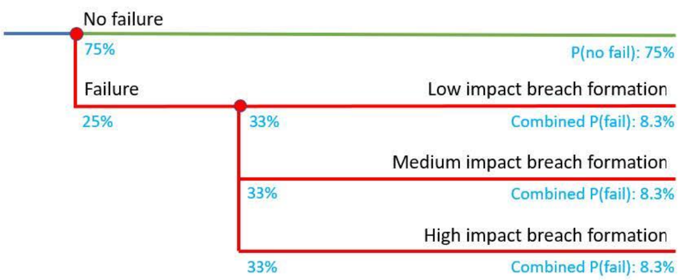
Incorporating Diversion Dam Failures

1. Define probabilities
2. Execute simulations with no failure
3. Execute additional breach simulations for cases with overtopping (three formation assumptions)
4. Apply probability of breach to each simulation based on depth of overtopping without failure





Breach formation	Probability
Froehlich	33%
Von Thun and Gillete	33%
MacDonald	33%

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Combining Uncertainty

- 16 outer loop realizations (Sobol' QMC)
- 3,000 simulations per outer loop realization
- Fixed culvert blockage in separate sensitivity analysis

Realization ID	Precipitation frequency	Hydrologic parameters	Temperature shift	Precipitation shift	Dam Breach parameters	Manning's N
0	0.58	0.8	0.69	0.79	0.79	0.25
1	0.00	0.02	0.36	0.39	0.17	0.99
2	0.4	0.62	0.97	0.72	0.37	0.58
3	0.94	0.33	0.04	0.08	0.74	0.16
4	0.78	0.7	0.44	0.2	0.57	0.38
5	0.33	0.49	0.51	0.62	0.44	0.87
6	0.21	0.89	0.15	0.26	0.02	0.72
7	0.64	0.17	0.83	0.94	0.89	0.04
8	0.71	0.54	0.21	0.52	0.22	0.25
9	0.13	0.27	0.77	0.16	0.85	0.51
10	0.27	0.86	0.38	0.96	0.68	0.92
11	0.82	0.08	0.57	0.35	0.3	0.34
12 (Highest)	0.9	0.95	0.91	0.49	0.38	0.12
13	0.45	0.23	0.11	0.83	0.51	0.63
14	0.09	0.64	0.74	0.06	0.97	0.78
15 (Median)	0.51	0.42	0.3	0.63	0.09	0.46

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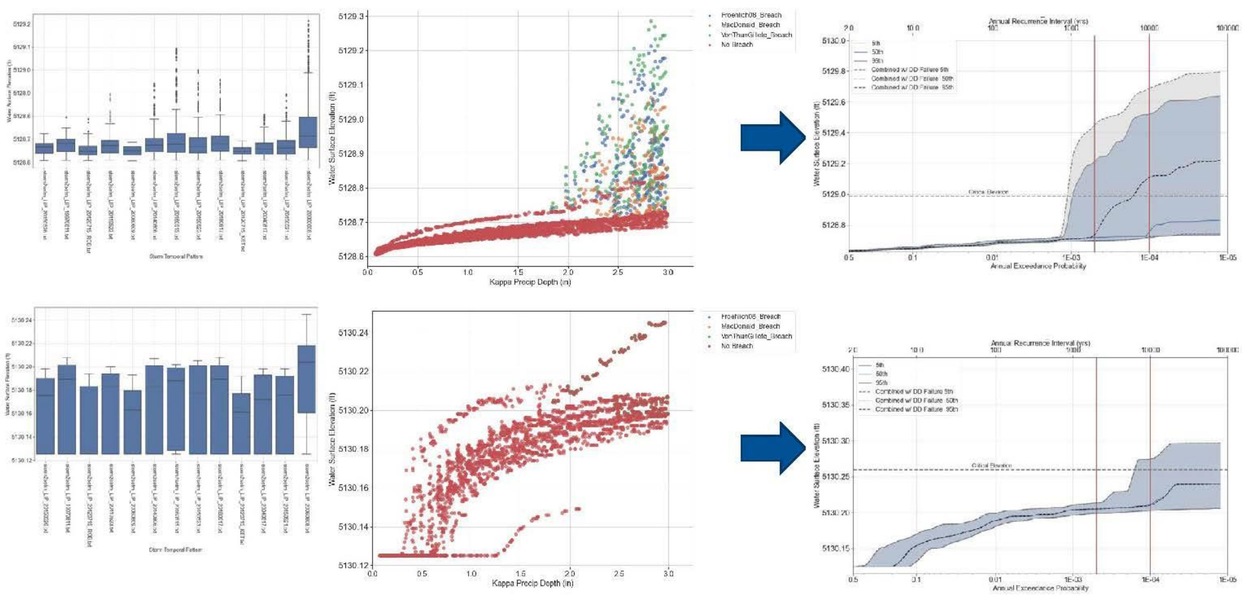
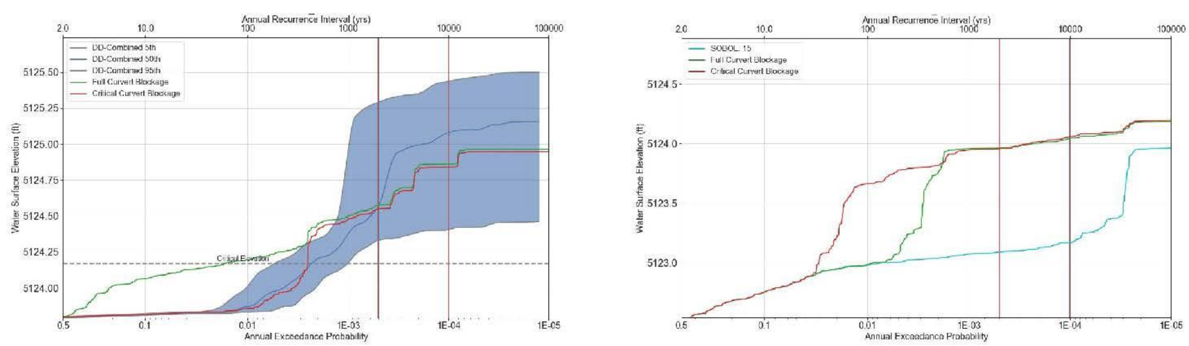
Results Uncertainty Impact



Results-Culvert Blockage Impacts



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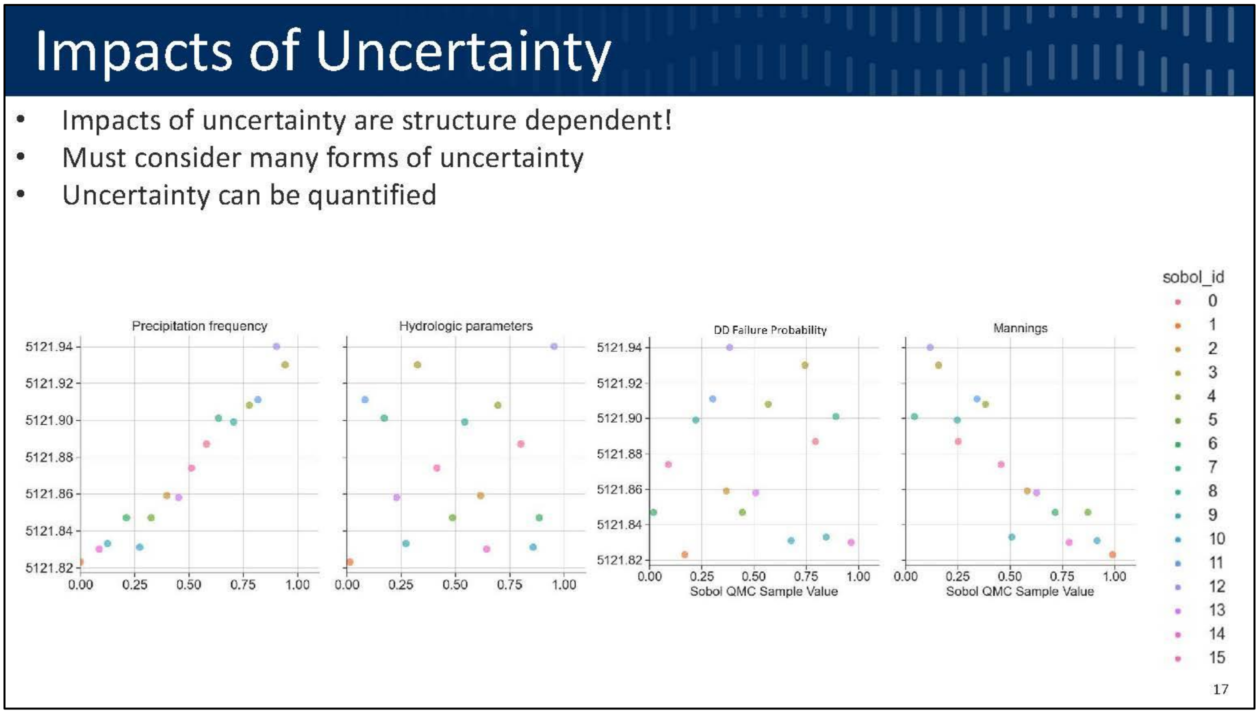


3.4.3.3 Questions and Answers

Question:

Did you say that riverine [flooding] is screened out everywhere on the INL site?

Answer:

Yes.

Question

So, for this LIP example you presented, is this the only part of the INL site where LIP is an issue? Did the other sites not matter or have you just not shown that?

Answer:

Actually, this was our third site and we're doing another one now. LIP is always an issue. We always have to look at it because LIP could happen anywhere on the site. Here there is no major river going by the site, so it wasn't important.

Question:

I've heard they've been a little concerned about Big Lost River and a Mackay Dam failure. But you don't think that's an issue?

Answer:

We looked at a site during last year's analysis that was closer to the Big Lost. The Mackay Dam failure is really the biggest concern there. But there was a diversion structure downstream. We compared to paleoflood analyses and when we ran the flows to be expected for certain return intervals, what actually makes it past the diversion structure was low enough that it wasn't creating water surface elevations that were in the realm of LIP and so LIP was actually the more dominant source there.

Question:

What was the greatest 1-hr LIP depth from these simulations? Was that based on stochastically derived rainfall amounts from observed events or maximized observational data in the region? And how did that compare to the HMR 57 1-hr local storm PMP for the site?

Answer:

The 95^{th} percentile [1-Hr LIP] depth the at 10^{-6} [annual exceedance probability] I think was 3, to 3 ½ inches depth or somewhere in there. As far as how it's developed, I'm not completely expert in that. That's MGSs and DTNs world, but I know that they developed a gridded L-moment analysis looking at historical records and maximums and a gridded L-moment output for the entire property. From that, they fit a four-parameter Kappa distribution to develop the precipitation frequency curves.

Question:

Do you have any information about how that compares to HMR 57?

Answer:

I didn't look at that personally.

3.4.4 Presentation 2B-4: Back to the Future: Paleoflood Hydrologic Analyses Provide Insights into Extreme Flood Risk in the Tennessee River Basin

Authors: Lisa Davis[1], Ray Lombardi[2], Matthew Gage[1]; [1]University of Alabama, [2]University of Memphis

Speaker: Lisa Davis

3.4.4.1 Abstract

Extreme floods are likely underrepresented in many flow records. Quantitative paleoflood hydrologic (QPH) techniques can reliably estimate the timing and magnitude of past extreme floods, helping to increase their observations. Including paleoflood hydrologic data greatly reduces the uncertainty associated with flood frequency analyses of low annual exceedance probability floods. Because of their proximity to major population centers and river infrastructure, many alluvial rivers urgently need new flood frequency analyses that incorporate a wider range of hydroclimate regimes than possible with instrumented records alone. Erosion and deposition cause channel dimensions to change over time in alluvial rivers, challenging the application of many QPH methods originally developed in bedrock channels. In this presentation, we will discuss several advances in QPH methods we used to develop paleoflood hydrologic data in the Tennessee River (USA), which were then applied in probabilistic flood hazard assessments made in collaboration with the Tennessee Valley Authority.

3.4.4.2 Presentation (ADAMS Accession No. ML23177A171)

Paleoflood hydrologic analyses provide insights into extreme flood risk in the Tennessee River Basin

Lisa Davis, Associate Professor
Department of Geography
University of Alabama
lisa.davis@ua.edu

Ray Lombardi, Assistant Professor
Department of Earth Sciences
University of Memphis

Matthew Gage, Director
Office of Archeological Research
University of Alabama

RATIONALE

Journal of Infrastructure Systems / Volume 26 Issue 3 - September 2020

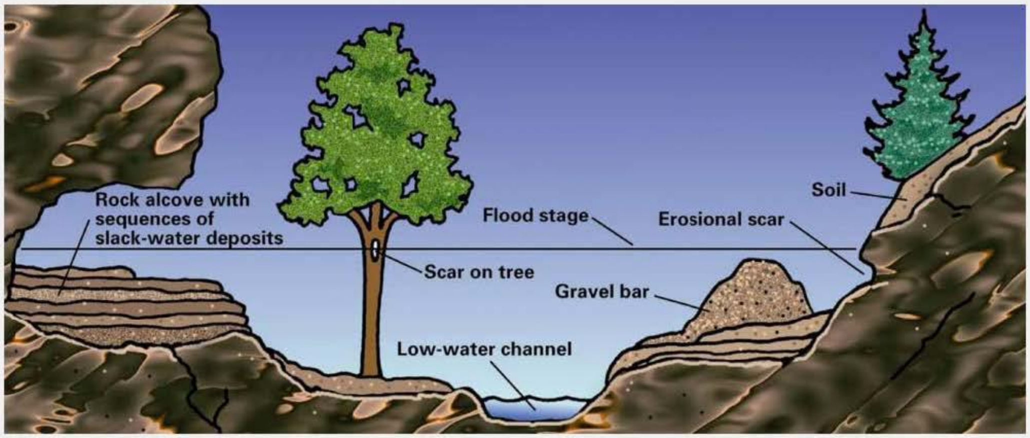
Technical Papers | Downloaded 455 times

Past and Present Design Practices and Uncertainty in Climate Projections are Challenges for Designing Infrastructure to Future Conditions

B. Shane Underwood, A.M.ASCE; Giuseppe Mascaro; Mikhail V. Chester, A.M.ASCE; Andrew Fraser Show all authors

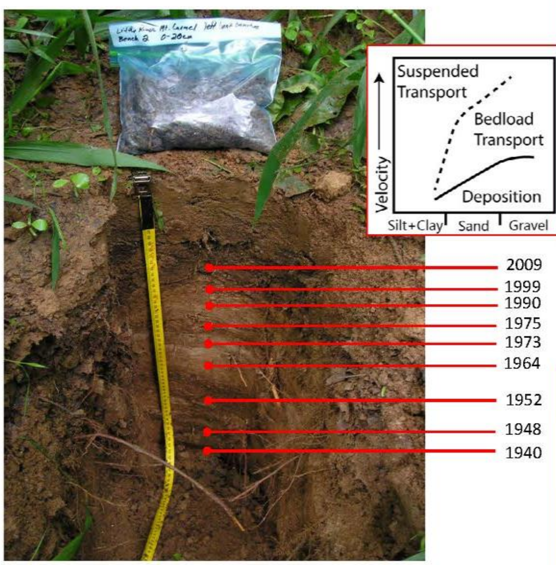
Problem: Large and extreme floods are underrepresented in instrumented records

Problem: Many socially significant rivers may have infrastructure not adequately designed for current & future climate



The elevation of slackwater deposits identified in bedrock channels typically is used in a 1-D, step-backwater model to derive paleodischarges. England et al., 2019. NRC 4th Annual Probabilistic Flood Hazard Assessment Workshop.

Rivers are self gauging systems: retain flo



Paleofloods are reconstructed from the physical evidence left by floods

Journal of Hydrology 612 (2022) 128085

Contents lists available at ScienceDirect

Journal of Hydrology

journal homepage: www.elsevier.com/locate/jhydrol

Research papers

Incorporating alluvial hydrogeomorphic complexities into paleoflood hydrology, magnitude estimation and flood frequency analysis, Tennessee River, Alabama

Ray Lombardi, M.A. Lisa Davis

Department of Geography, University of Alabama, Box 870322, Tuscaloosa, AL 35487-870322, USA

Tennessee River, Blue Ridge Mountains, USA

David S. Leigh

Department of Geography, The University of Georgia, Athens, GA 30602-2502, USA

chronostratigraphy and late Holocene flood history from a temperate river confluence

Ben Pears[1], Antony G. Brown[1,9], Phillip S. Toms[3], Jamie Wood[3], David Sanderson[4] and Richard Jones[5]

[1]Palaeoenvironmental Laboratory, Department of Geography and Environmental Science, University of Southampton,

amplified by river engineering

Samuel E. Munoz[1,2,3], Liviu Giosan[1], Matthew D. Therrell[4], Jonathan W. F. Remo[5], Zhixiong Shen[6,7], Richard M. Sullivan[1,8], Charlotte Wiman[1], Michelle O'Donnell[1] & Jeffrey P. Donnelly[1]

Lower Rhine historical flood magnitudes of the last 450 years reproduced from grain-size measurements of flood deposits using End Member Modelling

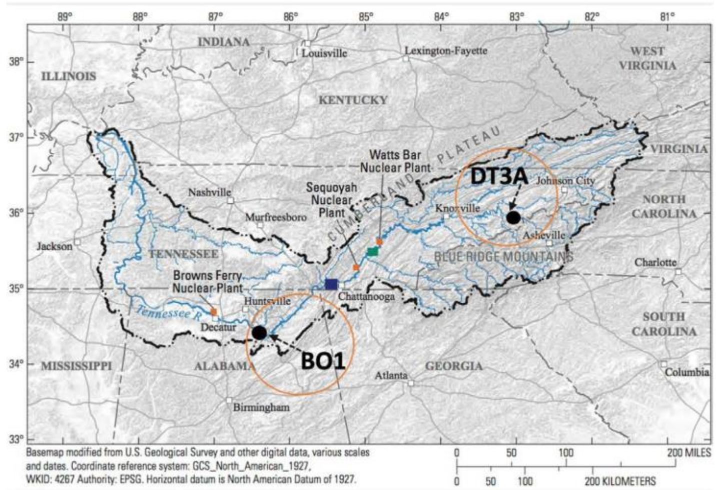
W.H.J. Toonen[a,b,*], T.G. Winkels[a], K.M. Cohen[a,b], M.A. Prins[c], H. Middelkoop[a]

[a] Department of Physical Geography, Utrecht University, Utrecht, The Netherlands
[b] Department of Applied Geology and Geophysics, Deltares BGS, Utrecht, The Netherlands
[c] Department of Earth Sciences, VU University Amsterdam, Amsterdam, The Netherlands

Paleoperspectives on extreme floods

- How exceptional are historic floods of record? → **Design Flows**
- Have there been larger floods? → **FFA**

"The Great Freshet of 1867," Chattanooga, TN Chattanooga Times Free Press

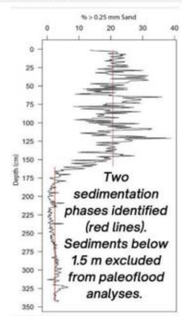


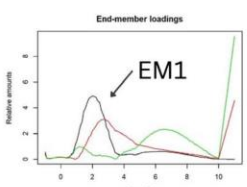
Base map modified from Harden et al. 2018, USGS Scientific Investigations Report 2020-5138.

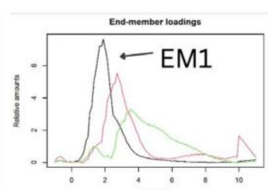
5

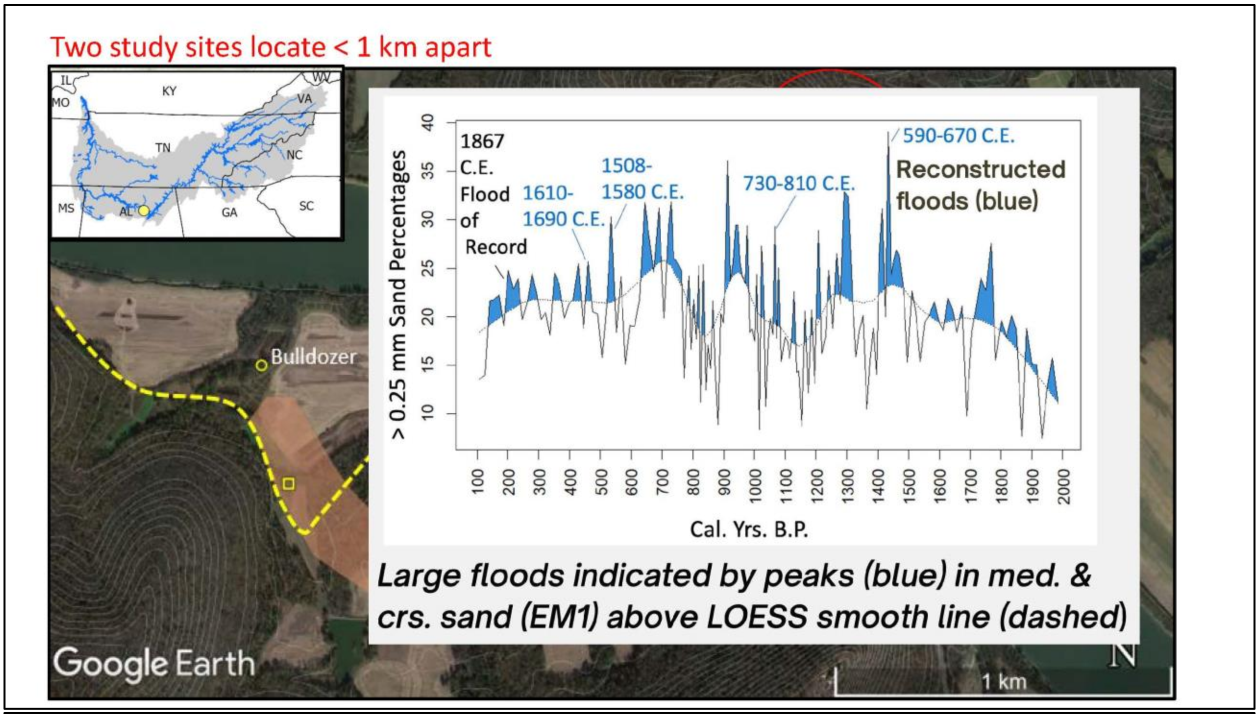
When did the floods happen? | **Which deposits are from floods?** | **Which deposits are from extreme floods?**

1. **Flood Deposit Age Modeling: 'rBacon' cran.r-project.org** — *Deterrmines age of sediment layers captured in core sample*
2.  *Particle size analysis of sediment cores, 1 cm resolution, Bettersizer S3Plus*
3. **Change Point Analysis: 'changepoint' cran.r-project.org** — *Helps identify sedimentation changes in particle size distributions not related to flood deposition*
4. **End Member Analysis: EMMAgeo cran.r-project.org** — Unmixes particle size data to identify sediment sub-populations, such as flood deposits
5. **LOESS Regression Modeling: R Core Team (2022)** — Moving regression fits smoothed line to particle data; peaks (positive residuals) above line interpretted as flood events

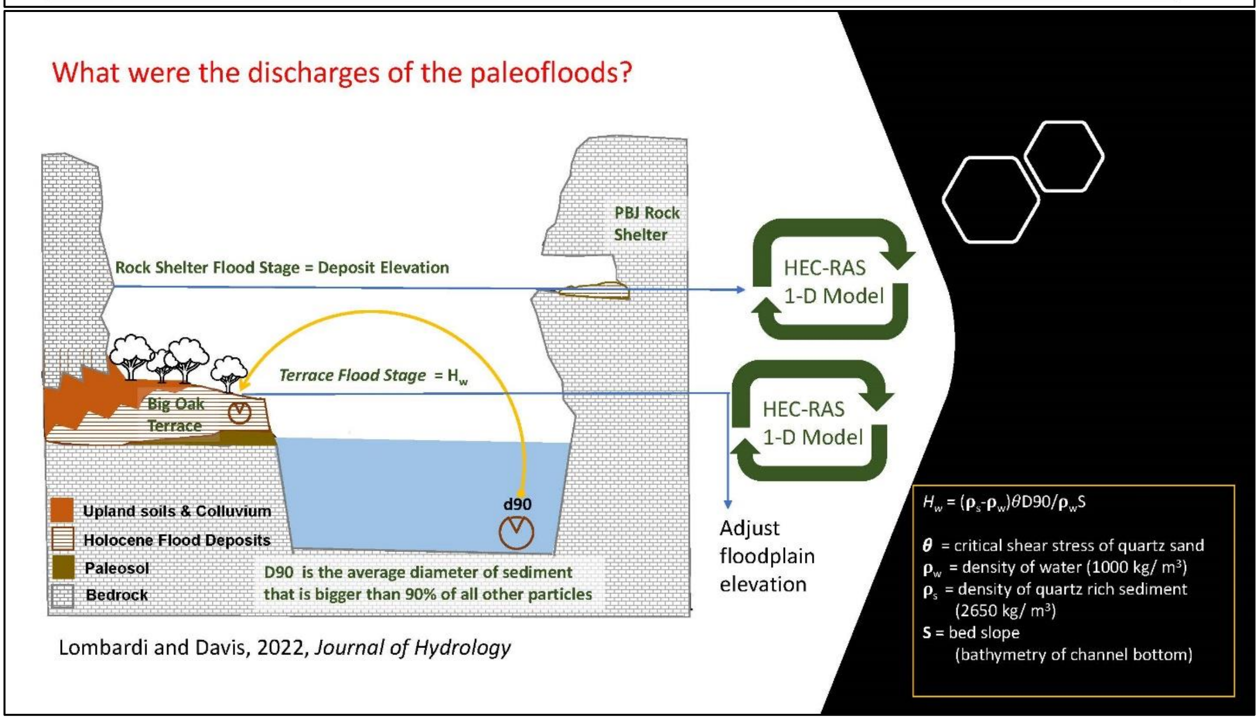








Two study sites locate < 1 km apart
KY
TN
NC
VA
MS
AL
GA
SC
1867 C.E. Flood of Record
1610-1690 C.E.
1508-1580 C.E.
730-810 C.E.
590-670 C.E.
Reconstructed floods (blue)
> 0.25 mm Sand Percentages
Cal. Yrs. B.P.
Bulldozer
Large floods indicated by peaks (blue) in med. & crs. sand (EM1) above LOESS smooth line (dashed)
Google Earth
1 km



What were the discharges of the paleofloods?
PBJ Rock Shelter
Rock Shelter Flood Stage = Deposit Elevation
HEC-RAS 1-D Model
Terrace Flood Stage = H_w
Big Oak Terrace
HEC-RAS 1-D Model
d90
Adjust floodplain elevation
Upland soils & Colluvium
Holocene Flood Deposits
Paleosol
Bedrock
D90 is the average diameter of sediment that is bigger than 90% of all other particles
Lombardi and Davis, 2022, Journal of Hydrology
$H_w = (\rho_s - \rho_w)\theta D90/\rho_w S$
θ = critical shear stress of quartz sand
ρ_w = density of water (1000 kg/ m³)
ρ_s = density of quartz rich sediment (2650 kg/ m³)
S = bed slope (bathymetry of channel bottom)

FFA for BO1 (lower TN, Guntersville Dam)

FFA generated with Bulletin 17C Guidelines using RMC Best Fit (USACE), Bayesian MCMC flood frequency model

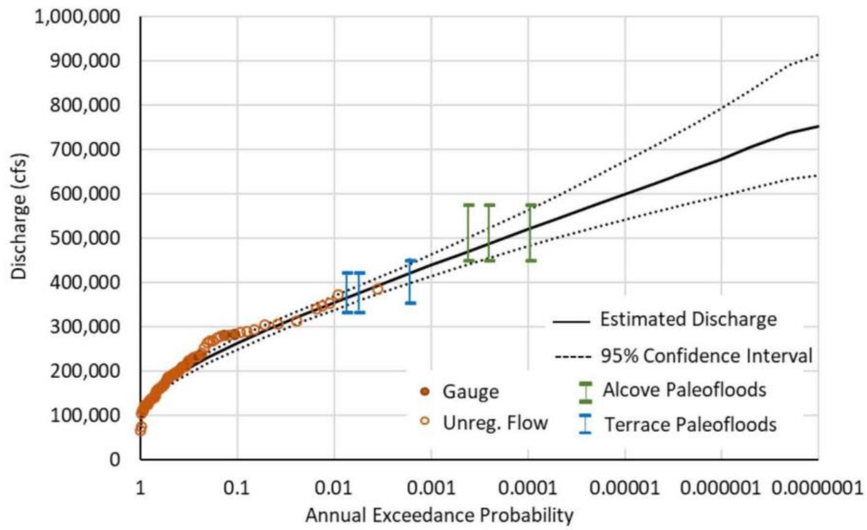


Figure 12. *Flood frequency curves for the middle Tennessee River using paleoflood data from the terrace and rock alcove. Dashed lines represent the 95% confidence interval.*

FFA for BO1 (lower TN, Guntersville Dam)

FFA generated with Bulletin 17C Guidelines using RMC Best Fit (USACE), Bayesian MCMC flood frequency model

Uncertainty for 10,000 yr event reduced by 80%

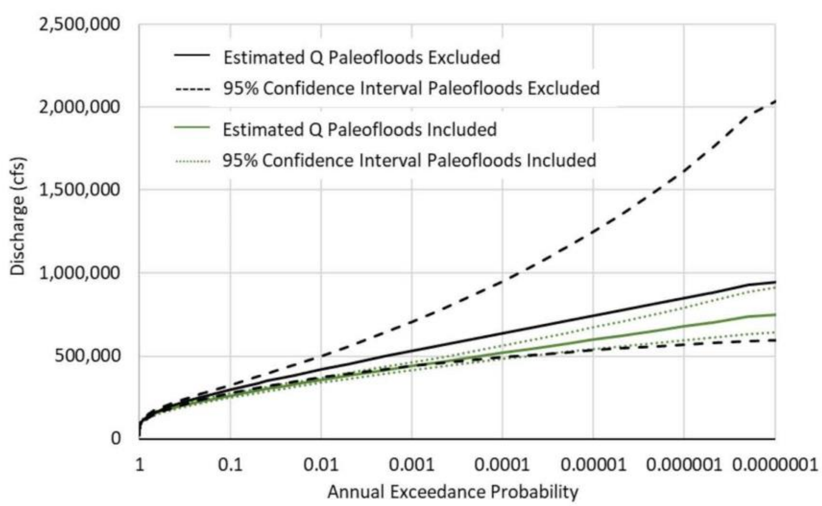
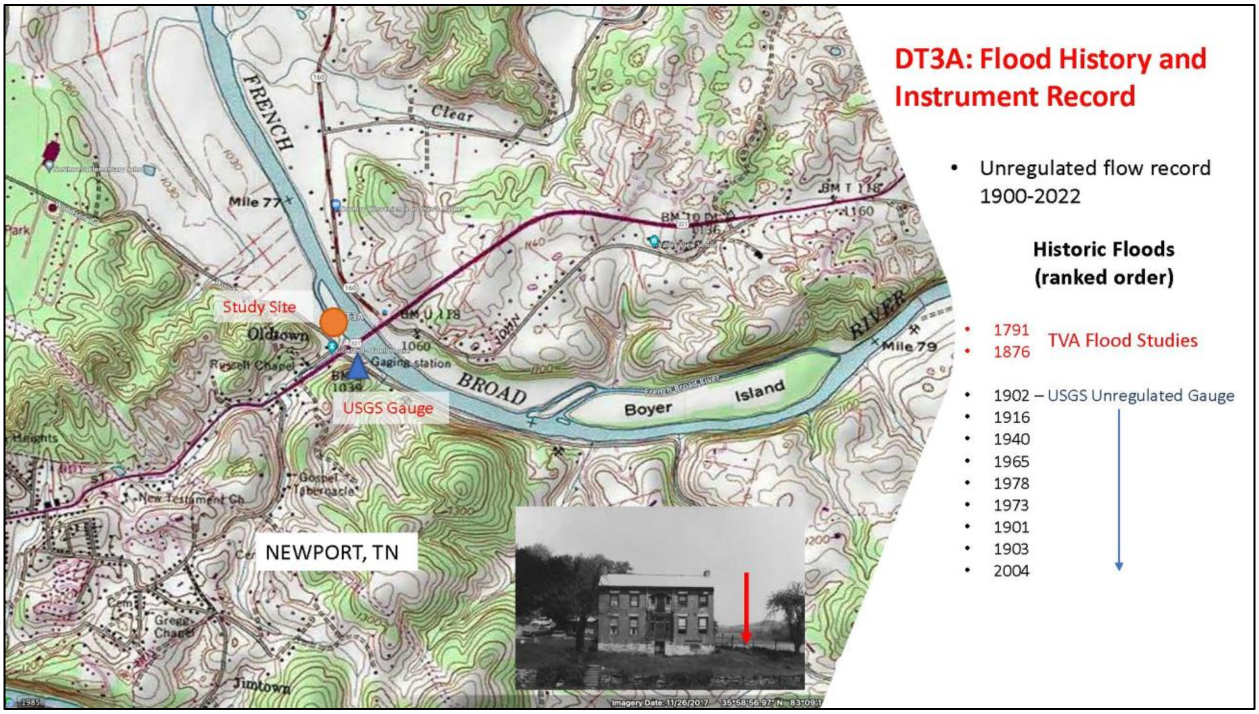
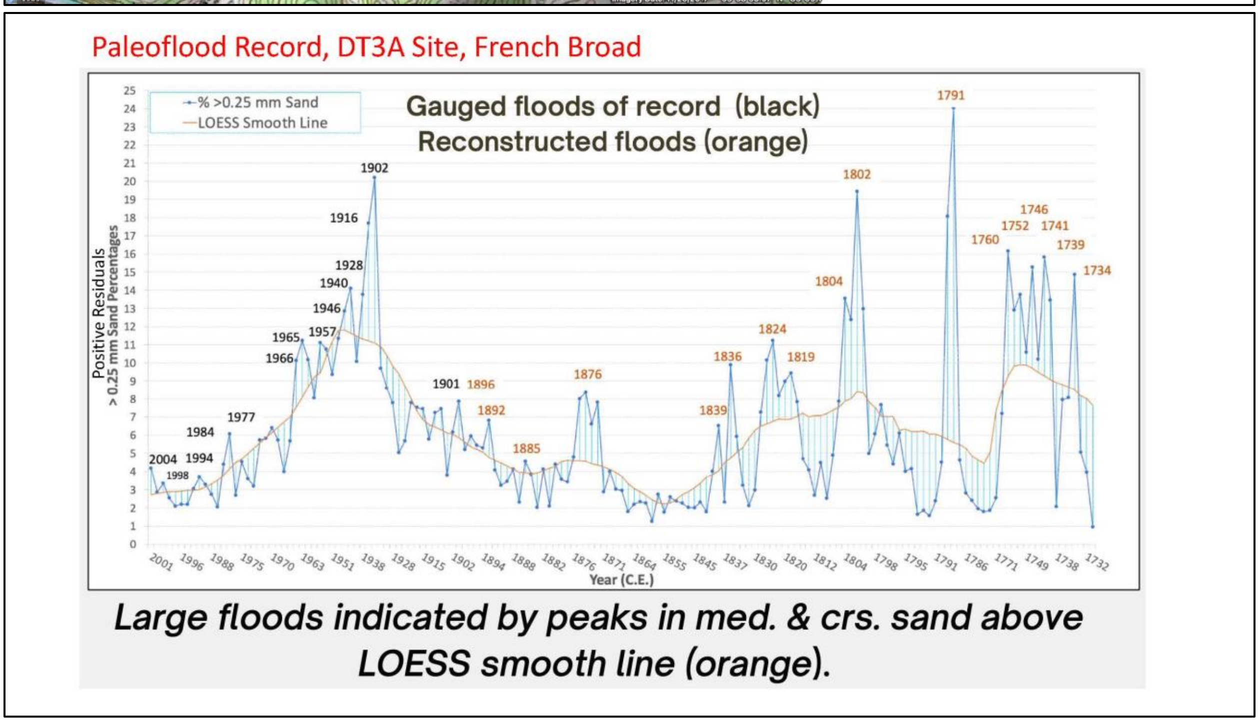
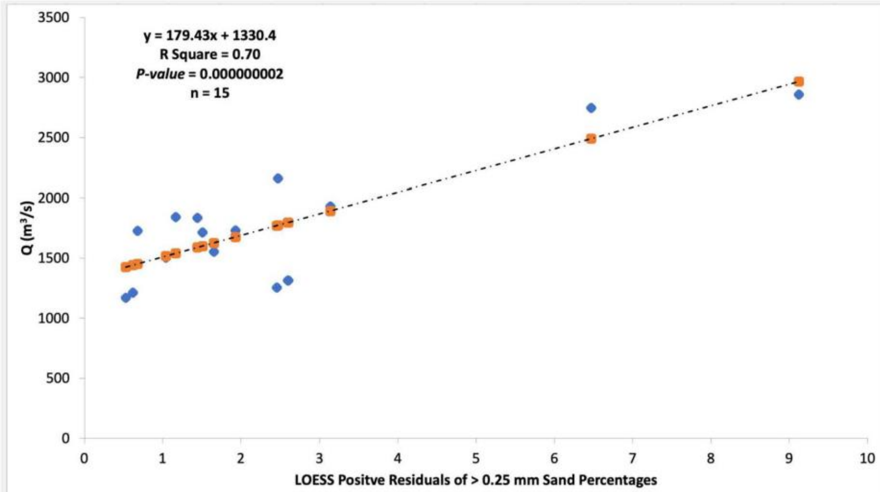


Figure 13. *The comparison of flood frequency curves generated without paleoflood data (black) and with paleoflood data (green).*


DT3A: Flood History and Instrument Record
Unregulated flow record 1900-2022
Historic Floods (ranked order)
1791
1876
TVA Flood Studies
1902 – USGS Unregulated Gauge
1916
1940
1965
1978
1973
1901
1903
2004
Study Site
USGS Gauge
NEWPORT, TN
FRENCH
BROAD
RIVER
Boyer
Island
Oldtown
Gaging station
Mile 77
Mile 79
Clear
Gospel Tabernacle
New Testament Ch
Jimtown


Paleoflood Record, DT3A Site, French Broad
% >0.25 mm Sand
LOESS Smooth Line
Gauged floods of record (black)
Reconstructed floods (orange)
Positive Residuals > 0.25 mm Sand Percentages
Year (C.E.)
Large floods indicated by peaks in med. & crs. sand above LOESS smooth line (orange).

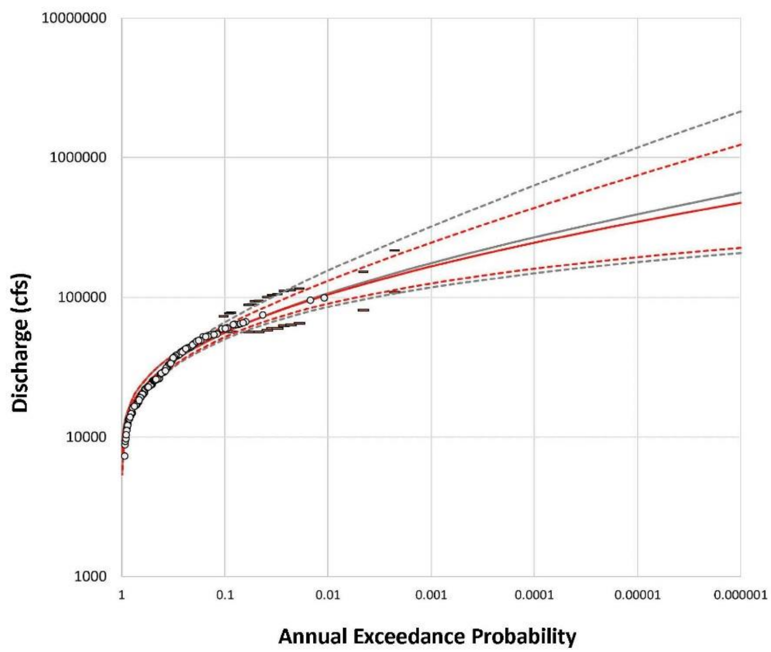


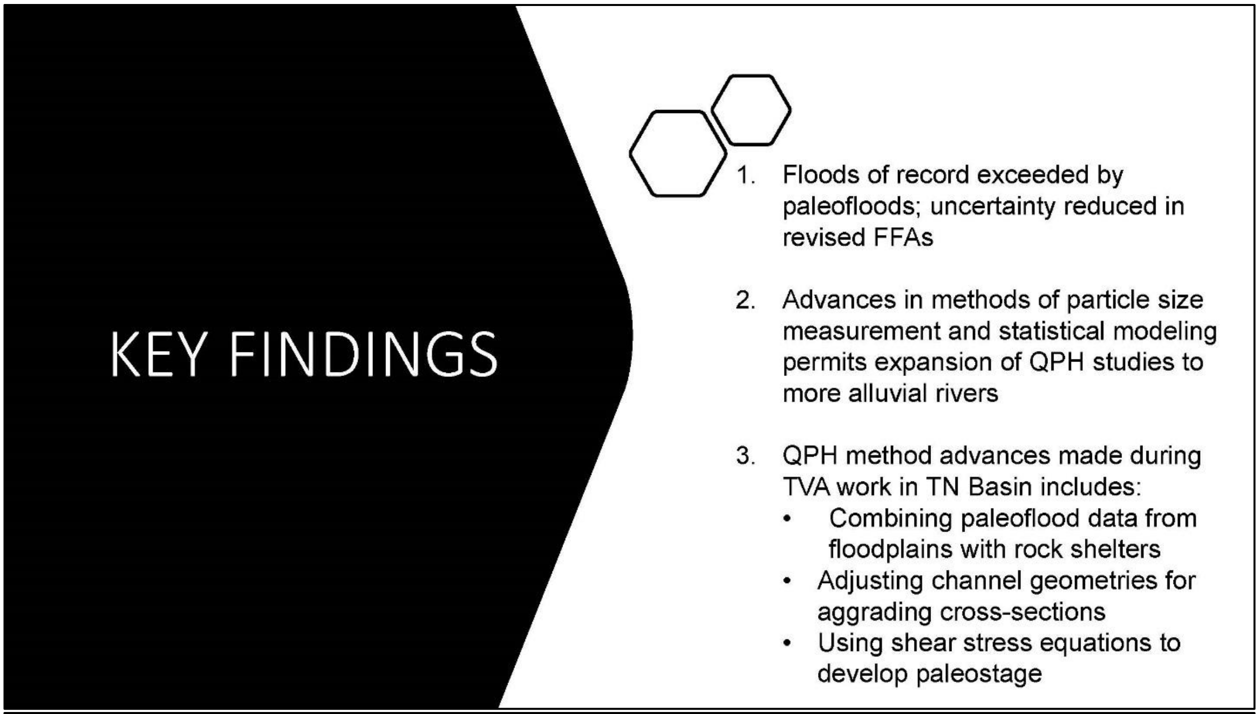
Linear regression model used to predict discharge from LOESS positive residuals. Positive residuals correspond to med.-crs. sand peaks.

DRAFT FFA for DT3A (French Broad, Douglas Resevoir)

FFA generated with Bulletin 17C Guidelines using RMC Best Fit (USACE), Bayesian MCMC flood frequency model

Uncertainty for 10,000 yr event reduced by 42%





3.4.4.3 Questions and Answers

Question:

How should the possibility of change in watershed area, land use type, topography, surface conditions, etc. be treated when estimating the probable maximum flood on rivers under future climate change conditions?

Answer:

Paleofloods are not quite the same as the PMF, but they can provide info about what extreme floods are like under climate drivers in isolation of human changes to hydrology and the landscape.
Thinking about you question a little more, one line of thinking is that if you can reconstruct floods from warmer phases of past climates, this might help provide extreme flood information under a warming climate. That could certainly help with validating simulations of worst-case scenarios.

Question:

Do you do any correction for grain shape, which will affect transport?

Answer:

There are no corrections for shape because we're only working with sand particles, which are the most transportable fraction of the sediment load for most rivers.

3.4.5 Presentation 2B-5: Testing New Approaches to Integrating Sediment-Based Flood Records into Flood Frequency Models

Authors: Ray Lombardi[1], Lisa Davis[2], Tessa Harden[3,4], John F. England, Jr.[5]; [1]University of Memphis, [2]University of Alabama, [3]Thomas College, [4]U.S. Geological Survey, [5]U.S. Army Corps of Engineers, Risk Management Center

Speaker: Ray Lombardi

3.4.5.1 Abstract

Increasingly probabilistic flood risk assessments for infrastructure (e.g., dams and levees) use paleoflood hydrologic data (geomorphic and botanical evidence of past floods). Statistical procedures, such as the Expected Moments Algorithm, incorporate paleoflood data into flood frequency analyses (FFA) as a number of exceedances over perception thresholds (PTs). Similarly, Non-exceedance bounds (NEBs) can constrain the right-tail of flood distributions by defining a threshold that has not been exceeded over a specified period. Rivers vary in their hydrogeomorphic complexities, and this can complicate the selection and application of PTs and NEBs. We revisited these concepts, using case studies from previous work, to examine challenges and potential alternatives for defining critical thresholds for FFA. We found that when moderate and extreme paleoflood discharges are available selecting the smallest identified paleoflood discharge as the PT discharge overestimates model certainty and reduces the discharge estimates for flood with rare exceedance probabilities (< 0.01). In these cases, one alternative involves using the 90th percentile discharge of the flood distribution to set a higher PT and to determine which paleofloods are opportunistic peaks. Additionally, in locations where evidence for a NEB is spatially inconsistent across a topographic surface, we one of the following approaches can be taken: 1) defining a "hydrogeomorphic bound," which is a surface elevation representing the natural upper limit to fluvial activity identified using geomorphic evidence of where the hillslope process domain ends and the fluvial process domain begins; or 2) using NEBs for years with known paleoflood estimates. By expanding these concepts, we can apply paleoflood hydrologic data more consistently and in understudied regions.

3.4.5.2 Presentation (ADAMS Accession No. ML23177A172)

8th Annual Probabilistic Flood Hazard Assessment Research Workshop

Testing new approaches to integrating sediment-based floods records into flood frequency models

Dr. Ray Lombardi (Presenting), Assistant Professor
Dept. of Earth Sciences, Univ. of Memphis,
rlmbardi@memphis.edu

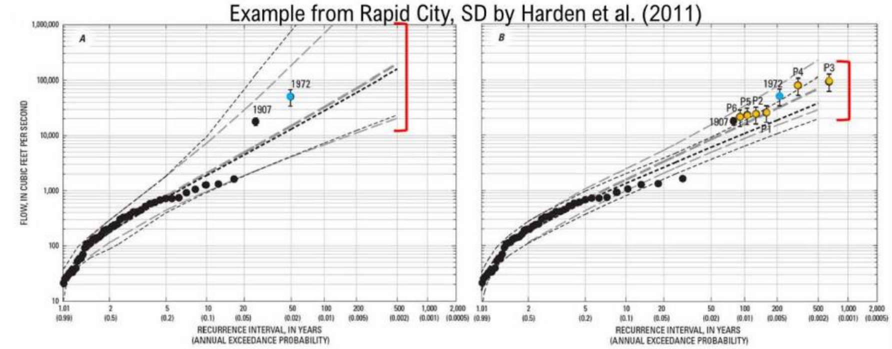
Dr. Lisa Davis, Associate Professor
Dept. of Geography, Univ. of Alabama

Dr. Tessa Harden, Hydrologist, Assistant Professor
U.S. Geological Survey, Thomas College

Dr. John F. England, Jr., Lead Civil Engineer - Hydrologic Hazards, U.S. Army Corps of Engineers, Risk Management Center

Risk-Informed Decision Making With Paleoflood Hydrological Data

Example from Rapid City, SD by Harden et al. (2011)



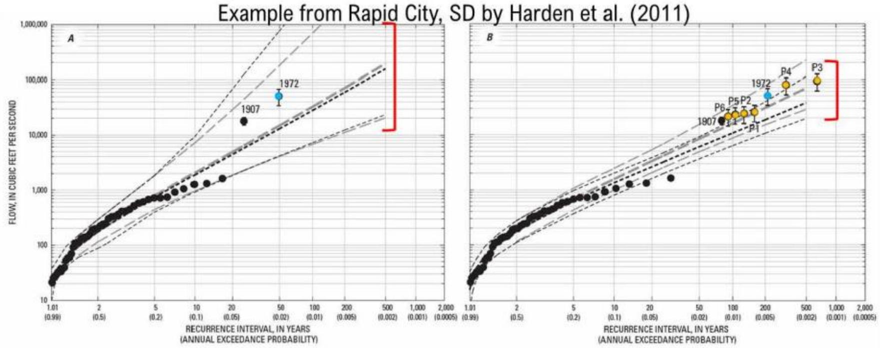
Gauge Data Only → With Paleoflood Data

Risk-Informed Decision Making With Paleoflood Hydrological Data

Key components of PFH Data in FFAs:

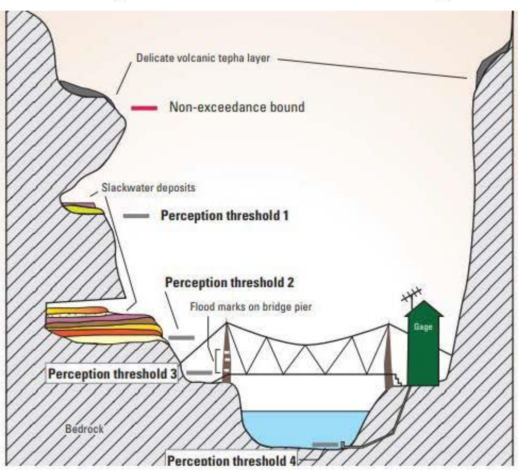
1. Estimating Age and Discharges
2. Selecting **Perception Threshold**
3. Estimating **Non-exceedance Bounds**

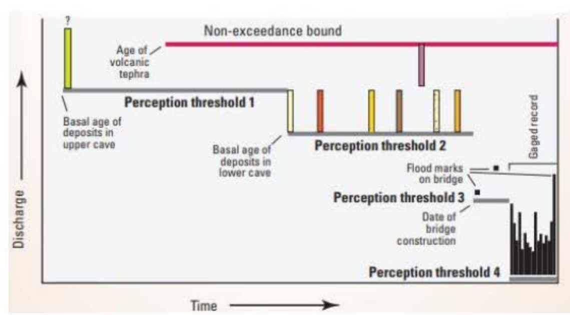
Example from Rapid City, SD by Harden et al. (2011)



Gauge Data Only ⟶ With Paleoflood Data

Physical evidence of flooding ------------→ Bulletin 17C flood frequency analyses



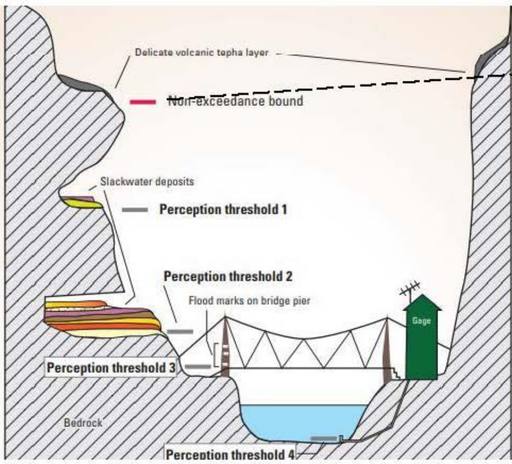


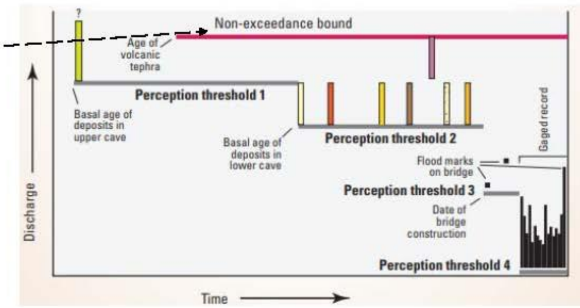
Perception Thresholds (PT):
A discharge level above which a flood would have been recorded if that flood occurred in a given year.

Non-exceedance Bound (NEB):
Time interval that a given discharge level has not been exceeded.

Modified from: Harden, T.M., Ryberg, K.R., O'Connor, J.E., Friedman, J.M., and Kiang, J.E., 2021, Historical and paleoflood analyses for probabilistic flood-hazard assessments—Approaches and review guidelines: U.S. Geological Survey Techniques and Methods, book 4, chap. B6, 91 p.,

Physical evidence of flooding ------------→ Bulletin 17C flood frequency analyses





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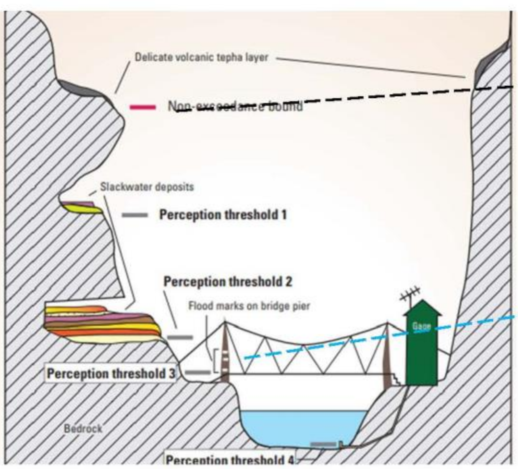
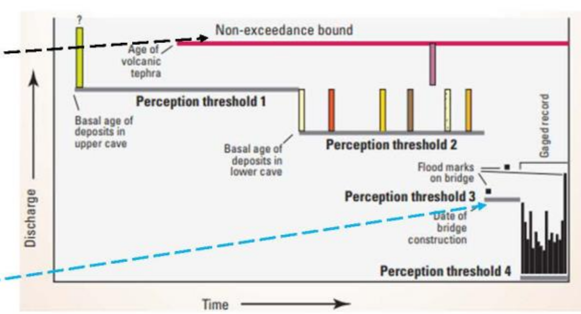
Physical evidence of flooding ------------→ Bulletin 17C flood frequency analyses





Perception Thresholds (PT):
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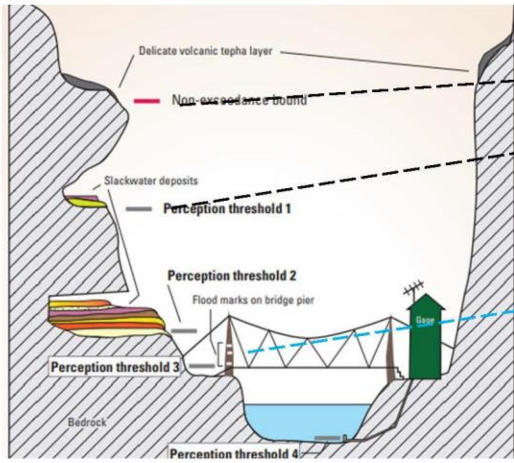
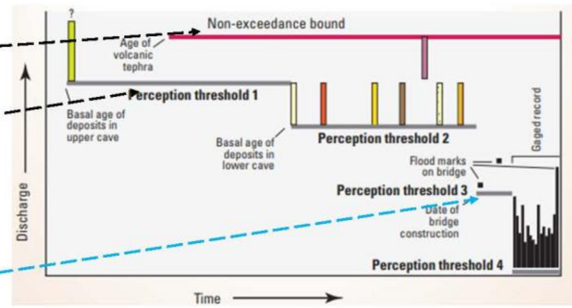
Modified from: Harden, T.M., Ryberg, K.R., O'Connor, J.E., Friedman, J.M., and Kiang, J.E., 2021, Historical and paleoflood analyses for probabilistic flood-hazard assessments—Approaches and review guidelines: U.S. Geological Survey Techniques and Methods, book 4, chap. B6, 91 p.,

Physical evidence of flooding ------------→ Bulletin 17C flood frequency analyses





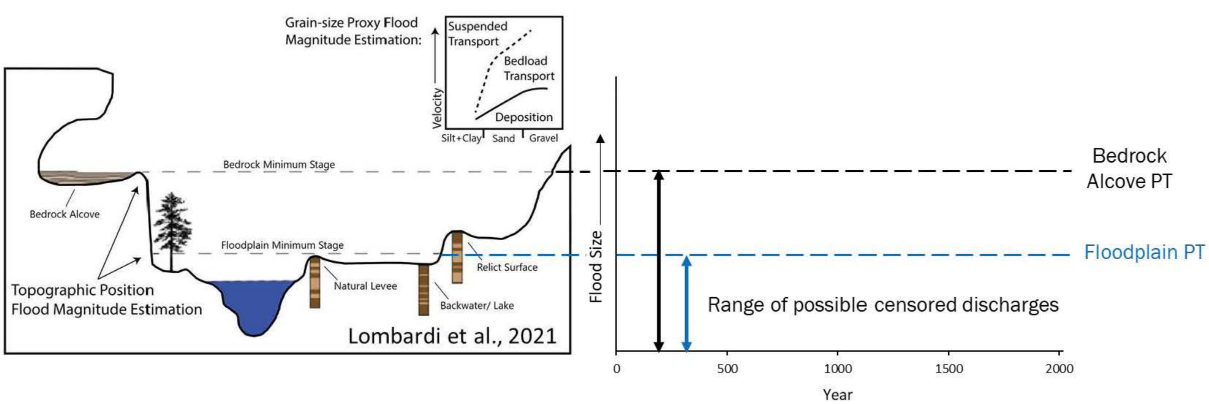
Perception Thresholds (PT):
A discharge level above which a flood would have been recorded if that flood occurred in a given year.

Non-exceedance Bound (NEB):
Time interval that a given discharge level has not been exceeded.

Benito et al. (2020). *Reference Module in Earth Systems and Environmental Sciences*, 0–22.

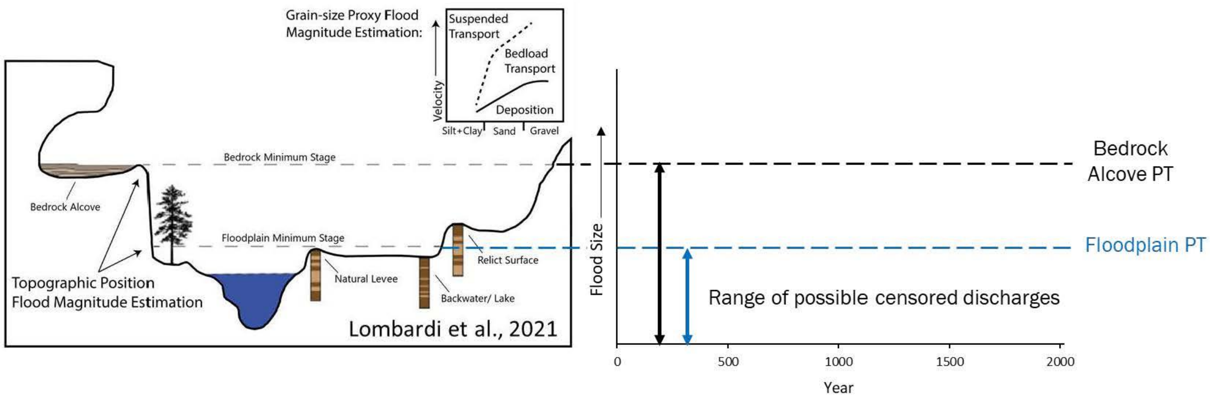
First challenge: Wider range of possible flood flows

Physical evidence of flooding ------------------→ Bulletin 17C flood frequency analyses



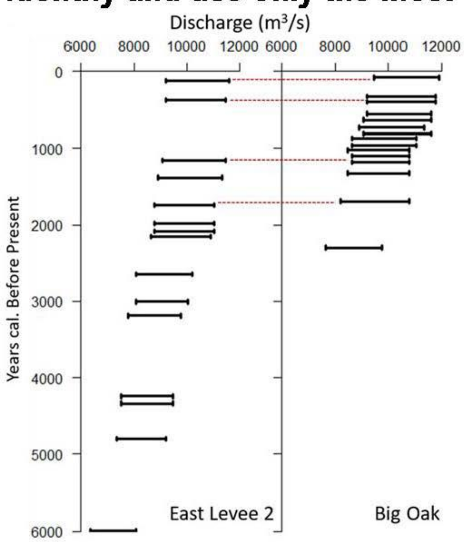
First challenge: Wider range of possible flood flows

Physical evidence of flooding ------------------→ Bulletin 17C flood frequency analyses



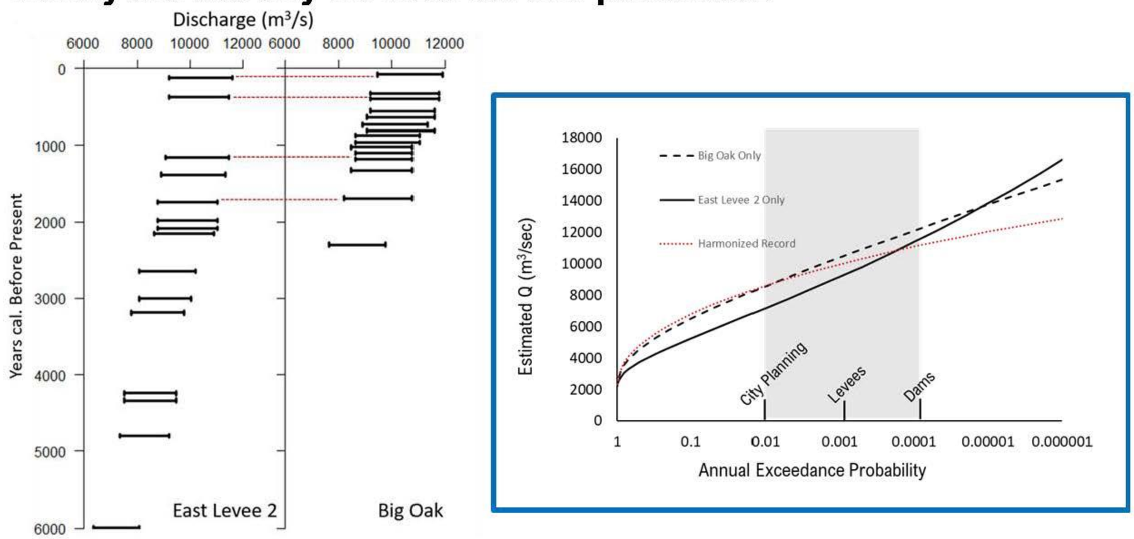
"Opportunistic" Peaks: A peak flow that was recorded outside of the systematic record and collected based on factors other than the exceedance of a perception threshold.

1. Identify and use only the most extreme paleofloods



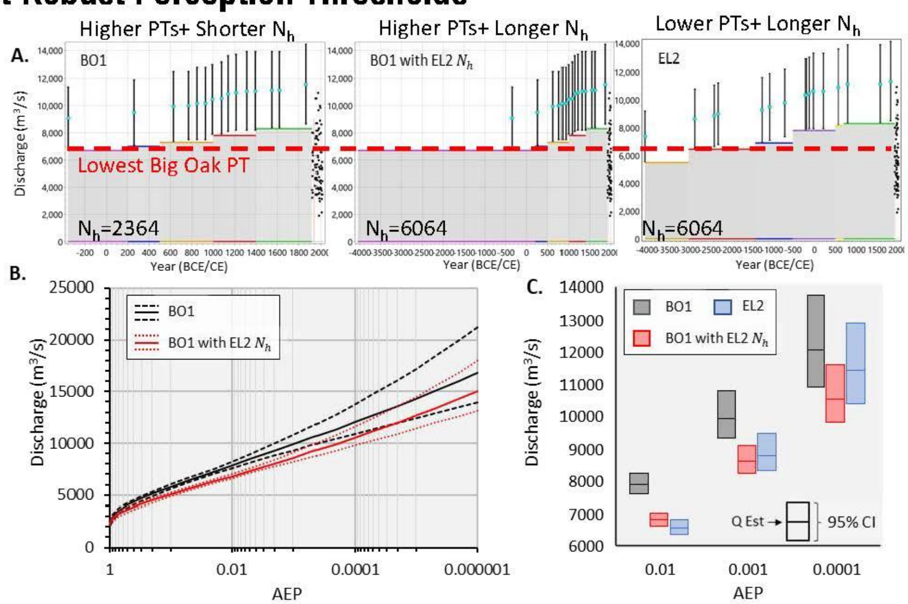
Example from Lombardi and Davis (2022) *The Journal of Hydrology.*

1. Identify and use only the most extreme paleofloods



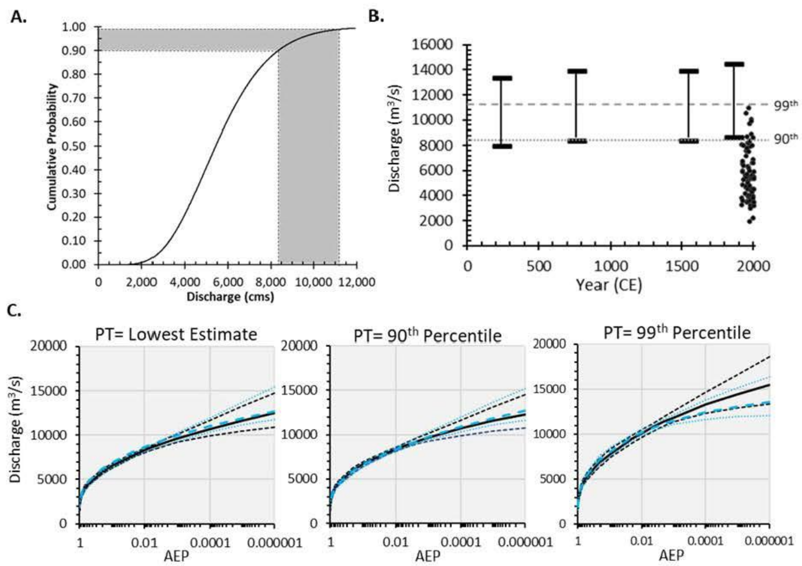
Example from Lombardi and Davis (2022) *The Journal of Hydrology*.

2. Select Robust Perception Thresholds



2. Select Robust Perception Thresholds

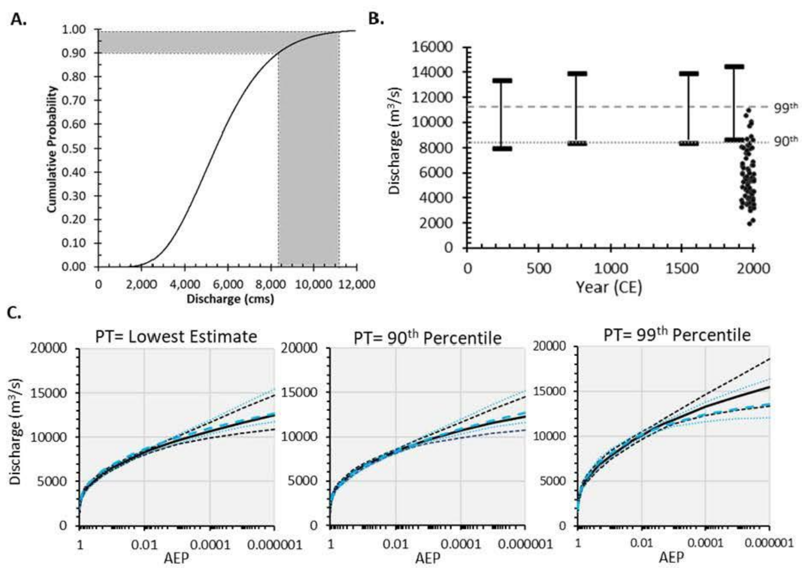
An alternative approach to assign perception thresholds:

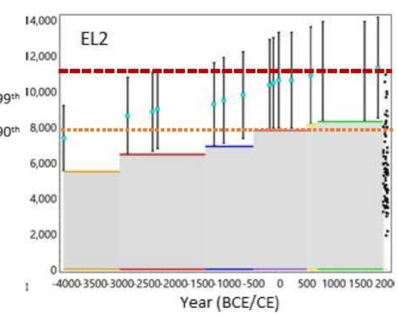


6 of 10

2. Select Robust Perception Thresholds

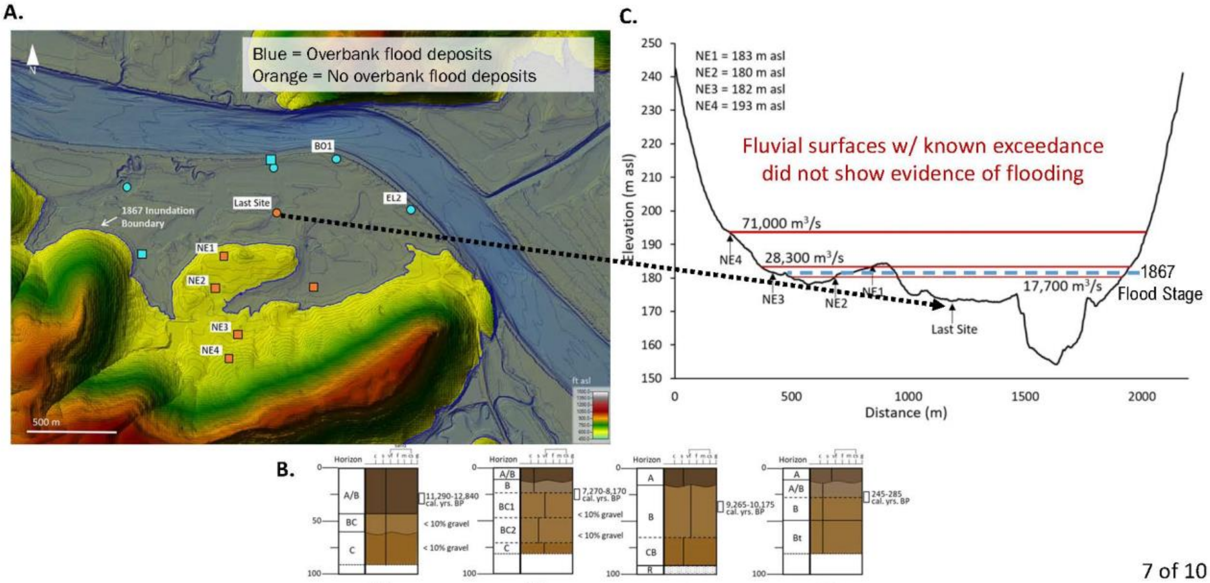
An alternative approach to assign perception thresholds:



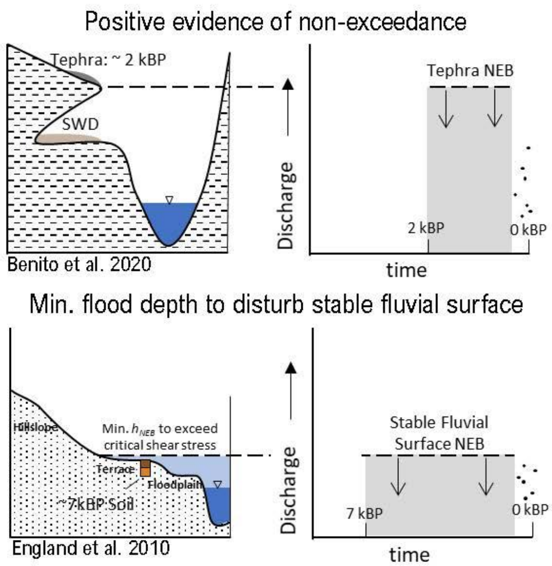


6 of 10

Second challenge: Flood disturbance does not always occur or is preserved

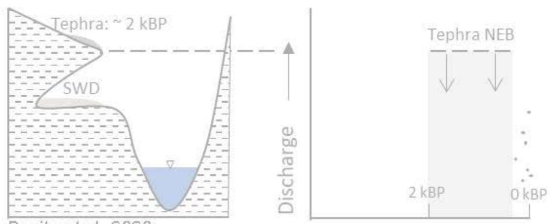


Robust options to assign non-exceedance bounds



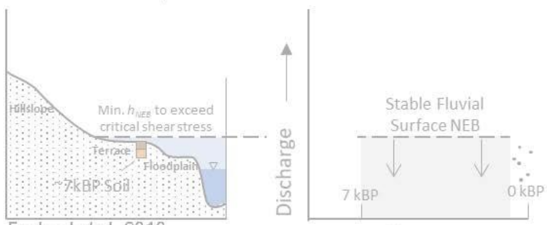
An additional alternative to NEBs

Positive evidence of non-exceedance



Benito et al. 2020

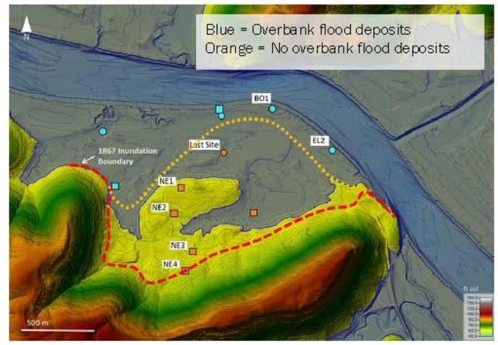
Min. flood depth to disturb stable fluvial surface

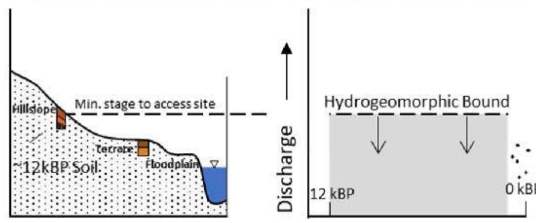


England et al. 2010

A Hydrogeomorphic Bound:

the upper limit of fluvial processes





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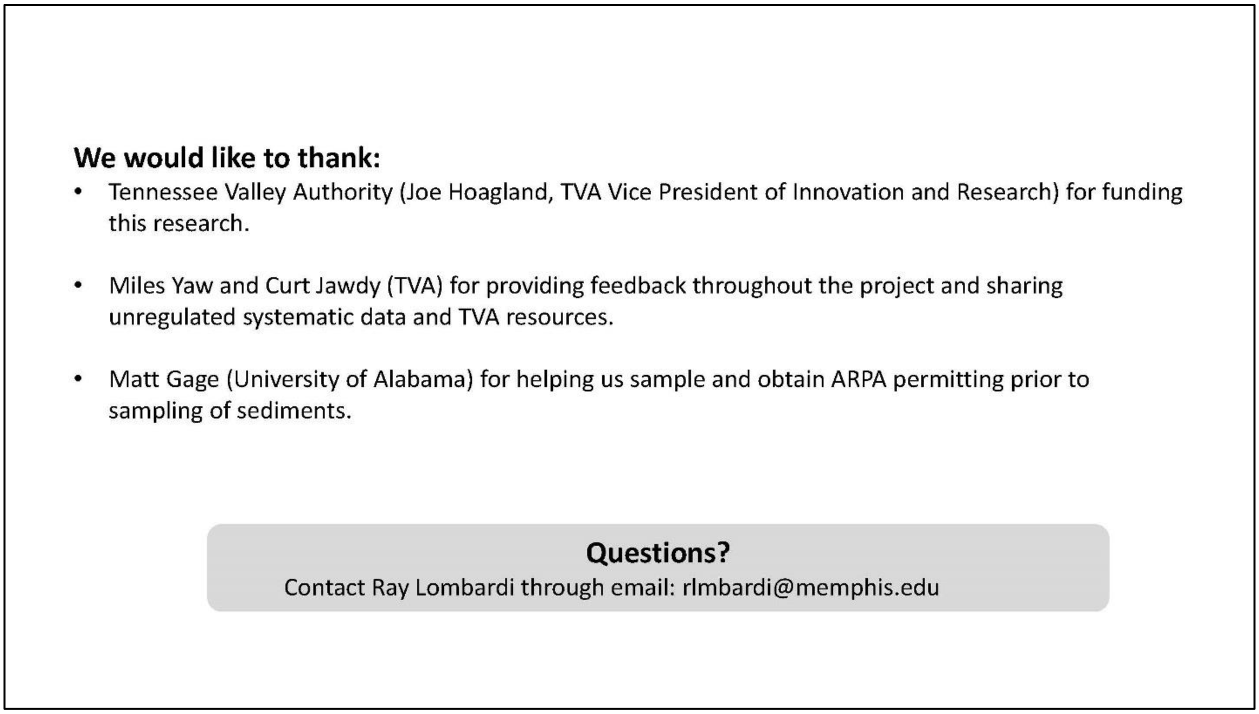
To Wrap-up

10 of 10



3.4.5.3 Questions and Answers

There were no questions for this presentation.

3.4.6 Presentation 2B-6: Using Paleoflood Analyses to Improve Hydrologic Loading for USACE Dam Safety Risk Assessments: A Nationwide Approach

Authors: Keith Kelson[1], Justin Pearce[2], Amy LeFebvre[2], Ryan Clark[3], Bryan Freymuth[4], Nathan Williams[5], John England[2]; [1]US Army Corps of Engineers (USACE), South Pacific Division Dam Safety Production Center, [2]USACE Risk Management Center, [3]USACE Dam Safety Modification Mandatory Center of Expertise, [4]USACE Northwest Division Risk Cadre, [5]USACE Lakes and Rivers Division Risk Cadre

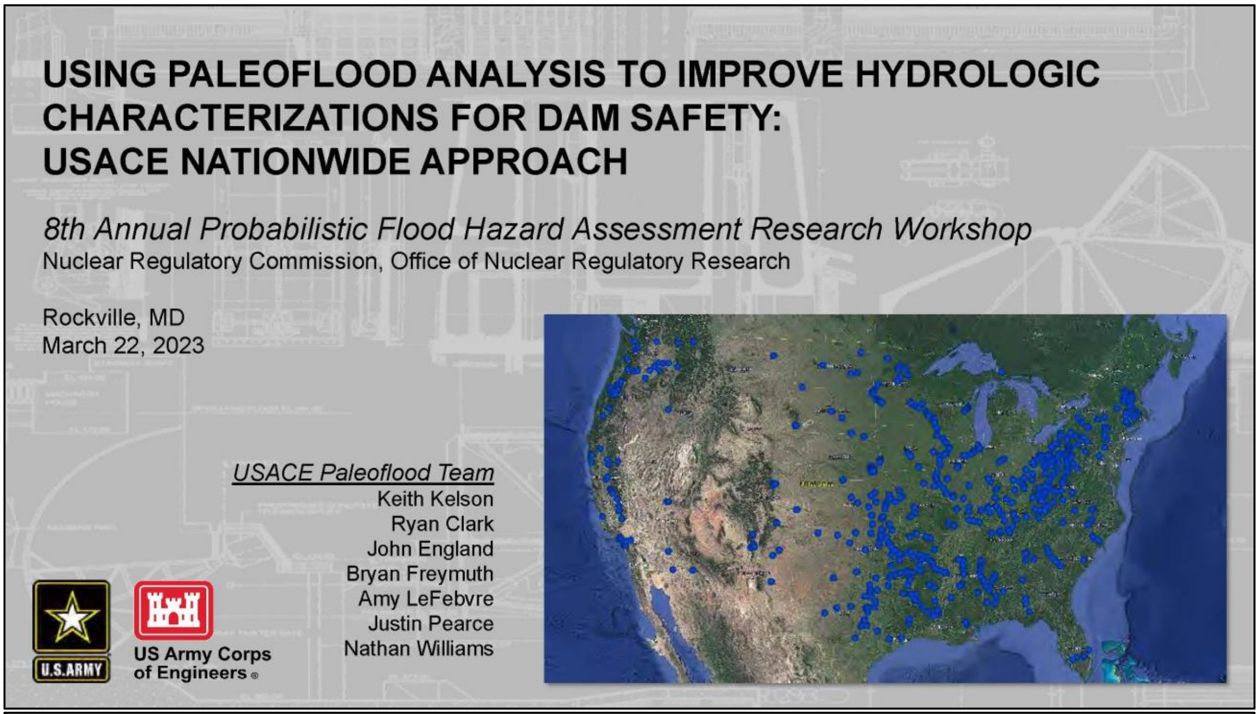
Speaker: Keith Kelson

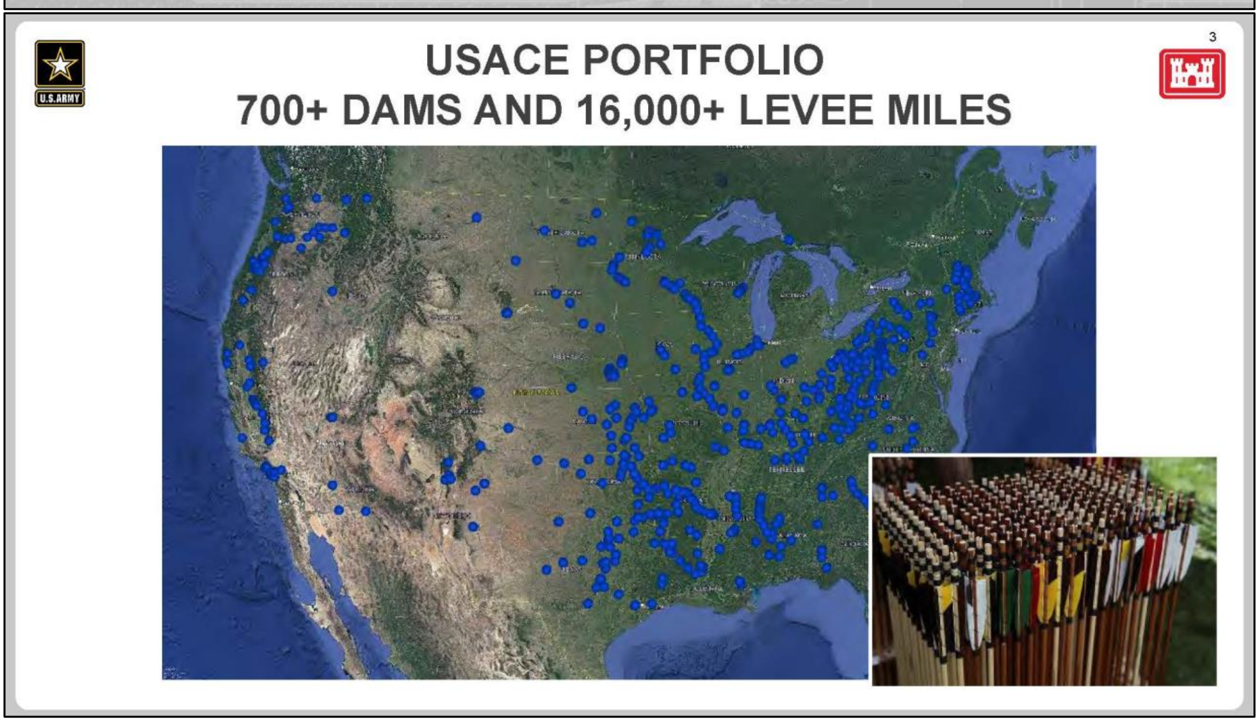
3.4.6.1 Abstract

Since 2015, results from paleoflood analyses (PFA) have been used to reduce uncertainties in hydrologic loading components of USACE dam-safety risk assessments. A tiered approach allows reductions of uncertainties through analyses having progressively greater detail, if supported within the risk-based decision framework. Tier 1 efforts are conducted to address watershed PFA viability and to recommend actions for minimizing uncertainties in initial hydrologic loading estimates. If appropriate, Tier 2 PFA are conducted where results are likely to improve confidence and reduce uncertainties in hydrologic loadings, and therefore benefit the risk assessment. Tier 2 PFA involve an integrated program of geologic and hydraulic analyses to identify and characterize paleostage indicators (PSI) and non-exceedance bounds (NEB) that constrain long-term paleoflood chronologies. Tier 2 often includes geologic and geomorphic characterization of riverine flood-terrace and slackwater deposits to identify and date specific flood events in the historic and pre-historic record, coupled with detailed hydraulic modeling to characterize peak flood magnitudes. These efforts involve state-of-art deposit and soil

characterization, multiple age-dating techniques (i.e., relative soil development, radiometric, optically stimulated luminescence, mass spectrometry analyses), and 1D/2D hydraulic modeling using HEC-RAS software to define flood water-surface elevations. The best-estimates and ranges in peak discharge and age for all PSI/NEB are included into flow-frequency statistics through use of perception thresholds and flow intervals, and sensitivity analyses provide guidance on the value of PFA datasets in reservoir-stage frequency analyses. If needed, Tier 3 efforts are then conducted to resolve specific technical issues with a focus on characterizing specific uncertainties in parameters that drive hydrologic loading. Incorporating PFA results into flow-frequency curves has shown that frequencies of rare and extreme peak discharges can be either over- or under-estimated compared to analyses using only historical data. PFA have been successfully applied to USACE dam-safety risk assessments throughout many geographic and meteorologic domains including projects on the Willamette River in Oregon, Missouri River in North Dakota and South Dakota, and Carbon Canyon Wash and Mojave River in California. These projects demonstrate applicability of PFA across the Nation. PFA are currently being applied to ongoing risk assessments for USACE dams on the White River in Missouri and Arkansas, the Naugatuck River in Connecticut, the Guadalupe, North Concho, and Red Rivers in Texas, the Kootenai River in Montana, and the Arkansas River in Colorado. Overall, these PFA add significant value to USACE dam-safety risk assessments by improving confidence and reducing uncertainty in hydrologic loadings.

3.4.6.2 Presentation (ADAMS Accession No. ML23177A173)





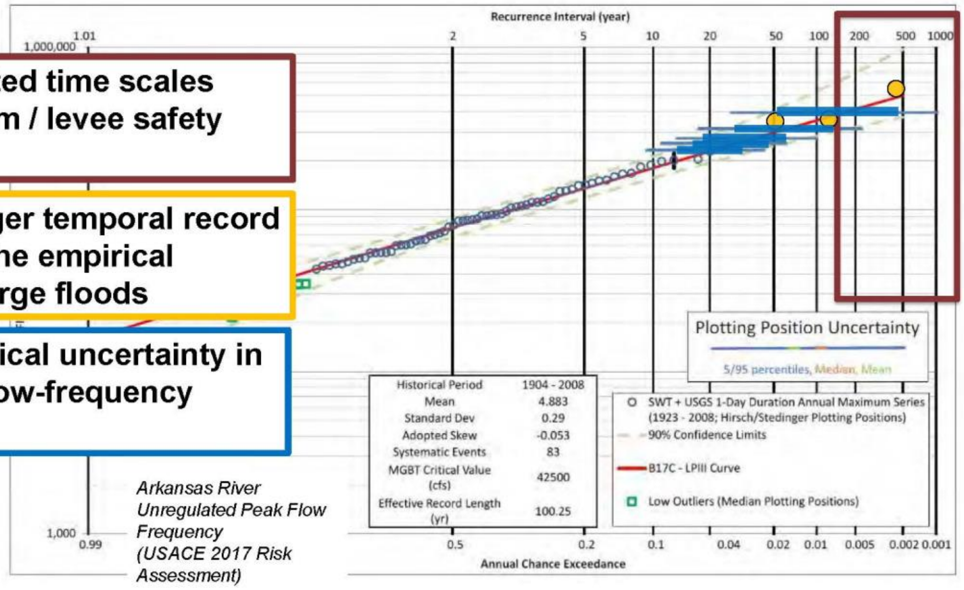
PALEOFLOOD ANALYSES- JUSTIFICATION

4

Focus on limited time scales relevant to dam / levee safety evaluations

Provide a longer temporal record that extends the empirical database of large floods

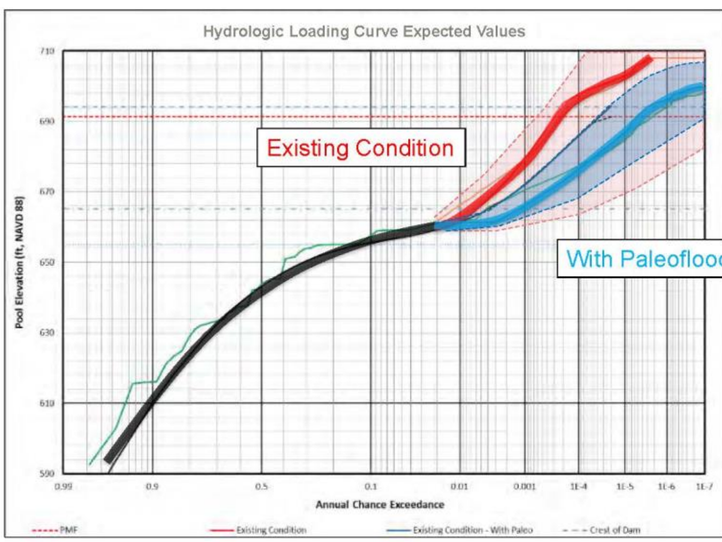
Reduce statistical uncertainty in unregulated flow-frequency analyses

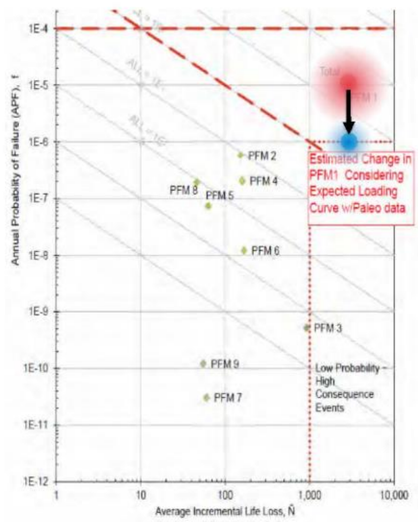


Arkansas River Unregulated Peak Flow Frequency (USACE 2017 Risk Assessment)

IMPROVE CONFIDENCE IN HYDROLOGIC LOADING

5





6

PALEOFLOOD ANALYTICAL FRAMEWORK

Portfolio Screening

- Which sites are viable for yielding paleoflood data?
- For which facilities would paleoflood data be useful?

Tier 1: Paleoflood Viability Assessment

- Is it possible to obtain paleoflood data?
- Would data result in narrower uncertainty or better confidence?
- Results should not be considered in risk assessments

Tier 2: Paleoflood Chronology and Flow-Frequency Evaluation

- Obtain expected values and estimate reasonable range
- Will additional data narrow level of uncertainty and/or improve confidence?
- If uncertainties are acceptable, may be considered in risk assessments

Tier 3: Detailed Characterization and Uncertainty Reduction

- Focus on characterizing uncertainties in hydrologic loading
- Develop understanding sufficient to support modification / design

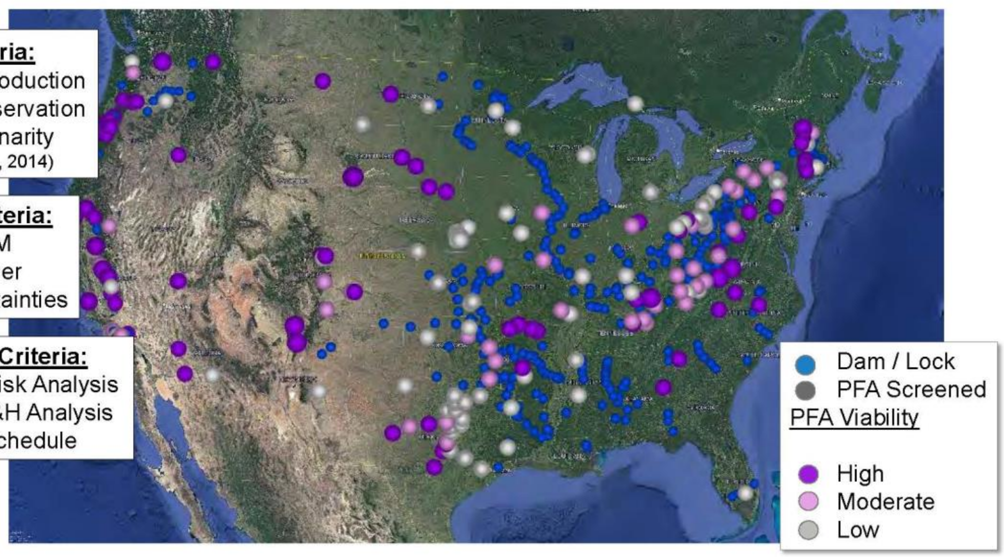
7

USACE PALEOFLOOD PROGRAM VIABILITY SCREENING

Geologic Criteria:
- Sediment Production
- Deposit Preservation
- Valley Stationarity (O'Connor et al., 2014)

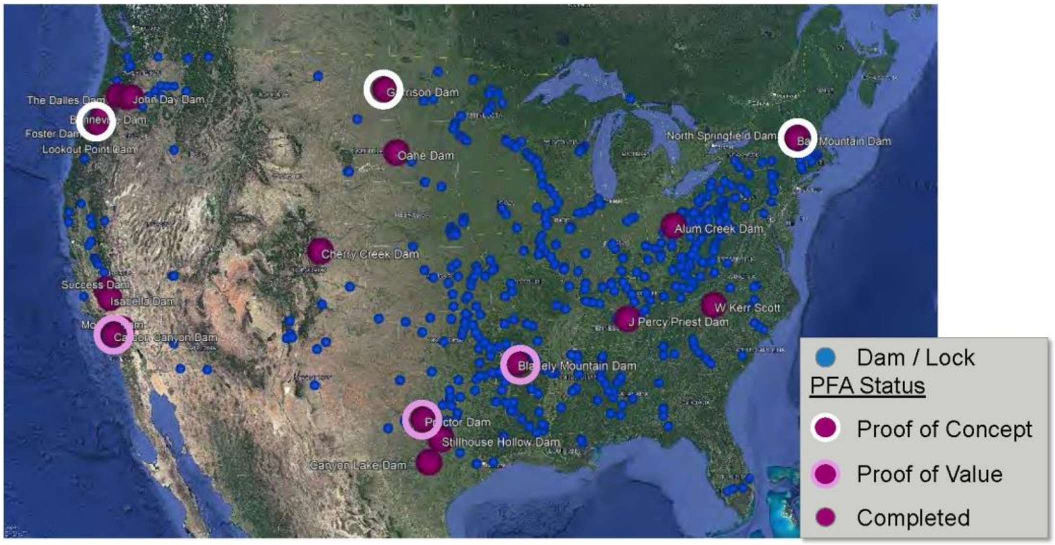
Hydrologic Criteria:
- Credible PFM
- OT Risk Driver
- Large uncertainties

Programmatic Criteria:
- Upcoming Risk Analysis
- Imminent H&H Analysis
- Favorable Schedule



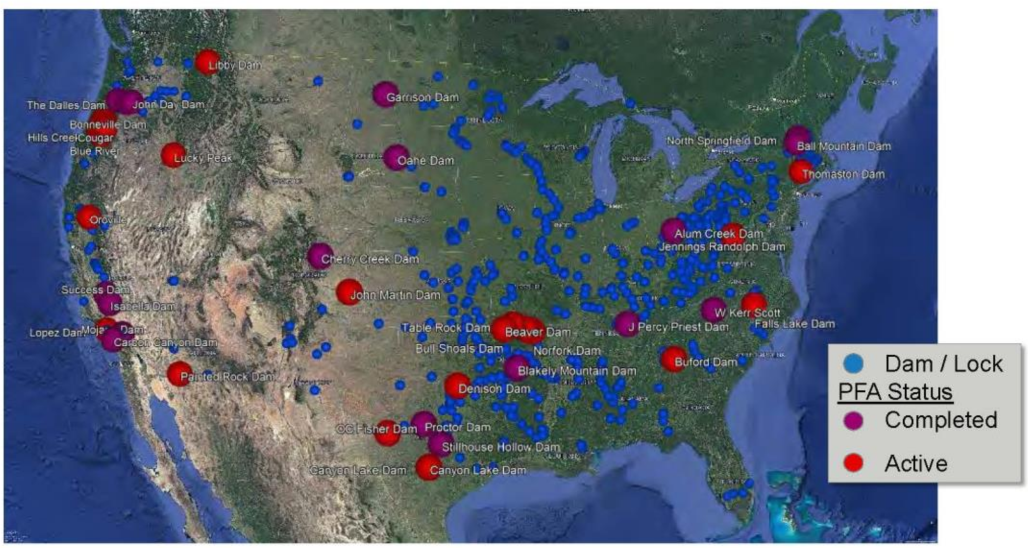
USACE PALEOFLOOD PROGRAM COMPLETED ANALYSES

8



USACE PALEOFLOOD PROGRAM COMPLETED AND ACTIVE ANALYSES

9



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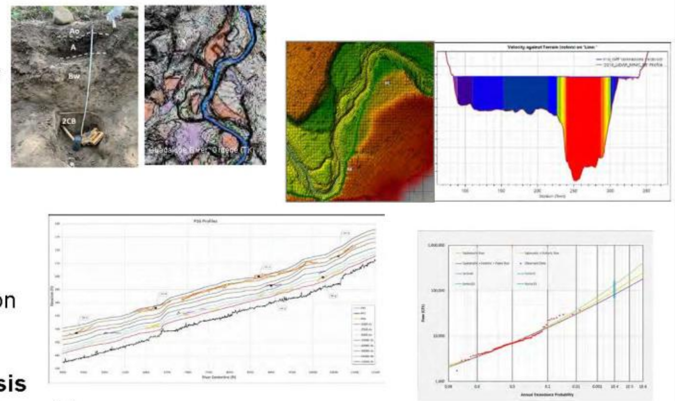
PALEOFLOOD TECHNICAL APPROACH:

Tiered and Progressively More Detailed (if/when needed)

Integrated and Multidisciplinary

- **Surficial Geology and Geomorphology**
  (Fluvial Processes, Soils Pedogenesis)
- **Hydraulic Modeling**
  (RAS Model Calibration and Validation)
- **Integrated Paleodischarge Estimation**
  (G&G and H&H Combined Team Elicitation
- **Hydrology and Flow-Frequency Analysis**
  (Historical, Systematic, and Paleoflood Records)



Result: Paleoflood Chronology and Magnitude

Geomorphic Datum	Estimated Age of Datum (prior to AD2015)	Low Estimate Discharge (cfs)	Best Estimate Discharge (cfs)	High Estimate Discharge (cfs)
Ht1 (PSI)	1,815 years	30,000	60,000	80,000
Ht2 (PSI)	335 years	10,000	20,000	30,000
[illegible]	March 1938	3,500	6,000	9,000

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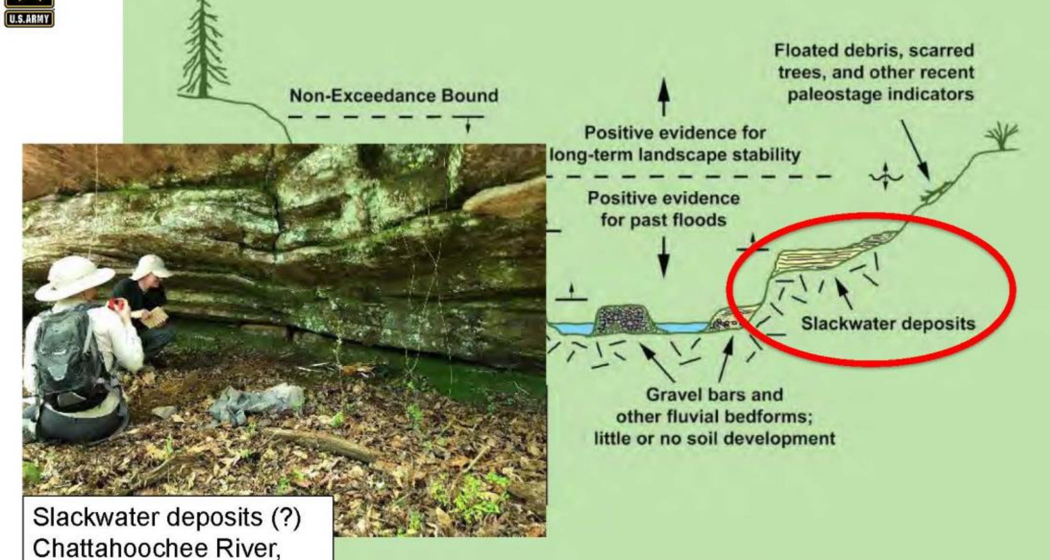
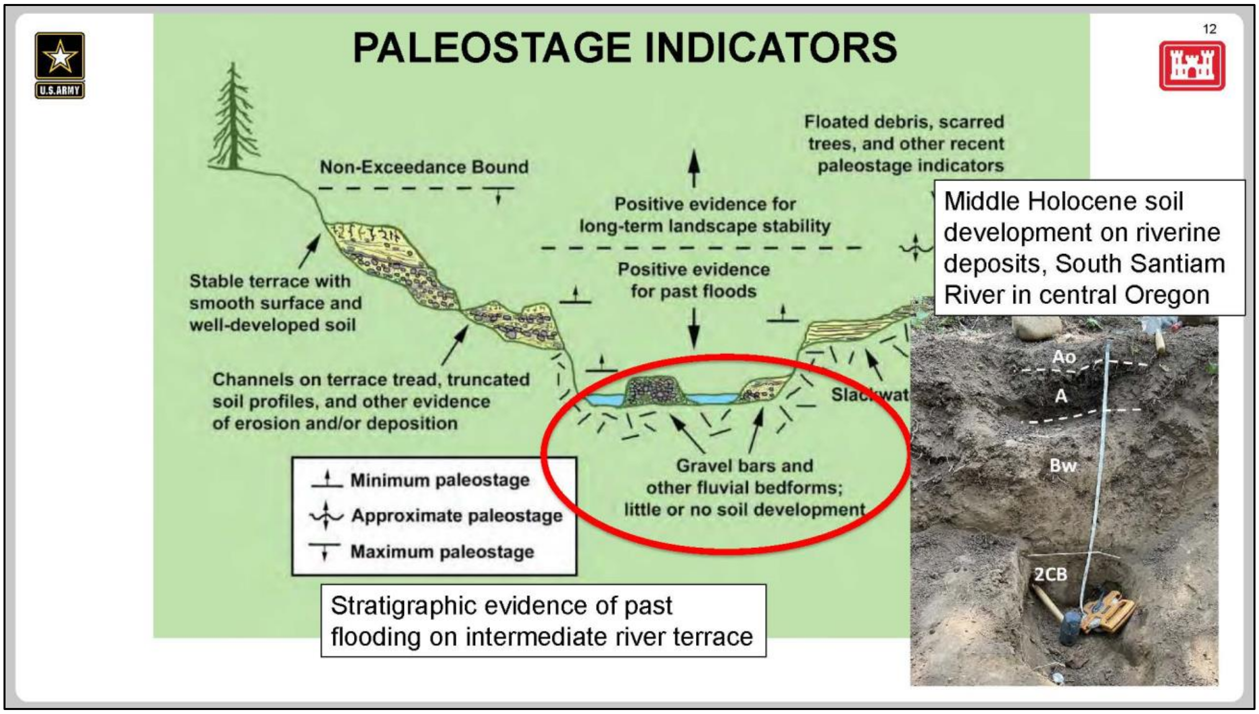
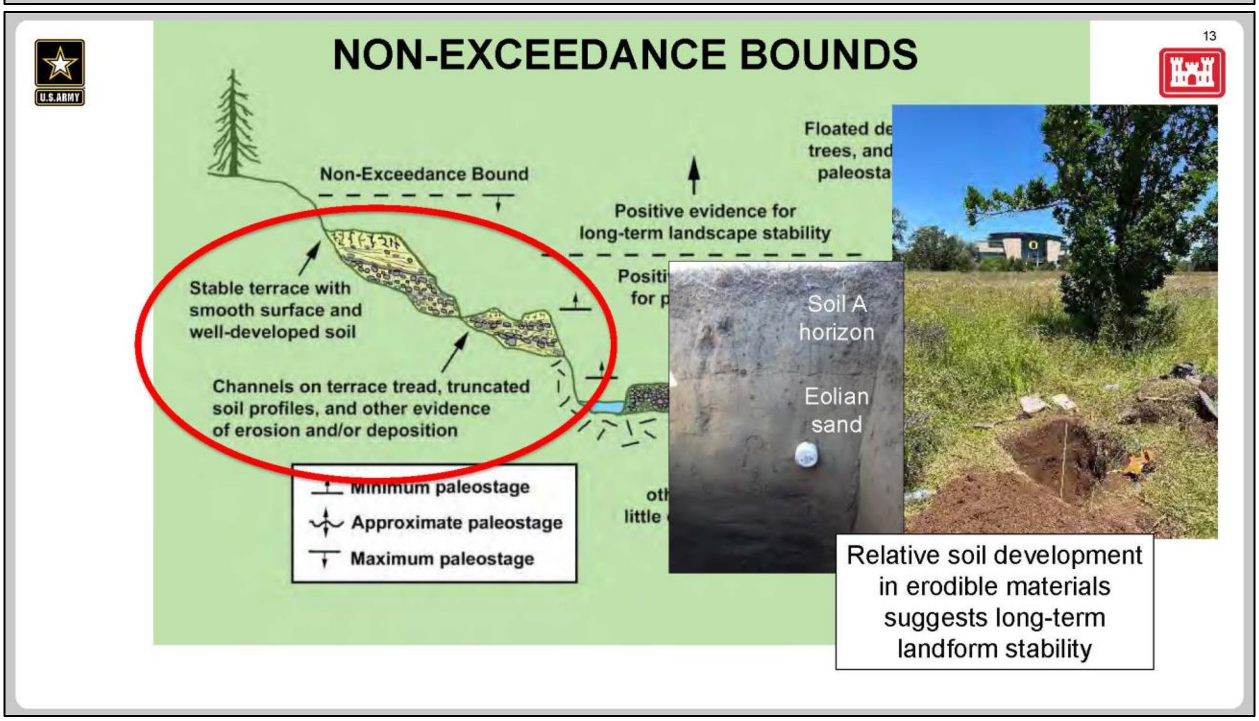
PALEOSTAGE INDICATORS



Slackwater deposits (?) Chattahoochee River, Georgia (Buford Dam)


12
PALEOSTAGE INDICATORS
Floated debris, scarred trees, and other recent paleostage indicators
Non-Exceedance Bound
Positive evidence for long-term landscape stability
Positive evidence for past floods
Stable terrace with smooth surface and well-developed soil
Channels on terrace tread, truncated soil profiles, and other evidence of erosion and/or deposition
Gravel bars and other fluvial bedforms; little or no soil development
Minimum paleostage
Approximate paleostage
Maximum paleostage
Stratigraphic evidence of past flooding on intermediate river terrace
Middle Holocene soil development on riverine deposits, South Santiam River in central Oregon
Ao
A
Bw
2CB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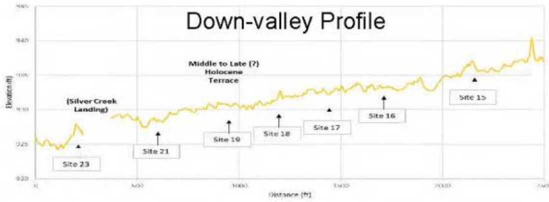
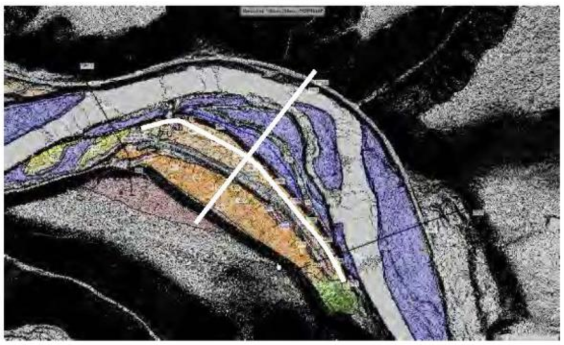
NON-EXCEEDANCE BOUNDS
Non-Exceedance Bound
Positive evidence for long-term landscape stability
Stable terrace with smooth surface and well-developed soil
Channels on terrace tread, truncated soil profiles, and other evidence of erosion and/or deposition
Minimum paleostage
Approximate paleostage
Maximum paleostage
Soil A horizon
Eolian sand
Relative soil development in erodible materials suggests long-term landform stability

TIER 2 PALEOFLOOD EVALUATION: GEOLOGY

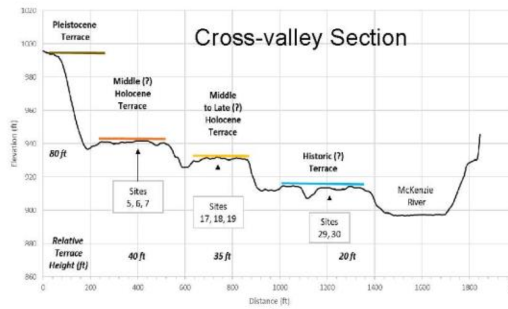
Identify and Characterize PSI / NEB





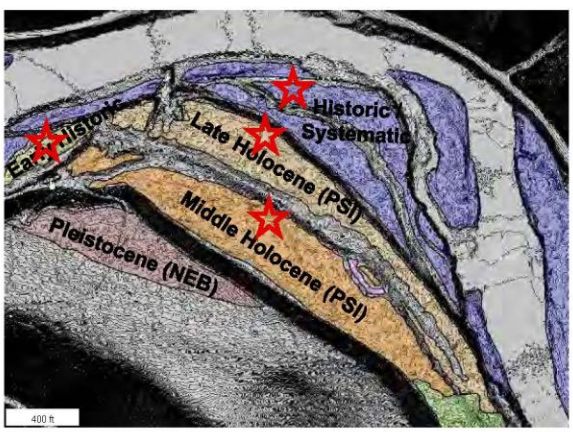
Technical Questions:

1) Are deposits associated with the geomorphic terraces related to axial river flooding?
2) If so, how old are the deposits?



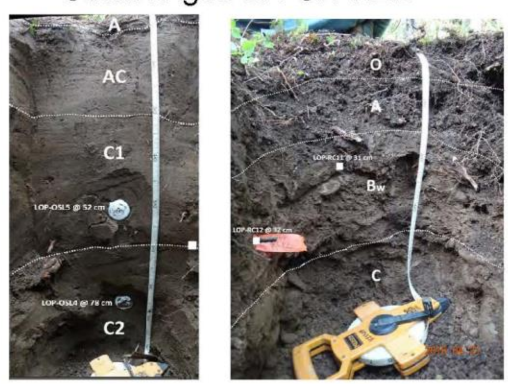
TIER 2 PALEOFLOOD EVALUATION: GEOLOGY

Identify and Delineate PSI / NEB



Detailed Stratigraphic / Soil Description Site

Obtain Ages of PSI / NEB

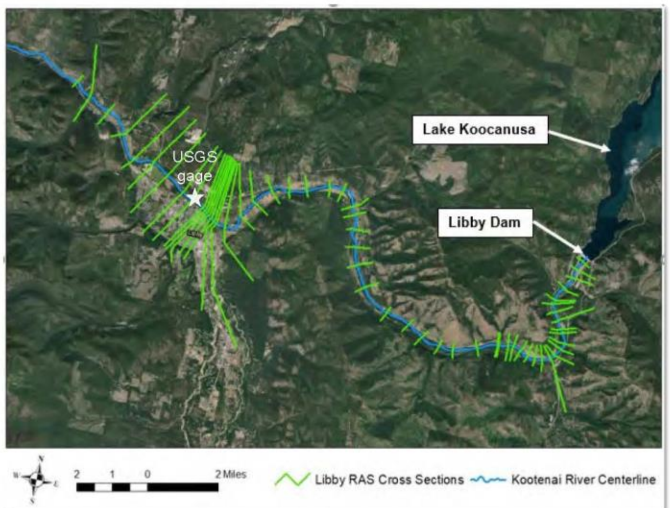


Age Estimates:

Relative soil development
Radiocarbon samples
OSL samples
Elemental concentrations

TIER 2 PFA: HYDRAULIC MODELING (1D OR 2D)

16



1D HEC-RAS, Unsteady Simulation
- Incorporates Channel Bathymetry

Upstream Boundary
- Inflow hydrograph downstream of Libby Dam

Downstream Boundary
- Normal Depth (Energy Grade Line)

Floods of Record
- HFOR Jun 1894: 117,000 cfs
  (estimated from USGS gage)
- SFOR May 1948: 103,600 cfs
  (measured at USGS gage)

PMF Peak Discharge of 489,000 cfs

USACE PFA utilize either 1D or 2D HEC-RAS modeling, as appropriate

TIER 2 PFA: DISCHARGE ESTIMATION

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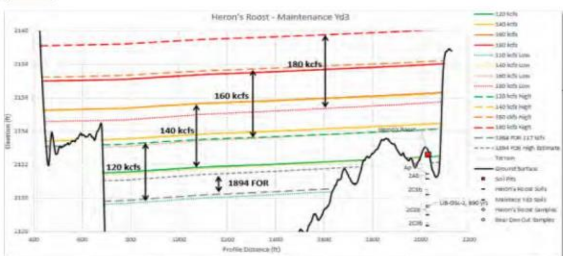
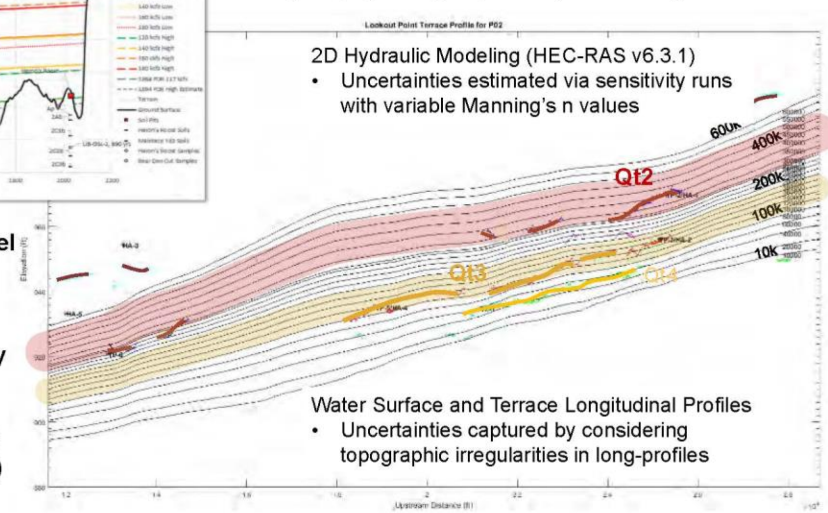


Interdisciplinary Collaboration
Geologists, Hydrologists, and Hydraulic Engineers



2D Hydraulic Modeling (HEC-RAS v6.3.1)
- Uncertainties estimated via sensitivity runs with variable Manning's n values

Water Surface and Terrace Longitudinal Profiles
- Uncertainties captured by considering topographic irregularities in long-profiles

Integrates Geology & WSE Model
- Down-valley profiles
- Cross-valley sections

Estimate Composite Uncertainty
- Channel Stationarity (Aleatory)
- Geologic Variability (Aleatory)
- Hydraulic Modeling (Epistemic)
- Sediment Transport (Epistemic)

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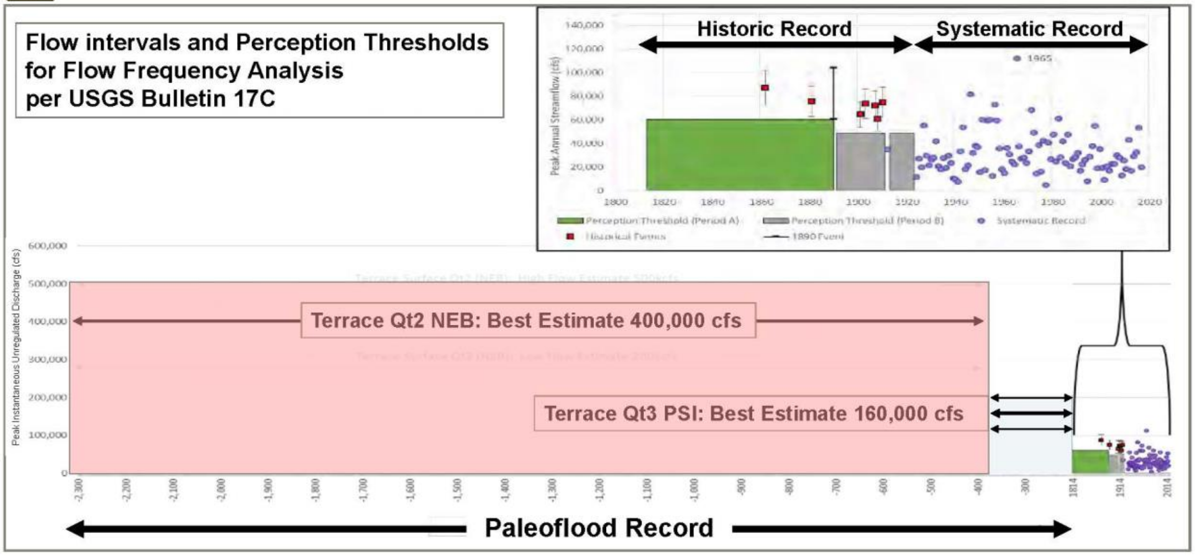
TIER 2 FLOW FREQUENCY ANALYSIS



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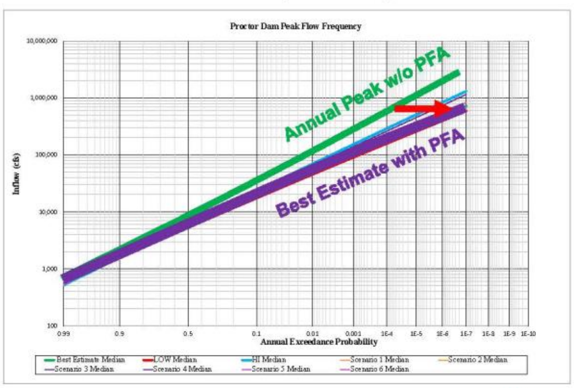
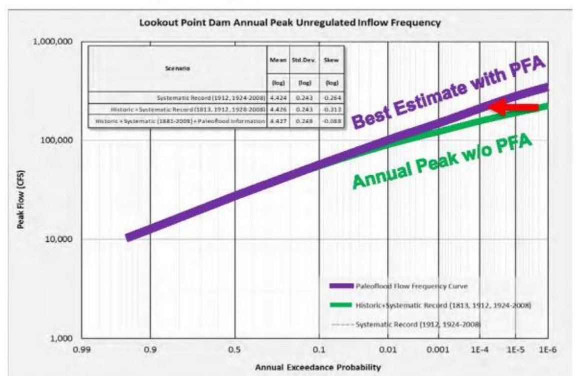
TIER 2 FLOW FREQUENCY ANALYSIS

Incorporating PFA results into flow-frequency curves…





… sometimes shifts the curve to the **right**

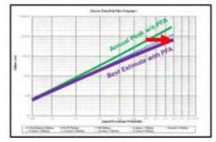
(extreme events LESS COMMON than thought)

… sometimes shifts the curve to the **left**

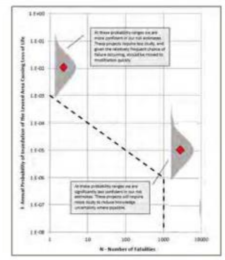
(extreme events MORE COMMON than thought)

USACE PALEOFLOOD ANALYSIS PROGRAM: RECENT LESSONS LEARNED

- **PFA works in watersheds across the Nation**
  - ➢ Successfully applied to USACE dam-safety risk assessments in many geographic and meteorologic domains



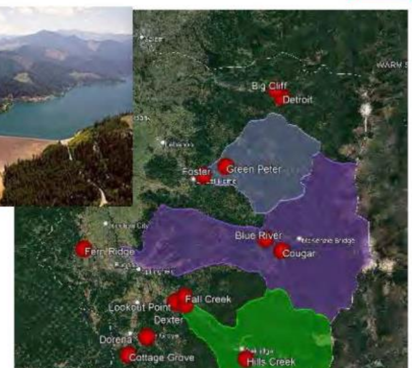
- **PFA data improves hydrologic characterization**
  - ➢ Using only historical + systematic records may over-estimate (or under-estimate) frequencies of extreme discharges



- **PFA provide credibility by capturing uncertainties**
  - ➢ Provides foundation for applying to risk-informed dam safety risk assessments.
- **PFA improve confidence and reduce uncertainty in hydrologic loadings**
  - ➢ Adds significant value to USACE dam-safety risk assessments.

ONGOING USACE PALEOFLOOD EFFORTS

Paleoflood Analyses: Production



- Individual Dam Risk Assessments
  - o Multiple ongoing PFA for individual dams
- Watershed-scale Assessments
  - o White River (Missouri, Arkansas; four dams)
  - o Willamette River (Oregon; nine dams, regional analysis)
  - o Missouri River (North Dakota, South Dakota; four dams)
  - o Central Texas Hill Country (Texas; six dams)

Policy and Guidance

- Methodology Documents (under construction)
- USACE Guidance (ETL 1100-2-4; USACE, 2020)
  https://www.publications.usace.army.mil/Portals/76/Users/182/86/2486/ETL1100-2-4%20corrected.pdf

3.4.6.3 Questions and Answers

Question:

Have you looked at the data if a dam failure was due to a seismic event?

Answer:

That has nothing to do with paleoflood, but I can answer that question anyway. There's only been a couple of dam failures related to seismic events and one of them was in the 2011 Tōhuku earthquake[14]. It killed 8 people and I happened to be the first geologist on site, so that's how I know about that. There are dam failures due to seismic events but they're pretty rare and rarely do they kill people. There's been the San Fernando event and Baldwin Hills, and there's a couple more. But, Fujinuma Dam, look that one up.

Comment (Joseph Kanney):

In your first stage screening analysis you referenced the report by Jim O'Connor, and I'm pleased to see that because that was work that Jim originally did for us. You mentioned the Army Corps 2020 guidelines, and we also worked with Jim, Tess Harden, Karen Ryberg, Julie Kiang and others at USGS to put together a set of guidelines for our purposes. I recommend if you haven't had a chance to look at that, you might find some of that useful for Army Corps applications as well.

Answer:

I'm fully aware of that and I helped review it. The work that Jim O'Connor did was funded by the NRC and we appreciate that. Tess was writing the USGS report at the same time that I was

[14] Fujinuma Dam. An earth-fill embankment dam in Sukagawa City, Fukushima Prefecture, Japan

writing the ETL[15] and we were doing it independently. When we were out in the field, shed mentioned that she was doing this methodology document and I said so am I. It turns out that they are independent but they're still significantly well-overlapped. They have different purposes. Ours is a regulatory or a guidance document for the Army Corps and hers is more for the NRC and for actual users. So, it's much broader and it's better. I hate to say it but, if you could only read one methodology, you should read Tess's. Ours is really addressing some of the internal issues that we had at the Army Corps where people were saying you shouldn't be doing that. I wrote it to say well, we should be doing this.

Question:

You mentioned a lot about reducing uncertainty. When I think about this, it's not always true. Certain data points or paleoflood information may be confounding sometimes. Should we be creating this expectation that it will always reduce your uncertainty? I know we hope it will.

Answer:

Keith Kelson: That's bigger than the science of paloeflood. The only way to decrease uncertainty is to collect additional and critical data or collect additional information on process-based models. If we collect more data and our uncertainty bands go up, that tells us we didn't have a good understanding of uncertainty before we started. That initial band of uncertainty that we estimated was wrong. My opinion is, if you collect more data, you should always be able to narrow your uncertainty, if you're doing it right. Lisa, Ray?

Ray Lombardi: You've hit on it, but I want to re-iterate on the process understanding. If you use the word confounding, perhaps what you have is a mixed distribution of flood drivers. Sometimes, I guess you could in theory, by including this mixed population, increase uncertainty, because you have essentially, two distinct distributions of events. But again, the paleoflood information, if used in tandem with other paleoflood records, could help us decipher what those distributions are, because I still don't think that the gage record is telling a clear story about distinct floods. Extreme flood drivers are distinct, but what are they? We don't really have a good sense of it. And so paleoflood information is beneficial in both those ways. It just might be that at the present time there's not a good way to split up that mixed population of flood events.

Question:

Given the widespread the data that you're collecting, have you ever thought about doing a 'space for time' substitution to apply that to sites with no paleodata?

Answer:

Keith Kelson: Of course. The ergodic assumption is part of geomorphology, so of course. But you can only do that if you're, I'll use the hydrologic term, if you are transposing within a given [homogeneous] domain. We would not want to use the ergodic assumption to transfer out of one area into another domain that has a different hydrologic loading. That's why we're looking at storm typing and runoff production. But within any given domain where everything else can be held constant, then yes, you could use space for time. Hydrologists have always known we have different storm types, and we've always known we have different runoff coefficients. Thats why we have NOAA Atlas 14. So, there are boundaries we can use that ergodic assumption within, and we've got to be aware of those.

[15] USACE Guidance (ETL 1100-2-4; USACE, 2020).

I want to address one other thing. When the uncertainty broadens (thank you Ray for pointing this out, and I think the lightbulb just went on for me), what that tells us is that our understanding is not complete. That's pretty basic, but it sheds light that we're not understanding the processes, and the processes are actually bimodal, and we have to then extract those two different populations within the one population. That means it's epistemic. If you can collect more information and go from a single population that has a broad uncertainty, you collect more information and you gain a better understanding and then you can say, well these are actually two sub-populations, but the uncertainty of each of those are smaller. And then you could use the space for time solution on one of those, but you shouldn't be using it on the other. I see Ray you are nodding your head, so I think you are agreeing.

Ray Lombardi: I think paleoflood information is very dynamic and useful for just generally understanding flood process and I hope that we can use it in other ways, beyond curve fitting.

3.4.7 Riverine Flooding Panel Discussion (Session 2B-6)

Moderator: Joseph Kanney, NRC/RES

Participants:
Daniel Wright, University of Wisconsin-Madison
Sudershan Gangrade, Oak Ridge National Laboratory
Ryan Johnson, RTI International
Lisa Davis, University of Alabama
Ray Lombardi, Lisa Davis, University of Memphis
Keith Kelson, US Army Corps of Engineers,

Question:

How can we improve the synergy between mechanistic physics-based modeling and the use of paleoflood information? I think we've seen lots of examples of paleoflood information being used to refine flood frequency analysis, but I think a broader question is: how do we use paleoflood information to inform our mechanistic flood models, whether they be looking at a particular event or an ensemble approach or a probabilistic approach? I'd like to ask this question from both sides. For the mechanistic modelers, what would you like to see in terms of paleoflood information that would really be helpful? From the other side, from the paleoflood folks, is there something that you've identified that you think could be used to improve physics-based modeling?

Answer:

Daniel Wright: Where the synergies could really come in is getting as specific as possible about how a specific flood has happened. I believe it was Keith that mentioned storm typing. That would be very difficult to do, if not impossible, when it comes to prehistoric events. But even in the historical and gaged records, that's really important for distinguishing different types of floods and how they happened. So, storm typing on the meteorologic side, and then the other ingredients that were involved, such as snowpack and snow melt. So one concern that I generally have about paleofloods is did they occur in the same kinds of ways that modern floods occur, and do the conditions under which they occurred still exist? Or could they happen in some tail low probability sort of thing? So, thinking about ways of bringing that kind of information together with process-based modeling could be a fruitful way forward.

Keith Kelson: I agree with that Daniel. I appreciate your expertise on that. We've given a little bit of thought on how to do that because it's important. We're coming out with two things (or one and it's hybrid into two different things). We want to branch out in a watershed perspective.

Originally our first analyses were just to understand the reach that is directly below a dam. We were concerned about what goes on, say, on the Feather River between Oroville Dam and the town of Oroville, a two-mile stretch. But what we found is that they might be the same [in adjacent watersheds].If they are, then that tells you that these are big storms. That's why we're working in central Oregon, taking three different watersheds, to see if there's synchronicity in the paleoflood chronology amongst these watersheds that are hundreds of miles apart. There might be a storm in January and another storm the following December and the age dating techniques are not good enough to differentiate that, I get that. But the presumption would that be a big storm in CE 500 in one watershed was the same storm as the one that occurred in CE 499 [in an adjacent watershed]. The other hybrid approach is in the Texas Hill country where we're working on these watersheds that flow from west to east, and the storm track goes from south to north. What we're seeing is a storm track from historical storms, like 1936, 1898, track from south to north, and they effect only parts of those watersheds. So we're looking at the parts of the watersheds, fortunately that's where a dam was, and we're finding the record there. But as you go upstream out of that storm track, we have a different flood of record, or a different paleoflood of record, and a different paleoflood chronology depending on where you are in the watershed. So, we are able to kind out suss out how those paleoflood storms tracked from south to north and whether they are coincident with the historical storm tracks or whether they're something different. That's our thoughts and open to discussion.

Lisa Davis: What we've basically been presenting today is what's called the quantitative paleoflood hydrology approach, where the goal is a stage, which can be integrated into a flood frequency analysis. But there are other flavors of this work that some people may consider as Quaternary geomorphology, where you get more of a sense of what are the drivers of the particular changes to flood frequency and their magnitude over time. Those kind of studies don't necessarily give you discharge estimates, but they will definitely give you information about changes in flood frequency. A lot of scientists have done a good job at looking at long-term temperature changes and a whole bunch of other climatic variables, but I will kind of go back to this idea that Keith presented earlier. That is thinking a little bit more about site selection and broadening your horizon in terms of the scope of that really gives you more data. It's something that we've been doing in the Tennessee River Basin, looking at multiple sites across the basin and different kinds of paeloflood sites.

The presentation I gave today focused on the quantitative flood frequency analysis but a lot of the work that Ray and I have been doing is trying to look at floods throughout the basin, and when they tend to occur. A lot of them have occurred during really abrupt climate transition times. Not necessarily warm phases or cold phases of climate, but the transition times seem to be where we have the most frequent and the most extreme floods. The other thing that we've done is targeted specific sites for information. That DT3A site that I showed is actually a site that's prone to hurricane induced extreme floods and that 1791 flood happened to occur when there was a very large hurricane in the Caribbean that made landfall in the Northern Gulf of Mexico. We know that by comparing our data to the work of paleotempestologists (people who look at past hurricanes), there is a lot of this information available, particularly in the academic literature. The dots just have to be connected. But like Keith mentioned before, , if you think a little bit more about site selection when you're doing these studies, you can actually get to some of that mechanistic information if you choose your sites thoughtfully.

Ray Lombardi: Building off that a little bit, one thing that I'm trying to do with my research is to marry the insights from modern hydrology with paleoflood information. Our capabilities with watershed modeling and landscape evolution modeling give us a very good spatial understanding of process and the connections of those systems, particularly how it's related to the atmospheric system. Then building hypotheses with the paleoflood information based off this really extensive temporal insight that we get from longer, generally 5000-year records, because that's when effective moisture is about the same as modern day. We can look at all of the variable response of floods over that time period to give insights. Maybe we don't have the temporal resolution to say "it was a hurricane" or "it was an atmospheric river", but we could then move into the modeling space a little bit and kind of synthetically use watershed models to hypothesis test some of these processes and see if it plays out. I will also mention that the three of us have presented very much sedimentary paleoflood approaches. There are also botanical approaches like tree scars and any kind of tree ring records that you can look at actual anatomical failures of the trees and years that are related to actual extreme floods. That's going to give you down to a seasonal resolution over the last, in best case, in most cases about 1000 to 2000 years before present. And so there are ways to use multi-proxy paleorecords to get insights, and when possible, we always do this. For example, let's use lipid biomarkers and plants in the flood deposits to see what the oxygen isotope was, and then we can determine was this water coming from the Gulf of Mexico or was it water coming from the Arctic? I often tell my students I'm a dirt detective because I'm putting together all these clues to say beyond a reasonable doubt that something occurred. Then, once we have that collection of evidence, go and test that in the model space, or even trade space for time in the modern sense. Because maybe we have only one observation of a particular flood, say, on the lower Missouri River, but maybe floods like that have occurred globally that we can then compare, and ask is there something to this configuration of antecedent and atmospheric conditions that lead to the most severe floods.

Keith Kelson: I would concur with that. You gave some really good examples of what I was glossing over as different arrows in our quiver. You're right, botanical is good; archeological is incredible. We've had some features that were flooded and no longer used that we can date because of archaeology. So, there's all kinds of things. Another tool that we use is to integrate with folks who have good understanding of physical models like Dan. Part of that is we need to be able to make sure whether the process-based modeling effort is consistent with, or not consistent with, the empirical database. This is what paleoseismology does. We have paleoseismologists and earthquake seismologists, and the biggest jumps in our understanding in earthquake hazards are when those two groups get together. And now, in earthquake hazards forecasting, you always have those two different things. What I really appreciate about what Joe has done with this workshop is to have us talking. My question for Dan (I think Ray asked it also): is there a way that you could use the physics-based, process-based modeling on an extreme event, could you do that in the Tennessee Valley (or with the Big Thompson flood, there Bob Jarret has a good record of it)? What we're talking about is turning knobs and flipping the switches in the process-based model to make sure that you retro-dig correctly. Maybe you've done that. That's my question.

Daniel Wright: Using earlier, let's say non-physically-based hydrologic models (I don't know how familiar you are with the hierarchy of these hydrologic models), there's reason to doubt the realism of blasting those things with a really big storm that's way outside of your calibration record. I am not familiar (maybe this exists, and I've just not looked for it) with people interrogating these more modern models for realism in terms of really big events, you know 5000-year events. Do they even seem to give anything feasible? You know of course there are good reasons why that's challenging to do, but it's a good point. I think one obvious connection to the sorts of things that I've been doing is the storm transposition concept because extremely rare storms are only extremely rare at a local scale. If you look over some large enough domain, they're not all that uncommon. Of course there are limits to how far you can look away from the actual watershed of interest, but being able to pull in storms (it doesn't have to be in a very rigorous probabilistic framework like the way that I've been doing it, but identifying one or two large storms), putting them into a model of a particular watershed of interest that has a lot of paleoflood data, and essentially seeing whether there seems to be any story that can be drawn from that. I think that can be an interesting pathway towards kind of addressing your question here. I'm not familiar with much work that's been done on that. We have a little bit of that in one or two or our papers, but not very much.

Ryan Johnson: I'll just comment on Keith's last question on comparing the two. During the break here I talked with some of my colleagues that are doing the PFHA analysis for TVA and comparing to what Lisa is doing. I asked them how it's looking in the initial comparisons, I think it was near Guntersville [dam]. The two methods are fairly close. But to Dan's point, looking at hydrologic models, sometimes when we plot these huge events onto parameters that maybe calibrated for more operational-based or even observed large events, they can cause some very high responses or response that we don't have a lot of confidence in. So I think having paleorecords to compare to can help inform, or maybe start that discussion of the drivers.

Sudershan Gangrade: I think in some of the cases we have implemented very large-scale flood modeling applications through these hydrologic models and hydraulic models. For instance, we have been talking about probable maximum precipitation and probable maximum flood in the earlier sessions. I think generating some sort of comparisons against that with the paleofloods that may have occurred in the past and also having some sort of a long historical reanalysis inundation data base that can also help validate some of the paleoflood data that may be available. So, I think I agree on that.

3.5 Day 3: Session 3A – Posters

Session Chair: Thomas Aird, NRC/RES

3.5.1 Poster 3A-1: Identifying and Cataloging Major Storm Events from Gridded Quantitative Precipitation Estimates for use in Stochastic Storm Transposition

Authors: Alyssa Dietrich, Eric King, Seth Lawler; Dewberry

Speakers: Alyssa Dietrich, Eric King

3.5.1.1 Abstract

Stochastic Storm Transposition (SST) is a modern technique used to move observed precipitation associated with a storm event from its original location to multiple, randomly selected alternate locations within a climatologically comparable region. Storm transposition has its root in deterministic probable maximum precipitation studies for the purpose of supplementing storm data in locations with limited observed historical events. Advancements in computational speed and technology allow for the "stochastic" component of storm transposition, where a suite of realistic spatial precipitation patterns can be created that are suitable for probabilistic modeling.

In order to do SST, there is first a need for a storm catalog or database from which the suite of moderate to extreme storms can be selected. Selecting storms for a catalog has traditionally been a subjective process, limited by a storm being observed at a precise location and the quality of gauge-based precipitation observations. Combining computational approaches with the availability of CONUS-wide, remotely sensed, gridded daily and hourly precipitation datasets provide a unique opportunity to overcome many of these traditional limitations. Utilizing published gridded datasets eliminates the requirement for a storm to be analyzed from gauge data to determine total storm magnitude; and their use ensures that a large event, no matter where it occurred, is not missed due to lack of ground observations. While remotely sensed gridded datasets remain imperfect, a notable flaw being their relatively short record lengths, year after year datasets continue to grow. For example, the Stage IV dataset from the National

Center for Environmental Prediction now has over two decades worth of data, and the Analysis of Record for Calibration (AORC) dataset from the National Weather Service contains hourly data back to the 1970s.

To populate the storm catalog an unsupervised python-based algorithm was developed to iterate over an entire period of record (POR) and identify storms contained in gridded precipitation data. For a given SST transposition domain, a storm is identified as a contiguous group of grid cells that accumulate statistically significant precipitation over some defined duration. The unsupervised learning concepts of thresholding and clustering are applied to a sliding window (based on event duration) over each date in the POR. For each of these windows, the time-series grids are aggregated, an accumulated precipitation threshold is calculated, and all grid cells with precipitation greater than the threshold are grouped in clusters. Statistics such as size, mean, total volume, and maximum are gathered for each cluster and stored in a searchable and filterable database. Storm criteria can then be applied as filters to retrieve storms for use in SST.

This poster will present a reproducible methodology to download, analyze, and objectively catalog historical precipitation data suitable for SST studies, including regional precipitation and flood frequency analyses.

3.5.1.2 Presentation (ADAMS Accession No. ML23177A174)

Dewberry

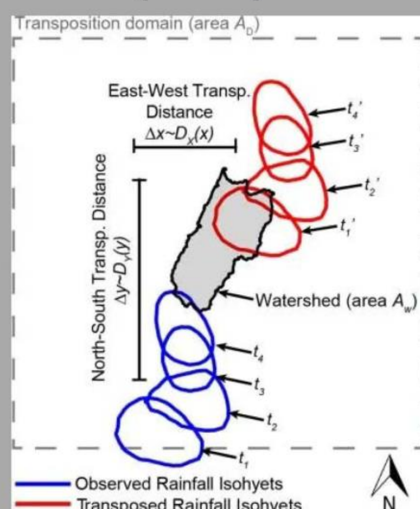
Identifying and Cataloging Major Storm Events from Gridded Quantitative Precipitation Estimates for use in Stochastic Storm Transposition

Alyssa Hendricks Dietrich, Eric King, Seth Lawler

NRC Probabilistic Flood Hazard Assessment Research Workshop Rockville, Maryland - March 23, 2023

Stochastic Storm Transposition (SST)

- Process of moving an observed storm event from its original location to a new, randomly selected location
- Increase number of realistic storm patterns in a study area



(Wright et al, 2020)

2 NRC PFHA Research Workshop March 23, 2023 Dewberry

Storm Selection

Historical Limitations

- Storm observed at precise location
- Quality of observational data
- Short record length of remotely-sensed quantitative precipitation estimates

Computational Improvements

- CONUS-wide Quantitative Precipitation Estimates (QPE)
- Automated, open-source algorithms
- Objectively (statistically) identify storms

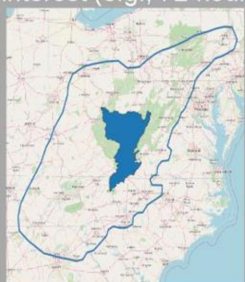
Data Technology

- Open-source geospatial ***python*** libraries: xarray, numpy, rasterio, shapely, etc.
- ***AWS*** cloud technology: S3, EC2, ECR, ECS, Batch
- ***Meilisearch***: search engine and NoSQL database
- ***React*** InstantSearch: UI and frontend widgets

Storm Catalog – Pipeline

INPUTS

- Watershed geometry
- Transposition region geometry
- Storm duration of interest (e.g., 72 hours)



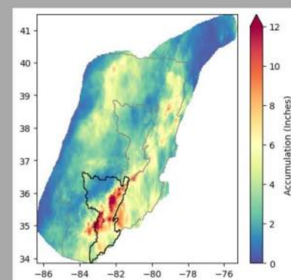
STORM IDENTIFICATION

AWS Batch

AWS Batch distributes the pipeline over multiple machines, allowing for quicker data processing

OUTPUTS

- NoSQL documents (JSON)
- Plots
- DSS files

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Storm Catalog – Data Preparation

EXTRACT

Gather hourly 4km AORC grids from FTP server

Index of /aorc-historic

Name Last modified Size Description

- Parent Directory
- AORC_ABRFC_4km/
- AORC_CBRFC_4km/
- AORC_CNRFC_4km/
- AORC_LMRFC_4km/
- AORC_MARFC_4km/
- AORC_MBRFC_4km/
- AORC_NCRFC_4km/
- AORC_NERFC_4km/
- AORC_NWRFC/
- AORC_NWRFC_4km/
- AORC_OHRFC_4km/
- AORC_SERFC_4km/
- AORC_WGRFC_4km/
- AORC_license_disclaimer
- Documents/

Name	Last modified	Size
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AORC_APCP_4KM_ABRFC_197903.zip	2021-01-28 22:24	7.2M
AORC_APCP_4KM_ABRFC_197904.zip	2021-01-29 00:38	6.6M
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AORC_APCP_4KM_ABRFC_198008.zip	2021-01-30 12:42	7.0M

LOAD

Copy zipped NetCDF files to S3 mirror

Name

- AORC_ABRFC_4km/
- AORC_CBRFC_4km/
- AORC_CNRFC_4km/
- AORC_LMRFC_4km/
- AORC_MARFC_4km/
- AORC_MBRFC_4km/
- AORC_NCRFC_4km/
- AORC_NERFC_4km/
- AORC_NWRFC_4km/
- AORC_OHRFC_4km/
- AORC_SERFC_4km/
- AORC_WGRFC_4km/

Name

- AORC_APCP_4KM_ABRFC_197902.zip
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- AORC_APCP_4KM_ABRFC_197912.zip
- AORC_APCP_4KM_ABRFC_198001.zip
- AORC_APCP_4KM_ABRFC_198002.zip

TRANSFORM

Merge the separate RFC grids for every hour in the POR and convert to Zarr

- 1979020100.zarr/
- 1979020101.zarr/
- 1979020102.zarr/
- 1979020103.zarr/
- 1979020104.zarr/
- 1979020105.zarr/
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- 1979020108.zarr/
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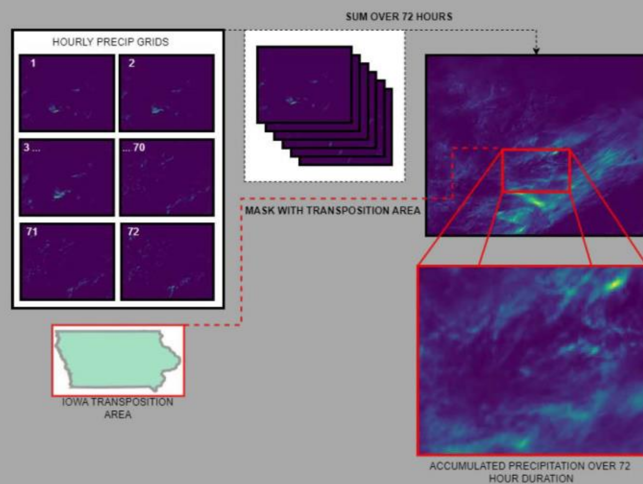
- 1979020111.zarr/
- 1979020112.zarr/
- 1979020113.zarr/

- .zattrs
- .zgroup
- .zmetadata
- APCP_surface/
- latitude/
- longitude/
- spatial_ref/
- time/

Methodology – Mask & Sum AORC Grids

For the entire 40-year AORC dataset, a sliding XX-hour window (e.g., 72-hours) is applied.

For each given window, grids are loaded, masked by transportation region, and summed.



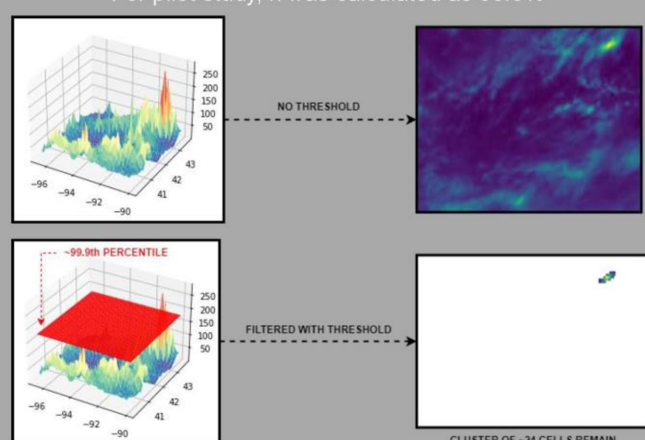
Methodology – Calculate Exclusion Threshold

For each sliding window, an exclusion threshold is calculated as a k-th percentile score.

$$percentage\ k = 1 - \frac{\#\ cells\ in\ watershed}{\#\ cells\ in\ transposition\ domain}$$

Cells with values below the exclusion threshold are removed.

For pilot study, k was calculated as 99.9%

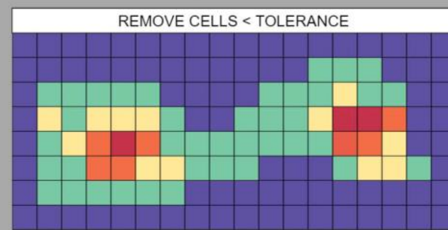


Methodology - Clustering

Remaining cells where precipitation > exclusion threshold are clustered into a single storm using density-based clustering.

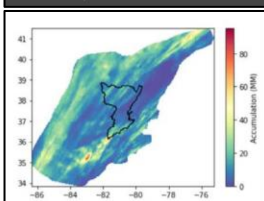
To remove any size bias when comparing results, all clusters are adjusted until it matches the target watershed size.

In the pilot study, the thresholding / clustering algorithm output a cluster matching the target size ~25% of the time. The other ~75% required either adding or removing cells from the cluster to match the target size.

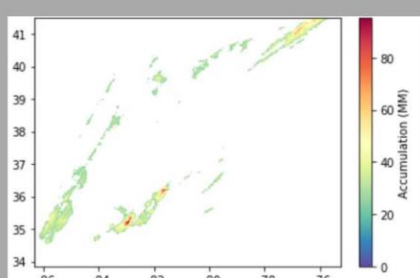


10		123.4	126.3	149.8	161.1	166.4
133.2	136.1	149.2	163.9	185.6	179.2	166.6
152.3	158.1	175.4	185.1	193	164.3	142.4
161.3	171.1	184.3	177	163.6	140.1	123.8

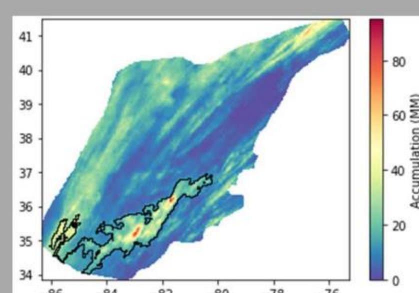
Evolving Methodology



When the k value is too small (as in the case of the Kanawha basin) due to a large target watershed size, the calculated exclusion threshold was resulting in a lot of noise.



Additionally, the final "storm area" was creating bizarre shapes largely due to no storms being large enough to completely comprise the watershed.

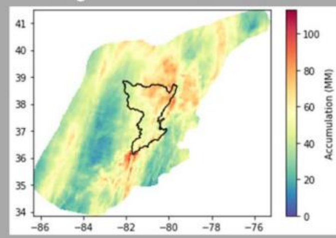


Evolving Methodology – Sliding Watershed

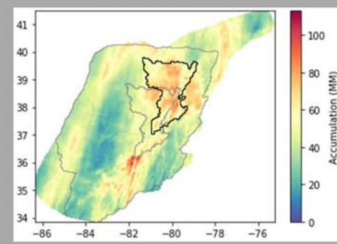
A new, performant algorithm to maximize total accumulation over the watershed area was developed.

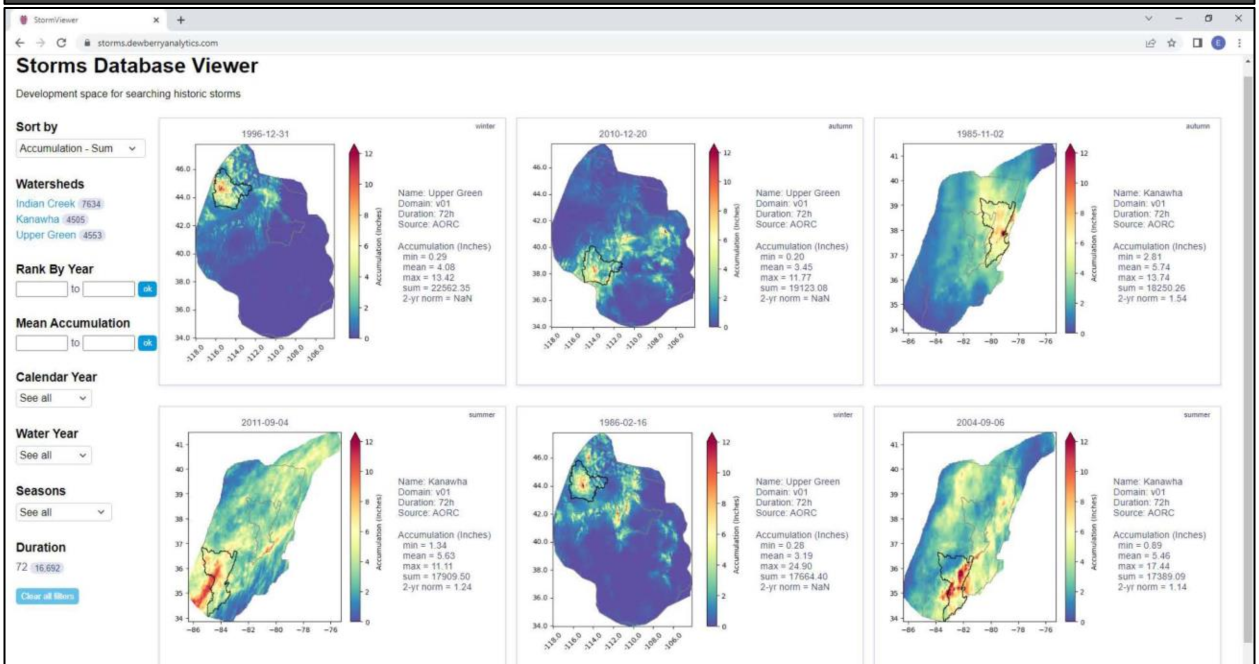
This involved translating the watershed "mask" around the transposition domain and selecting the translation with the greatest total accumulation.

original watershed mask



translate with greatest total accumulation





Selecting Storms

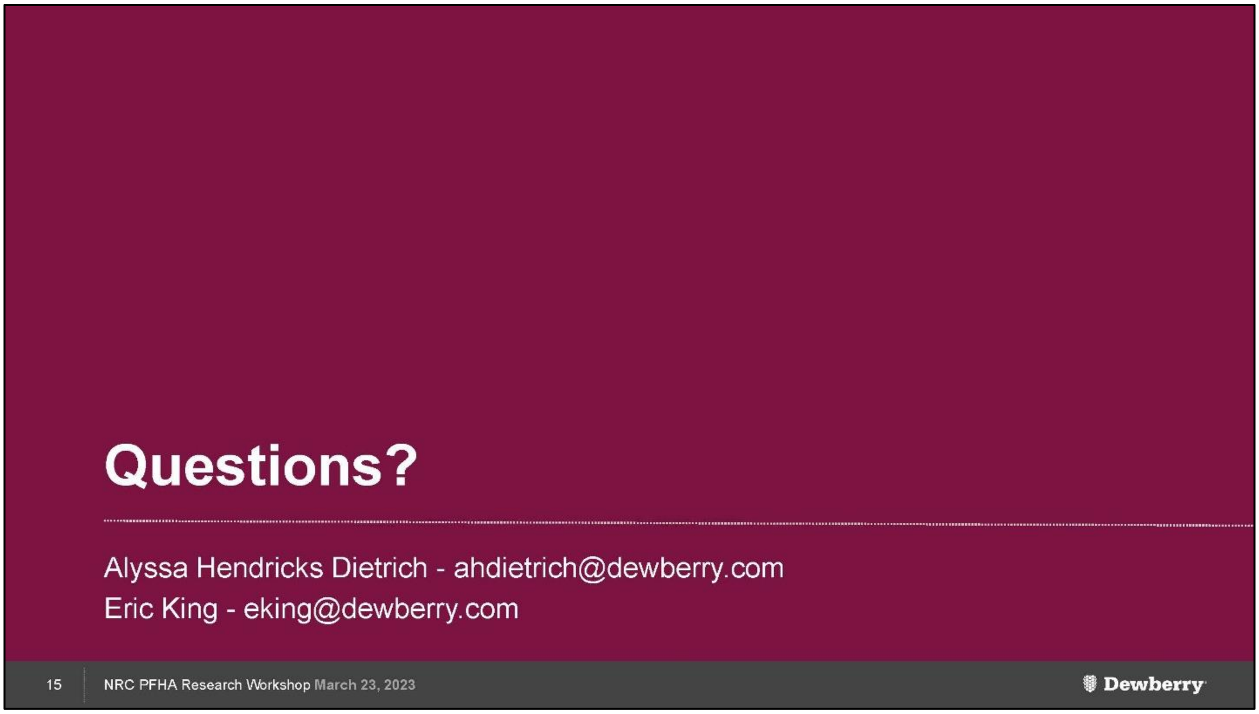
For a processed watershed and transposition domain, statistics on each event in the POR are stored in a NoSQL database for quick retrieval and supported by a front-end for visualization.

There are two primary options for selecting "storms" for use in SST modeling

- Option 1: Top N events per year
- Option 2: All events greater than X average accumulation

Applications

- Storm Search and Analysis
  - Easily and objectively determine large events in study area
- Inputs to Hydrologic Models
  - Realistic spatial and temporal precipitation vs point time series
- Probabilistic Hazard and Risk Analyses
- Next step – Storm Typing
  - Use observations and reanalysis data combined with algorithms to determine the storm type for each event



3.5.1.3 Questions and Answers

Question:

Do you plan to include topography somewhere in that pipeline, either in the initial transposition mask or maybe in that storm typing part that you mentioned? Because at least for some storm types in certain regions you may get orographic effects enhancements, which could be important.

Answer:

Alyssa Dietrich: What I think you're referring to is called enhanced transposition often, where you normalize precipitation based on some underlying topography or frequency information. That can be done in both the transposition itself or beforehand like this. We're still kind of in the pilot study portion, but yes, that's a good point to include.

3.5.2 Poster 3A-2: A Bayesian Network and Monte Carlo Simulation PRA Approach for External Flood Probabilistic Risk Assessments at Nuclear Power Plants

Authors: Joy Shen, Michelle Bensi, Mohammad Modarres; University of Maryland, College Park

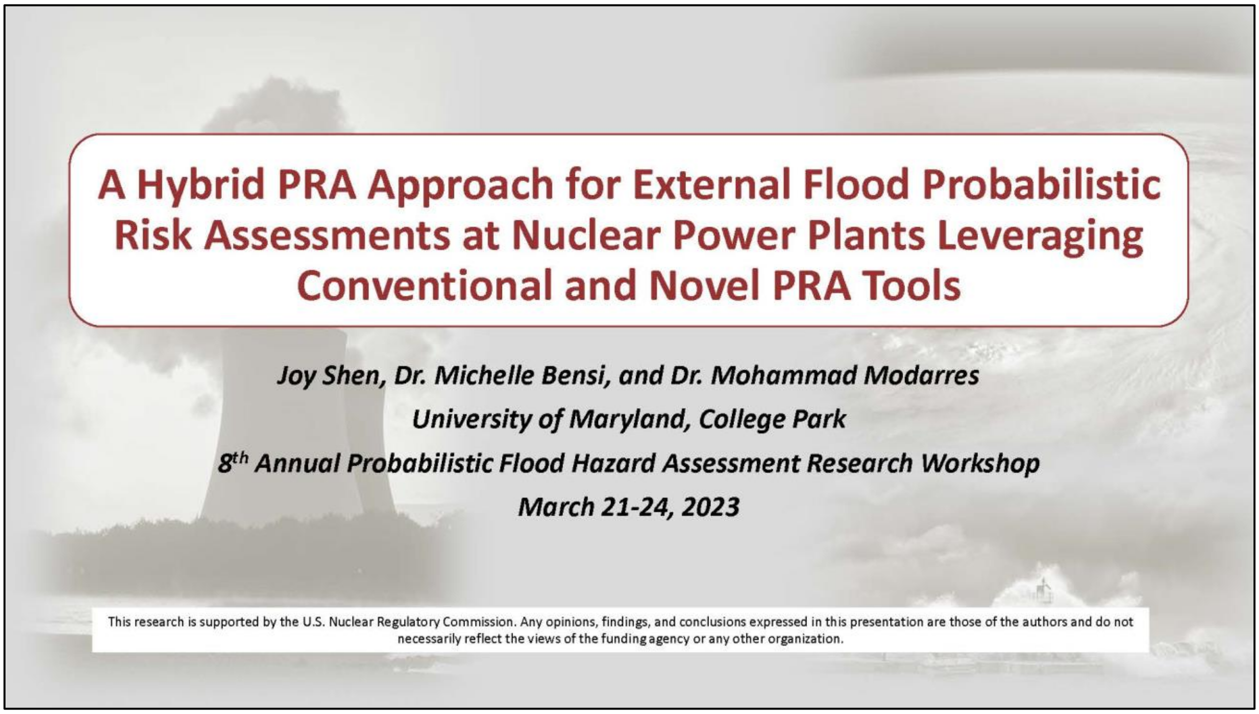
Speaker: Joy Shen

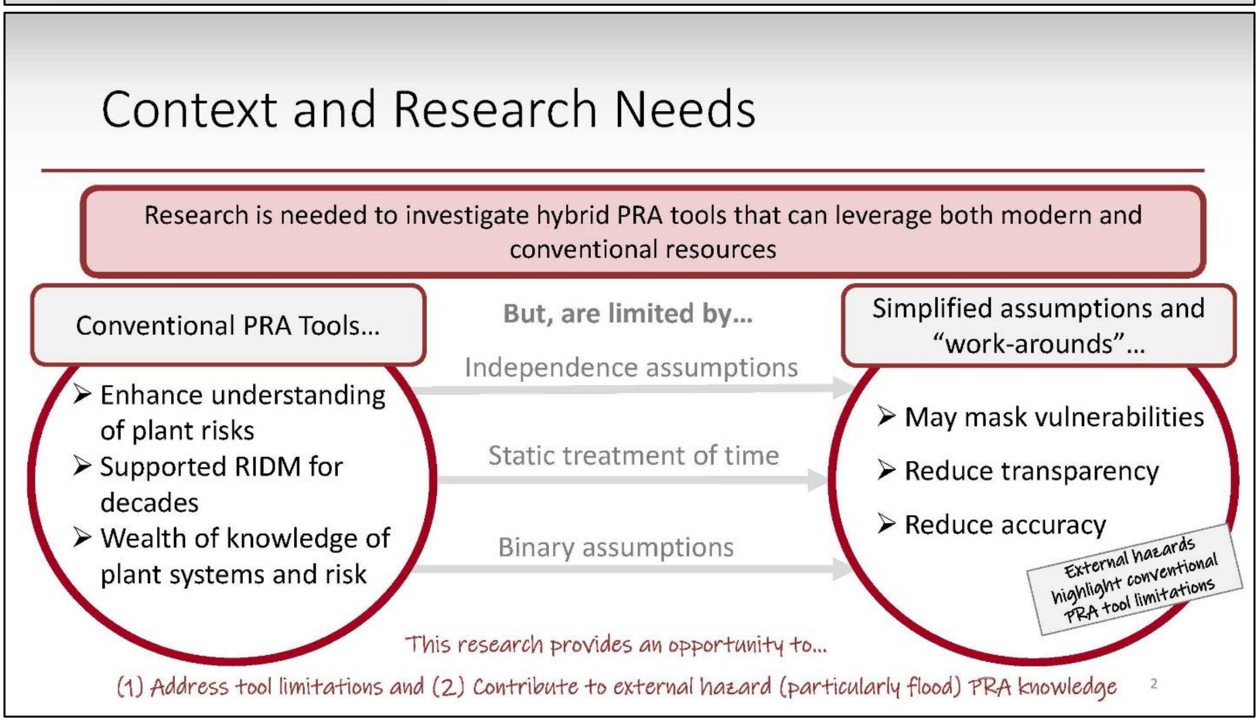
3.5.2.1 Abstract

This poster presents a hybrid probabilistic risk assessment (PRA) methodology, augmented by a Bayesian network and Monte Carlo simulation to assess external flood risks at nuclear power plants (NPPs). The nuclear industry has employed event trees (ETs) and fault trees (FTs) in the PRA framework to assess potential accidents and the resulting consequences. This methodology has provided a wealth of knowledge and experience over the decades, particularly

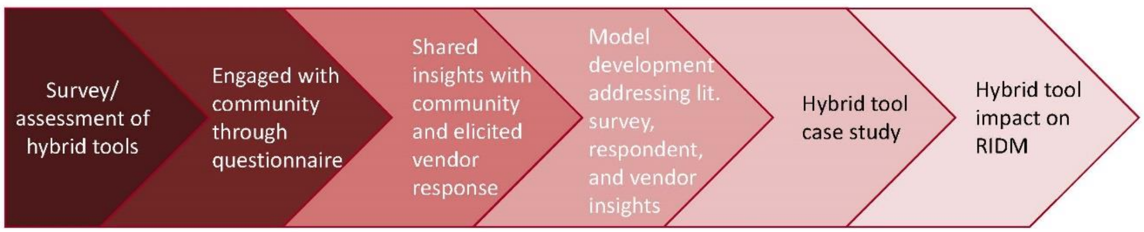
for static level 1 internal event PRAs. However, conventional PRA tools are limited by the binary component state assumption, system, structure, and component (SSC) independence assumption, and the static treatment of time. These limitations may mask significant vulnerabilities and reduce model accuracy. These limitations are particularly relevant to external flood PRAs, external floods are a spatially and temporally dependent hazard with varying impact on the NPP. Research is needed to investigate hybrid PRA methodologies to develop a framework that utilizes both conventional and novel PRA tools to overcome limitations. This research provides an opportunity to address limitations, as well as contribute to external flood PRA knowledge. This poster proposes to augment the conventional PRA framework with a Bayesian network and Monte Carlo simulation to model the significant external flood considerations. These novel tools address the conventional limitations by modeling partial damage states by incorporating multiple component states, SSC dependencies, and temporal dependencies. Two hybrid approaches are considered in linking the conventional and novel PRA tools. The first approach adapts a hybrid causal logic model to link the Bayesian network to the FT, and the other is a function-focused model to link the Bayesian network to the ET.

3.5.2.2 Presentation (ADAMS Accession No. ML23177A175)





Research Activities

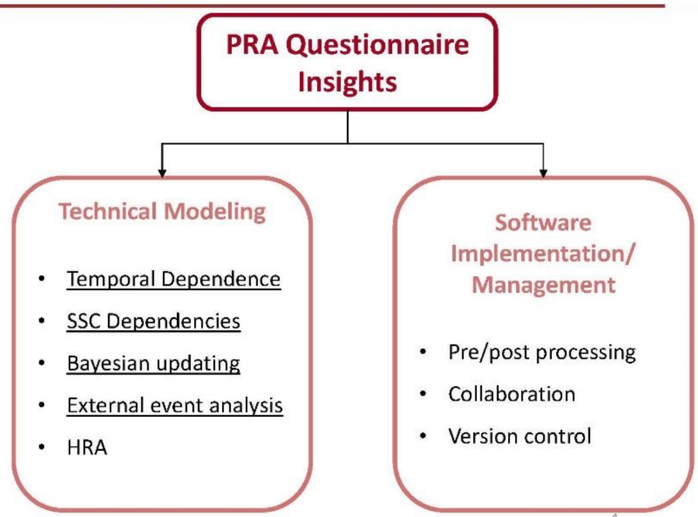


3

Questionnaire

- Sent to the PRA community
  - Over 50 anonymous responses
- Supplemental engagement with vendors
- Gathered insights on:
  - Advantages/limitations
  - Trending needs
- Identified inconsistencies in advantages and limitations perceived by respondents

Scan here to share your insights



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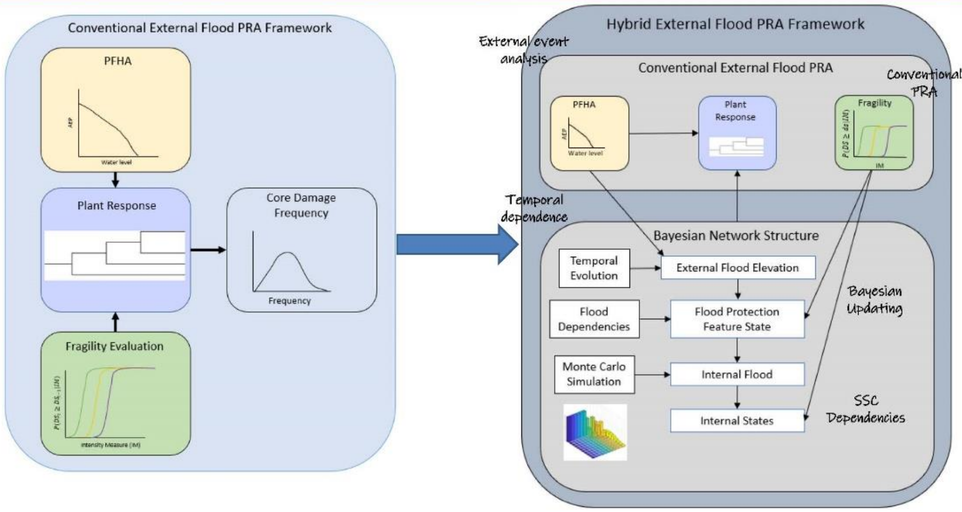
Proposed Hybrid Framework



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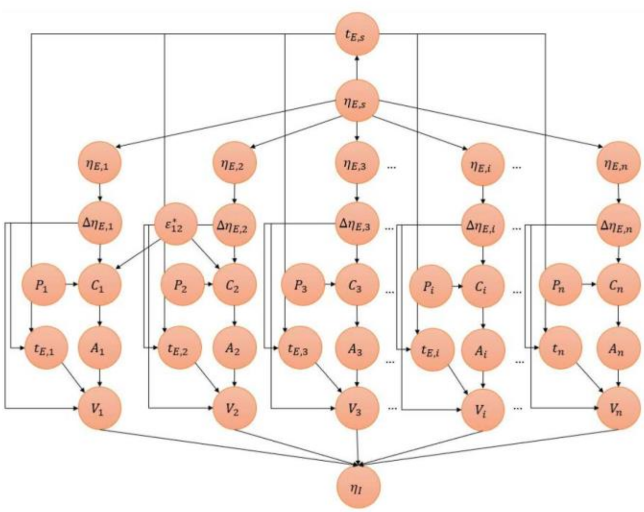
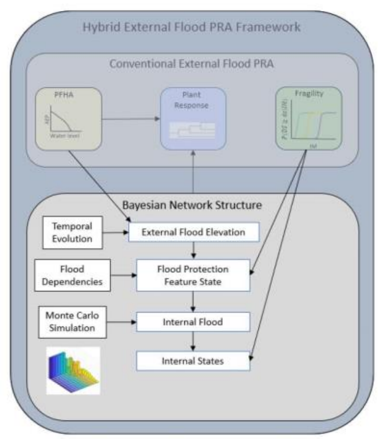
External Flood Bayesian Network Structure





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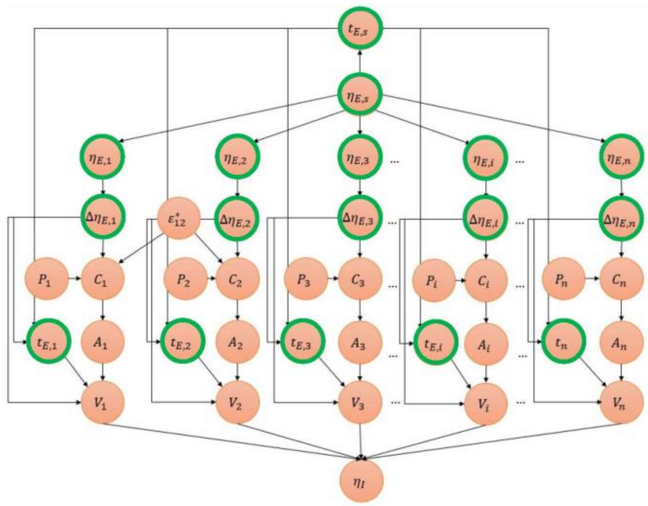
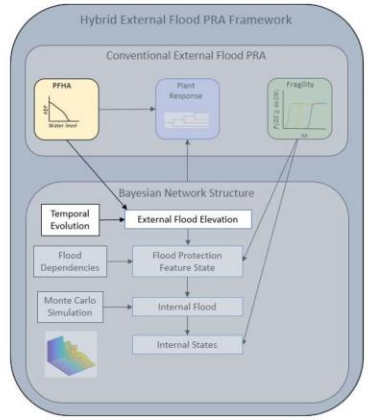
External Flood Bayesian Network Structure



External Flood Variables



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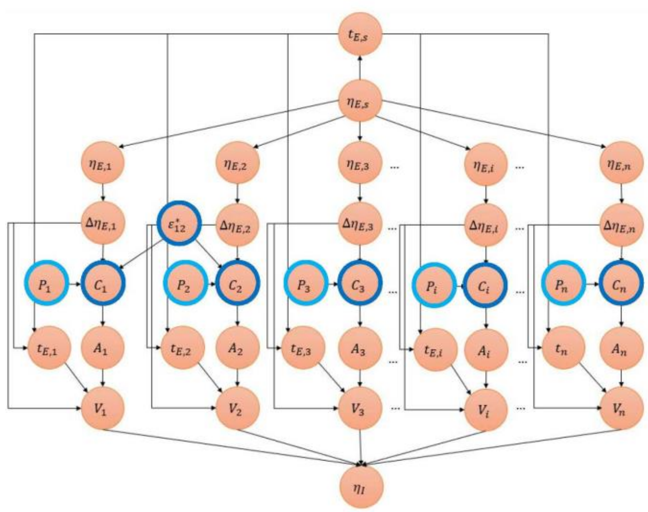
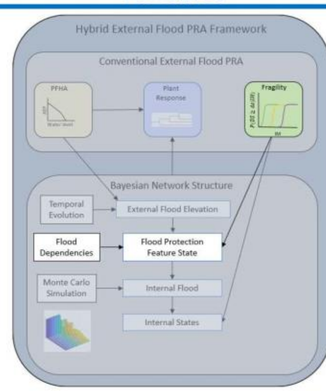
External Flood Bayesian Network Structure



Pre-Existing Flood Protection Feature Variable States

Flood Protection Feature Fragility Variables



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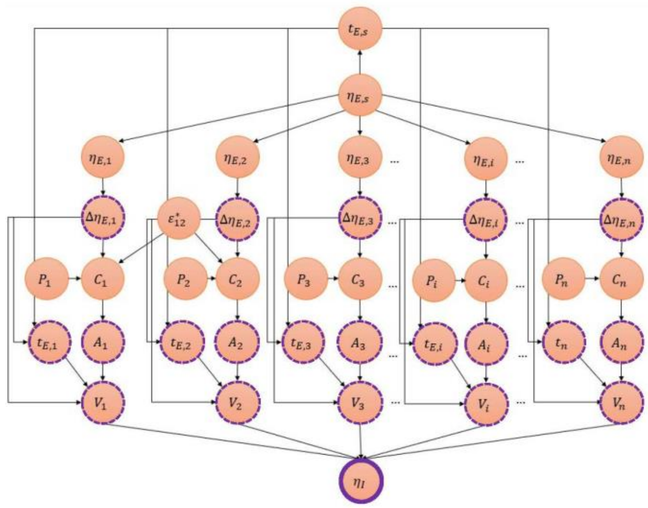
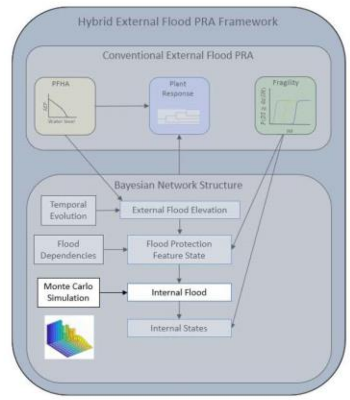
External Flood Bayesian Network Structure



Internal Flood Variable

Monte Carlo Simulation



Hybrid Framework Approaches

Hybrid Causal Logic Modeling Framework

Function-focused Framework

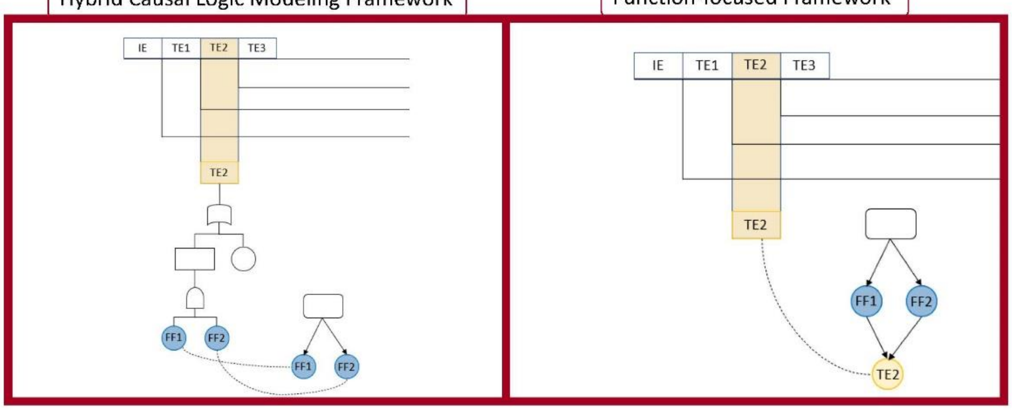


Figure adapted from Groth, et al. (2008) "Hybrid Methodology and Software Platform for PRA" RAMS8

3.5.2.3 Questions and Answers

Question:

Was it a national or multinational poll?

Answer:

It was international. We sent it out to people who were attending PSAM[16], ANS[17], and other conferences. I've been presenting to an international audience and inviting them to share their thoughts. We're hoping to get as much of an international and widespread lay-of-the-land, if you will, of the insights that they have.

Question:

When you do this work, what event trees would you be feeding this into? For example, slow moving floods often give the operators of the plant a chance to trip the plant, basically go to a shutdown condition well in advance. So it's not a surprise (sometimes there are surprise flooding events like the St. Lucie event from a few years ago). But the Fort Calhoun event was a very slow-moving event. So how do you figure out, once you do all this work with the Bayesian network and the SSCs and the fragilities of the external flood, how do you identify which event trees to feed it into whether it be a reactor trip, or loss of offsite power event trees? How do you decide that?

Answer:

As of right now, we are in the development phase, but if I'm understanding your question correctly, this does go into HRA space of operator reaction time or warning time. I think it would

[16] Probabilistic Safety Assessment and Management
[17] American Nuclear Society

be a really good opportunity to connect HRA capabilities and incorporate response time into that.

3.5.3 Poster 3A-3: Probabilistic Compound Flood Hazard Assessment Using Two-Sided Conditional Sampling

Authors: Somayeh Mohammadi[1], Ahmed Nasr[2], Muthukumar Narayanaswamy[1], Celso Ferreira[1], Arslaan Khalid[1]; [1]Michael Baker International Inc, [2]University of Central Florida

Speaker: Somayeh Mohammadi

3.5.3.1 Abstract

Compound floods are flood events caused by more than one coincident or nearly coincident flood mechanisms and usually have severe impacts on people, and the natural and built environment. Coastal areas are usually exposed to compound floods due to storm surge, precipitation, and tides. A holistic assessment of flood hazard in coastal areas requires consideration of compounding impacts of these drivers.

This study is focused on probabilistic assessment of compound flood hazard, in a coastal area located in LA, due to surge and precipitation. This study is conducted using NOAA gage data and Analysis of Record for Calibration (AORC) precipitation data. Two-sided conditional sampling is used to generate paired data samples related to both variables. In this method two types of data samples are generated. Each sample is generated by considering the extremal value related to one variable and the maximum value of the second variable within a time window. In the next step after fitting the marginal distributions to the data, a best-fit copula function is used to capture the dependence between variables and generate compound flood return periods. Furthermore, this study has compared the impact of only analyzing the tropical events as opposed to analyzing the entire dataset. Based on the results of this study a stronger correlation is observed between data for hurricane events.

3.5.3.2 Presentation (ADAMS Accession No. ML23177A176)

Compound Flood Hazard Analysis Using Two-Sided Conditional Sampling

Somayeh Mohammadi, Technical Specialist - Water at Michael Baker International

Ahmed Nasr, Graduate Research Assistant, University of Central Florida

Muthukumar Narayanaswamy, Operations Manager – Innovation at Michael Baker International

Celso Ferreira, Technical Consultant - Water at Michael Baker International

Arslaan Khalid, Engineer - Water at Michael Baker International

8th Annual Probabilistic Flood Hazard Assessment (PFHA) Research Workshop

March 21-24, 2023

U.S. Nuclear Regulatory Commission's Office of Nuclear Regulatory Research

Michael Baker INTERNATIONAL | *We Make a Difference*

Introduction

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- Coastal areas are frequently exposed to simultaneous occurrence of multiple flood mechanisms
- Compound flood hazard analysis provides a more realistic assessment of flood hazard
- Challenges
  - Preparation of long record of simultaneous data for multiple variables
  - Capturing the dependence between multiple flood mechanisms

We Make a Difference 2

Steps for the analysis

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1. Preparation of long records of simultaneous data and preprocessing the data
2. Extreme value analysis to select extremal values for each variable
3. Stratifying tropical and non-tropical POT values
4. Decluster the events
5. Generate conditional data samples
6. Fit marginal GPD distribution to POT values
7. Fit marginal distribution to non-extremal values
8. Capture the dependence between data pairs (best fit Copula)
9. Generation of isolines related to compound flood return periods
10. Locate historical storms on the compound flood isolines and assign associated bi-variate return period to each storm

Case Study Location and Input data

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- Location: Grand Isle, LA
- Non-tidal residual (NTR) data:
  - NOAA tide gage 8761724 [1980-2021]
  - Extracted daily max NTR
- Precipitation data:
  - AORC data [1980-2021]
  - Daily and hourly data
  - 4km resolution

Case study location and NOAA Tide Gages along with the length of observational records for each gage

Two-Sided Conditional Sampling

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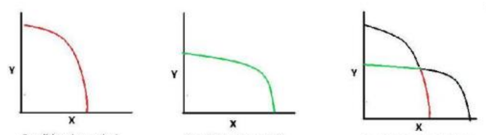
- Applied in similar studies related to compound flood hazard assessment

  (Bender et al., 2016; Jane et al., 2022; Kim et al., 2022)
- Two types of conditional samples generated
  - Each sample generated by considering the extremal values for one variable and maximum values related to the other variable within a time lag
- Fit the marginal distribution to the data
- Capture the dependence between data, generate isolines
- Combine two isolines by considering the outer envelope of two isolines



Conditional sample 1 isoline — Conditional sample 2 isoline — Combining two isolines

Preparation of Simultaneous Data and Extreme Value Analysis

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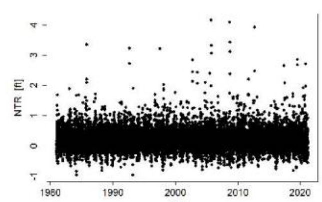
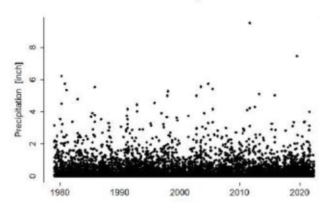
- **Data preparation:** Extract max daily non-tidal residual (NTR), and daily precipitation
- **Extreme value analysis:** Peak Over Threshold (POT)
  - A threshold of 0.94 inches for precipitation and 0.85 ft for NTR is selected
- **Stratify tropical and non-tropical POT events:**
  - A radius of 500 km from the study location
  - Classify an event as tropical if a storm passing inside this radius within a time lag of three days from the event time
- **Decluster POT values:**
  - To generate POT values related to independent events
  - Declustering time of 10 days for precipitation data and 6 days for NTR data



Historical max daily NTR data



Historical daily AORC precipitation

Generation of Conditional Samples

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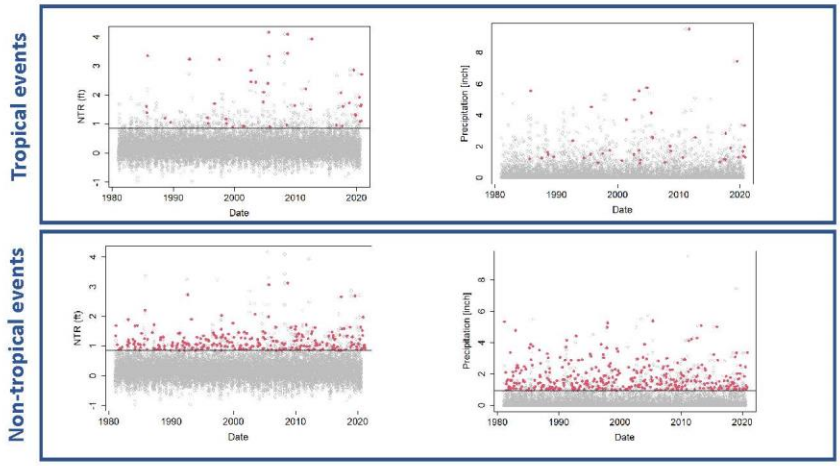
Declustered POT values related to NTR and precipitation (red circles)



	Tropical		Non-tropical	
	Conditioned on NTR	Conditioned on precipitation	Conditioned on NTR	Conditioned on precipitation
Sample size	45	44	253	342

Conditional Sample sizes

We Make a Difference

Fitting Marginal Distributions to Data

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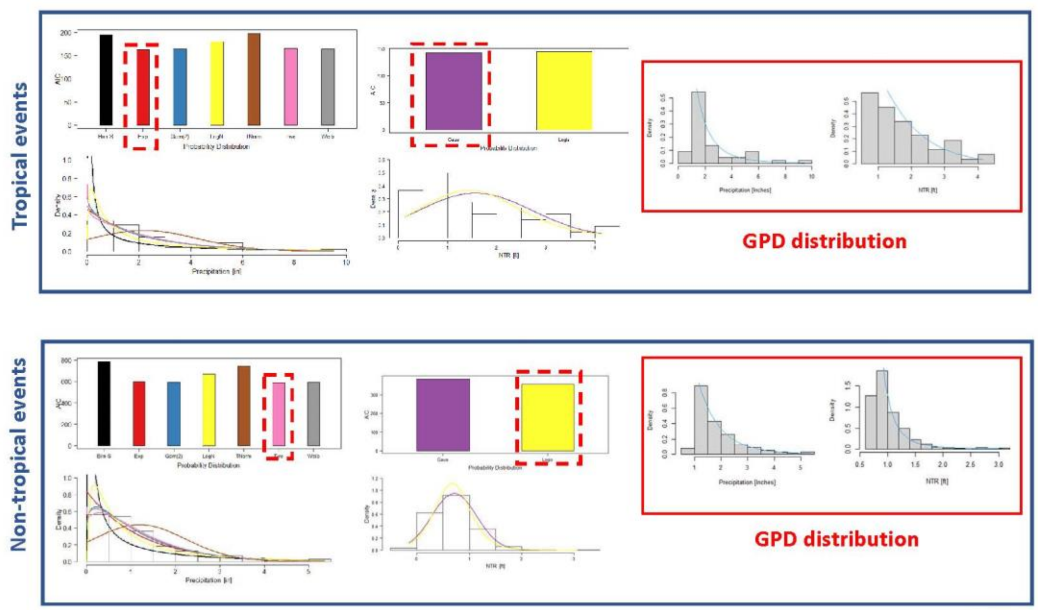

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Best Fit Copula for Conditional Samples of Paired Data

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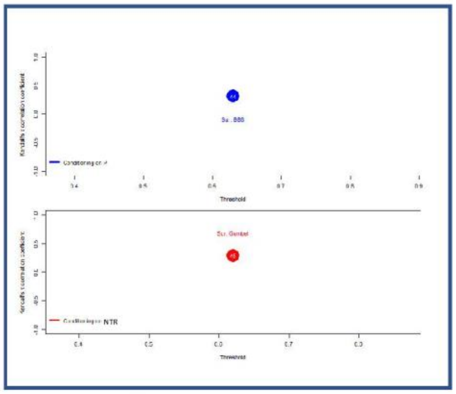
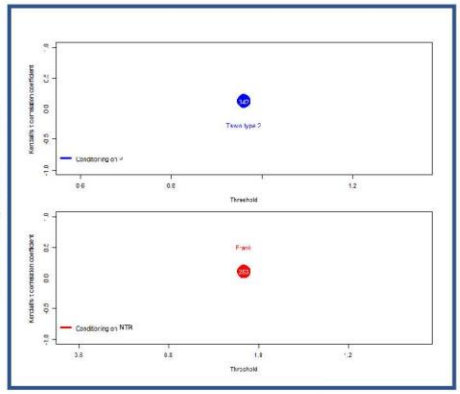
Tropical events



Non-tropical events



	Sample1: conditioned on NTR	Sample 2: conditioned on precipitation
Tropical events	0.29	0.31
Non-tropical events	0.12	0.1

Kendall coefficients for conditional samples of tropical and non-tropical events

Compound Flood Return Periods

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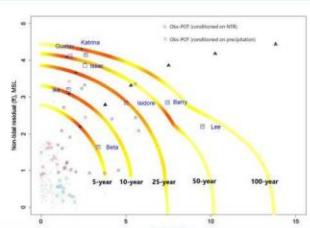
Tropical events



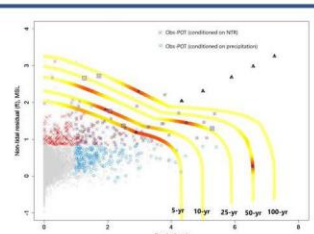
Storm	Bivariate Return period	Start date	End date	Daily precipitation (in)	NTR (ft)
Beta	5-year	9/17/2020	9/25/2020	3.36	1.65
Ike	10-year	9/10/2008	9/16/2008	1.62	3.42
Isidore	25-year	9/14/2002	9/27/2002	5.01	2.84
Issac	50-year	8/27/2012	9/3/2012	2.58	3.86
Gustav	50-year	8/29/2008	9/6/2008	1.7	4.11
Katrina	100-year	8/26/2005	9/1/2005	2.62	4.15
Barry	75-year	7/10/2019	7/16/2019	7.44	2.85

Historical events along with assigned bivariate return periods

Diamonds: the most likely design events

Triangles: Values under the assumption of full dependence

Non-tropical events



Bivariate rerun period	Date	Daily precipitation (in)	NTR (ft)
100-year	1982-08-25	1.76	2.72
50-year	2017-05-04	1.25	2.66
25-year	1998-01-07	5.27	1.29
10-year	1999-12-21	2.06	1.76
5-year	1998-04-29	1.8	1.37

Historical events along with assigned bivariate return periods

Next Steps

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- Incorporating the climate change effects to compound flood hazard analysis
- Incorporating other variables to the analysis, including wave and tidal effects
- Conducting the analysis using other approaches to capture the dependence between variables and making a comparison on robustness of different approaches

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Thank you!

Questions??

Somayeh.Mohammadi@mbakerintl.com

3.5.3.3 Questions and Answers

There were no questions for this presentation.

3.5.4 Poster 3A-4: Estimation of Probabilistic Flood Hazard Curve at the NPP Site Considering Storm Surge

Authors: Beom-Jin Kim, Minkyu, Kim; Korea Atomic Energy Research Institute (KAERI)

Speaker: Beom-Jin Kim

3.5.4.1 Abstract

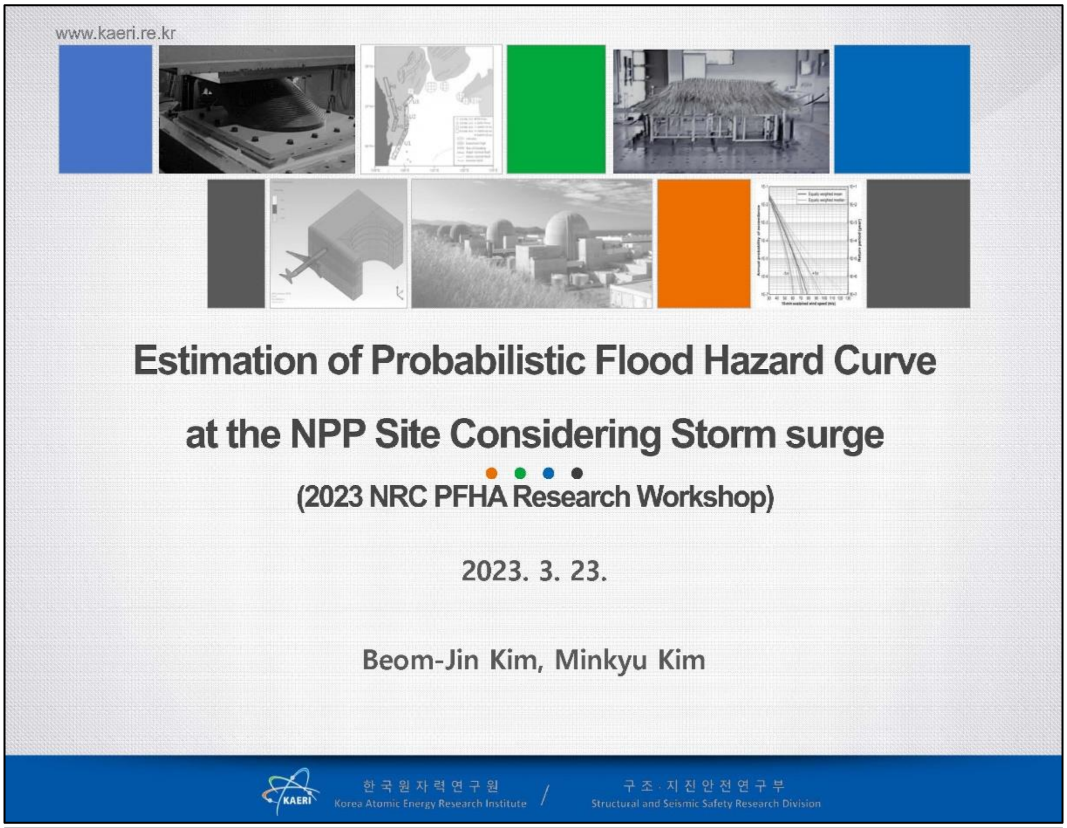
The intensity of typhoons hitting Korea is recently increasing due to climate change. Eight typhoons occurred from August to September 2020. Among the eight typhoons, Typhoons Bavi, Maysak, and Haishen, category two or higher, hit Korea, and flood damage occurred due to heavy rain. In particular, nuclear power plants in Korea are installed and operated nearby the coast. Therefore, it is necessary to identify the risk of external hazards that may occur due to typhoons in nuclear power plants. Also, it is necessary to assess the safety of nuclear power plants through risk analysis of external hazards.

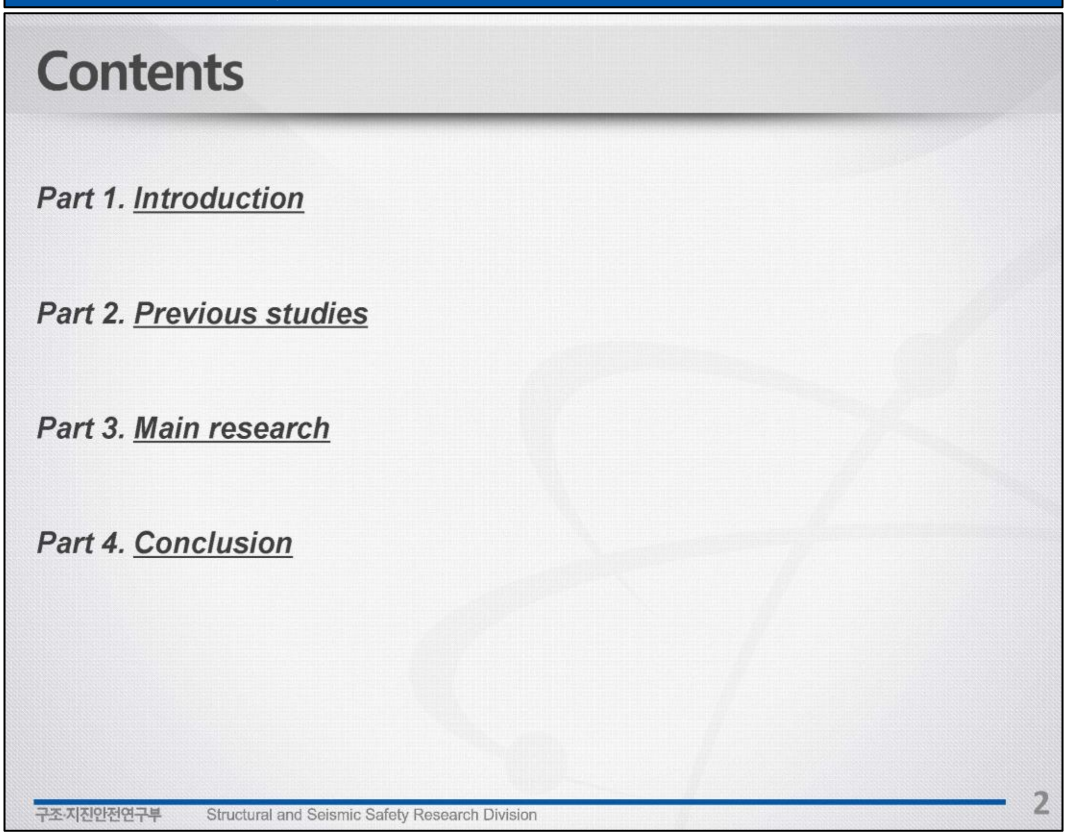
To this end, in previous studies, a probabilistic wave height hazard curve by storm surge was estimated at the coast near a nuclear power plant. After that, the overtopping discharge was calculated using the EurOtop model. And based on the results, a two-dimensional flood analysis was conducted at the nuclear power plant site. This study applied a probabilistic method to the flood depth estimated through a two-dimensional flood analysis according to the return period. First, flood probability distribution was estimated through AIC verification. Second, the estimated probability distribution was applied to the flood depth according to the return period. Finally, Monte Carlo simulations were applied to estimate 5%, mean, median, and 95% flood depths by return period. Based on the analyzed flood depth, a probabilistic flood hazard curve due to storm surge was estimated and presented.

The results of this study are expected to be the basis for the waterproofing design of nuclear power plant sites and the planning of various flood prevention measures caused by combined hazards such as local intensive precipitation (LIP) and storm surges.

Acknowledgment: This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government (RS-2022-00144493)

3.5.4.2 Presentation (ADAMS Accession No. ML23177A177)





Part 1. Introduction

- The intensity of typhoons hitting Korea is recently increasing due to climate change. Eight typhoons occurred from August to September 2020. Among the eight typhoons, Typhoons Bavi, Maysak, and Haishen, category two or higher, hit Korea, and flood damage occurred due to heavy rain. In particular, nuclear power plants in Korea are installed and operated nearby the coast. Therefore, it is necessary to identify the risk of external hazards that may occur due to typhoons in nuclear power plants. Also, it is necessary to assess the safety of nuclear power plants through risk analysis of external hazards.

- To this end, in previous studies, a probabilistic wave height hazard curve by storm surge was estimated at the coast near a nuclear power plant. After that, the overtopping discharge was calculated using the EurOtop model. And based on the results, a two-dimensional flood analysis was conducted at the nuclear power plant site. This study applied a probabilistic method to the flood depth estimated through a two-dimensional flood analysis according to the return period. First, flood probability distribution was estimated through AIC verification. Second, the estimated probability distribution was applied to the flood depth according to the return period. Finally, Monte Carlo simulations were applied to estimate 5%, mean, median, and 95% flood depths by return period. Based on the analyzed flood depth, a probabilistic flood hazard curve due to storm surge was estimated and presented.

- The results of this study are expected to be the basis for the waterproofing design of nuclear power plant sites and the planning of various flood prevention measures caused by combined hazards such as local intensive precipitation (LIP) and storm surges.

Part 2. Previous studies

➢ *Estimated for SWAN(Simulation Waves Nearshore) model parameters*

- In this study, EPRI report 3002008111 (Probabilistic Storm Surge Hazard Assessment, PSHA) was referred to estimate the parameters of the SWAN model.
- Korean deep-water design wave points were used to estimate the parameters of the SWAN model.
- Finally, the results of estimating wave height, period, sea wind and sea level height according to the return period are as follows.

<Table 1> Results of major parameter estimation

Return period (y)	Estimation Hs (m)	Estimation Tp (s)	Estimation Wind (m/ss)	Estimation Sea level (m)
200	12.2328	14.5	25.09	1.1705
500	13.6766	15.2	26.37	1.2220
1000	14.7219	15.6	27.27	1.3010
2000	15.7327	16.1	28.12	
5000	17.0229	16.7	29.19	
10000	17.9684	17.0	29.95	1.6560
20000	18.8904	17.4	30.69	
50000	20.0769	17.9	31.63	
100000	20.9523	18.2	32.31	1.9365
200000	21.8102	18.5	32.97	
500000	22.9199	18.9	33.81	
1000000	23.7422	19.2	34.43	2.0680

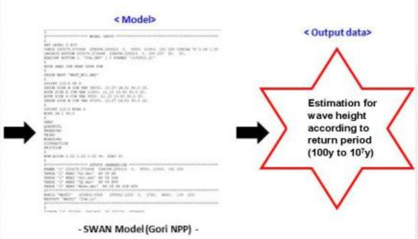
Part 2. Previous studies

- *SWAN simulation*

- The nesting function of SWAN is used to analyze the wave height of the Gori nuclear power plant.
- A 50 × 50 m grid was constructed in the distant ocean of the nuclear power plant, and a 20 × 20 m grid was constructed in the ocean near the nuclear power plant.
- According to the return period, wave height analysis was analyzed through SWAN using estimated data of wave height, period, and wind, as shown in the figure 1.

< Input data >

No.	112-3				
Direction	S	Hs (m)	Tp (sec)	Wind (m/s)	Sea level (m)
RETURN	EXCEEDANCE	Weibull	Robust	Weibull	KAERI Rport
10	0.1	6.7	11.2	19.81	
20	0.05	8.2	12.2	21.26	
30	0.03	8.9	12.6	22.02	
50	0.02	9.9	13.2	22.92	
100	0.01	11.1	13.9	24.05	1.0465
200	0.005	12.2	14.5	25.09	1.1705
500	0.002	13.7	15.2	26.37	1.2220
1000	0.001	14.7	15.6	27.27	1.3010
2000	0.0005	15.7	16.1	28.12	
5000	0.0002	17.0	16.7	29.19	
10000	0.0001	18.0	17.0	29.95	1.6560
20000	0.00005	18.9	17.4	30.69	
50000	0.00002	20.1	17.9	31.63	
100000	0.00001	21.0	18.2	32.31	1.9365
200000	0.000005	21.8	18.5	32.97	
500000	0.000002	22.9	18.9	33.81	
1000000	0.000001	23.7	19.2	34.43	2.0680
2000000	0.0000005	24.6	19.5	35.03	
5000000	0.0000002	25.6	19.8	35.80	
1E+07	0.0000001	26.4	20.1	36.36	



<Fig. 1> Wave height analysis method

Part 2. Previous studies

- *Wave overtopping estimated*

- The probabilistic wave height hazard value was applied to the EurOtop model.
- The main parameters of the EurOtop model are wave height, period, wave angle, and structures such as coastal barriers.

9호 태풍 마이삭...삼척 임원항 6m 방파제 넘은 파도(MBC뉴스 2020년9월3일)

Part 2. Previous studies

➢ *2D flood analysis*

- In this study, the FLO2D model approved by FEMA was applied. The grid of the nuclear power plant site model was constructed in 3 m * 3 m. After that, the wave overtopping estimated by the EurOtop model was selected as an external boundary condition.
- Finally, a flooding analysis of the nuclear power plant site by overturning waves according to the return period by storm surge conditions was performed.

<Fig. 2> 2D external boundary condition and Simulation result

Part 3. Main research

➢ *Probabilistic flood hazard assessment*

- Probabilistic flood Hazard Assessment (PFHA) by Storm surge is a preliminary step for probabilistic flood risk assessment due to storm surge at the nuclear power plant site.
- The maximum flood depth, minimum flood depth, mean, and standard deviation was estimated for each power plant's return period, and the probability distribution was verified through AIC verification by return period.

<Table 2> Apply to probabilistic distribution (NPP 1) Unit (m)

Return period	100y	500y	1,000y	10,000y	100,000y	1,000,000y
Max flood	0.320	0.376	0.383	0.417	0.461	0.459
Min flood	0.000	0.048	0.050	0.062	0.093	0.101
Mean flood	0.162	0.217	0.224	0.263	0.307	0.314
Std.	0.091	0.099	0.102	0.109	0.112	0.109
AIC Distribution	Triang	Triang	Triang	Triang	Triang	Triang

<Table 3> Apply to probabilistic distribution (NPP 2) Unit (m)

Return period	100y	500y	1,000y	10,000y	100,000y	1,000,000y
Max flood	0.268	0.292	0.299	0.325	0.345	0.349
Min flood	0.050	0.059	0.062	0.085	0.122	0.129
Mean flood	0.206	0.233	0.238	0.265	0.289	0.293
Std.	0.062	0.063	0.064	0.065	0.064	0.064
AIC Distribution	Triang	Triang	Triang	Triang	Triang	Triang

Part 3. Main research

➢ *Probabilistic flood hazard assessment*

- The @RISK program was used to estimate the probabilistic flood hazard curve caused by the storm surge.
- After applying the Latin hypercube sampling method to the flood depth according to the return period, statistical analysis was performed with a 95% confidence interval through 10,000 iterations.
- Based on the results, flood depth of 5%, Mean, and flood depth of 95% were estimated according to the return period of each power plant.

<Table 4> Probabilistic flood depth estimation result (NPP 1) Unit (m)

Return period	100y	500y	1,000y	10,000y	100,000y	1,000,000y
5% flood	0.010	0.084	0.086	0.093	0.100	0.103
Mean flood	0.135	0.251	0.255	0.278	0.307	0.306
95% flood	0.314	0.366	0.373	0.406	0.439	0.447

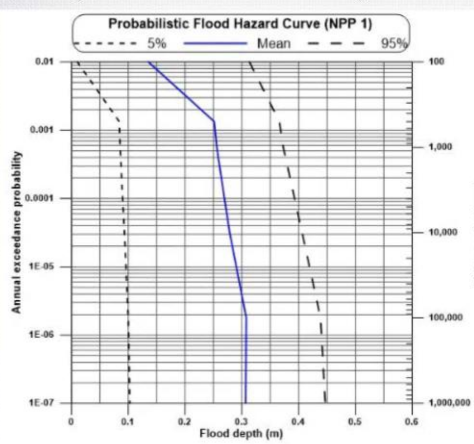
<Table 5> Probabilistic flood depth estimation result (NPP 2) Unit (m)

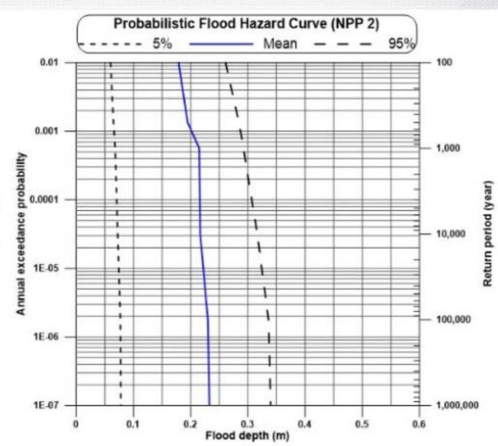
Return period	100y	500y	1,000y	10,000y	100,000y	1,000,000y
5% flood	0.060	0.065	0.068	0.073	0.077	0.078
Mean flood	0.179	0.195	0.215	0.217	0.230	0.233
95% flood	0.261	0.285	0.293	0.317	0.336	0.340

Part 3. Main research

➢ *Probabilistic flood hazard curves*

- Finally, the probabilistic flood hazard curves for power plants 1 and 2 by storm surge were estimated through statistical analysis using a probability distribution.





<Fig. 3>. Probabilistic flood hazard curves

Part 4. Conclusion

- This study analyzed the probabilistic flood depth caused by the storm surge according to climate change.
- Based on the results of the SWAN model, statistical analysis was applied to calculate the probability distribution for the possible wave heights in the ocean in front of the nuclear power plant.
- By applying the EurOtop model, the overtopping discharge was analyzed probabilistically according to the return period and presented. it is judged that valuable data will be utilized for the analysis of flooding caused by the overtopping of the nuclear power plant site.
- After then, the safety assessment for external hazards was performed by 2D flooding analysis of the nuclear power plant site caused by storm surges.
- Finally, statistical techniques were applied based on the 2D external flood analysis results. As a result, a probabilistic external flood assessment and a probabilistic flood hazard curve for the target nuclear power plant were presented.

Acknowledgements

This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government (RS-2022-00144493).

<u>Thank you for listening to my presentation</u>

If you have any questions at any time, please contact me by my email.

beomjin88@kaeri.re.kr

3.5.4.3 Questions and Answers

Question:

In the FLO-2D modeling, did you include the subsurface drainage system or is that just assumed not to be active in this sort of an event?

Answer:

We are not considering drainage system because we don't have drainage system data.

3.5.5 Poster 3A-5: Compound Flood Risk Assessment of the Coastal Watersheds of Long Island and Long Island Sound in Connecticut and New York

Authors: Liv Herdman, Robert Welk, Robin Glas, Salme Cook, Kristina Masterson; U.S. Geological Survey New York Water Science Center

Speaker: Liv Herdman

3.5.5.1 Abstract

Long Island Sound (LIS) has 600 miles of coastline in New York and Connecticut with over 23 million people living within 50 miles of its shores. Flooding associated with either combined or individual incidents of shallow water tables, heavy rainfall events, and elevated coastal water levels has been reported in multiple locations around LIS and for many communities is a frequently occurring hazard. In recent years, the occurrence of extreme events has amplified the need for an integrated assessment of the vulnerability of coastal communities and infrastructure to compound flood events. For this assessment we have designed a compound flooding vulnerability framework to show the susceptibility to shallow water tables, rainfall events, and elevated coastal water levels at an 800-meter scale. Each process is evaluated individually and jointly to understand the likelihood of compound or simultaneous flood events and conditions. Historical data is used to determine the temporal relationship between each of the drivers (rainfall, water table level, coastal water levels). Groups consisting of one precipitation station, groundwater level station, and coastal level station (triads) are identified to analyze the geographic variability in the occurrence of compound events. Within each time series a peak over threshold approach is used to identify flood events, and the correlation between the timeseries is explored with a lag of plus or minus three days to identify locations where flood types are likely to co-occur. Over the domain, coastal water levels and rainfall tend to have a statistically significant correlation. The slower response time and frequency of measurement (approximately monthly) at many groundwater observation wells makes identifying a correlation difficult. Here we present the results of the analysis of these triads over the study area, as well as a semi-quantitative framework that combines geospatial attributes of compound flood susceptibility.

3.5.5.2 Presentation (ADAMS Accession No. ML23177A178)

USGS
science for a changing world

Compound Flood Risk Assessment of the Coastal Watersheds of Long Island and Long Island Sound in Connecticut and New York

March 24, 2023

This information is preliminary and is subject to revision. It is being provided to meet the need for timely best science. The information is provided on the condition that neither the U.S. Geological Survey nor the U.S. Government shall be held liable for any damages resulting from the authorized or unauthorized use of the information. January 2023

U.S. Department of the Interior
U.S. Geological Survey

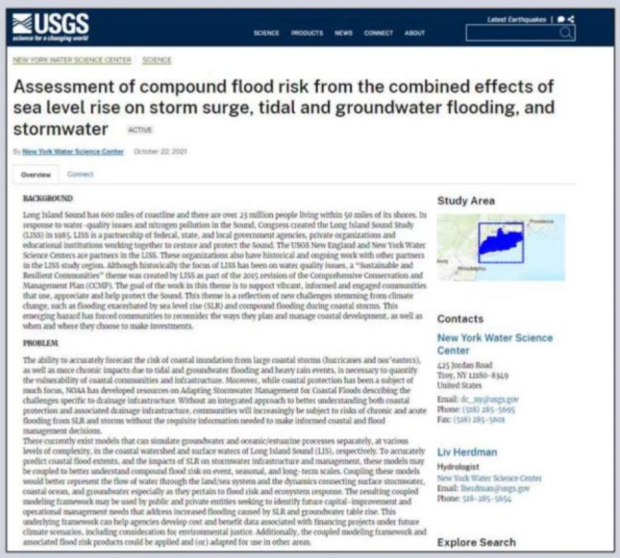
Long Island Sound Study

UNITED STATES ENVIRONMENTAL PROTECTION AGENCY

Agenda

- Project Overview
  - Background
  - Study Area
- Compound Flooding Analysis
- Summary and Discussion

https://www.usgs.gov/centers/new-york-water-science-center/science/assessment-compound-flood-risk-combined-effects-sea#overview



USGS

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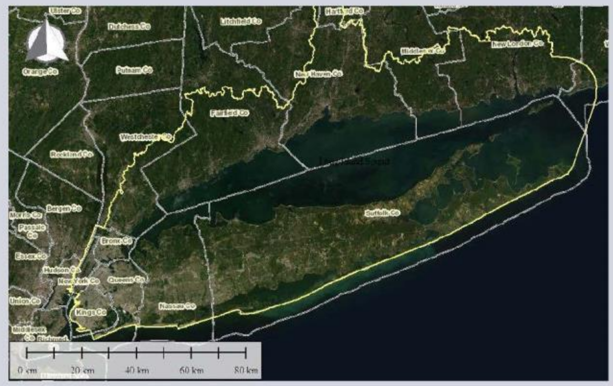
Project Background

- Funded by EPA's Long Island Sound Study (LISS), Sustainable and Resilient Communities Work Group
- Study area comprises Long Island Sound watershed (CT and NY), but has been expanded to include Bronx, Brooklyn, Queens, Manhattan, Nassau and Suffolk counties (FEMA Supplemental Funding)
- Study approach combines application of statistical spatial data analysis (Phase 1) and numerical groundwater, coastal and stormwater simulation models (Phase 2)



LISS Project Duration: October 2021 – September 2024

Hurricane Ida FEMA Supplemental Funding: March 2022 – September 2025

USGS

3

Compound Flood Risk - Risk associated with the co-occurrence of multiple flooding drivers

Coastal Storms

Groundwater Emergence

Rainfall

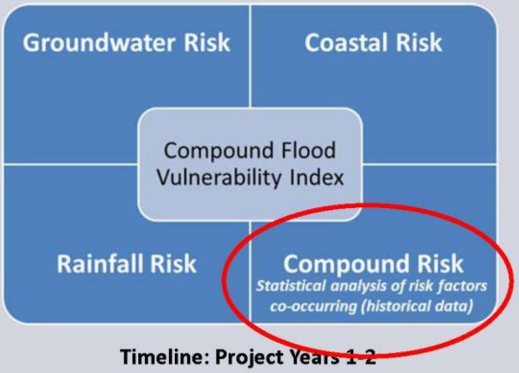
Coastal Nuisance Flooding

USGS

4

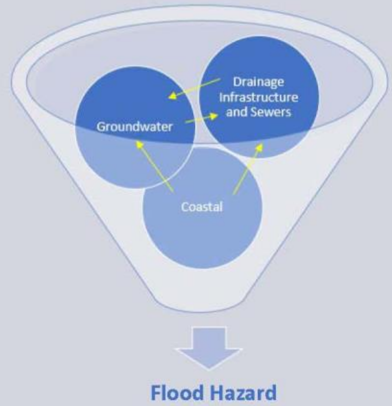
Project Phases

Phase 1: Statistical Spatial Data Analysis will cover entire project area



Timeline: Project Years 1-2

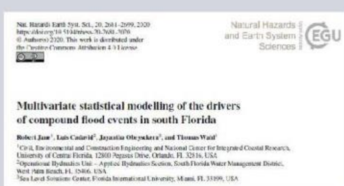
Phase 2: Process Based Modeling ("Inset Models") for selected focus locations



Timeline: Project Years 2-3

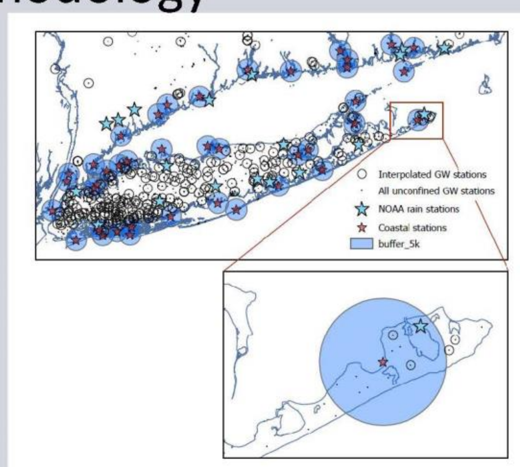
Statistical Analysis methodology

- Create complete time series
- Compute Rank correlations
- Evaluate changes to return period events.



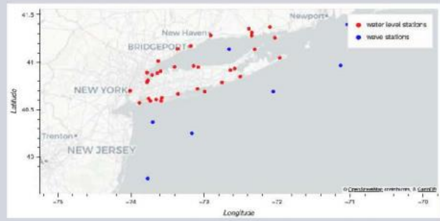
Natural Hazards and Earth System Sciences EGU

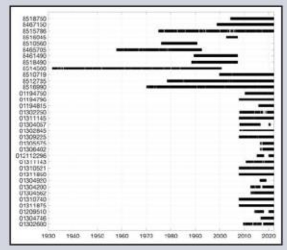
Multivariate statistical modelling of the drivers of compound flood events in south Florida



Preliminary Information Subject to Revision. Not for Citation or Distribution.

Statistical Analysis : Data Gathering





- Time-series data (1970 – 2022) compiled for
    - 20 precipitation gauges
    - 34 coastal stations
    - 287 groundwater monitoring locations
- Missing data estimated (imputed) based on nearby station measurements
- Objective: create complete time series of measurements for 1970-2022.

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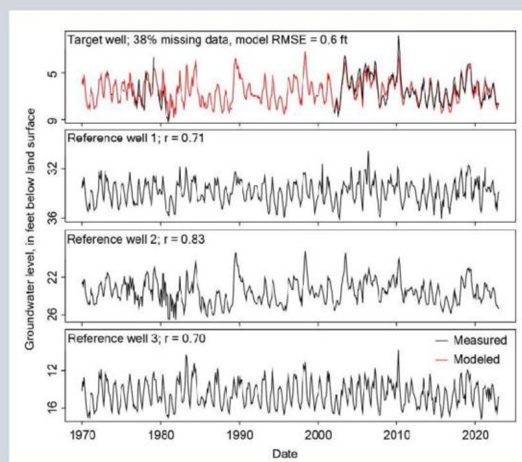
Preliminary Information Subject to Revision.
Not for Citation or Distribution.

Statistical Analysis: Data Gathering



- Time-series data (1970 – 2022) compiled for
    - 20 precipitation gauges
    - 34 coastal stations
    - 287 groundwater monitoring locations
- Missing data estimated (imputed) based on nearby station measurements
- Objective: create complete time series of measurements for 1970-2022.

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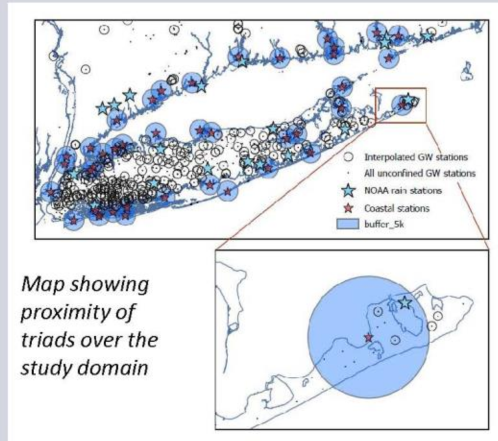
Spatial Analysis of Past Compound Events

- Triads – proximate groundwater, coastal and precipitation stations
- 27 triads identified to evaluate degree of correlation between time series



Map showing proximity of triads over the study domain

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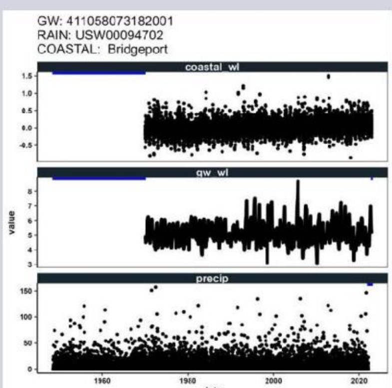
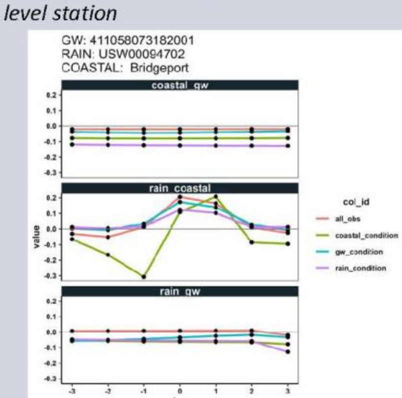
Time Series Correlations



Correlations between each of the three variables are computed with a lag of plus or minus 3 days

Example of time series from stations proximate to the Bridgeport coastal water level station



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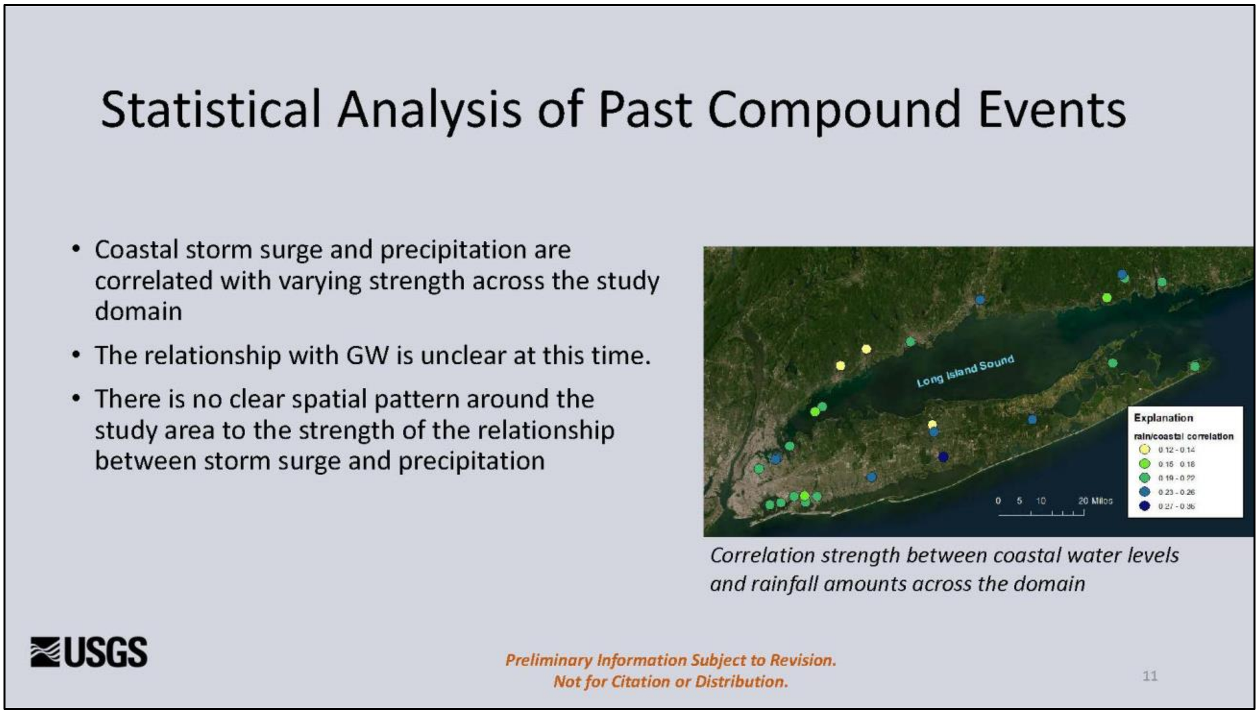


3.5.5.3 Questions and Answers

Question:

When your analyze the correlation between storm rainfall and surge, which metric do you use for the storm rainfall. Do you use storm rainfall intensity?

Answer:

Salme Cook: For looking for a rainfall event, it's 5 inches in 24 hours and we have the rainfall time series. We started looking at 2 inches in an hour because our stakeholders were interested in that as an event too, but this analysis is 5 inches in 24 hours.

Question:

So, it's total rainfall of the storm?

Answer:

Salme Cook: Yes, where that time series is located, where that station is. We have other analysis where we are looking at spatial analysis of rainfall across the entire domain and that's a different part of the study. This is just looking at that each triad, where that one observation location is.

Question:

What is the duration of the storm events like 24-hour or 48-hour?

Answer:

Salme Cook: All of these are on daily time steps. When we are using the coastal station, for example, we also do an non-tidal residual analysis, to get the peaks. 33 hours is our filter for water level time series at the coast and then it's a daily time step. So everything is on a daily time step here.

Question:

You referred to coastal stations. Are those strictly tide gages or are they a combination of tide gages and other gages?

Answer:

Salme Cook: They are primarily tide gages if you are talking about NOAA stations, but we use NOAA and USGS gages. Some of those USGS gages have also record atmospheric and water quality parameters as well, but we just look at the water level.

Question:

I also noticed in one of the plots, you had these blue dots that were way out there. Were those buoys?

Answer:

Yes. We have wave analysis and there are 5 buoys that we use (not in this part of the study, but we're using that same graphic). We're looking at coastal storm surge everywhere for the spatial analysis and we also have similar wave discharge risk as one of the other presenters. So that's part of the other three parts of this study and this is sort of the compound part. But yes, we have looked at waves and those are buoys.

3.5.6 Poster 3A-6: Steps Toward Extensions of Existing Probabilistic Coastal Hazard Analysis for Coastal Compound Flood Analysis Leveraging Bayesian Networks

Authors: Ziyue Liu[1], Michelle, Bensi[1], Meredith Carr[2], Norberto Nadal-Caraballo[2], Madison Yawn[2], Luke Aucoin[2]; [1]University of Maryland, College Park, [2]U.S. Army Corps of Engineers, Engineer R&D Center, Coastal & Hydraulics Laboratory

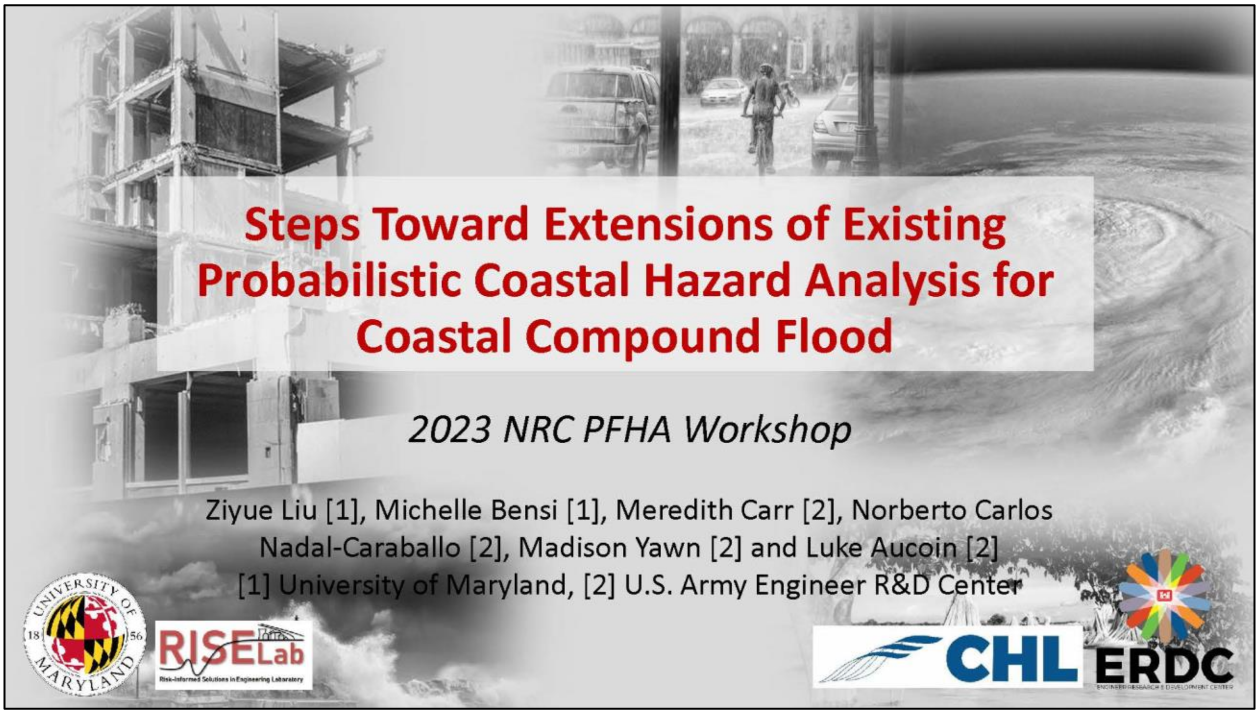
Speaker: Ziyue Liu

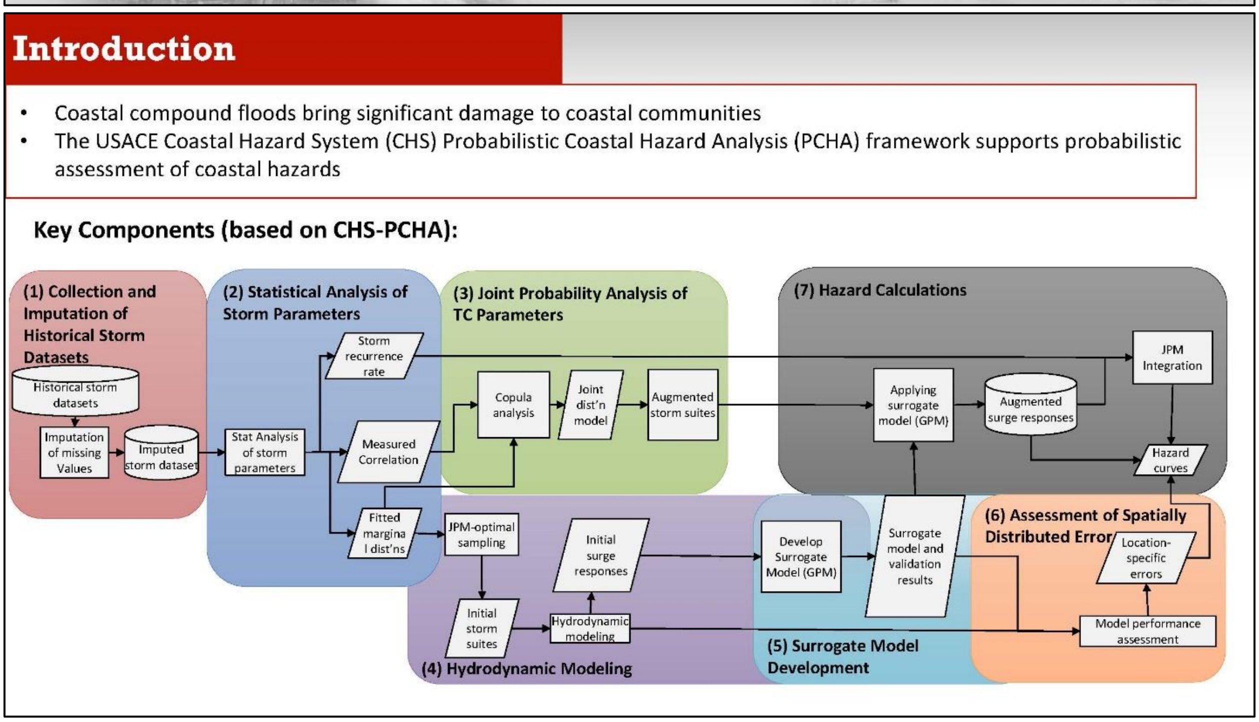
3.5.6.1 Abstract

In the past decades, coastal floods have caused significant losses to coastal communities. To develop an accurate and complete probabilistic framework for assessing coastal floods, the U.S. Army Corps of Engineers established the Probabilistic Coastal Hazard Analysis (PCHA) framework. To date, implementations of the PCHA framework have focused primarily on a subset of coastal hazards, particularly storm surges. This poster summarizes recent research activities seeking to build upon the PCHA framework by developing a multi-tier PCHA framework extension to consider compound hazards using Bayesian networks (BNs). In pursuit of that goal, we begin by assessing some of the assumptions and modeling approaches in the PCHA to better understand their use in the compound PCHA framework. We perform a comparative assessment of a series of different Joint Probability Method (JPM) assumptions for modeling dependence among tropical cyclone (TC) atmospheric parameters, which include parameter independence, partial dependence (i.e., only considering dependence between central pressure deficient and radius to maximum winds), and full dependence. Candidate full-dependence models include meta-Gaussian copula and vine copulas combining linear-circular copulas with Gaussian or Frank copulas. Emphasis is placed on modeling the circular behavior of storm heading and its dependencies with other linear parameters since the heading

parameter is hypothesized to be comparatively more important when modeling compound hazards. Next, a BN of storm-induced coastal hazards is constructed, where the conditional probability tables of TC atmospheric parameters are computed using copulas. A deaggregation method is implemented to identify the dominant TC parameter combinations for coastal hazard events of interest. The dependence between storm surge and storm rainfall is explored based on the BN. Finally, based on the outcomes of the analysis described, the PCHA is extended and leveraged to develop multiple tiers of BN for modeling compound coastal hazards. The tiers are intended to be useful under different levels of data availability and computational resources for compound flood analysis. Machine learning-based predictive models are used to develop several conditional probability tables required by the BN model.

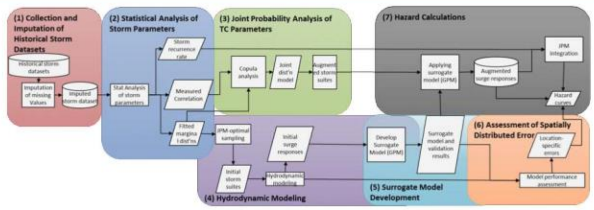
3.5.6.2 Presentation (ADAMS Accession No. ML23177A179)

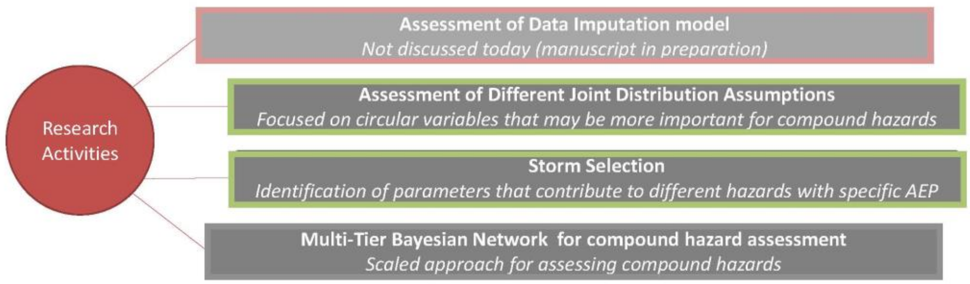


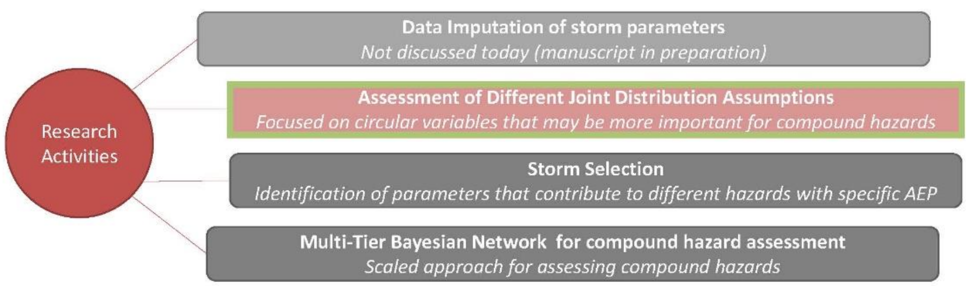


Introduction

- To date, implementations of the CHS-PCHA framework have focused primarily on storm surge
- We aim to expand the framework to consider compound coastal hazards



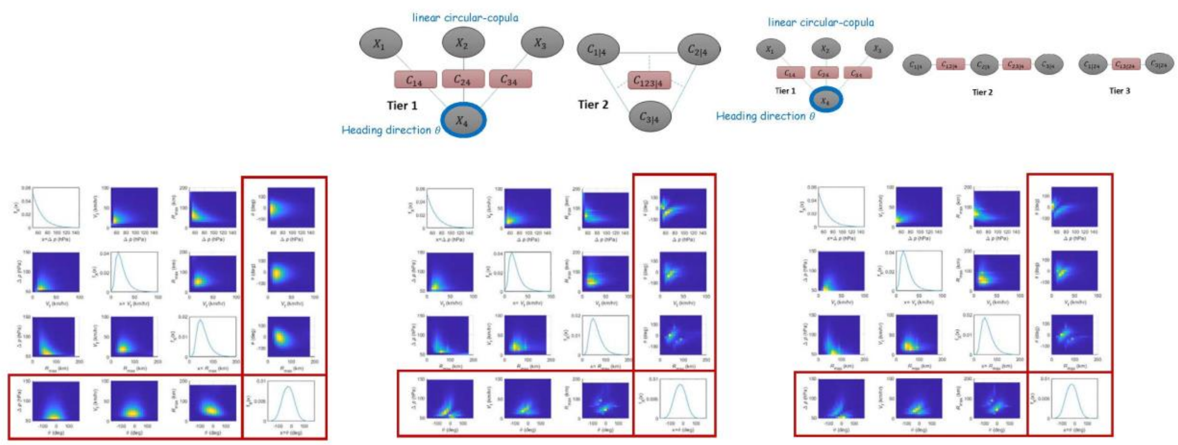




Assessment of Different Joint Distribution Assumptions

A series of different joint distribution assumptions have been assessed

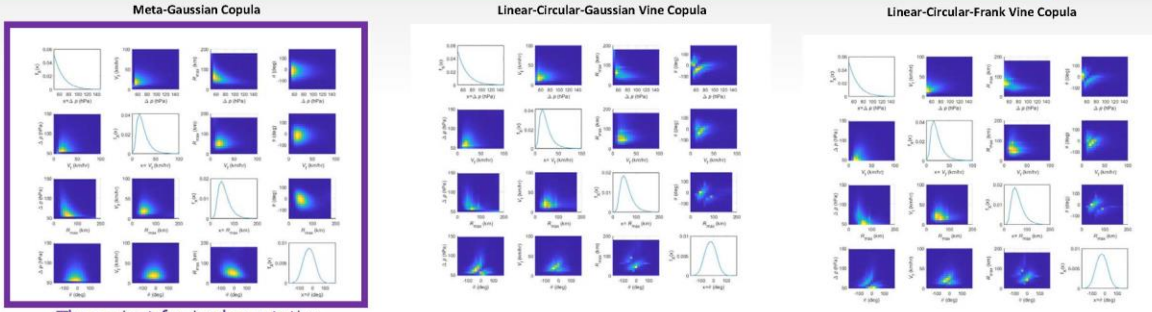
Meta-Gaussian Copula | **Linear-Circular-Gaussian Vine Copula** | **Linear-Circular-Frank Vine Copula**



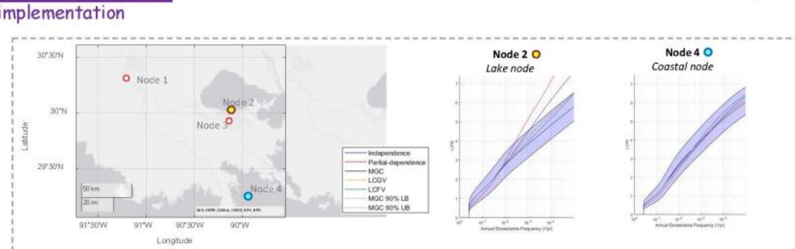
Preliminary/In-progress results and graphics

Assessment of Different Joint Distribution Assumptions

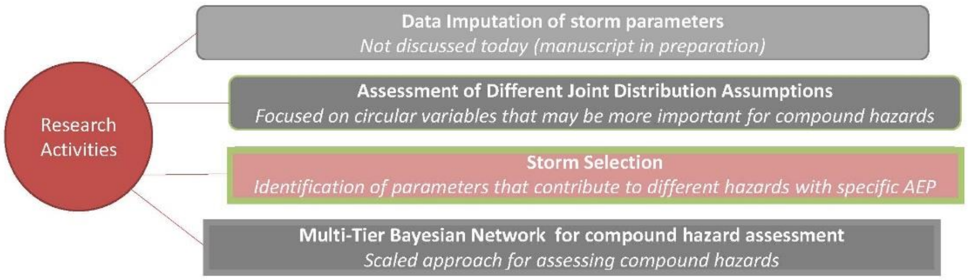
Meta-Gaussian Copula | **Linear-Circular-Gaussian Vine Copula** | **Linear-Circular-Frank Vine Copula**



The easiest for implementation

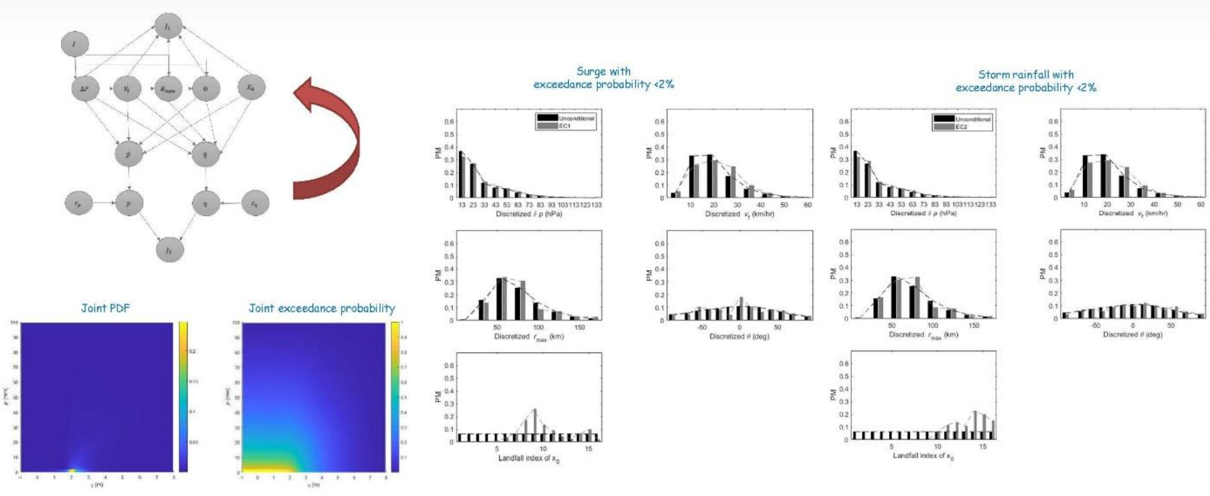


Preliminary/In-progress results and graphics

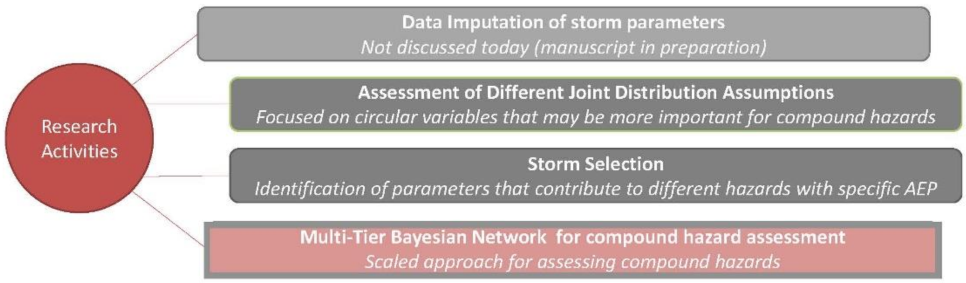


Storm Selection

A framework for the identification of the dominant TC parameter combinations

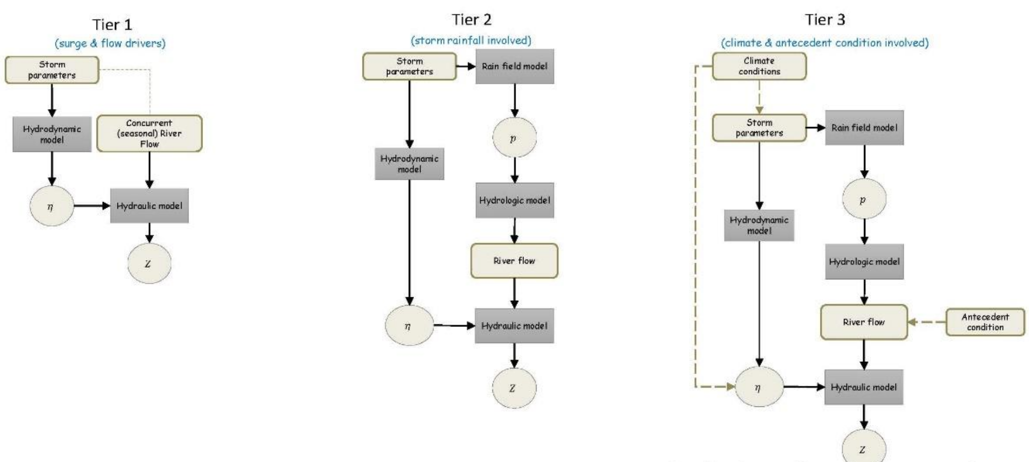


Preliminary/In-progress results and graphics



Multi-Tier Bayesian Network Concept

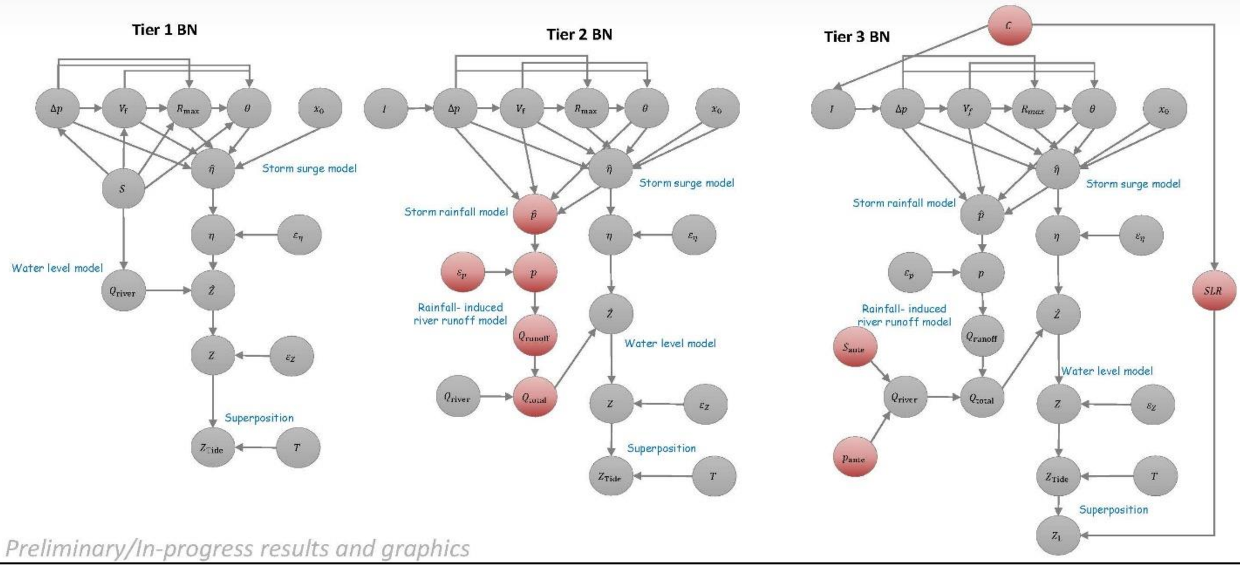
High-level concept of multiple tiers of BN for PCHA of CCF
With the increase of tier number, the required data and computation effort increase



Preliminary/In-progress results and graphics

Constructed Bayesian Network in Case Study--NOLA

Multiple tiers of BN constructed for case study region (New Orleans, LA)

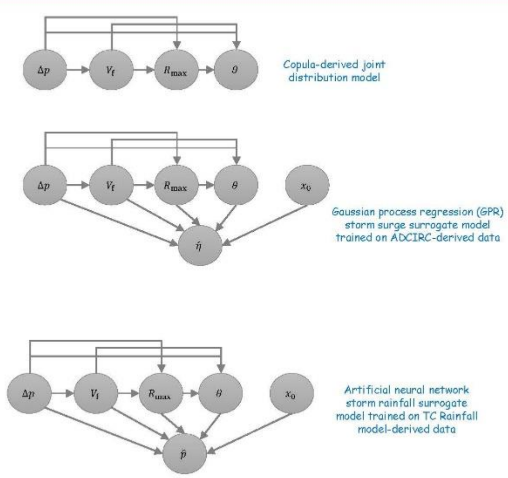


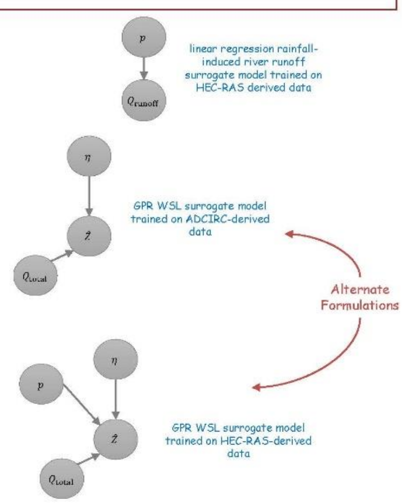
Preliminary/In-progress results and graphics

Constructed Bayesian Network in Case Study--NOLA

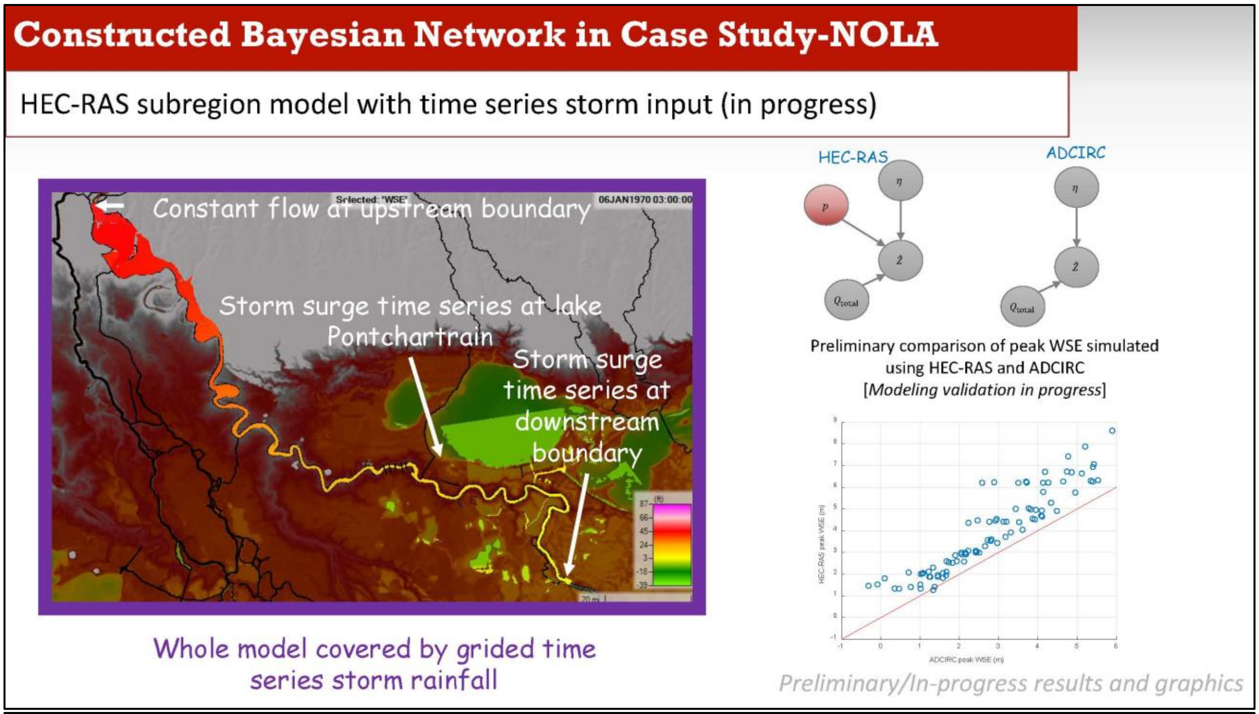
Derviation of BN conditional probability tables

→ Motivated by a series of joint probability, numerical, and machine-learning models





Preliminary/In-progress results and graphics



3.5.6.3 *Questions and Answers*

Question:

In the New Orleans case study, does that domain include things like the Morganza Floodway, and would you include the operation of that? Or is that too far up out of the domain. My knowledge of the geography there isn't that good so I don't know whether your domain would include that floodway or not.

Answer:

So currently, the case study is still in progress, so now we start with some nodes inside the river, but generally we will cover a bigger region in the New Orleans study. So now we only have a couple of nodes studied.

Question:

Can I put Meredith on the spot. Meredith, I think you know that area a lot better than I, how far up is the Morganza Floodway?

Answer:

Meredith Carr: This is going up to the Bonne Carré spillway. I'm not sure about Morganza. The gage is up above where the Atchafalaya joins. That's outside of the model, but it's included in the flow calculation.

3.5.7 Poster 3A-7: Assessing Uncertainty Associated with Hurricane Predictions and Duration to Inform Probabilistic Risk Assessments for Nuclear Power Plants

Authors: Kaveh Faraji Najarkolaie, Michelle Bensi; University of Maryland, College Park

Speaker: Kaveh Faraji Najarkolaie

3.5.7.1 Abstract

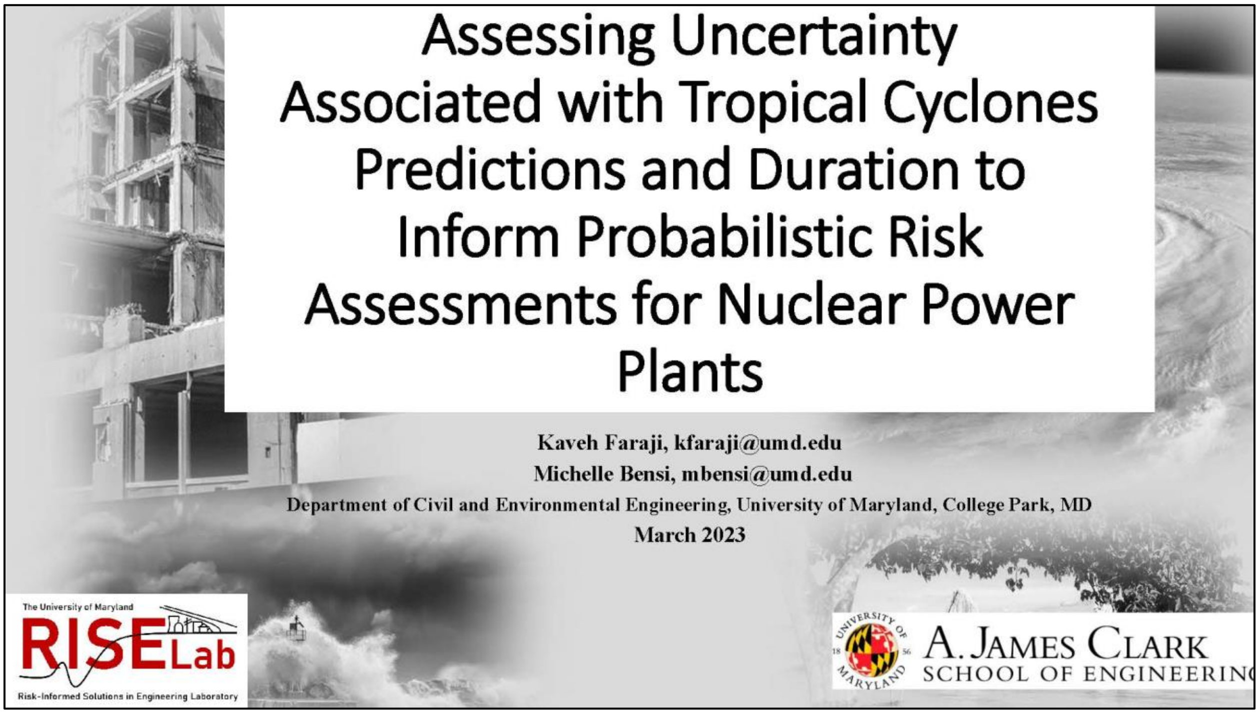
Hurricanes can cause damage to infrastructure facilities located along the storm track. Critical infrastructure facilities, such as nuclear power plants, will typically take actions to protect against the impacts of hurricane events (e.g., wind, rain, or storm surge). As a result, probabilistic risk assessments for critical infrastructure facilities require information about the warning time available to take action and the duration during which storm conditions will prevail. However, to date, existing literature has not addressed this information need. This presentation describes the recent progress of an ongoing research activity focusing on temporal uncertainties related to probabilistic risk assessment for nuclear power plants exposed to hurricane events.

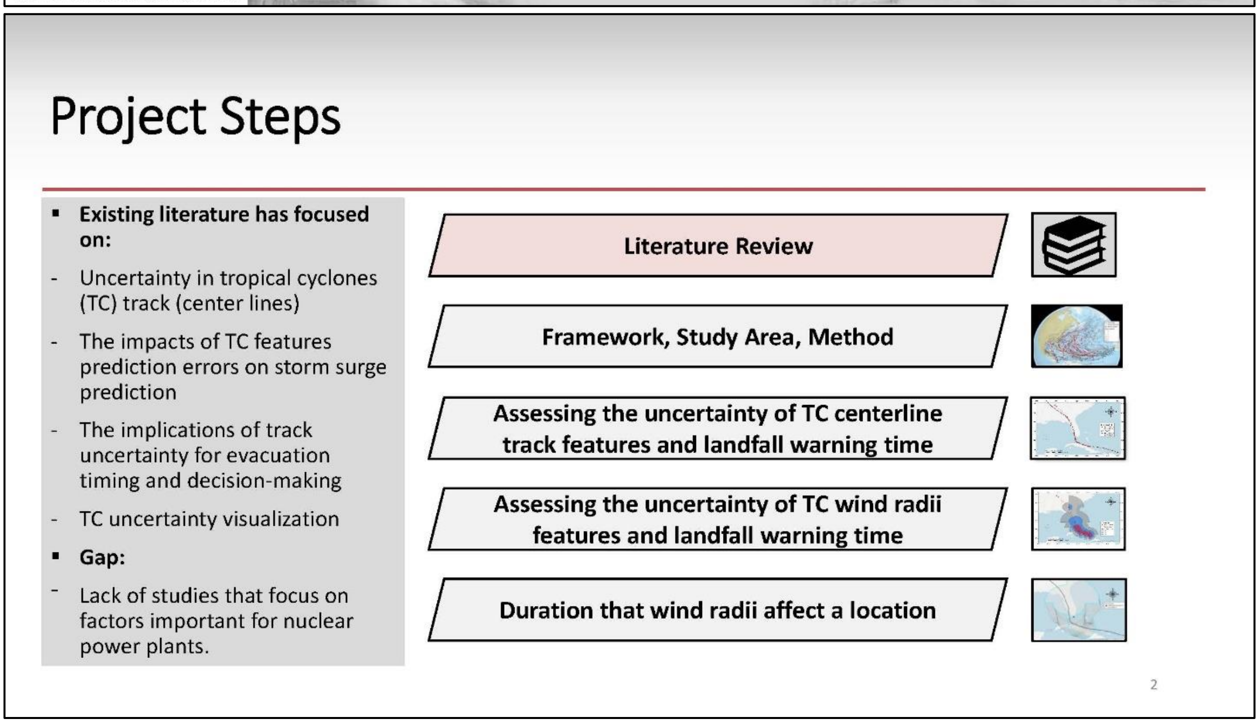
The National Hurricane Center (NHC) tracks hurricane features and generates forecasts for storm locations and characteristics up to 120 hours in the future. However, these predictions are associated with uncertainty. In this study, we aim to identify and characterize the uncertainty associated with hurricane prediction in a way that could be useful for probabilistic hazard assessment of critical infrastructure like nuclear power plants.

We used the NHC database to gather information on observed and forecasted hurricane tracks. We processed and prepared the storm track data for geospatial and statistical analysis, focusing on storms that originated in the Atlantic Ocean between 2008 and 2022. We analyzed the prediction errors of the track landfall location, wind radii landfall location, and their timing using analyses that extend beyond previously published error assessments. We calculated an hourly interpolation of hurricane features and wind radii for 34, 50, and 64-knot wind speeds. We extracted track and wind landfall location and timing information using the intersection of hurricane track centerlines and wind radii polygons with the land boundary. The wind radii landfall location and timing provide important information regarding when the hurricane winds start to impact a region. We then estimated the duration that a hurricane would affect locations

within a region affected by the storm. This helps to develop an understanding of the duration that infrastructure would be affected by the winds generated by a hurricane. Finally, we present the results of this study using visualizations that are intended to help inform external hazard probabilistic risk assessment.

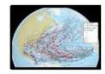
3.5.7.2 Presentation (ADAMS Accession No. ML23177A180)





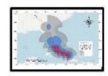
Project Steps

- Literature Review
- Framework, Study Area, Method



- Assessing the uncertainty of TC centerline track features and landfall warning time

- Assessing the uncertainty of TC wind radii features and landfall warning time



- Duration that wind radii affect a location

3

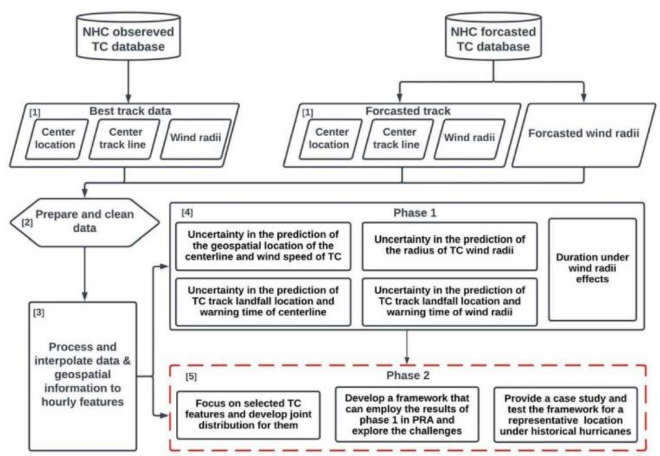
Framework

[1] Data downloaded from NHC GIS database

[2] Prepare and clean shapefile data

[3] Processing and developing hourly interpolation for data

[4] Characterizing errors of predictions for TC features that are important for critical infrastructure



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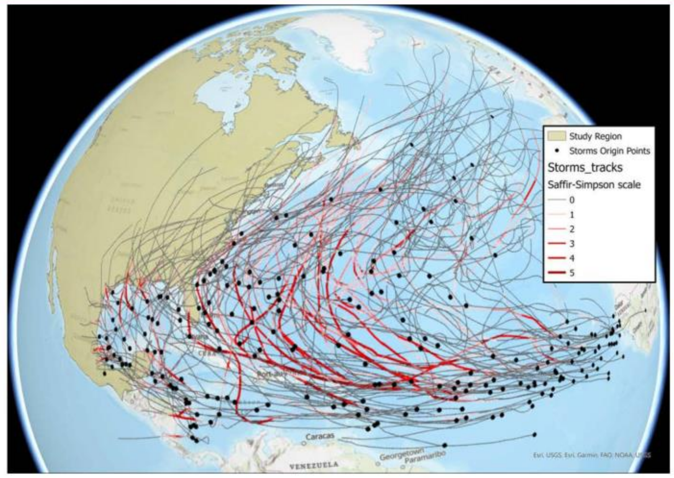
Study Area

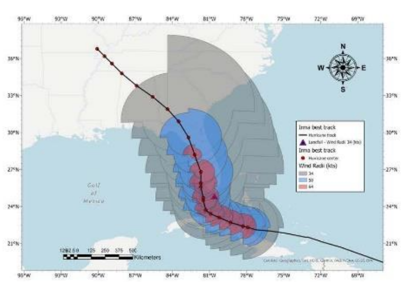
- North America region
- TC originated on North Atlantic between 2008 to 2022
- Origin points of TC
- Centerline track and hurricane category



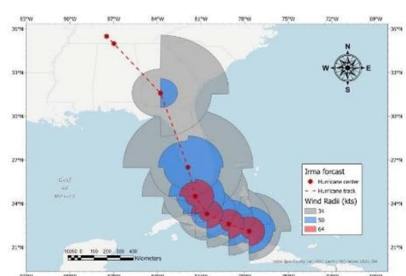
Observed vs. Predicted Storms

- Observed TC data is usually available every 6 hours. For the forecast, it is available every12-24 hours
- The predicted tracks are the official forecast of the center of a TC made by NHC, typically for 12, 24, 36, 48, 72, 96, and 120 hours in future
- NOAA publishes errors of predicting hurricane center and maximum wind speed every year.

a) Observed track

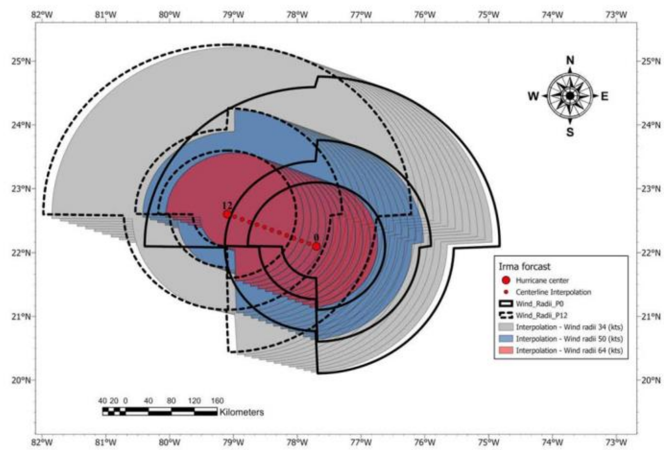


b) Predicted track



Method - Interpolation of TC Features

- We wrote a series of scripts to automate the collection and processing of GIS data
- Data includes center points, center line, and wind radii information
- The information is interpolated hourly

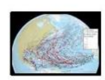


7

Project Steps

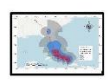
Literature Review

Framework, Study Area, Method



Assessing the uncertainty of TC centerline track features and landfall warning time

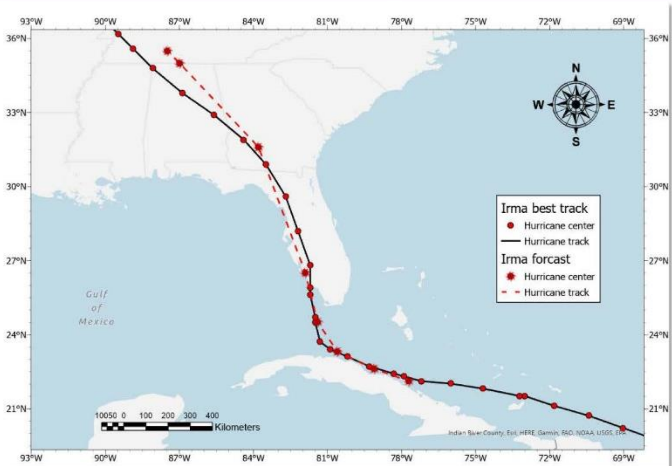
Assessing the uncertainty of TC wind radii features and landfall warning time



Duration that wind radii affect a location

8

Uncertainty Associated with Prediction of Center Location

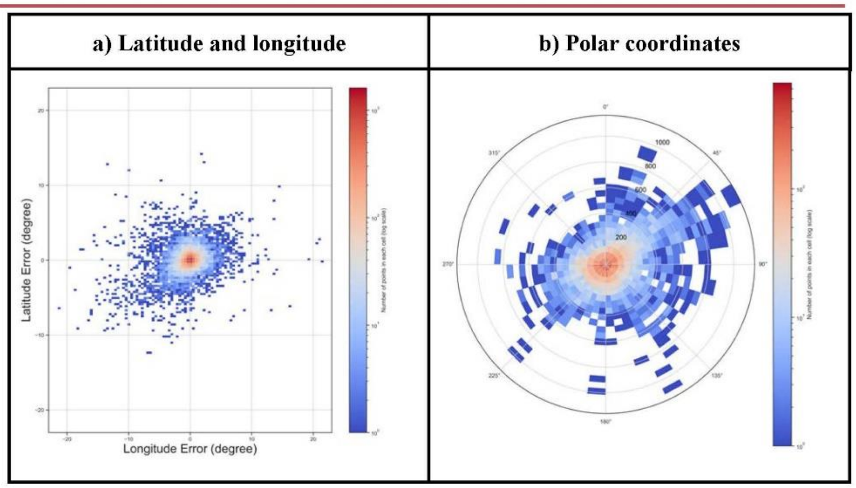


9

Uncertainty Associated with Prediction of Center Location

- **2-D histogram of longitude and latitude prediction error shows the error in each of those directions and their relationship together.**

- **Polar plot histogram provides information about the distance and angle between observed hurricane centers and predictions.**



Preliminary Results

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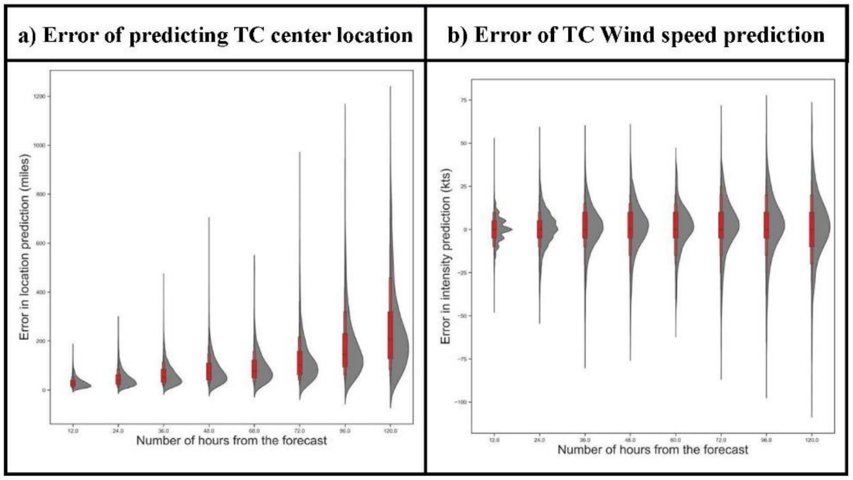
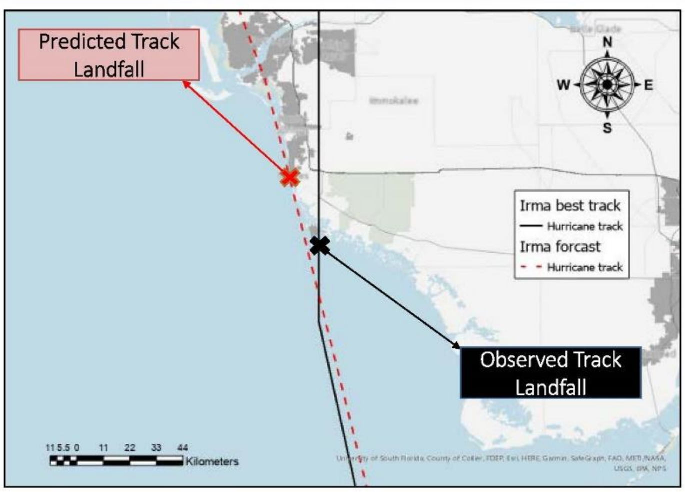
Error Associated with Prediction of Hurricane Track Features

- **Combination of half violin plot and box plot of error**
- **The overall trend in error increases with the increase in the number of hours from the forecast**
- **Half violin plot distribution expands with an increase in the number of hours from the forecast**

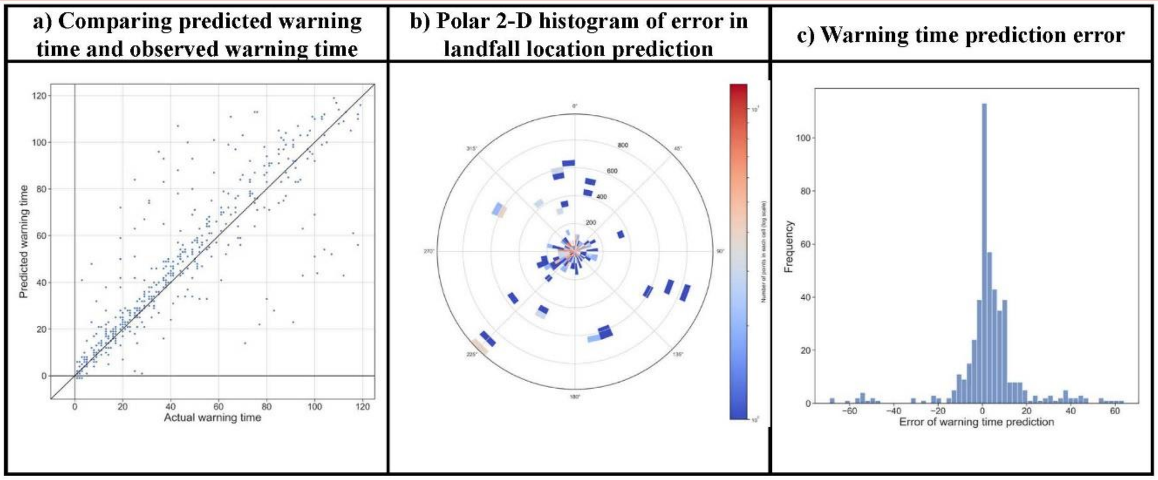


Preliminary Results

Uncertainty in Prediction of Centerline Landfall Location and Warning Time



Uncertainty in Prediction of Centerline Landfall Location and Warning Time

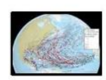


Preliminary Results

Project Steps

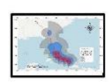
Literature Review

Framework, Study Area, Method



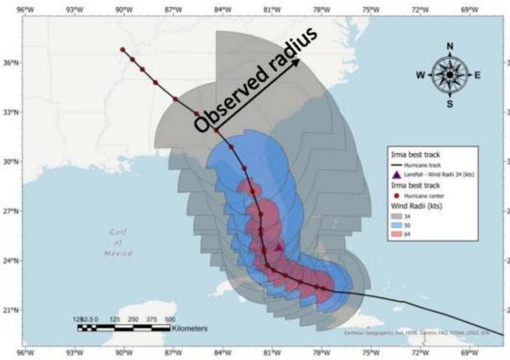
Assessing the uncertainty of TC centerline track features and landfall warning time

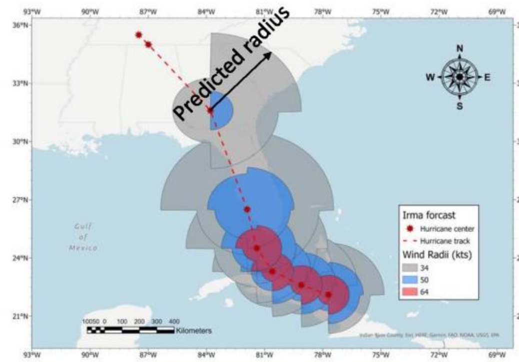
Assessing the uncertainty of TC wind radii features and landfall warning time



Duration that wind radii affect a location

Wind Radii Forecast Uncertainty





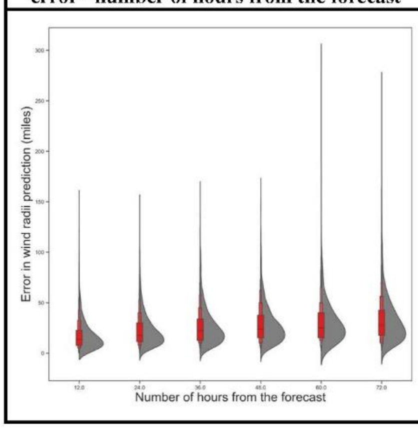
Observed track **Predicted track**

15

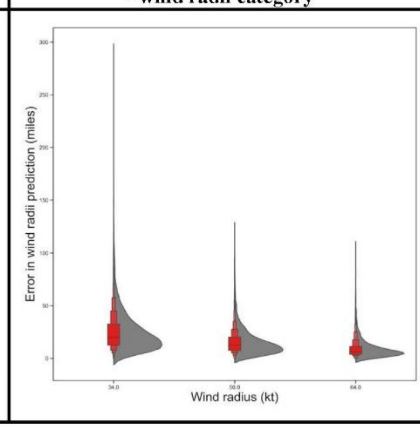
Wind Radii Prediction Errors

- **The mean of absolute error of prediction of wind radii 34 kts**
- **As the number of hours from the forecast increases, we observe an increase in the variance of error of wind radii prediction**

a) Violin plot wind radii 34 kts prediction error - number of hours from the forecast



b) Violin plot error of wind radius prediction - wind radii category



Preliminary Results

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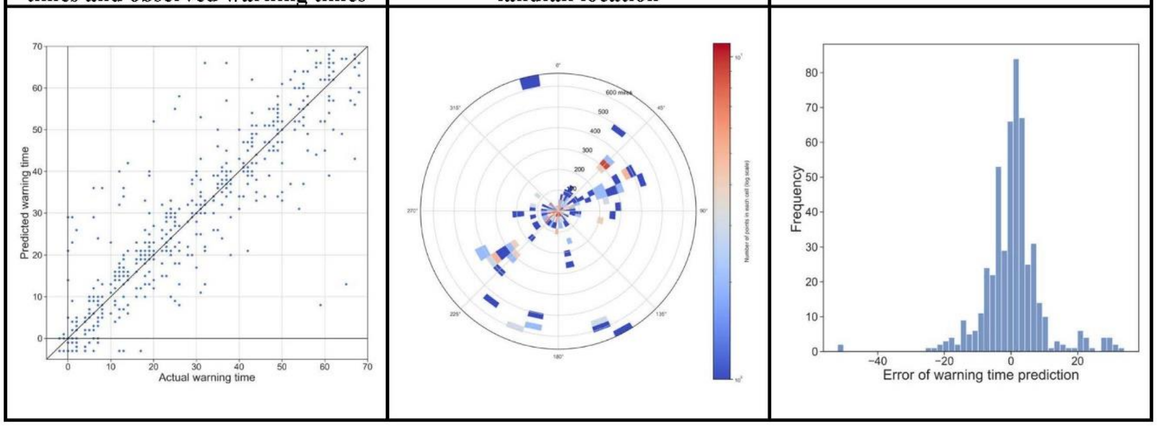
Wind Radii Landfall Location and Warning Time Prediction Errors

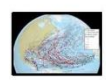
a) Comparing predicted warning times and observed warning times	b) Polar 2-D histogram of error in landfall location	c) Warning time prediction error



Preliminary Results

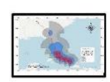
Project Steps

- Literature Review
- Framework, Study Area, Method



- Assessing the uncertainty of TC centerline track features and landfall warning time

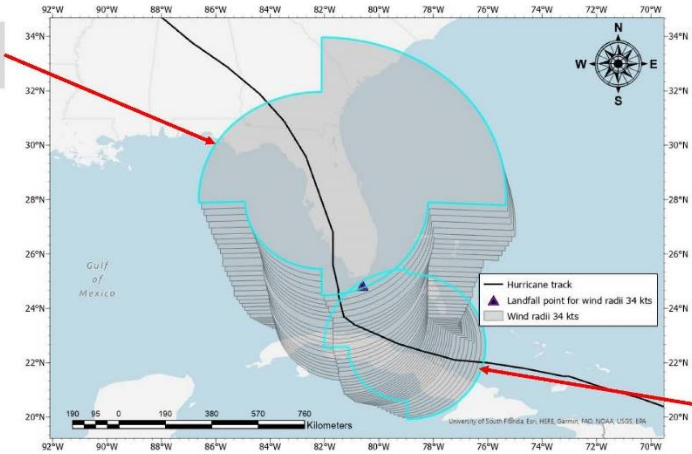
- Assessing the uncertainty of TC wind radii features and landfall warning time



- Duration that wind radii affect a location

Duration under Effects of Wind Radii

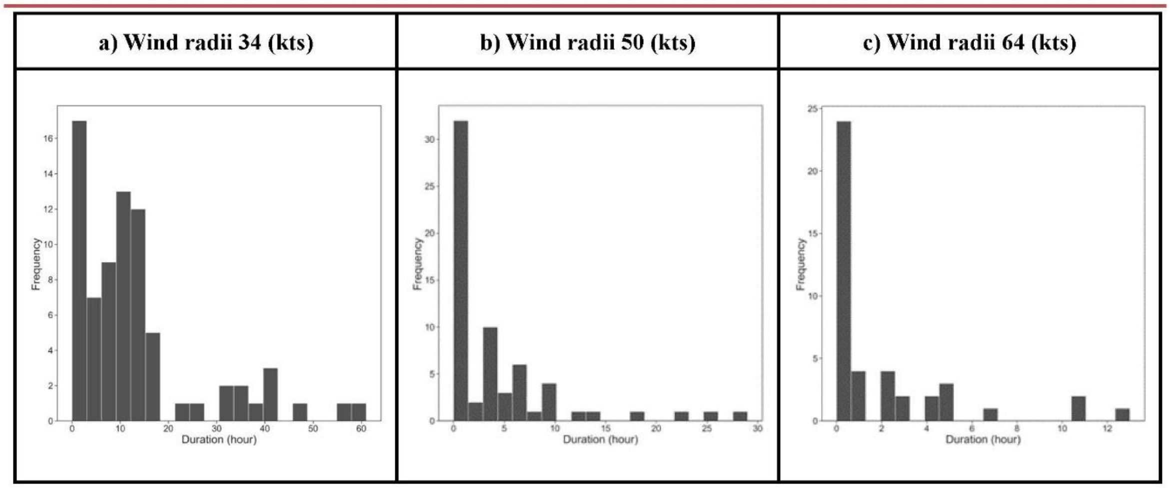
End (after 43 hours):
05:00 September 11



Start (Wind radii landfall):
10:00 September 9

19

Duration under Effects of Wind Radii



Preliminary Results

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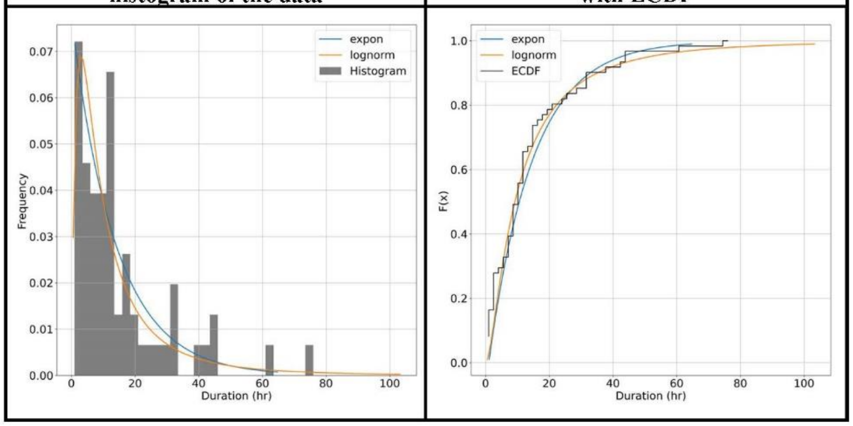
Providing Results in a Format Amenable to Support PRA

- **Fit distributions to the error data**
- **Select the most suitable using goodness of fit approaches (e.g., AIC, BIC).**
- **The characterized error here can be used in external hazard PRA**

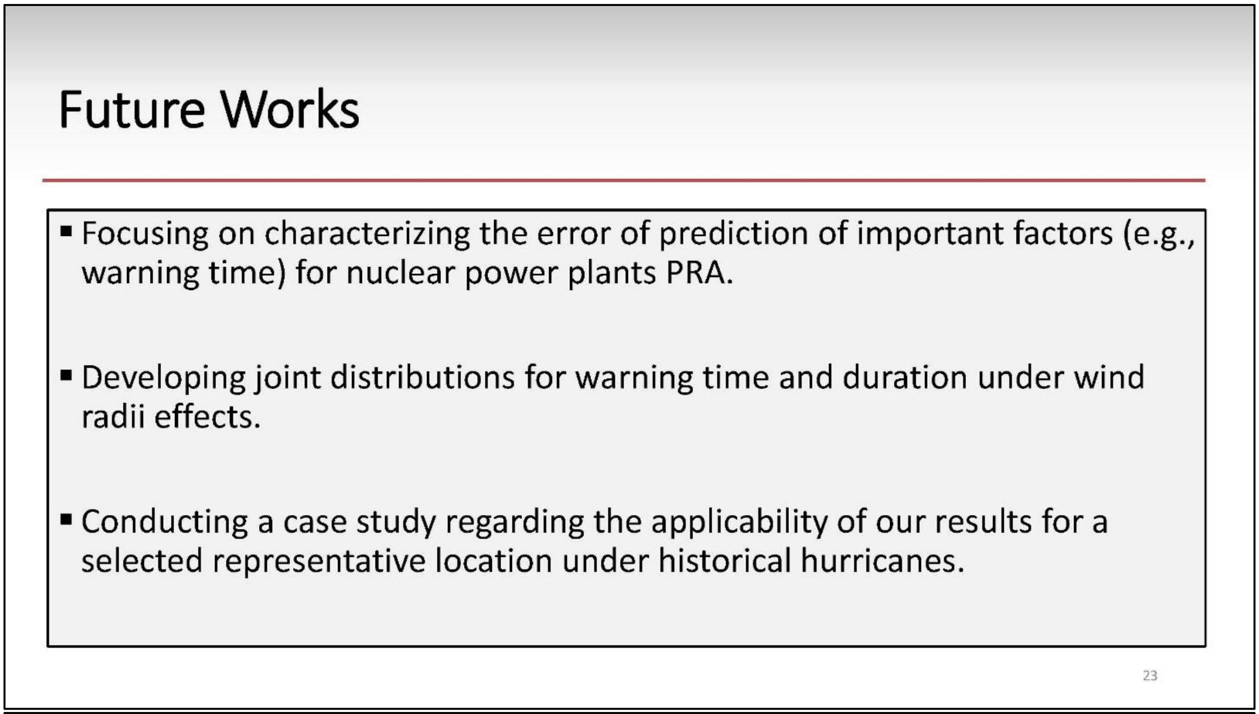
a) Comparing PDF of distributions histogram of the data | **b) Comparing CDF of distributions with ECDF**

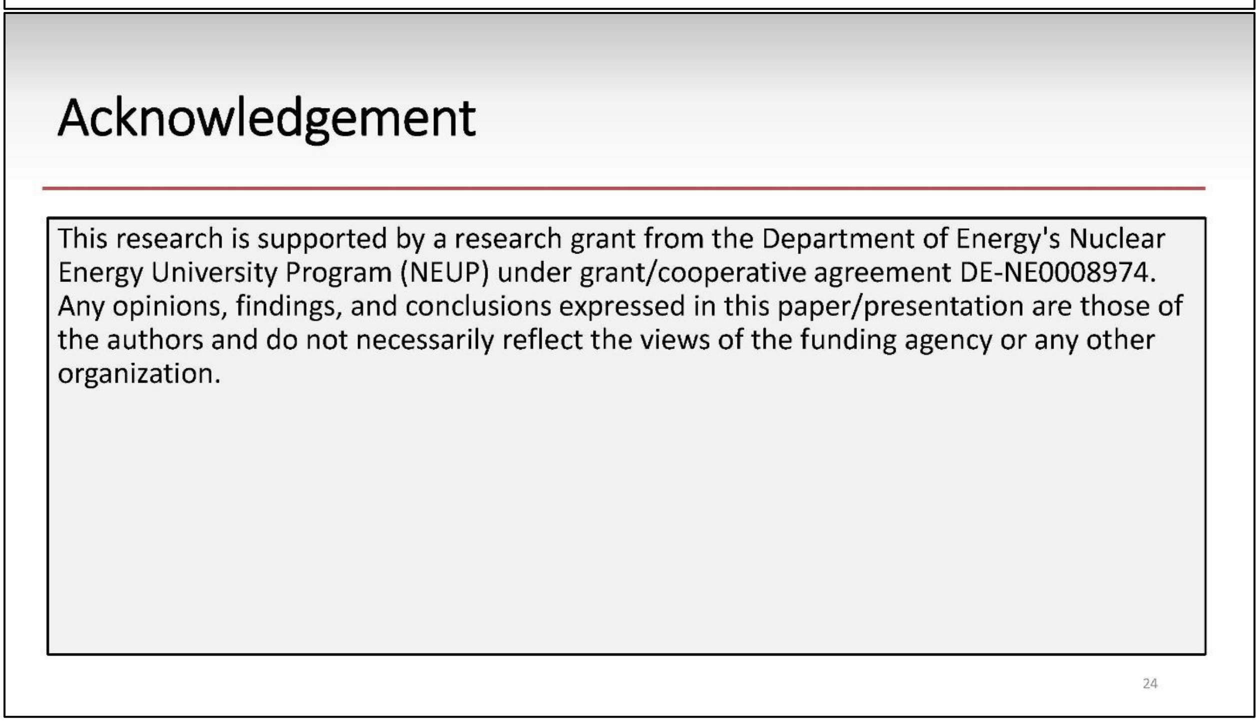


Preliminary Results

Conclusions

- There is a significant gap in the literature regarding the investigation of hurricane feature forecasts that focus on critical infrastructure.
- When considering the TC as a track line & 2D polygons (wind radii), the uncertainty associated with the prediction of TC features increases significantly with the number of hours from the forecast time. However, this effect is less pronounced when considering wind radii prediction.
- For hurricane track and wind radii, the forecasts usually overestimate the warning time for hurricane landfall.





3.5.7.3 Questions and Answers

Question:

Do the various uncertainty statistics depend on where the nuclear plants are located (e.g.., Gulf Coast of the US, east coast of the US)?

Answer:

We want to consider this in the next phase of our study. We want to consider the effect of location in our analysis and see are we going to get different results if we consider nuclear power plants located in the Gulf of Mexico or in the North Atlantic region. We didn't consider that yet.

Question:

I think that's an important thing to consider [dependency on location]. I think you probably would see some differences as you go up the east coast and some differences in the Gulf [of Mexico]. Specifically the [Gulf of Mexico] Loop Current gets really warm late in the hurricane season, which leads me to my question: Have you thought about looking at how that error may depend upon the hurricane intensity? You may have some different populations there where the errors are not so great for Category 1 and 2 storms, but the errors are bigger for bigger storms. Or maybe it's vice versa I don't know.

Answer:

We are thinking about that. We are thinking about considering both location and intensity in our analysis. When I talked about developing joint distributions, it was about considering these things in producing some charts that shows the difference that hurricane intensity and hurricane landfall location will make on the uncertainty we have regarding warning time, regarding other factors that are important here.

Question:

Have you looked at uncertainties at potential locations for advanced reactors in the U.S. territories?

Answer:

No, we did not consider that.

3.5.8 Poster 3A-8: Assessment of Uncertainty Associated with the Development of Intensity Duration Frequency Curves under Changing Climate for the State of Maryland

Authors: Azin Al Kajbaf[1], Michelle Bensi[2], Kaye Brubaker[2]; [1]Johns Hopkins University, [2]University of Maryland, College Park

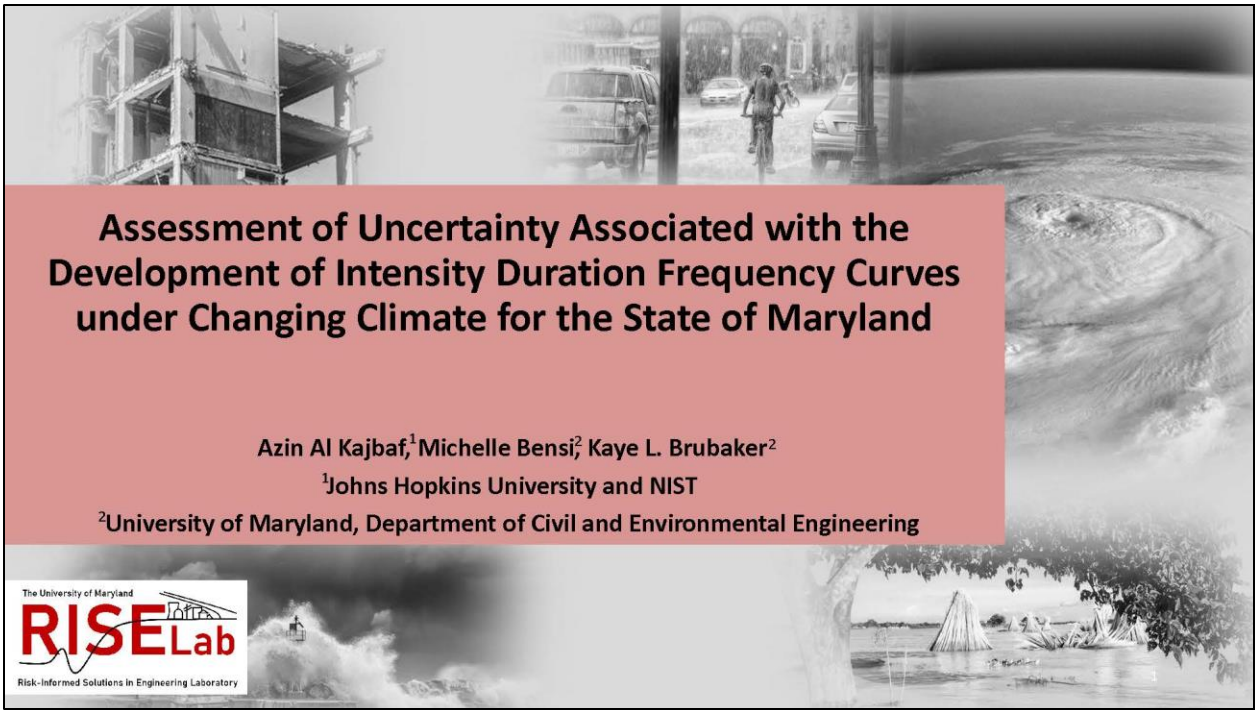
Speaker: Azin Al Kajbaf

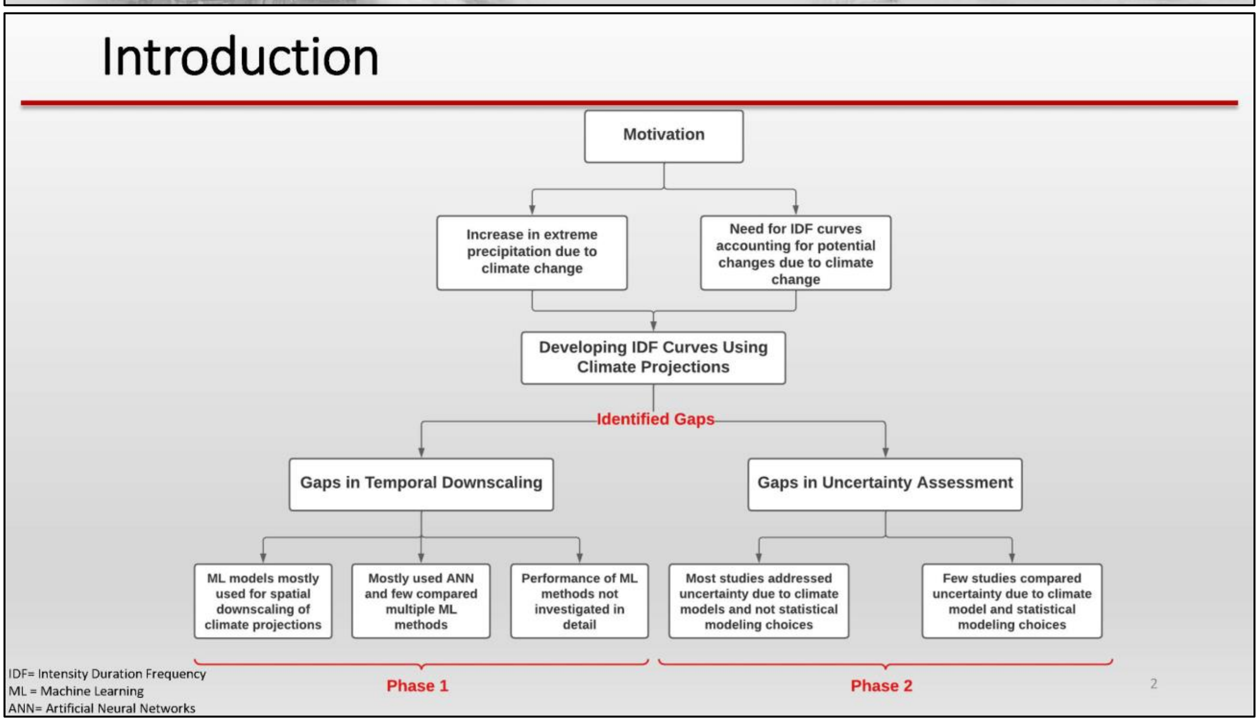
3.5.8.1 Abstract

The contiguous United States has experienced an increase in mean average precipitation in each decade beginning in the 1950s. These trends, which are expected to continue, will affect water infrastructure and require updates to the associated planning and design policies. Intensity Duration Frequency (IDF) curves are often used as the basis for engineering design decisions involving water infrastructure. However, IDF curves developed using conventional approaches based on historical/observational data may not reflect hazards under a changing climate. Synthetic climate model projections provide information to account for the potential effects of climate change in developing IDF curves. This poster is intended to share with the probabilistic flood hazard assessment (PFHA) community a summary of a recently completed project focused on exploring the uncertainty associated with the development of IDF curves under current and future climate conditions for the State of Maryland. We first apply machine learning to temporally downscale synthetic time-series outputs of climate model projections from

the North American Regional Climate Change Assessment Program (NARCCAP) (available at a 3-hour temporal resolution) to durations as short as 15 minutes. We then assess the epistemic uncertainty associated with development of IDF curves on two levels: across model and within model. Across model uncertainty refers to the uncertainty arising from the differences in synthetic precipitation and other meteorological variable time-series resulting from different NARCCAP climate model projections. Within model uncertainty refers to the uncertainty arising from the modeling choices, including temporal downscaling methods, time-series types, distributions, and parameter estimation methods used to develop IDF curves using the synthetic time-series from a single climate model projection. We provide a graphical framework to explore and compare the contribution of sources of uncertainty.

3.5.8.2 Presentation (ADAMS Accession No. ML23177A181)

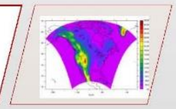




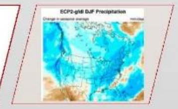
Introduction

This study applies two strategies to enhance model-based precipitation frequency estimates under current and projected future climate in Maryland:

Phase 1: Application of Machine Learning for Temporal Downscaling of Climate Model Projections[1]



Phase 2: Assessment of Uncertainty in Precipitation Frequency Under Current and Future Climate[2]



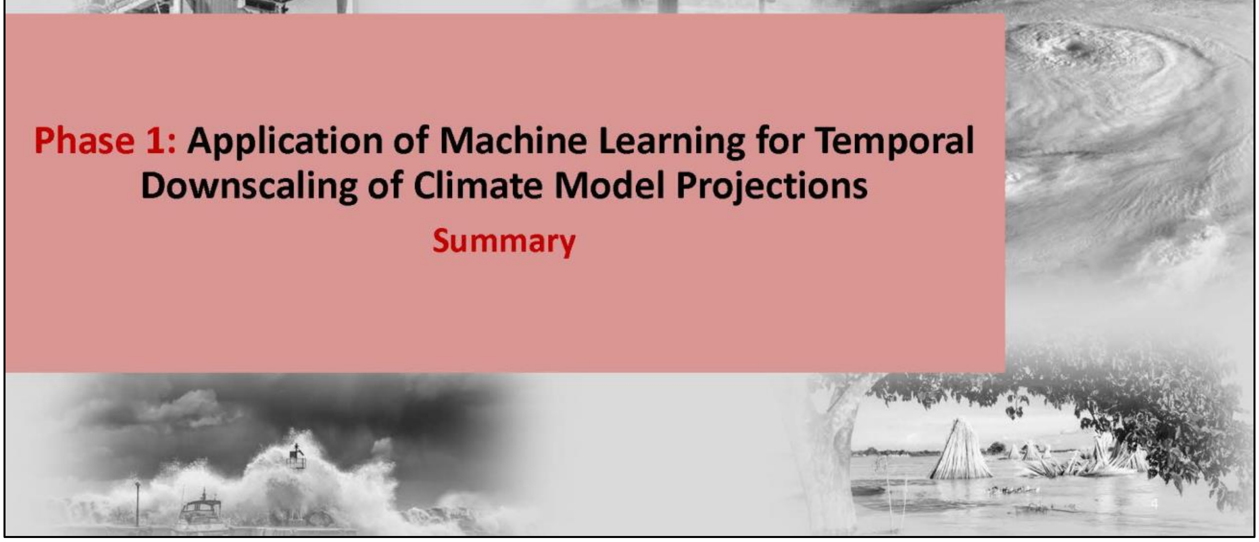
[1] Al Kajbaf, A., Bensi, M. and Brubaker, K.L., 2022. "Temporal downscaling of precipitation from climate model projections using machine learning." *Stochastic Environmental Research and Risk Assessment.*

[2] Al Kajbaf, A., Bensi, M. and Brubaker, K.L., 2023. "Drivers of uncertainty in precipitation frequency under current and future climate– application to Maryland, USA." *Journal of Hydrology.*

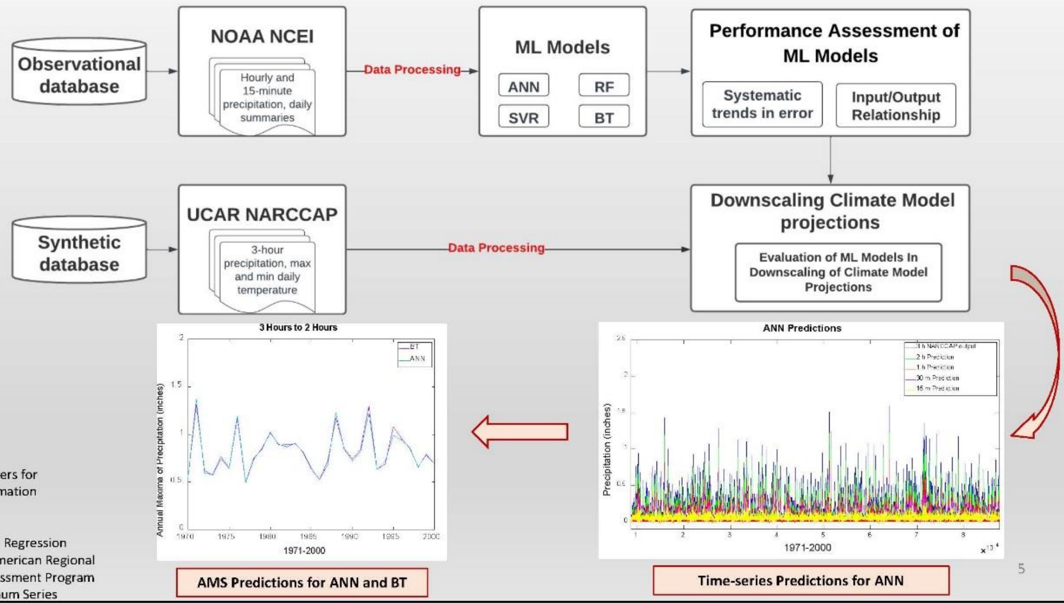
3

Phase 1: Application of Machine Learning for Temporal Downscaling of Climate Model Projections

Summary



Application of Machine Learning for Temporal Downscaling of Climate Model Projections



NCEI = National Centers for Environmental Information
BT = Boosted Trees
RF= Random Forest
SVR= Support Vector Regression
NARCCAP = North American Regional Climate Change Assessment Program
AMS= Annual Maximum Series

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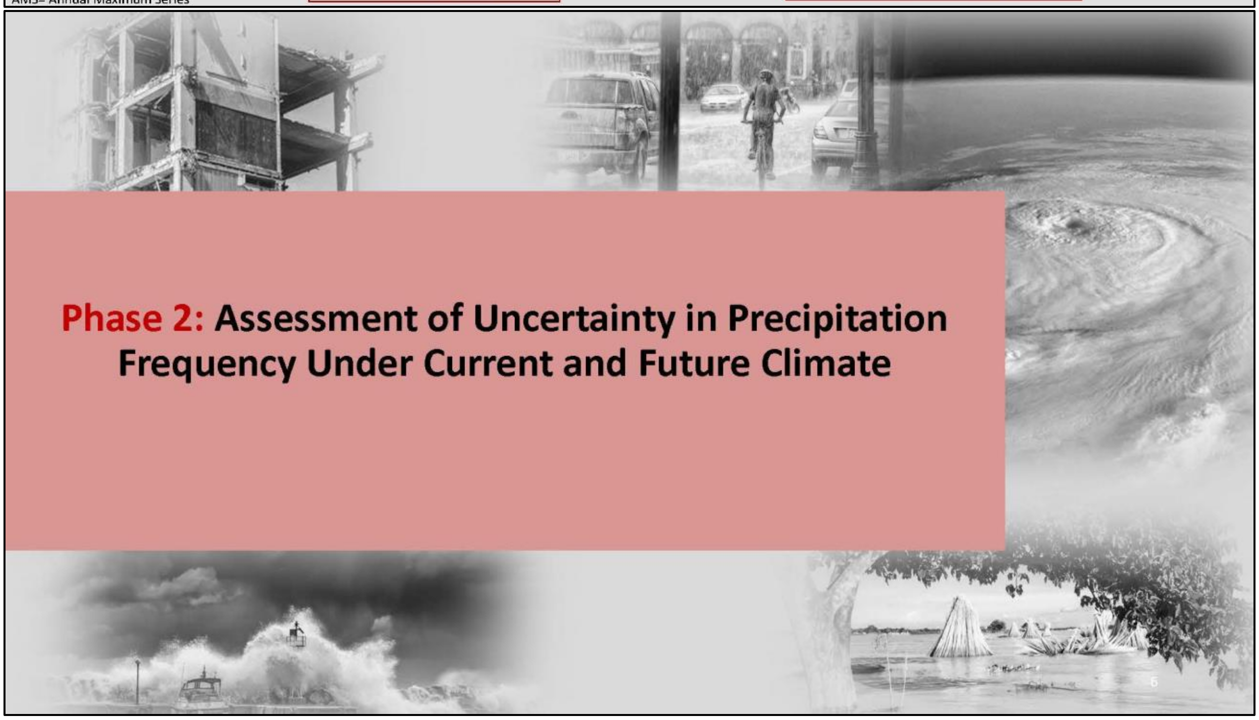
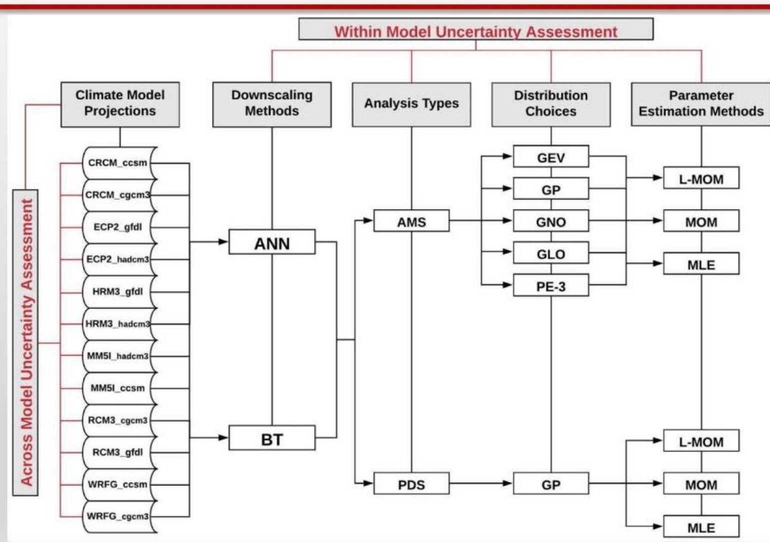


Assessment of Uncertainty in Precipitation Frequency Under Current and Future Climate



AMS = Annual Maximum Series
PDS = Partial Duration Series
GEV = Generalized Extreme Value
GP = Generalized Pareto
GNO = Generalized Normal
GLO = Generalized Logistic
PE-3 = Pearson type III
L-MOM = L-moments
MOM = Method of Moments
MLE = Maximum Likelihood Estimation

Study Framework

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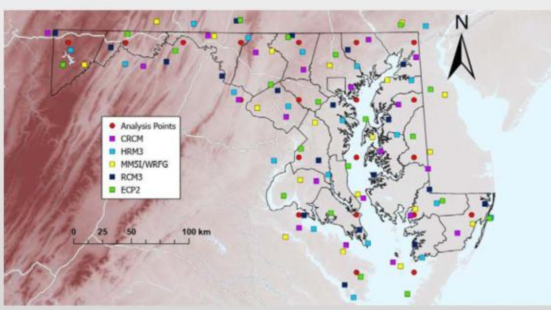
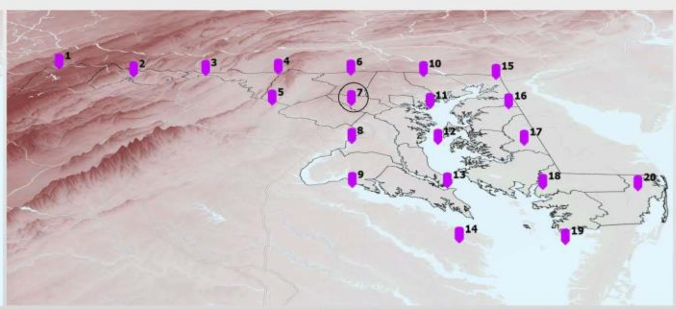
Assessment of Uncertainty in Precipitation Frequency Under Current and Future Climate



Location of grid centers within Maryland for the six NARCCAP regional models

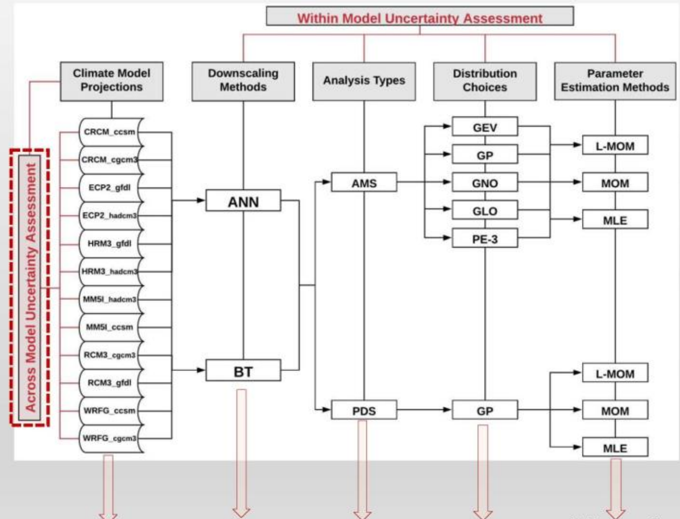


Nearest neighbor analysis points

Region of Study

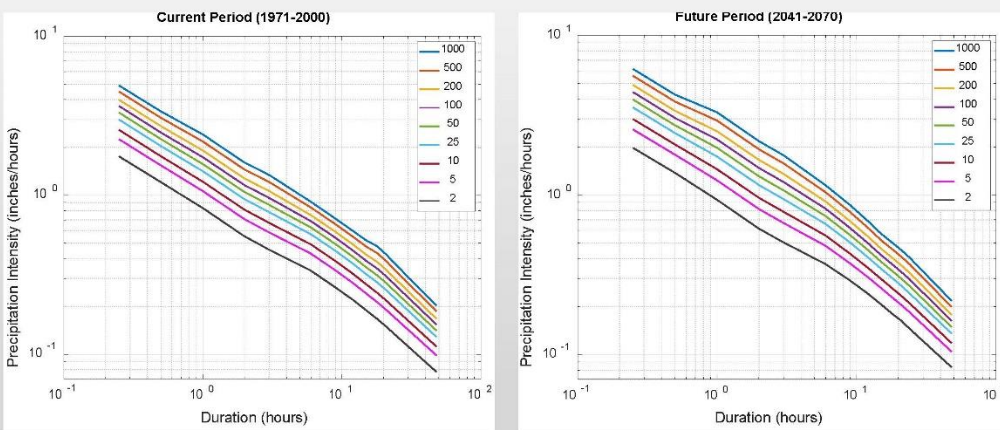
8

Assessment of Uncertainty in Precipitation Frequency Under Current and Future Climate



12 Climate Models × 2 Downscaling Methods × 2 Analysis Types × 6 Distributions (AMS(5)+PDS(1)) × 3 Parameter Estimation Methods = 432 Cases

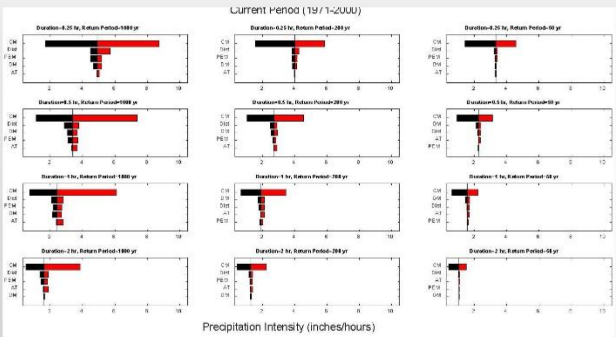
Assessment of Uncertainty in Precipitation Frequency Under Current and Future Climate

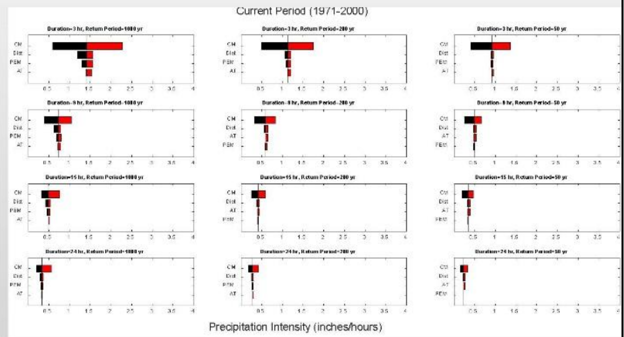


Averaged IDF curves in the current (left) and future (right) periods considering all eligible branches of logic trees for grid point 7

Assessment of Uncertainty in Precipitation Frequency Under Current and Future Climate

Tornado Plots





Current Period (1971-2000)

CM= Climate model
Dist = Distribution
PEM = Parameter Estimation Method
AT = Analysis type
DM = Downscaling method

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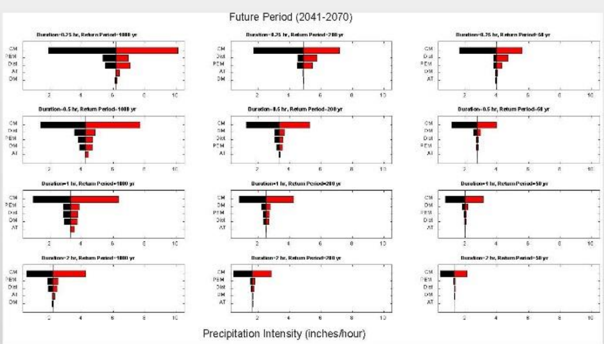
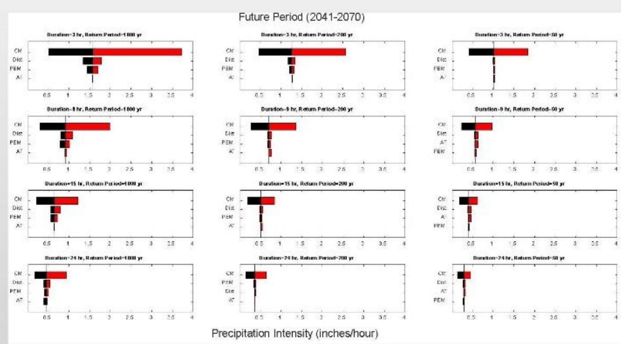
Assessment of Uncertainty in Precipitation Frequency Under Current and Future Climate

Tornado Plots





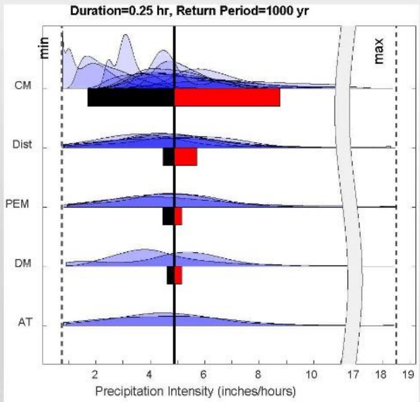
Future Period (2041-2070)

CM= Climate model
Dist = Distribution
PEM = Parameter Estimation Method
AT = Analysis type
DM = Downscaling method

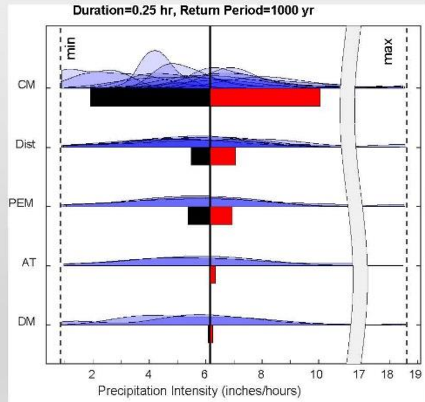
12

Assessment of Uncertainty in Precipitation Frequency Under Current and Future Climate

Kernel Density Tornado (KDT) Plots



Current Period (1971-2000)



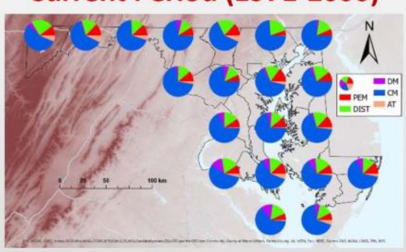
Future Period (2041-2070)

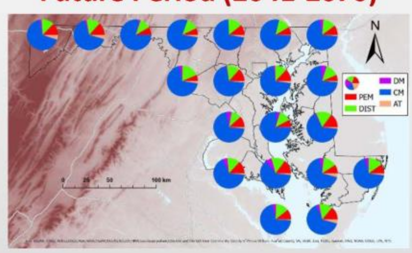
CM= Climate model
Dist = Distribution
PEM = Parameter Estimation Method
AT = Analysis type
DM = Downscaling method

Assessment of Uncertainty in Precipitation Frequency Under Current and Future Climate

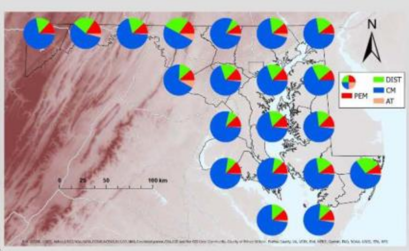
Current Period (1971-2000) **Future Period (2041-2070)**

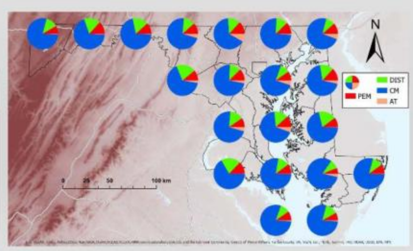
Duration: 15 minutes
Return Period: 1000 years





Duration: 24 hours
Return Period: 1000 years

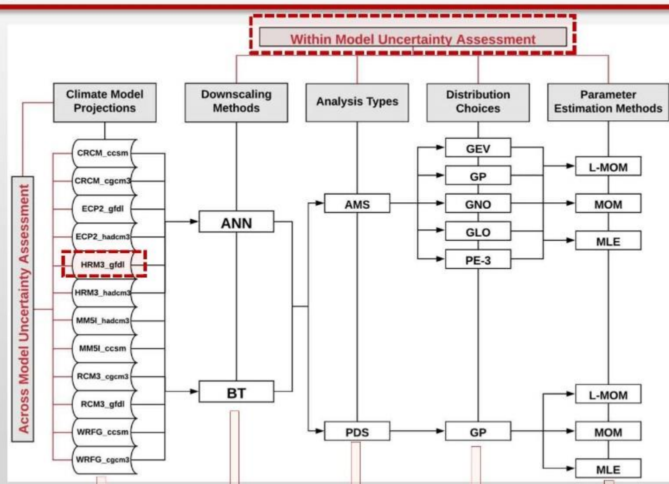




CM= Climate model
Dist = Distribution
PEM = Parameter Estimation Method
AT = Analysis type
DM = Downscaling method

Contribution of sources of uncertainty over the study region for the current (right) and future (left) periods

Assessment of Uncertainty in Precipitation Frequency Under Current and Future Climate

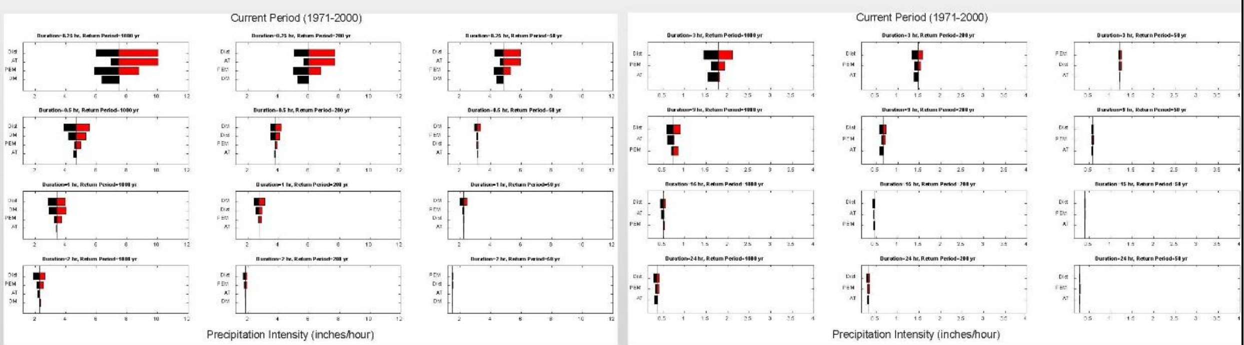


1 Climate Model × 2 Downscaling Methods × 2 Analysis Types × 6 Distributions (AMS(5)+PDS(1)) × 3 Parameter Estimation Methods = 36 Cases

15

Assessment of Uncertainty in Precipitation Frequency Under Current and Future Climate

Tornado Plots



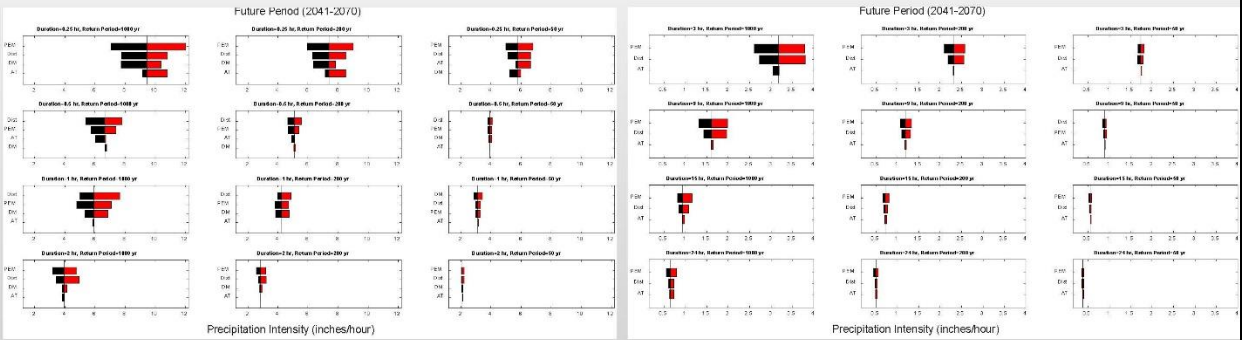
Current Period (1971-2000)

CM= Climate model
Dist = Distribution
PEM = Parameter Estimation Method
AT = Analysis type
DM = Downscaling method

16

Assessment of Uncertainty in Precipitation Frequency Under Current and Future Climate

Tornado Plots



Future Period (2041-2070)

CM= Climate model
Dist = Distribution
PEM = Parameter Estimation Method
AT = Analysis type
DM = Downscaling method

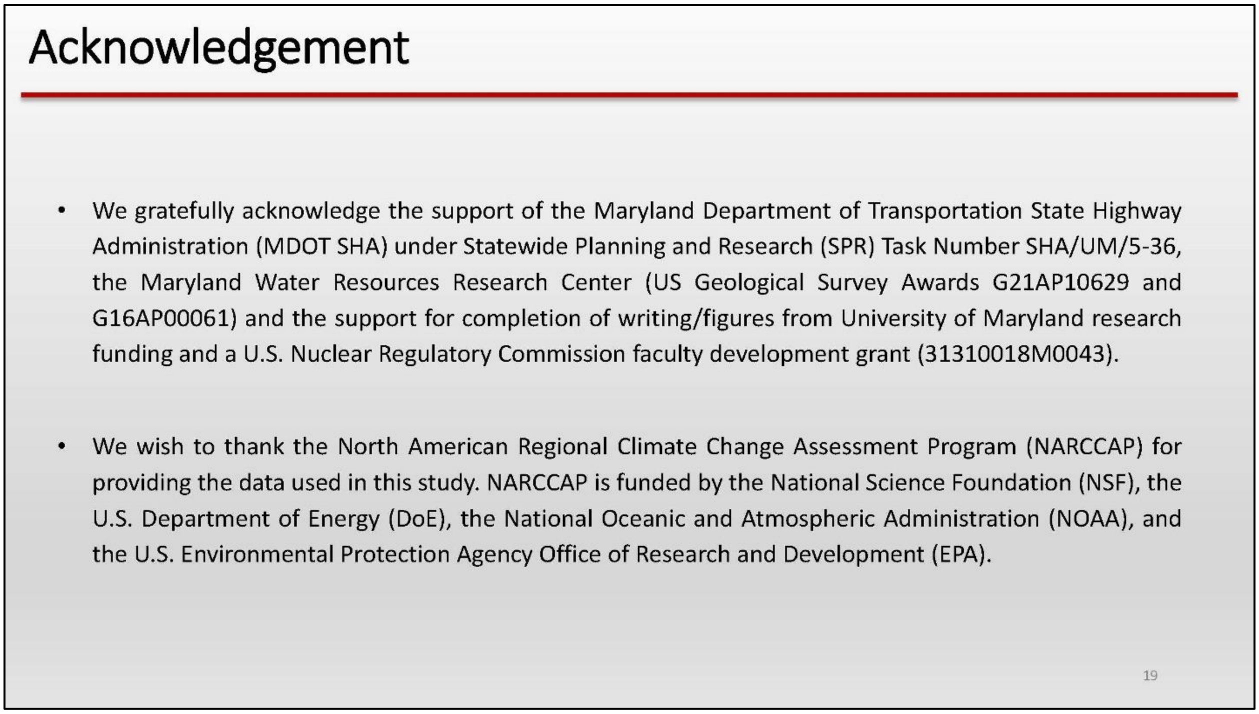
17

Conclusions

- The climate model choice is the dominant contributing factor to the uncertainty in both current and future climate conditions.
- The order of contribution of modeling choices can change from one climate model to another.
- For a given climate model, the order of contribution of modeling choices can change in current and future climate conditions.
- After the climate model, which is ranked first, distribution choice and PEM most frequently are ranked second and third in terms of producing the highest variability. Downscaling method and analysis type contribute less to the uncertainty.

Azin Al Kajbaf

Email: *aalkajb1@jhu.edu*



3.5.8.3 Questions and Answers

Question:

With respect to the climate models, are all the climate models were running the same emissions scenarios? Or did you look at different emissions scenarios?

Answer:

Emission scenarios are the same.

Question:

Which scenario was that?

Answer:

I need to check that, but I did not select the emission scenarios myself. These are the outputs of the NARCCAP[18] climate models. So, these are the already down-scaled regionally with a specific scenario.

Question*:*

As far as I understand machine learning models, their capabilities are mainly within the boundaries of their training sets. Climate model results are almost guaranteed to exceed these boundaries in some respects, as these training sets are based on current climate. Some parameters will be outside of the training regime. How do you account for these exceedances?

Answer:

[18] North American Regional Climate Change Assessment Program

In order to train the machine learning models, you have a have a ground truth and that is not the case with the result that you get from the climate models. With observational data we can train the models based on the observational data and then test the accuracy of the models using the observational data as well. So yes, I agree that this is a limitation that we face in the models, but this is what is possible with the available data.

Michelle Bensi: I just want to give more credit to Azin than she gave herself right there. In the paper that she wrote on this, she spent a lot of time looking at visualizations that look at the input-output pairs of the machine learning, basically looking at the response function. This allowed her to see the physical reasonableness of those models so she could sort of see the predicted response function and see if that produced physically reasonable results.

3.6 Day 3: Session 3B – Coastal Flooding

Session Chair: Joseph Kanney, NRC/RES

3.6.1 Presentation 3B-1: Flood Inundation Modelling on Nuclear Power Plant Site due to Complex Disasters

Authors: Byunghyun Kim[1], Jaewan Yoo, Beomjin Kim[2], Minkyu Kim[2]; [1]Kyungpook National University, [2]Korea Atomic Energy Research Institute

Speaker: Byunghyun Kim

3.6.1.1 Abstract

Recently, the intensity and frequency of typhoons and local intense precipitation are increasing worldwide due to climate change, and Korea is no exception. On July 23, 2020, heavy rain of 83 mm per hour occurred in Busan, South Korea, where the nuclear power plant is located. In addition, the maximum tide level rose to D.L.176cm, which was a record value far exceeding the D.L.46cm of the existing approximately highest high tide level.

The purpose of this study is to provide basic data for reducing flood damage to nuclear facilities and establishing systematic disaster prevention plans through two-dimensional (2D) flood analysis under complex disaster conditions including storm surge and localized heavy rain on the nuclear power plant sites located on the coast. The amount of external inflow into the nuclear power plant site according to the simultaneous occurrence of storm surge and local intense precipitation, which are increasing in frequency and intensity due to climate change, was estimated, and the flood depth and velocity were calculated through 2D flood modeling applying these as boundary conditions. The run-up and overtopping amounts affected by the storm surge on the nuclear power plant site were calculated based on EurOtop (2018). The estimated amount of overtopping was applied as an inflow boundary condition of a 2D flood inundation model that generated a grid with a resolution of 3m. In the case of a complex disaster considering the return period of 10,000 years and the duration of 5 hours, the maximum flood depth was 0.928m in area 1 and 0.522m in area 2.

This study was intended to help decision-making for flood prevention, flood reduction, and preparation of alternatives related to external flooding in nuclear power plant sites due to complex disasters.

3.6.1.2 Presentation (ADAMS Accession No. ML23177A182)

8th Annual NRC PFHA Research Workshop

Flood Inundation Modelling on NPP Site due to Compound Disasters

\- 2023. 3. 23 -

Byunghyun Kim[1], Jaehwan Yoo[1], Beom-Jin Kim[2] , Minkyu Kim[2]

[1]Kyungpook National University (KNU)
[2]Korea Atomic Energy Research Institute (KAERI)

Contents

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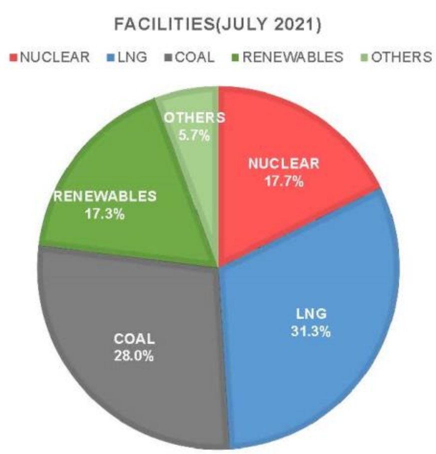
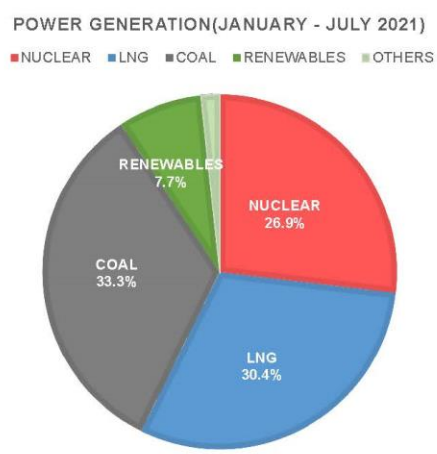
1. Introduction

3

Power Generation Capacities in Korea

1. Introduction





* Korea Electric Power Corporation

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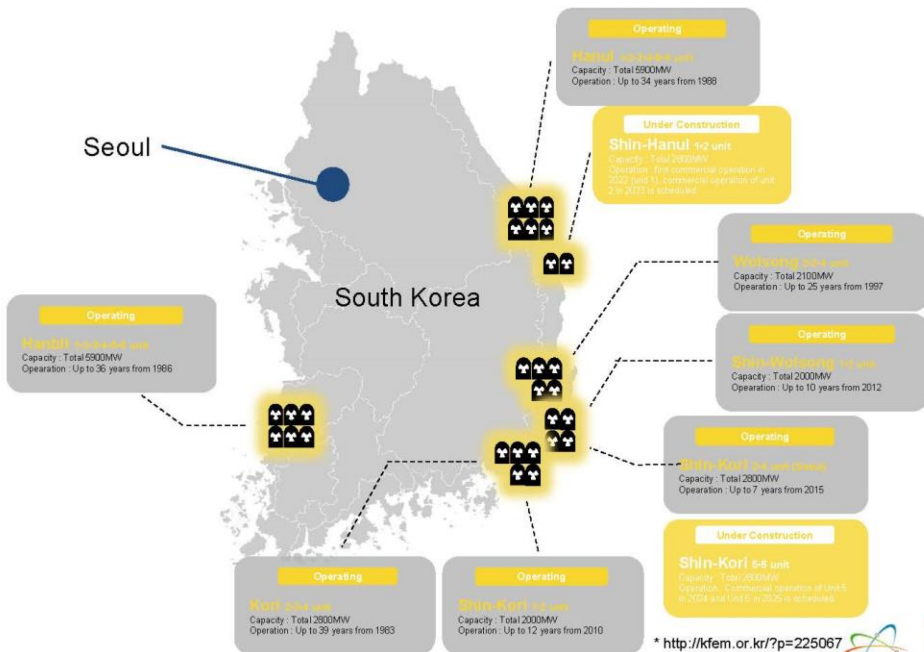
Nuclear Power Plants in Korea



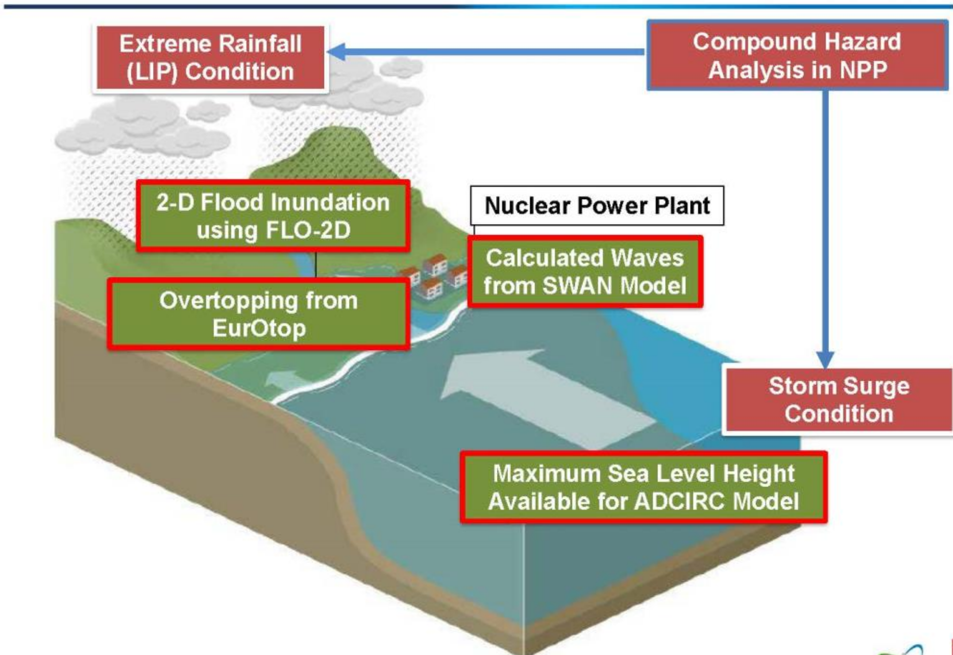
* http://kfem.or.kr/?p=225067

Research Background

- Recently, the intensity and frequency of typhoons and local intense precipitation are increasing worldwide due to climate change, and Korea is no exception.
- On July 23, 2020,
  - heavy rain of 83 mm per hour occurred in Busan, South Korea, where the nuclear power plant is located.
  - In addition, the maximum tide level rose to D.L.176cm, which was a record value far exceeding the D.L.46cm of the existing approximately highest high tide level.
- Therefore, this study aimed to
  - provide basic data for reducing damage and
  - establish systematic disaster prevention measures through flood modeling of nuclear facilities under compound risk conditions such as storm surge and localized heavy rain at coastal nuclear power plant sites.

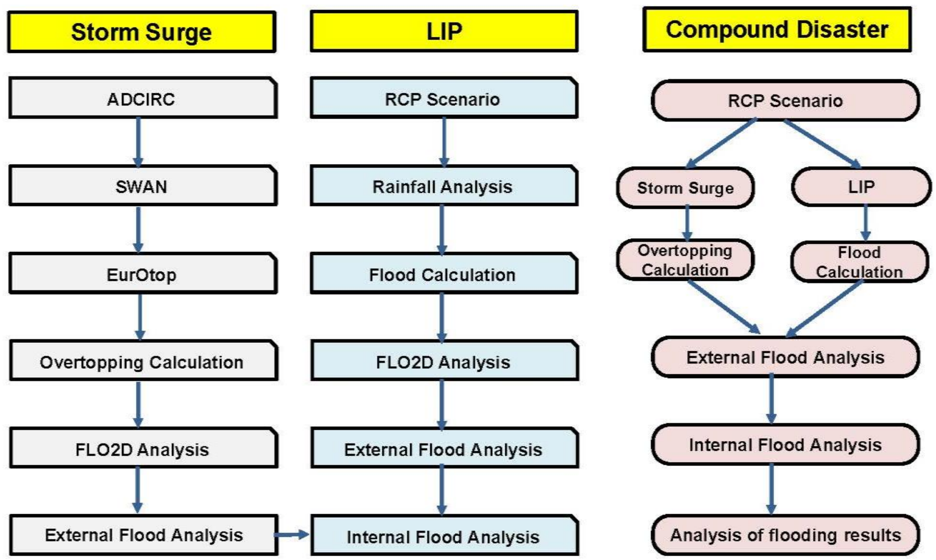
2. Methodology

Research Flow Chart



Research Flow Chart

2. Methodology



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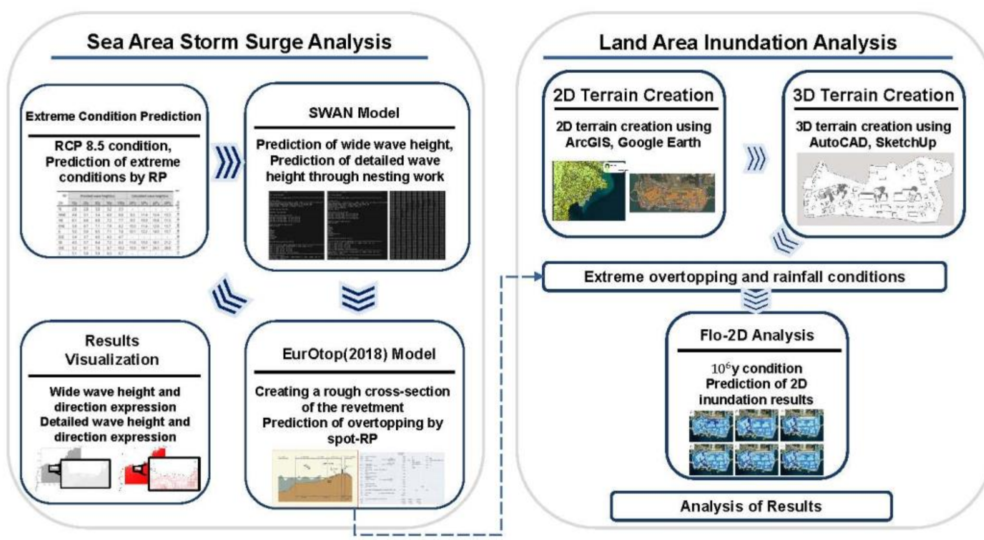
Research Method

2. Methodology



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Research Method

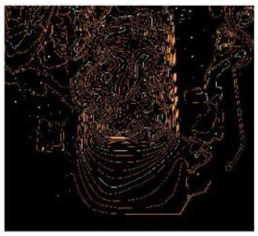
- To mitigate the impact of storm surge on Kori Units 1 and 2, 10m barriers with heights of 5.4m and 7.8m were considered, respectively.
- EurOtop(2018) was used to estimated the run-up and overtopping amounts on the nuclear power plant site.
- The estimated overtopping was then considerd as an inflow boundary condition for a 2D flood inundation model, which generated a grid with 3m resolution.
- The simulation covered return periods ranging from 100 years to 1,000,000 years and durations from 1 to 5 hours.

3. Application

Topography

Study Area

- Study Area : Kori Nuclear Power Plant site, Korea
- Area : 0.38km^2
- Precipitation : Probability Precipitation considering Climate Change



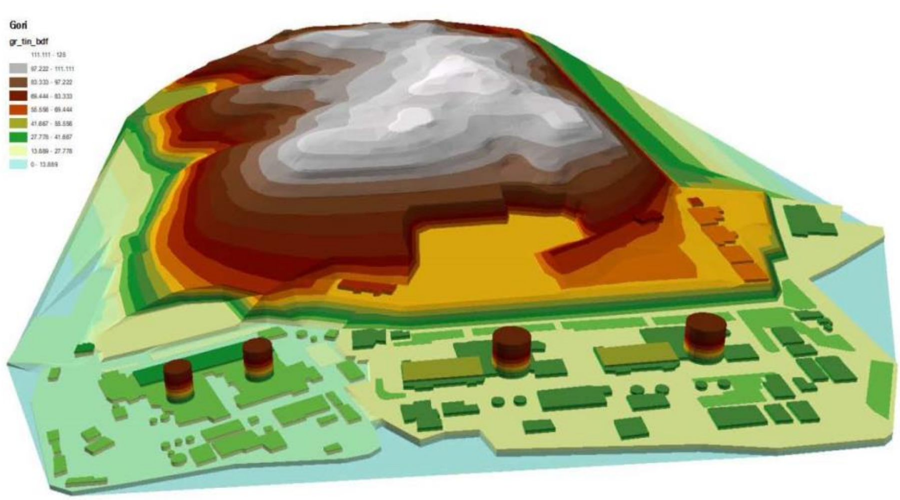
<1:5000 digital map>

<Satellite image>

<Topographic map>

Topography

Topographic Map

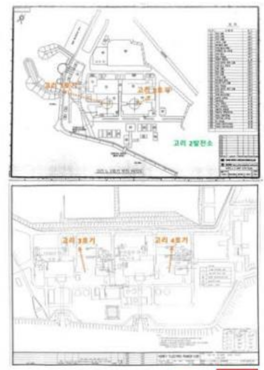


Topography

3.1 Study Area

External Site Analysis

- ▶ The grid size was 3m x 3m for 2d analysis, and total simulation time was 12 hr.
- ▶ FLO-2D model was applied to external flood inundation for the simulation of flood depth and velocity.



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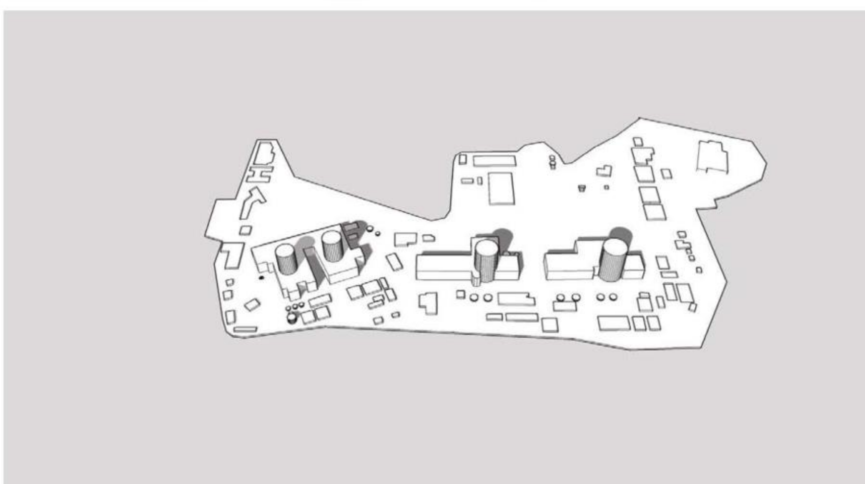
Topography

3.1 Study Area

External Site Analysis



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Scenario Generation

3.1 Study Area

<Storm Surge> <Storm Surge + LIP>

Return period condition(six)
10^2, 5×10^2, 10^3, 10^4, 10^5, 10^6

Duration(five)
1h, 2h, 3h, 4h, 5h

Probability conditions of wave/period
Median condition

+ LIP

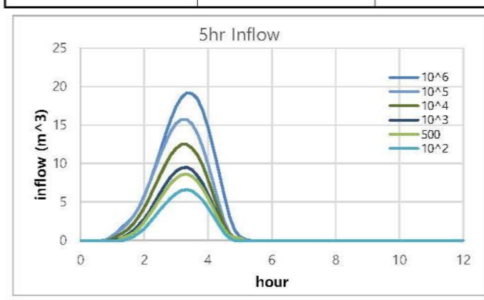
(Direct Precipitation & External Inflow)

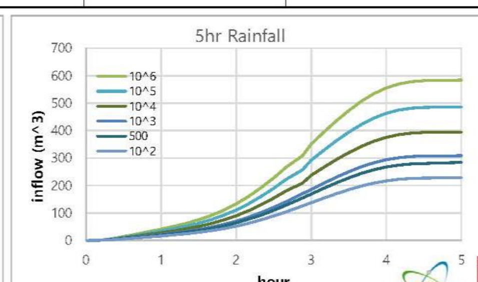
Rainfall-Runoff Hydrologic Analysis

3.1 Study Area

▶ Thirty different flood scenarios were generated by combining six return periods and rainfall durations ranging from 1 hour to 5 hours

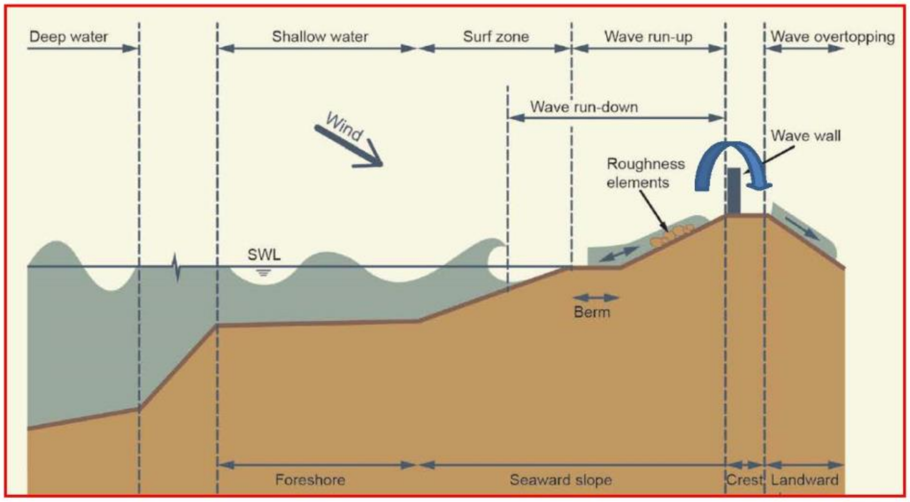
NPP 2 site	10^2 probability		10^6 probability	
	Rainfall(mm)	Peak Discharge(m^3/sec)	Rainfall(mm)	Peak Discharge(m^3/sec)
1hr	100.0	9.09	254.1	29.51
2hr	148.5	8.53	369.3	27.11
3hr	178.6	7.81	444.2	23.51
4hr	204.2	7.21	511.7	20.81
5hr	227.9	6.60	583.9	19.21





EurOtop(2018) Modeling

▶ Run-up and Overtopping over a vertical wall



EurOtop(2018) Modeling

▶ Equation used for empirical calculation

$$\frac{q}{\sqrt{g \cdot H_{m0}^3}} = \frac{0.026}{\sqrt{\tan\alpha}} \gamma_b \cdot \xi_{m-1,0} \cdot \exp\left[-\left(2.5 \frac{R_c}{\xi_{m-1,0} \cdot H_{m0} \cdot \gamma_b \cdot \gamma_f \cdot \gamma_\beta \cdot \gamma_v}\right)^{1.3}\right] \quad 8.27$$

with a maximum of: $$\frac{q}{\sqrt{g \cdot H_{m0}^3}} = 0.1035 \exp\left[-\left(1.35 \frac{R_c}{H_{m0} \cdot \gamma_f \cdot \gamma_\beta \cdot \gamma^*}\right)^{1.3}\right] \quad 8.28$$

$$\gamma_b = 1 - r_B(1 - r_{db}) \quad \text{for: } 0.6 \le \gamma_b \le 1.0 \quad 5.40$$

$r_{db} = 0.5 - 0.5\cos(\pi \frac{d_b}{R_{u2\%}})$ for a berm above still water line

$r_{db} = 0.5 - 0.5\cos(\pi \frac{d_b}{2 \cdot H_{m0}})$ for a berm below still water line 5.42

$r_{db} = 1$ for berms lying outside the area of influence

For practical purposes, it is recommended to use the following expressions for short-crested waves to calculate the influence factor γ_β for *wave run-up*:

$$\gamma_\beta = 1 - 0.0022|\beta| \quad \text{for: } 0^\circ \le \beta \le 80^\circ \text{ (short-crested waves)}$$
$$\gamma_\beta = 0.824 \quad \text{for: } |\beta| > 80^\circ \quad 5.28$$

and for *wave overtopping*:

$$\gamma_\beta = 1 - 0.0033|\beta| \quad \text{for: } 0^\circ \le \beta \le 80^\circ \text{ (short-crested waves)}$$
$$\gamma_\beta = 0.736 \quad \text{for: } |\beta| > 80^\circ \quad 5.29$$

$$r_B = \frac{B}{L_{Berm}} \quad 5.41$$

$$\frac{R_{u2\%}}{H_{m0}} = 1.65 \cdot \gamma_b \cdot \gamma_f \cdot \gamma_\beta \cdot \xi_{m-1,0} \quad 5.1$$

The influence factor is a function of the dimensionless promenade width G_c (with $L_{m-1,0}$ the deep water wave length and $T_{m-1,0}$ measured at the toe of the structure) and is expressed as follows:

$$\gamma_{prom} = 1 - 0.47 \frac{G_c}{L_{m-1,0}} \quad 5.49$$

$$\gamma_{prom\_v} = 0.87 \gamma_{prom} \gamma_v \quad 5.50$$

EurOtop(2018) Modeling

3.2 Storm Surge

EurOtop(2018) Modeling in NPP1					
		Hs_(m)_5%	Hs_(m)_mean	Hs_(m)_median	Hs_(m)_95%
H_{m0}	significant wave height	3.62	5.25	5.33	6.62
tanα	slope	0.50	0.50	0.50	0.50
γ_b	effect of berms	0.86	0.86	0.86	0.86
γ_B		0.24	0.18	0.17	0.16
$\xi_{m-1,0}$	breaker parameter based on $s_{m-1,0}$ ($\xi_{m-1,0} = \frac{tan\alpha}{\sqrt{H_{m0}/L_{m-1,0}}}$)	6.18	5.13	5.09	4.57
$L_{m-1,0}$	width of berm ($L_{m-1,0} = \frac{gT^2}{2\pi}$)	553.00	553.00	553.00	553.00
γ_f	effect of roughness (Concrete : 1)	1.00	1.00	1.00	1.00
γ_β	effect of oblique waves (run-up)	0.93	0.93	0.93	0.93
γ_β	effect of oblique waves (overtopping)	0.90	0.90	0.90	0.90
γ_v	effect of wave wall ($\gamma_v = \exp(-0.56\frac{h_{wall}}{R_c})$)	0.65	0.65	0.65	0.65
γ^*	($\gamma^*=\gamma_{prom\_v}$)	0.57	0.57	0.57	0.57
γ_{prom}	effect of promenade	1.00	1.00	1.00	1.00
R_c	crest freeboard of structure	6.57	6.57	6.57	6.57
L_B	Berm으로부터 Hm0만큼 높은 지점에서 Hm0만큼 낮은 지점의 x거리	21.19	28.48	28.84	30.98
db	Berm Height (d_b =Berm Elevation-SWL)	1.57	1.57	1.57	1.57
q	(l/s/m) , 위의 식 인용	1.3084	2.4873	2.5521	3.6779

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EurOtop(2018) Modeling

3.2 Storm Surge

EurOtop(2018) Modeling in NPP2					
		Hs_(m)_5%	Hs_(m)_mean	Hs_(m)_median	Hs_(m)_95%
H_{m0}	significant wave height	5.39	7.58	7.44	10.26
tanα	slope	0.75	0.75	0.75	0.75
γ_b	effect of berms	0.60	0.60	0.60	0.60
γ_B		0.57	0.51	0.51	0.46
$\xi_{m-1,0}$	breaker parameter based on $s_{m-1,0}$ ($\xi_{m-1,0} = \frac{tan\alpha}{\sqrt{H_{m0}/L_{m-1,0}}}$)	7.60	6.41	6.47	5.51
$L_{m-1,0}$	width of berm ($L_{m-1,0} = \frac{gT^2}{2\pi}$)	553.00	553.00	553.00	553.00
γ_f	effect of roughness (Concrete : 1)	1.00	1.00	1.00	1.00
γ_β	effect of oblique waves (run-up)	0.92	0.92	0.92	0.92
γ_β	effect of oblique waves (overtopping)	0.88	0.88	0.88	0.88
γ_v	effect of wave wall ($\gamma_v = \exp(-0.56\frac{h_{wall}}{R_c})$)	0.57	0.57	0.57	0.57
γ^*	($\gamma^*=\gamma_{prom\_v}$)	0.49	0.49	0.49	0.49
γ_{prom}	effect of promenade	0.98	0.98	0.98	0.98
R_c	crest freeboard of structure	6.57	6.57	6.57	6.57
L_B	Berm으로부터 Hm0만큼 높은 지점에서 Hm0만큼 낮은 지점의 x거리	42.20	47.79	47.55	52.25
db	Berm Height (d_b =Berm Elevation-SWL)	0.02	0.02	0.02	0.02
q	(l/s/m) , 위의 식 인용	2.9340	5.0755	4.9267	8.2063

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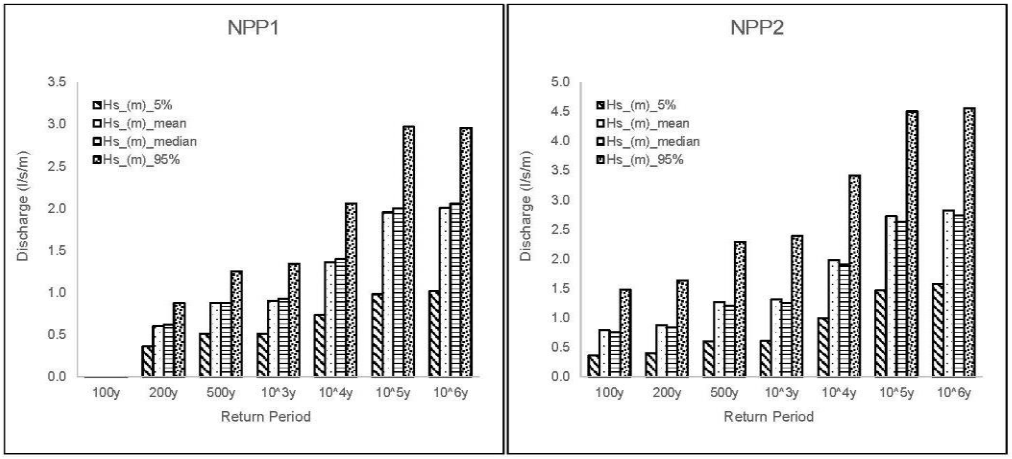
EurOtop(2018) Modeling

3.2 Storm Surge

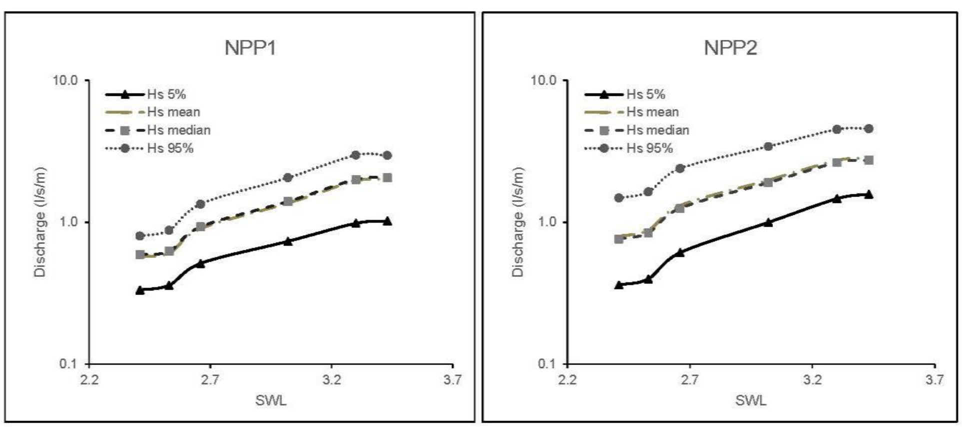
▶ Calculation of Overtopping by return period



EurOtop(2018) Modeling

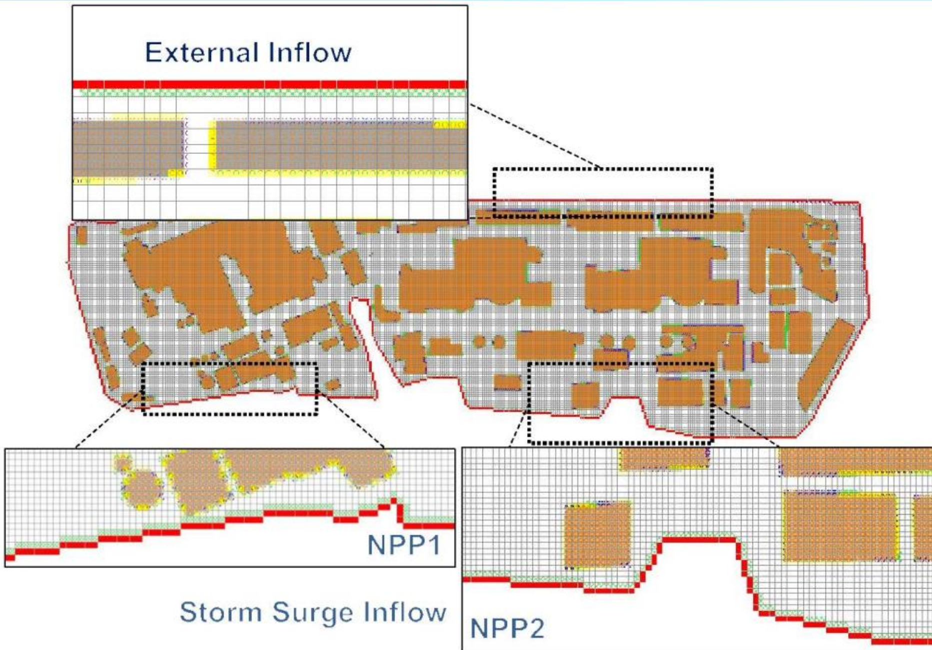
3.2 Storm Surge

▶ Overtopping according to sea level



Flood Inundation

3.2 Storm Surge



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Flood Inundation

3.2 Storm Surge

<30min>

<1hr>

<2hr>

<3hr>

<4hr>

<5hr>

<Time variation of external flood inundation depth(10^6 year)>

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Flood Inundation

3.2 Storm Surge

▶ **Flooding over time evolution due to storm surge**

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Flood Inundation

3.3 Storm Surge + LIP

▶ **Flooding over time evolution during LIP**

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Flood Inundation

3.3 Storm Surge + LIP

▶ **Flooding over time evolution during storm surge + LIP(Compound disaster)**

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Flood Inundation

3.3 Storm Surge + LIP

▶ **Flood depth comparison(Max Depth)**

<LIP condition>

<Storm Surge + LIP condition>

30

Flood Inundation

3.3 Storm Surge + LIP

▶ **Comparison of flood depth in case of LIP and Compound disaster**

<LIP condtion>

<Storm surge + LIP condition>

Comparison of Results

3.3 Storm Surge + LIP

❒ 2D flood inundation modeling for nuclear power plants under LIP and LIP+Storm Surge conditions with return periods ranging from $1x10^2$ to $1x10^6$ years was performed. Five points of NPP1 and five points of NPP 2 were selected and LIP conditions and LIP+Storm Surge conditions were compared.

<Maximum flooding point of nuclear power plant site>

Comparison of Results

▶ **Flood depth comparison(Max depth, 5hr duration)**

NPP1

Grid No.	5072	6545	6792	7350	8230	Grid No.	5072	6545	6792	7350	8230
100y	0.192	0.203	0.32	0.211	0.312	100y	0.436	0.467	0.655	0.481	0.656
500y	0.24	0.255	0.376	0.264	0.368	500y	0.499	0.556	0.766	0.576	0.768
1000y	0.248	0.264	0.383	0.271	0.378	1000y	0.531	0.589	0.802	0.604	0.797
10000y	0.279	0.299	0.417	0.308	0.409	10000y	0.655	0.686	0.921	0.706	0.928
100000y	0.31	0.333	0.453	0.343	0.447	100000y	0.748	0.793	1.024	0.809	1.030
1000000y	0.317	0.341	0.461	0.351	0.457	1000000y	0.822	0.859	1.100	0.875	1.109

NPP2

Grid No.	14275	14546	18992	21942	23089	Grid No.	14275	14546	18992	21942	23089
100y	0.166	0.268	0.255	0.252	0.268	100y	0.339	0.403	0.396	0.397	0.402
500y	0.178	0.292	0.279	0.278	0.292	500y	0.378	0.447	0.440	0.440	0.445
1000y	0.179	0.297	0.284	0.28	0.299	1000y	0.392	0.458	0.454	0.457	0.459
10000y	0.194	0.323	0.308	0.305	0.325	10000y	0.442	0.513	0.522	0.529	0.517
100000y	0.209	0.343	0.329	0.324	0.345	100000y	0.486	0.579	0.584	0.590	0.577
1000000y	0.212	0.347	0.333	0.329	0.349	1000000y	0.541	0.615	0.625	0.634	0.614

<Storm Surge condition> **<LIP + Storm Surge condition>**

4. Conclusions

Conclusions

4.Conclusion

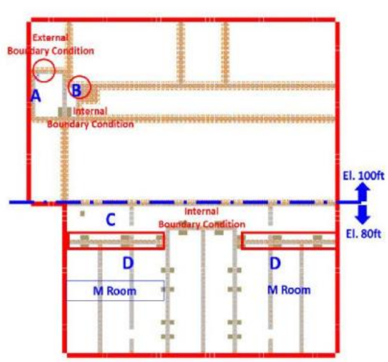
- ▶ In the case of a compound hazard considering the return period of 10,000 years and the duration of 5 hours, the maximum flood depth was 0.928m in area 1 and 0.522m in area 2.
- ▶ This study aimed to provide useful information for decision-making related to flood prevention, reduction, and preparation of alternatives for external flooding at nuclear power plant (NPP) sites, especially in the context of compound hazards.
- ▶ Additionally, the study aimed to identify suitable structural and non-structural measures, as well as regulatory tools, for addressing severe flooding events at major NPP sites.
- ▶ The findings of this study can be used to improve the overall resilience of NPPs to flooding and to support the development of effective flood risk management strategies.

Future Study

4.Conclusion

Internal Inundation and Hazard Analysis

- ▶ The grid size was 1m x 1m for 2D analysis, and total simulation time was 12 hr.
- ▶ A total of 4 areas form A to D in small flood areas.

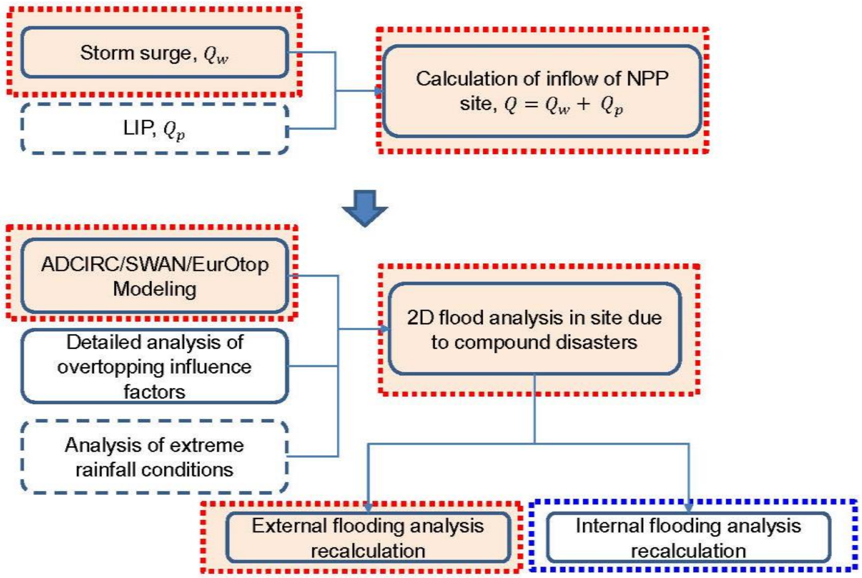


<Internal flood inundation analysis area>

Name of Building	100ft CB Door	100ft CB Stair Area	80ft M Facility Area	80ft M Facility Room
Area Mark	A	B	C	D

Future Study

Done Scheduled 4.Conclusion



Thanks for your attention.

bhkimc@knu.ac.kr

3.6.1.3 Questions and Answers

Question:

What sample spacing was applied along the overtopping boundary at the shoreline? Does it depend on wave attack angle and side slope?

Answer:

To calculate the amount of overtopping, we used the EurOtop empirical equations You can see the EurOtop parameters in this slide[19]. We considered all of the parameters: angles, the berm height, the wave height, slope. All of them were considered.

Question:

Why did you use the software FLO-2D versus other 2D modeling software?

Answer:

In this study we used FLO-2D, which is a finite difference model. My future plan is to use a finite volume model to simulate the flood inundation because the finite volume method has advantages to calculate the dry bed. So next time I'm going to use the two-dimensional finite volume model.

Question:

For the rainfall, you had the duration 1, 2, 3, 4, 5 hours. How did you deal with the distribution of the rainfall within that duration and sort of the uncertainty in how it's distributed within the time period?

Answer:

The Huff distribution is usually used in Korea for the distribution of the rainfall so we used the Huff distribution in this case.

Question:

I see in the south side[20] that you have a very wide boundary and it is storm surge inflow. How do you apply this boundary condition? Do you include the stage, I mean the water level directly or do you have a wind force input? How do you build the boundary condition of the south coastal line in your model?

Answer:

I'm going to explain briefly. As an input boundary condition, the storm surge inflow and that input were considered. To calculate the amount of the overtopping for storm surge inflow we used the EurOTop empirical equation. We considered wind and the other kind of parameters. The tide and wave height are calculated considering the wind.

Question:

So, if I understand correctly, you input your surge as a boundary condition. But I see the south side of your model has a long coastal line. Do you have one single input, a constant surge

[19] Referring to slide 21 of presentation

[20] Referring to slide 17 of presentation.

around the whole coastal line or you discretize it into different sections, each section have a different series of surges or surge values? Because it’s a long coastal line it’s not a single point.

Answer:

The height of the wave depends on the water depth so we considered several points, not a single point.

3.6.2 Presentation 3B-2: Probabilistic Flood Hazard Assessment for a Coastal Nuclear Power Plant Using Climate Change Projections

Author: Gorkem Gungor, Zeynep Arslan; Ministry of Energy and Natural Resources, Turkey

Speaker: Gorkem Gungor

3.6.2.1 Abstract

Risk analysts consider the seismic hazard the most critical external threat to the safety and reliability of NPPs. However, inundations caused by extreme rainfall triggered by climate change also has a significant threat to NPPs. Therefore, assessing and modeling flood hazards and their effects on NPPs is critical for preventing initiating events and evaluating NPP safety. The probability of occurrence of such initiating events and their effects on the facility are determined using various statistical data, mathematical models and probabilistic simulations. For example, researchers applied a model combining stormwater management and overland flooding to simulate the flooding process at a coastal NPP in China, using parameters such as extreme rainfall, wave overtopping, and tidal flow. Another study assessed the risk of a spent nuclear fuel storage facility exposed to flood hazards by applying the Bayesian network, in three different time scenarios at the Sizewell-B NPP in the UK. There are also studies testing the validity of flood hazard risk assessment on a synthetic sample by processing the event and fault trees constructed for system-level performance into the Bayesian network. Researchers have conducted risk assessment studies in Turkey to analyze the financial risks for the safety of life and property against seismic, earthquake, volcano, and flood hazards. However, to the author's knowledge, no researcher has conducted a probabilistic flood hazard assessment for nuclear facilities in Turkey considering the impacts of climate change. In the first part of the study, the authors aim to assess the flood hazard assessment using Bayesian inference on a potential site used for benchmark study. In the second part of the study, the authors aim to conduct an extreme value analysis to extrapolate the hazard curves by focusing on the uncertainties related to climate change.

3.6.2.2 Presentation (ADAMS Accession No. ML23177A183)

T.C. ENERJİ VE TABİİ KAYNAKLAR BAKANLIĞI

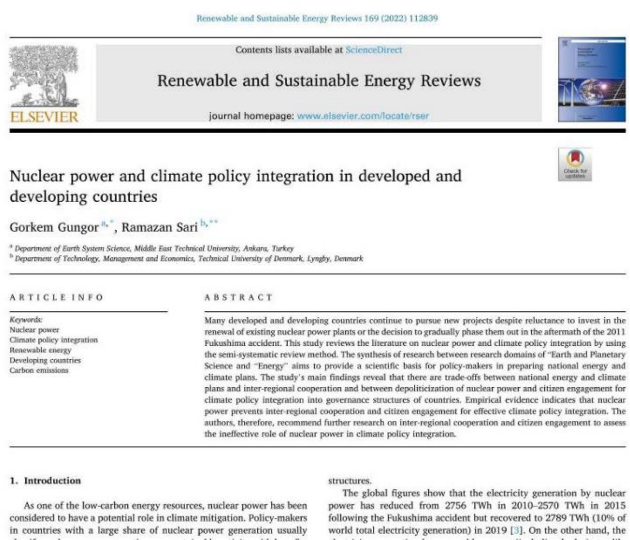
Probabilistic Flood Hazard Assessment for a Coastal NPP

Görkem GÜNGÖR - Zeynep ARSLAN

Ankara – 23 March 2023

About myself: education, employment and research carreer

- BS in Nuclear Engineering at Hacettepe University, modelling of TRIGA reactor with MCNP
- Sales person in chemical and mechanical industries
- Energy expert at Ministry of Energy and Natural Resources
- MS in Earth System Science at Middle East Technical University, mathematical modeling of Turkish energy system



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ELSEVIER

Nuclear power and climate policy integration in developed and developing countries

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ARTICLE INFO

Keywords:
Nuclear power
Climate policy integration
Renewable energy
Developing countries
Carbon emissions

ABSTRACT

Many developed and developing countries continue to pursue new projects despite reluctance to invest in the renewal of existing nuclear power plants or the decision to gradually phase them out in the aftermath of the 2011 Fukushima accident. This study reviews the literature on nuclear power and climate policy integration by using the semi-systematic review method. The synthesis of research between research domains of "Earth and Planetary Science and "Energy" aims to provide a scientific basis for policy-makers in preparing national energy and climate plans. The study's main findings reveal that there are trade-offs between national energy and climate plans and inter-regional cooperation and between depoliticization of nuclear power and citizen engagement for climate policy integration into governance structures of countries. Empirical evidence indicates that nuclear power prevents inter-regional cooperation and citizen engagement for effective climate policy integration. The authors, therefore, recommend further research on inter-regional cooperation and citizen engagement to assess the ineffective role of nuclear power in climate policy integration.

1. Introduction

As one of the low-carbon energy resources, nuclear power has been considered to have a potential role in climate mitigation. Policy-makers in countries with a large share of nuclear power generation usually

structures.

The global figures show that the electricity generation by nuclear power has reduced from 2756 TWh in 2010–2570 TWh in 2015 following the Fukushima accident but recovered to 2789 TWh (10% of world total electricity generation) in 2019 [3]. On the other hand, the

2

Spatial Strategy Plan of Turkey

- General objective:

To establish an inclusive, livable, innovative, competitive, sensitive to climate change and disasters, durable and sustainable country space by 2053.

- Plan dimensions

1. *Natural Structure, Natural Hazards and Sustainability in Ecosystem Services*
2. *Livable Settlements, Accessibility and Mobility*
3. *Climate Change Mitigation and Adaptation*
4. *Innovation and Technology*
5. *Population Dynamics and the Human Development*
6. *Competitiveness and Attractiveness*

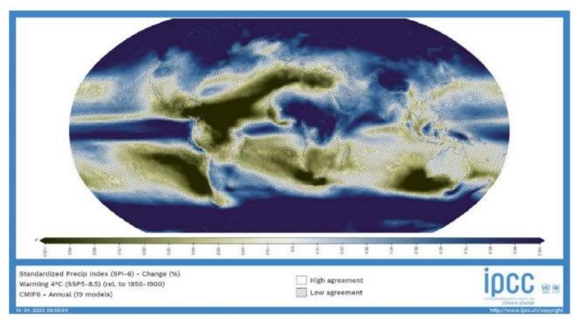
3

Natural Structure, Natural Hazards and Sustainability in Ecosystem Services

- Analysis and synthesis on three sections:

1. Climate change mitigation and adaptation
2. Spatial areas whose use and development are defined by special conditions
3. Natural hazards and resources

- Regional climate model based on RCP8.5
- Temperature increase higher in central and eastern regions
- Precipitation decrease in southern region
- Increase in drought period especially in central, western and north-western regions
- Decrease in cold weather front which is nearly eliminated in coastal areas
- Increase in very intense and extremely intense precipitation in all regions



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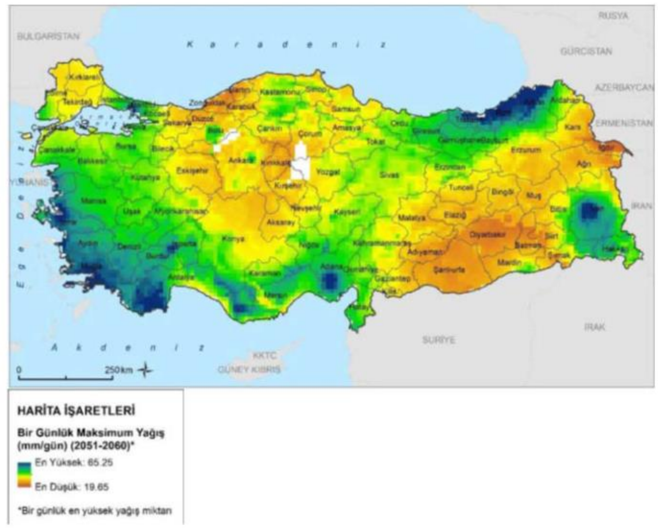
Natural Hazards

Hazard group	Hazard
Ground shifts	Earthquake
	Landslide
Heat sink effects	Drought
	Low water table
	River diversion
Site flooding	Intense precipitation
	Flooding caused by landslides or failure of dams or dikes
External fire	Forest fire
Biological events	Eutrofication



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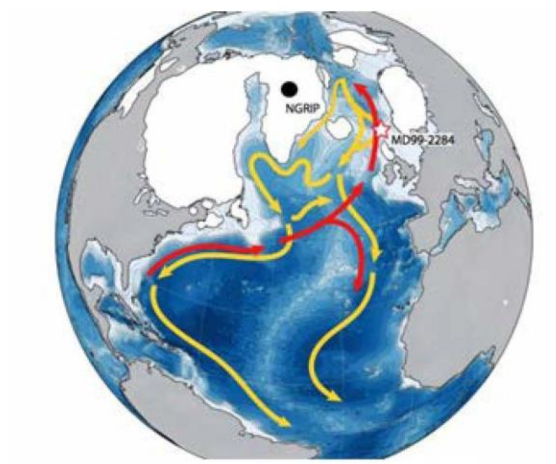
North Atlantic Oscillation

- NOA is one of the mechanisms which effects seasonal temperature and precipitation in Europe and Turkey (Pedersen et al, 2016*)
- However there are different climate control mechanisms in Turkey such as the land-water interaction in coastal regions and elevation in inner regions
- Figure gives the correlation plot between the NAO index and normalized temperature changes using data from NOAA National Climatic Data Center using the interface of University of Chicago
- The retreat of sea ice in the Arctic Ocean could also have a feedback in the NAO cycle



* Pedersen, R. A., Cvijanovic, I., Langen, P. L., & Vinther, B. M. (2016). The impact of regional Arctic sea ice loss on atmospheric circulation and the NAO. *Journal of Climate*, *29*(2), 889–902.

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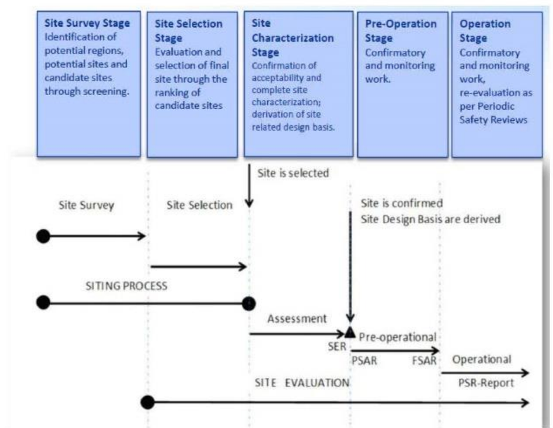
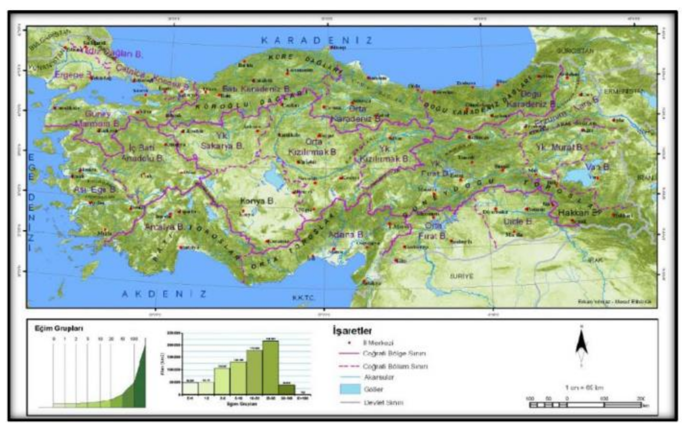
Objective and Scope

- Preparation of the plan for site survey of advanced LWRs
- Review of literature on natural hazards and climate scenarios for the regions
- Identification of natural hazards for regions
- Screening of external initiating events based on the identified natural hazards
- Site level probabilistic risk analysis for initial phase of siting



SMR Development Report

- Assesment of light water cooled SMR designs based on technology and licensing readiness levels
- Electrification of industrial and transport sectors and development of a regional hydrogen economy in Europe
- Requirements for environmental impact assessment and Nuclear regulatory authorization
- Survey of potential sites for multi-unit deployment based on national and international standards



Topography

Literature Review

- Naïve search using litsearchr (Grames et al., 2019*) package to generate non-author biased keywords
- Hazard analysis: 227 articles with 20.75 average citations per article (h-index of 33)
  - Final sample of 222 articles covering the period from 1993 to 2022 in 105 sources
- Flood hazard: 60 articles with 11.33 average citations per article (h-index of 16) covering the period from 2006 to 2022 in 39 sources
- Probabilistic assessment: 17 articles with 5.29 average citations per article (h-index of 4)
  - Final sample of 12 articles covering the period from 2010 to 2021 in 11 sources

Research groups	Search terms
Hazard analysis	AK=(\"decreas* flood* hazard*\" OR \"flood* hazard*\" OR \"geo-hydrolog* hazard*\" OR \"hazard* analysi*\" OR \"hazard* assess*\" OR \"hazard* evalu*\" OR \"hazard* link*\" OR \"hazard* review*\" OR \"landslid* hazard*\" OR \"natur* hazard*\" OR \"probabilist* tsunami* hazard*\" OR \"quantit* multi-hazard*\" OR \"region* natur* hazard*\" OR \"seismic* hazard*\" OR \"storm* hazard*\" OR \"tsunami* hazard*\") AND CU=Turkey (search date: 02.03.2023)
Flood hazard	AK=(\"decreas* flood*\" OR \"flood-pron* intens*\" OR \"flood* frequenc*\" OR \"flood* hazard*\" OR \"flood* prevent*\" OR \"flood* probabl*\" OR \"flood* suscept*\" OR \"flood* vulner*\" OR \"socioeconom* flood*\" OR \"spatiotempor* socioeconom* flood*\" OR \"urban* flood*\") AND CU=Turkey (search date: 01.03.2023)
Probabilistic assessment	AK=(\"best-fit* probabl*\" OR \"flood* probabl*\" OR \"heterogen* probabl*\" OR \"probabilist* method*\" OR \"probabilist* tsunami*\" OR \"probabl* distribut*\" OR \"probabl* occurr*\" OR \"suitabl* probabl*\") AND CU=Turkey (search date: 01.03.2023)

* Grames, E. M., Stillman, A. N., Tingley, M. W., & Elphick, C. S. (2019). An automated approach to identifying search terms for systematic reviews using keyword co-occurrence networks. *Methods in Ecology and Evolution*, *10*(10), 1645–1654.

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Hazard Analysis

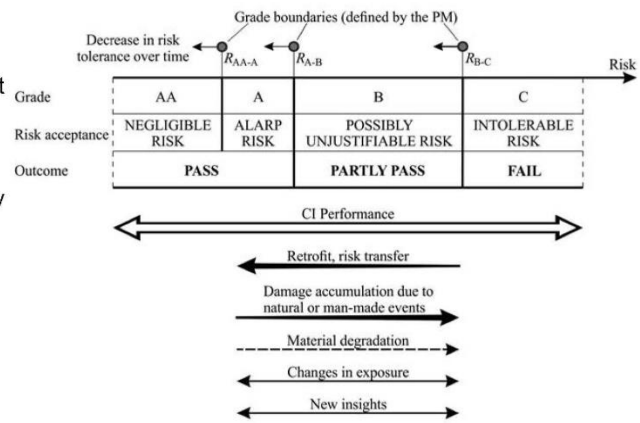
❖ **The role of increased land use on flood vulnerability**

- Case study on Güneysu river flooding in North East Turkey with improper land use
- Using HEC-RAS Model, the change in land use was found to increase the risk of flood more than the amount of rainfall and the rate of discharge flow change (Melisa et al, 2020*)

* Melisa, C. K., Varol, N., & Gungor, O. (2020). Investigation of the role of land use method on increased flood vulnerability in rural areas: a case study on Güneysu River, Turkey. *ARABIAN JOURNAL OF GEOSCIENCES*, *13*(13), 578.

❖ **Stress test of critical (non-nuclear) infrastructure**

- 1) oil refinery and petrochemical plant, 2) earth-fill dam in Switzerland, 3) transboundary oil pipeline, 4)national gas storage and distribution network, 5) port infrastructure and 6) industrial district
- Grading and penalty system based on the probabilities of failure exceeding confidence limit (Argyroudis, 2020**)



** Argyroudis, S. A., Fotopoulou, S., Karafagka, S., Pitilakis, K., Selva, J., Salzano, E., Basco, A., Crowley, H., Rodrigues, D., Matos, J. P., Schleiss, A. J., Courage, W., Reinders, J., Cheng, Y., Akkar, S., Uçkan, E., Erdik, M., Giardini, D., & Mignan, A. (2020). A risk-based multi-level stress test methodology: application to six critical non-nuclear infrastructures in Europe. *Natural Hazards*, *100*(2), 595–633.

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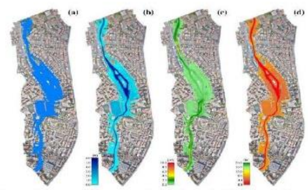
Flood Hazard

❖ **HEC-RAS hydrodynamic model simulations for urban flood hazard analysis**

- Used a 2D hydrodynamic HEC-RAS model for urban floodplain of Kılıçözü Creek (Kırşehir, Turkey),
- Produced simulations with 2D urban flood modeling under the 500-year flood scenario,
- Results - Kılıçözü Creek's channel capacity is insufficient to discharge waters (Yalçın, 2020*).

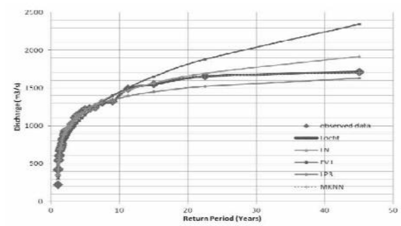


Results of the base model simulation: a. flood extent, b. inundation depths, c. flow velocities, d. arrival times

* Yalcin, E. (2020). Assessing the impact of topography and land cover data resolutions on two-dimensional HEC-RAS hydrodynamic model simulations for urban flood hazard analysis. *Natural Hazards*, *101*(3), 995-1017.

❖ **Nonparametric Approaches In Turkey**

- Analyzed the flood quantiles of return periods up to 500 years at Kayraktepe Dam (Mersin) with LOCFIT and K-NN models,
- Compared the suitability of nonparametric and parametric approaches,
- Results - nonparametric approaches better fit to historical data than parametric approaches (Şarlak, 2012**).



Quantile estimates for one of station

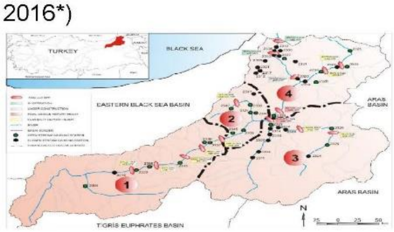
** Şarlak, N. (2012). Flood frequency estimator with nonparametric approaches in Turkey. *Fresenius Environmental Bulletin*, *21*(5), 1083-1089.

11

Flood Hazard

❖ **Regional flood frequency analysis with L-moments approach**

- Used L-moments method to perform a regional flood frequency analysis of the Çoruh Basin,
- Compared flow values and previously estimated values for the Yusufeli, Deriner, Borçka, and Muratlı dams,
- Results - the highest variations of 16.34% in the Borçka dam and 18.90% in the Muratlı dam (Aydogan et al., 2016*)

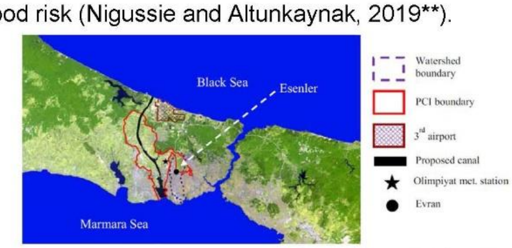


The Çoruh Basin development plan and stream gauging station.

* Aydoğan, D., Kankal & Önsoy, H. (2016). Regional flood frequency analysis for Çoruh Basin of Turkey with L-moments approach. *Journal of Flood Risk Management*, *9*(1), 69-86.

❖ **Flood risk in Ayamama Watershed, Istanbul**

- Used SLEUTH to model urbanization three different land-use policy scenarios,
- Findings revealed that allowing unrestricted urbanization will result in a significant increase in the amount of land inundated by flood,
- Results - If the PCI scenario is required, the level of development should be reduced in order to decrease flood risk (Nigussie and Altunkaynak, 2019**).



Location of the study watershed and the boundary of Project Canal İstanbul (PCI)

** Nigussie, T. A., & Altunkaynak, A. (2019). Modeling the effect of urbanization on flood risk in Ayamama Watershed, Istanbul, Turkey, using the MIKE 21 FM model. *Natural Hazards*, *99*, 1031-1047.

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Flood Hazard

❖ Modeling flood discharge using neuro-fuzzy and neural networks

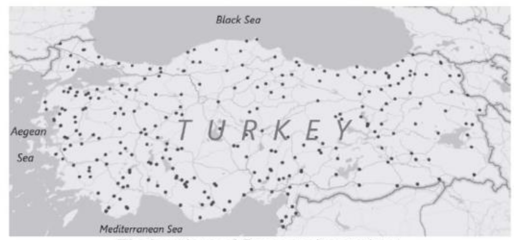
- Used neural network models to capture the nonlinear relationship between discharge and five independent variables,
- Watershed data from 543 catchments were used for the modeling study,
- Results - Multi-Layer Perceptron Neural Network outperformed others (Seçkin, 2011*).

River basin stations with boundaries of drainage areas in the study area.

* Seckin, N. (2011). Modeling flood discharge at ungauged sites across Turkey using neuro-fuzzy and neural networks. *Journal of hydroinformatics, 13*(4), 842-849.

❖ Parent Flood Frequency Distribution

- Annual peak series from 268 Turkish rivers were collected and an L-Moment ratio database was created,
- Using a framework of L-moment ratio diagrams, the probability distribution (PD) model was investigated among various distribution models,
- Results - generalized extreme value (GEV) distribution is accepted as a single parent PD for Turkey's annual maximum flow series (Aşıkoğlu, 2018**).



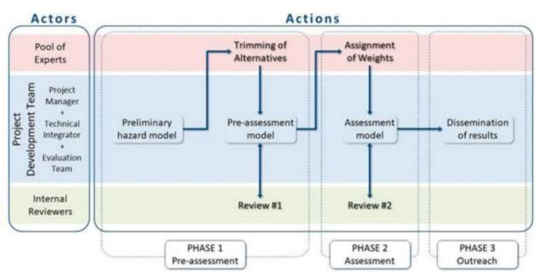
The locations of flow-gauging stations.

** Asikoglu, O. L. (2018). Parent flood frequency distribution of Turkish Rivers. Polish Journal of Environmental Studies, 27(2), 529-539.

Probabilistic Assessment

❖ Tsunami hazard modeling

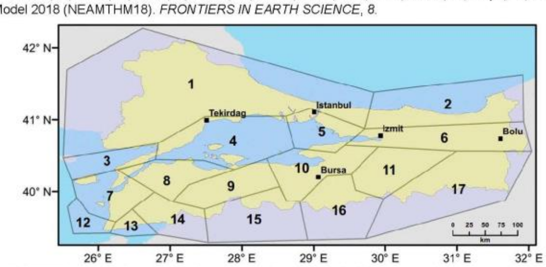
- Method: There phases with interaction between Project development, pool of experts and internal reviewers
- Output: an interactive hazard curve tool for tsunami inundation in the Mediterranean and Northeast Atlantic coast. https://tsumaps-neam.eu/ (Basili et al., 2021*)



* Basili, R., Brizuela, B., Herrero, A., Iqbal, S., Lorito, S., Maesano, F. E., Murphy, S., Perfetti, P., Romano, F., Scala, A., Selva, J., Taroni, M., Tiberti, M. M., Thio, H. K., Tonini, R., Volpe, M., Glimsdal, S., Harbitz, C. B., Lovholt, F., ... Zaytsev, A. (2021). The Making of the NEAM Tsunami Hazard Model 2018 (NEAMTHM18). *FRONTIERS IN EARTH SCIENCE, 8.*

❖PSHA Model for Marmara Region

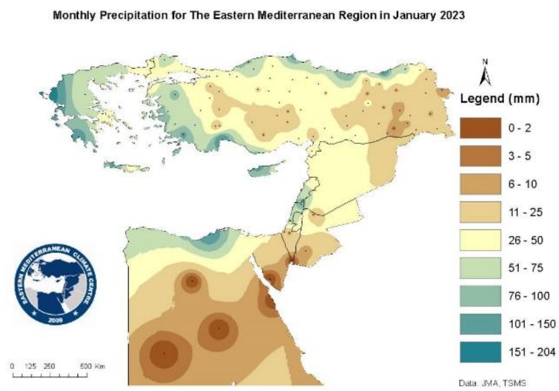
- Method: Propose a PSHA model based on the regional and historical earthquake magnitudes with region divided into zones
- The framework is also applicable where there are no active faults using Background Source Zones (Sianko et al., 2020**)



** Sianko, I., Ozdemir, Z., Khoshkholghi, S., Garcia, R., Hajirasouliha, I., Yazgan, U., & Pilakoutas, K. (2020). A practical probabilistic earthquake hazard analysis tool: case study Marmara region. *Bulletin of Earthquake Engineering, 18*(6), 2523–2555.

Prospects for Future

- Gathering of a core research team from climate science, environmental and geological engineering
- Development of collaboration with universities and research institutes
- Outreach for international cooperation with international organizations
- Participation to the workshop on probabilistic flood hazard assessment
- Development of a proposal for research on flood hazard assessment for an international project



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T.C. ENERJİ VE TABİİ KAYNAKLAR BAKANLIĞI

Thank you!

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3.6.2.3 Questions and Answers

Question:

You mentioned very briefly, the tsunami hazard. Is there much of a record of tsunamis affecting the Turkish coast and if so, what part of the coast?

Answer:

Yes, there are records of historical tsunamis. It's in the special plan of Turkey. It was not considered as a major hazard, more as an extraordinary hazard, which has happened in long time periods. However, last year in the earthquake in western Turkey, on the Izmir coast, there was a tsunami originating from a landslide in the sea, which resulted in both property damage and life damage actually.

Question:

With respect coastal storm surge hazards, what is the major storm type that's responsible for the storm surge hazard along the various parts of the Turkish coast? What type of storms and what seasonality is associated with those storms?

Answer:

The main risk is flooding from the increase of the water table in the country. We have different climate regions in Turkey and the seasonality is shifting, both the precipitation periods, the snowfall, things are shifting. So, it is difficult to say at which seasonality there is an increase in risk of flooding, but considering the elevation and the watersheds, and the mainly improper land use, the main risk comes from the increase of water table and flooding in the watersheds, which also damages the urban environment due to carriage of the debris from high elevations downstream to urban areas.

Question:

But is that also a factor in coastal areas?

Answer:

Yes, definitely. It's also a factor in coastal areas.

3.6.3 Presentation 3B-3: Probabilistic Coastal Compound Flood Hazard Analysis Pilot Study

Authors: Victor M. Gonzalez[1], Meredith L. Carr[1], Luke Aucoin[1], T. Chris Massey[1], Ning Lin[2], Dazhi Xi[2], Norberto C. Nadal Caraballo[1], Karlie Wellls[1]; [1]U.S. Army Corps of Engineers, Engineer Research and Development Center, Coastal and Hydraulics Laboratory, [2]Princeton University

Speaker: Meredith L. Carr

3.6.3.1 Abstract

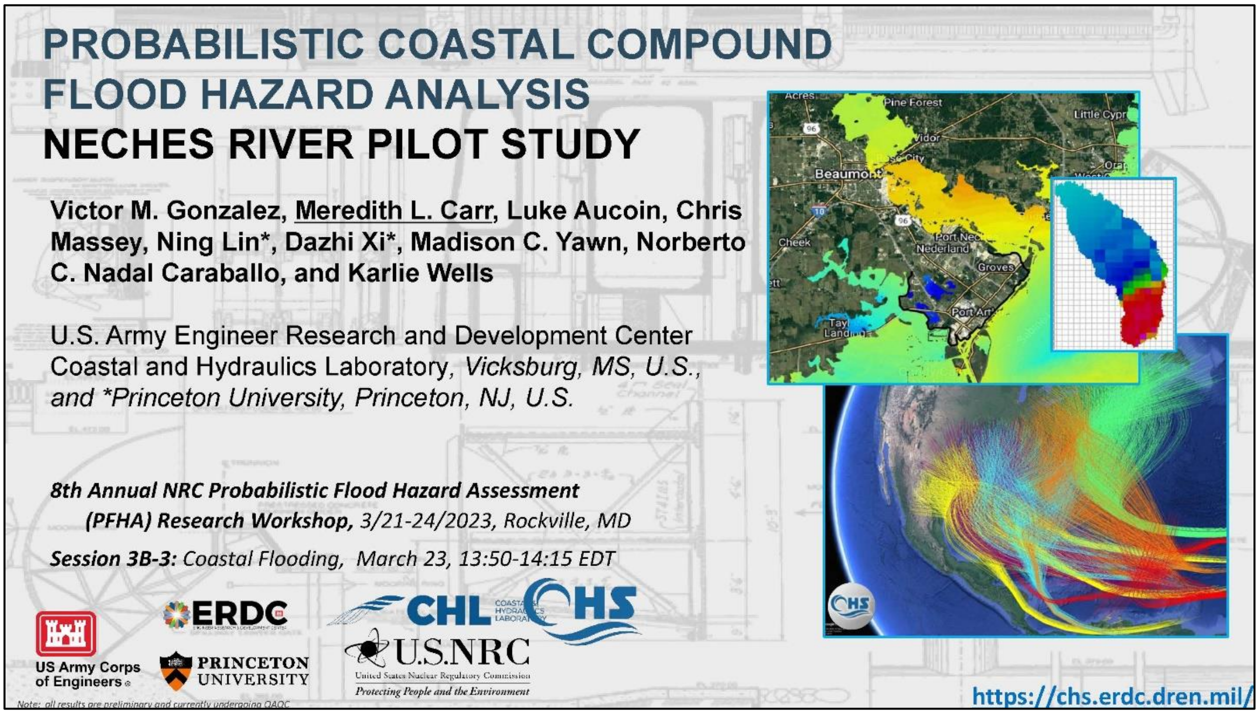
Coastal flooding due to storm surge and waves is often exacerbated by coincident weather events such as rainfall from extreme storms, including associated runoff and riverine flooding. This presentation will report on the Coastal Flooding Probabilistic Flood Hazard Assessment (PFHA) Pilot Study performed for the U.S. Nuclear Regulatory Commission by the U.S. Army Corps of Engineers' (USACE) Engineer Research and Development Center Coastal and Hydraulics Laboratory (USACE/ERDC/CHL). The pilot study demonstrates the application of PFHA to external flooding at a hypothetical nuclear power plant (NPP) location on the Lower Neches River watershed in Texas.

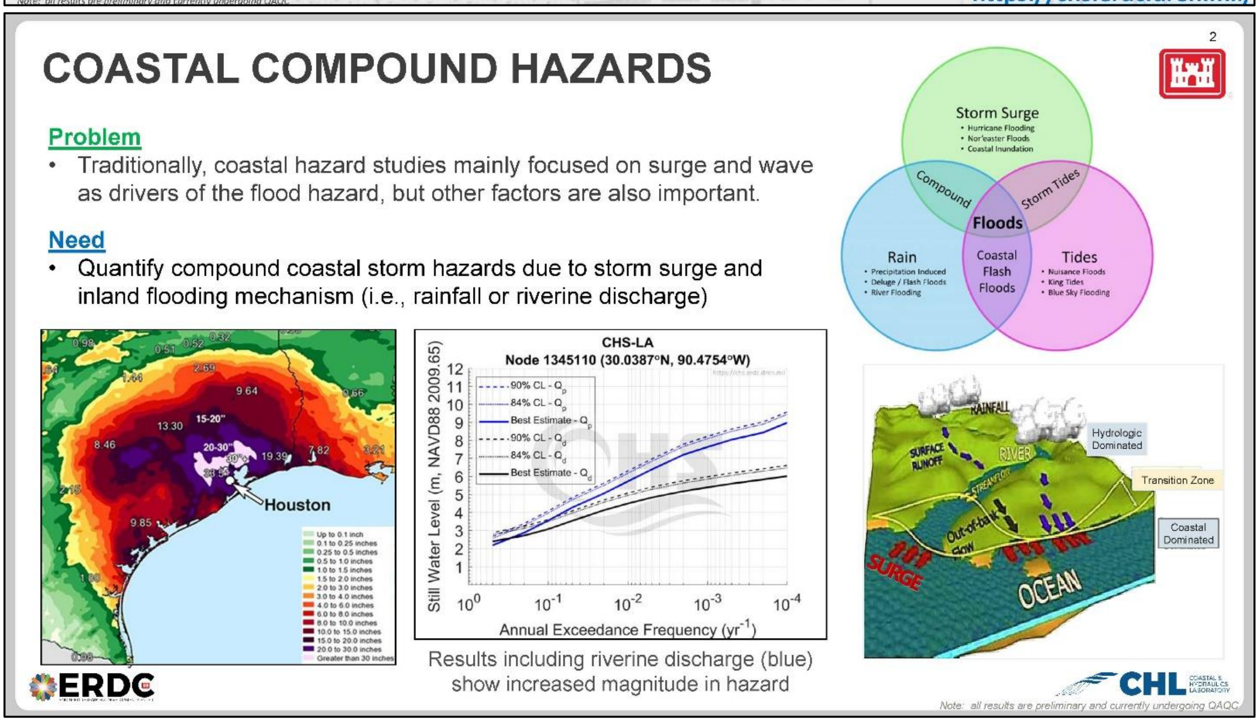
Characterization of the compound flooding hazard, including storm surge, astronomical tide, waves, rainfall, and coincident riverine flooding, along with associated uncertainties, is

necessary to fully address storm risk in coastal settings. A joint probability method (JPM)-type Probabilistic Coastal Hazard Analysis (PCHA) framework for quantifying coastal storm hazards was followed herein. It includes storm climatology characterization, high-resolution, high-fidelity numeric atmospheric, hydrodynamic, and wave modeling, and advanced joint probability analysis of atmospheric forcing to develop storm hazard curves and uncertainty. Incorporation of compound effects due to precipitation have previously relied on multivariate statistics and copula approaches of historical observations to quantify joint probability. However, TC rainfall-driven approaches have recently become more feasible, as precipitation models can be forced by the synthetic storm parameters that also drive the surge.

The compound probabilistic modeling approach being implemented here incorporates rainfall using a physics-based parameterized tropical cyclone rainfall (TCR) model driven by the same JPM atmospheric forcing developed for a regional Coastal Texas Coastal Hazard Study (CTX) available through the USACE Coastal Hazards System, allowing concurrent characterization of the compound flooding hazard and associated uncertainties. An optimally selected subset of 144 TCs were used to drive an HEC-HMS watershed model, coupled to a 2D HEC-RAS model of the Lower Neches River, and loosely coupled to the CTX surge at the boundary. A second coupling approach modified the CTX ADCIRC-STWAVE model to incorporate the time varying HMS outflow hydrograph as upstream boundary condition. The impacts of several model options were explored, including seasonally sampled relative humidity for the precipitation model, precipitation-based infiltration parameters, and antecedent riverine flow conditions. Coastal compound hazards were quantified through the integration of the combined water level responses at sites of interest. A Gaussian process metamodel was trained with the TC parameters and the TC responses to better represent the joint probability between atmospheric forcing parameters, hazard curves and their uncertainties through the development of an increased number of TCs. These results demonstrate the application of a Compound PFHA expansion of the ERDC/CHL PCHA with TC rainfall in the Lower Neches River. Modification of existing models and use of metamodeling in compound space were demonstrated as tools applicable to Compound Coastal Flood Hazard Analyses.

3.6.3.2 Presentation (ADAMS Accession No. ML23177A139)



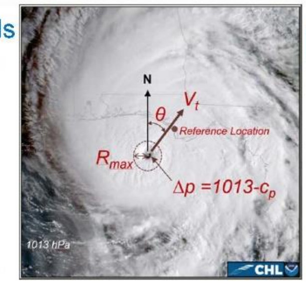


COMPOUND PROBABILISTIC FLOOD HAZARDS

GOAL: Characterize coastal flood hazards due to coastal surge and rainfall-induced streamflow from tropical cyclones (TCs)

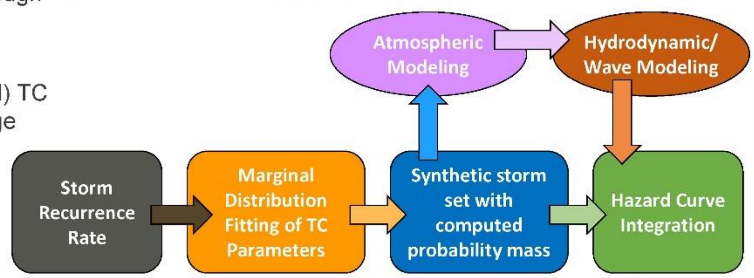
APPROACH:
Expand the ERDC-CHL Probabilistic Coastal Hazards Analysis (PCHA) Framework to compound flooding

- Explicitly incorporate rainfall hazard through a time-dependent spatially-varying parametric TC rainfall model
- Leverage Joint Probability Method (JPM) TC parameterization (typically used for surge modeling) as input for TC rainfall model
- Establish concurrent compound hazard characterization in a single workflow



$$\text{Response} = f(\hat{x}) = f(x_0, \Delta p, R_{\max}, V_f, \theta)$$

TC Parameters
Track position - (reference location, x_0).
Track angle - (heading direction, θ).
Intensity - (central pressure deficit, Δp).
Size - (radius of maximum winds, R_{max}).
Translational speed - (V_t)



ERDC

Note: all results are preliminary and currently undergoing QAQC

CHL

COMPOUND PROBABILISTIC FLOOD HAZARDS

GOAL: Characterize coastal flood hazards due to coastal surge and rainfall-induced streamflow from tropical cyclones (TCs)

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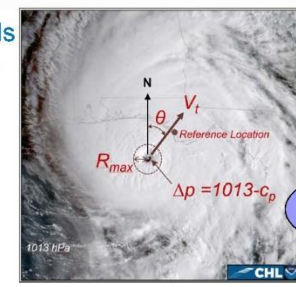
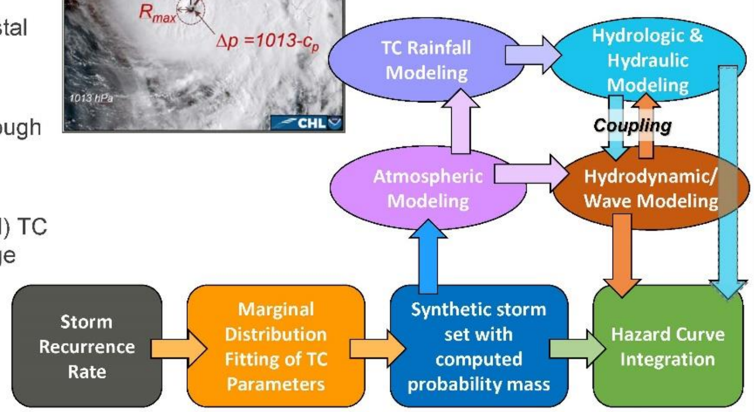


TC Parameters
Track position - (reference location, x_0).
Track angle - (heading direction, θ).
Intensity - (central pressure deficit, Δp).
Size - (radius of maximum winds, R_{max}).
Translational speed - (V_t)



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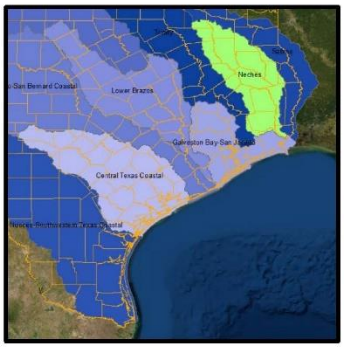
5

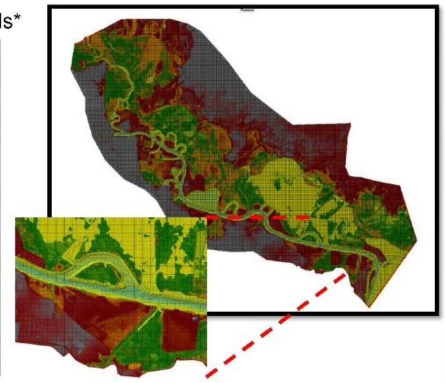
PILOT STUDY OBJECTIVE & LOCATION

Objective: Demonstrate application of PFHA to external flooding at a hypothetical location in a coastal setting

Adapt existing hydrology, hydraulics, & hydrodynamics models, data:

- USACE-CHL Coastal Texas Study (CTXS) PCHA results
  - 660 Synthetic Storm Suite and Statistics
  - ADCIRC and STWAVE models
- HEC-HMS & HEC-RAS inland models*





*Lower Neches Riverine Flooding Analyses (LNRFA), Forth Worth District, Mosser et al. 2019, courtesy SWG.

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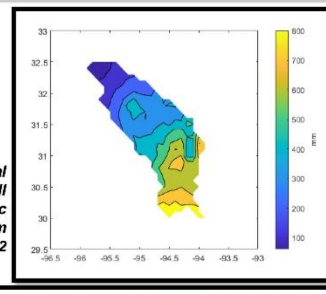
PILOT STUDY OBJECTIVE

Objective: Demonstrate application of PFHA to external flooding at a hypothetical location in a coastal setting

Expansion of PCHA to Compound Flooding:

- Optimized selection of representative local storm subset for compound site
- TCR Model rainfall using synthetic TC parameters from CTXS
- Spatial and temporal TC rainfall inputs drive hydrologic and hydraulic models with downstream boundary from coastal models
- Compound coastal models run with hydrologic output as inflow
- Hazard curves calculated for compound water level response

Total Rainfall Synthetic Storm 472



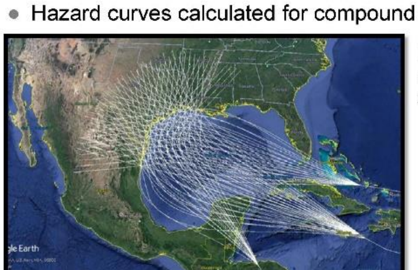
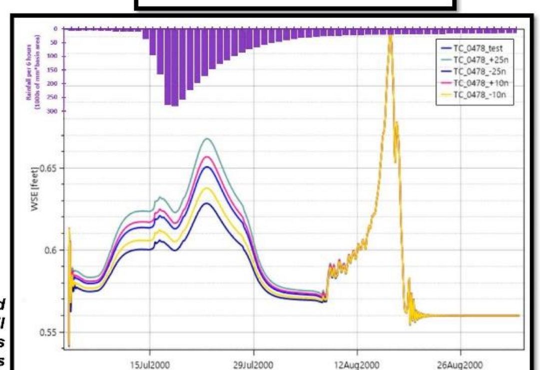


Illustration of the tracks developed for the 660 storm CTXS suite



Concurrently Plotted (a) Sample Rainfall (b) Hydrologic hydrographs (c)Surge Time Series

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SYNTHETIC TROPICAL CYCLONE RAINFALL

7

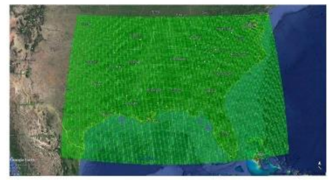
Model TC Rainfall to overcome sparse compound TC Record

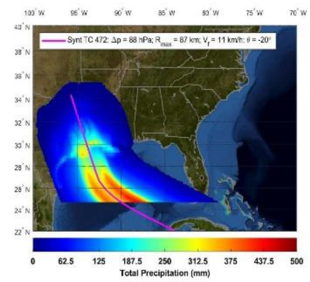
Selected Parametric Tropical Cyclone Rainfall Model (TCR, Lu et al. 2018)

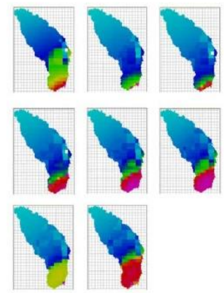
- Physics-based model; rainfall estimated by upward vapor flux
- Input: time-varying TC parameters (Wmax, Rmax, lat/lon)
- Output: hourly TC rainfall time series on 4 km grid for each synthetic TC

Limits of TC Rainfall Models

- Does not account well for storm's outer bands
- No interaction with other meteorological features
- Local bias correction may be significant







Lu, P., N. Lin, K. Emanuel, D. Chavas, and J. Smith. 2018. Assessing Hurricane Rainfall Mechanisms Using a Physics-Based Model: Hurricanes Isabel (2003) and Irene (2011). Journal of Atmospheric Science 75: 2337–2358.

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TC RAINFALL MODEL APPLICATION: NECHES PILOT

8

Historical Event Comparisons

- Computed event total rainfall (ETR) in TCR model for historical storms from PRISM observations
- TCR ETR underestimated measured ETRs, especially for large events

Adjustment of TCR Model and Bias Correction

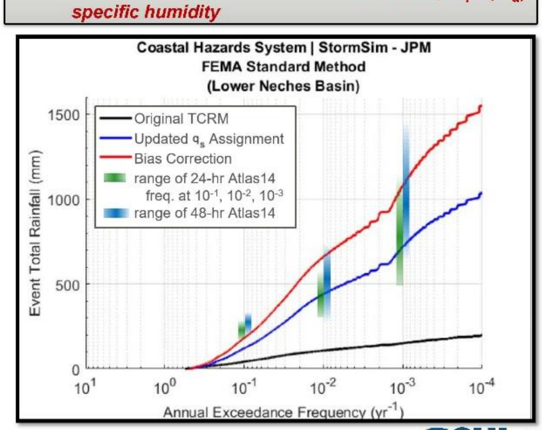
- Evaluated approaches for characterizing physical parameters of the TCRM (q_s, C_d)
  - Modified random sampling for q_s from entire southeast region to seasonal, regional sampling
- Local bias correction: at each grid point minimized error between the distributions of ETR observations vs. TCRM simulations

Calculated Bias-Corrected TC Rainfall for CTXS storms at each time step

Main Equation Driving the TCRM

$$P_{rate} = \epsilon_p \frac{\rho_{air}}{\rho_{liquid}} q_s (w_f + w_h + w_t + w_s + w_r)$$

Saturation specific humidity (q_s); *Friction, $w_f = f(C_d)$*



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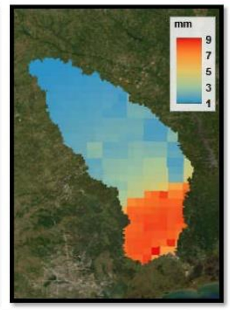
HYDROLOGICAL MODEL: AUTOMATING HEC-HMS

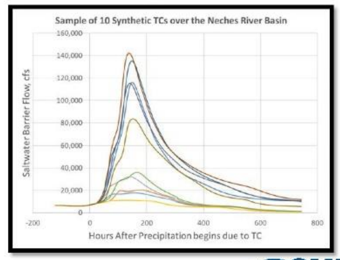
Adapted existing LFNRA HEC-HMS model

- 93 sub-basins, 8 reservoirs, calibrated to gridded rainfall, included precipitation-based frequency analysis flow results

Specific Implementation of Neches River Compound Pilot

- Automated outside of GUI using python with dynamically created input and run files for each of the 475 storms
- Input of TC Rainfall from TCR model for synthetic storms
  - Automated projection, weighting grid edge points, conversion to DSS
- Estimated TC frequency-dependent initial and constant loss rate
  - Employed LNRA frequency rainfall volume to assign 'equivalent frequency' to TC rainfall model volume for synthetic TCs; 'equivalent frequency' to assign loss parameters
- Automated unique antecedent flows curves for each TC
  - Selected ratio-to-peak baseflow parameter to produce equal mean baseflow at HMS outlet as rainfall-runoff began
  - Required unique antecedent flow curves due to storm dependent rainfall arrival speed and loss parameters





Calculated outflow hydrograph for each TC Synthetic Storm

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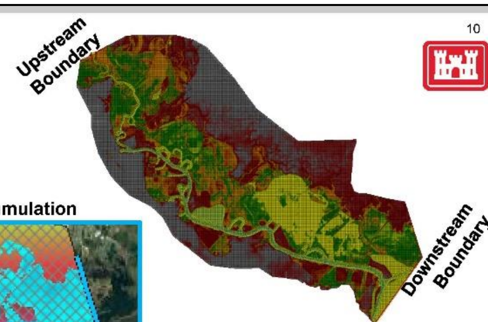
HYDRAULIC MODEL

Adapted 2D HEC-RAS model

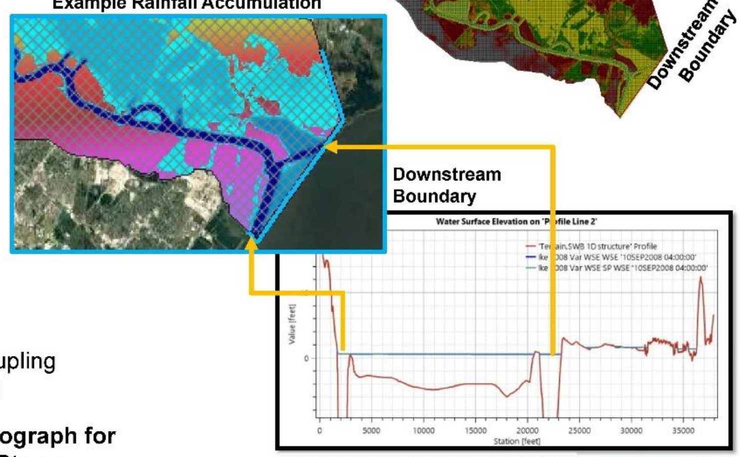
- Coupled with HEC-HMS model to a short 1D reach, 2D flow are for the rest of basin (very flat)
- Coupled downstream boundary with ADCIRC/STWAVE coastal model

Automation: HEC-RAS Python run and automated boundary conditions for each synthetic TC

- Driven by HMS inflow hydrograph at Saltwater Barrier and spatially and temporally varied TCR
  - Infiltration model as a reduction in rainfall; parameterized by land use and impervious area
- Downstream Boundary: One-Way coupling with ADCIRC-STWAVE CTXS results



Example Rainfall Accumulation



Test Results, Spatially Varied Boundary for two runs (Alex Sanchez, IWR-HEC)

Calculated outflow hydrograph for each TC Synthetic Storm

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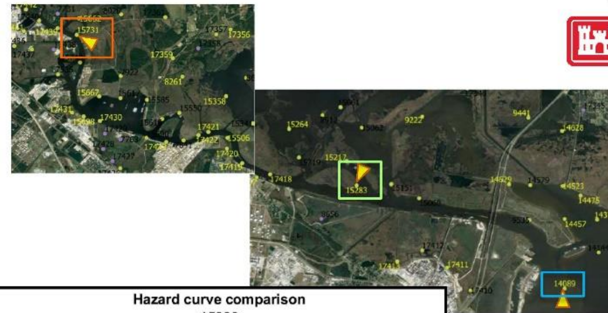
STORM SELECTION

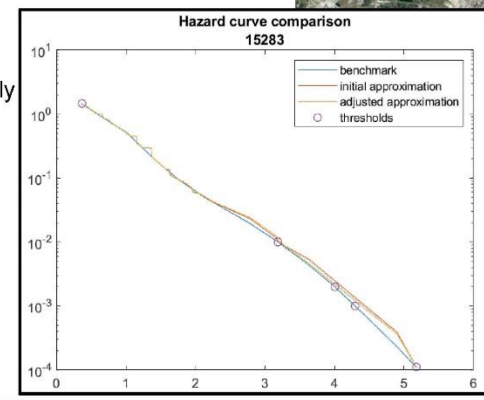


Based on CTXS Regional Coastal Study Storms

- Original 660 CTXS storms designed for entire Texas Coastal Region
- High fidelity ADCIRC/STWAVE storm response produced at ~ 18,000 savepoints

Selection of focused storm set for Compound Study

- Sub-sampled a smaller storm set to optimally characterize TC Response Hazard
  - Focused on downstream Neches River
  - Reduced computation expense
- Used a genetic algorithm-based design of experiments (DoE) optimization approach*
- Optimized for 3 locations



*Zhang, J., A. A. Taflanidis, N. C. Nadal-Caraballo, J. A. Melby, and F. Diop. 2018. Advances in surrogate modeling for storm surge prediction... Natural Hazards 94:1225-1253.

*Melby, J. A., T. C. Massey, A. L. Stehno, N. C. Nadal-Caraballo, S. Misra, V. M. Gonzalez. 2020. ERDC/CHL TR-21-15

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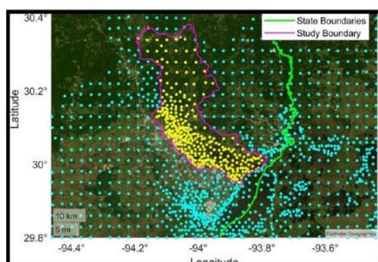
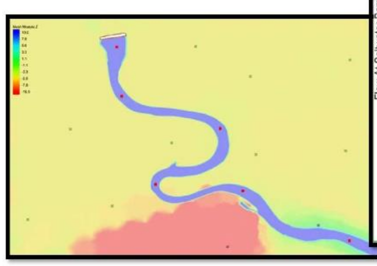
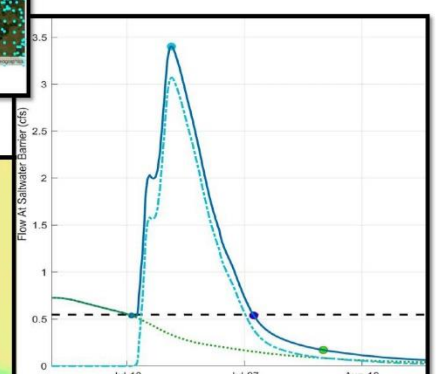
COMPOUND STORM SURGE AND INLAND MODELING

Compound ADCIRC/STWAVE

- Hydrodynamic model adjusted to include time-varying TC rainfall-induced inflow
- HMS outflow hydrograph used as new inflow boundary at Saltwater barrier in ADCIRC/ STWAVE mesh
- Grid refined and additional 300 savepoints added to capture Neches River and Saltwater Barrier area
- Water surface elevation response, which includes the rainfall induced riverine storm event flows, was used to quantify the flood hazard based on the 144 storms







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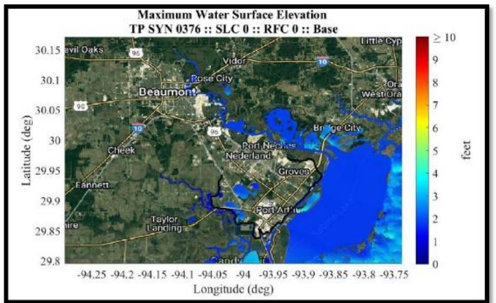
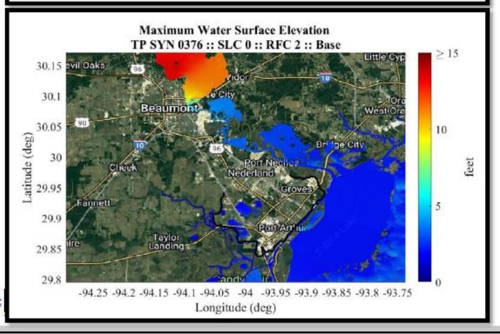
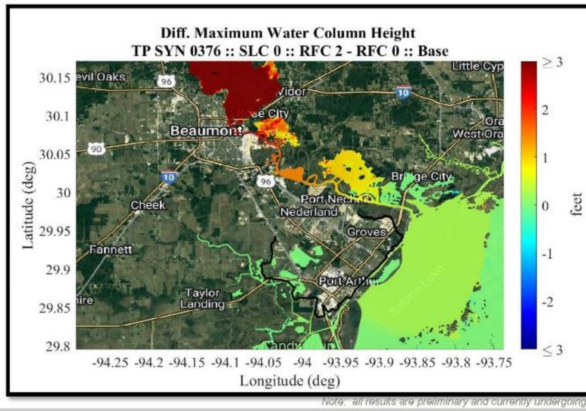
COMPOUND HAZARD MAXIMUM WSEL





Compound ADCIRC/STWAVE

- Example TC Storm 376
- Maximum Water Surface Elevation (WSEL) due to surge/wave with and without rainfall-driven inland hazard (left)
- Difference in Maximum WSEL (below)



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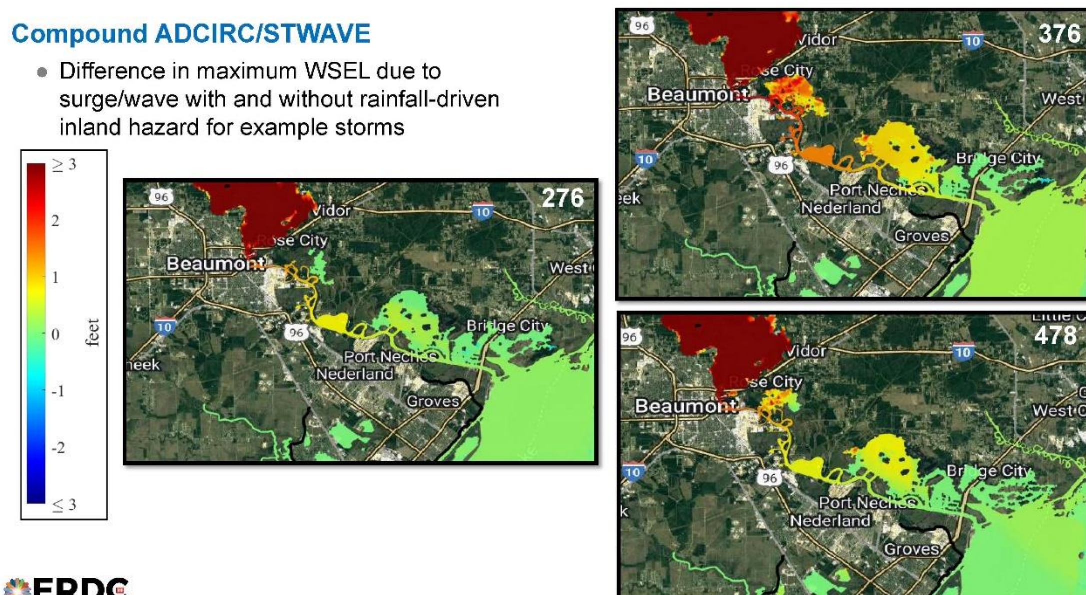
COMPOUND HAZARD DIFFERENCE FROM COASTAL

Compound ADCIRC/STWAVE

- Difference in maximum WSEL due to surge/wave with and without rainfall-driven inland hazard for example storms



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COMPOUND HAZARD DIFFERENCE FROM COASTAL

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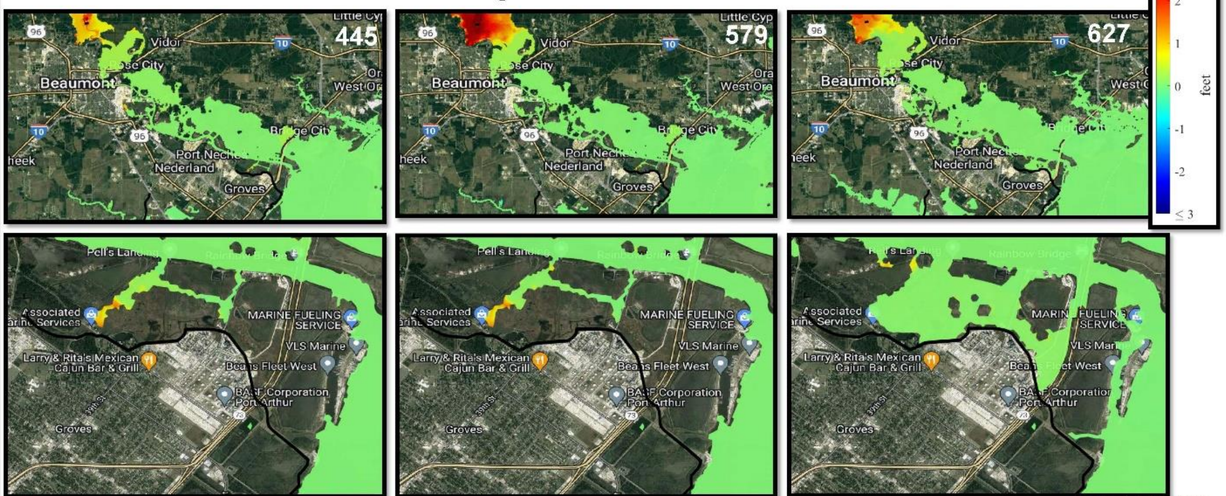
Compound ADCIRC/STWAVE

- Example Storms with Flooding during rain events in basin (top); in sample site area (bottom)
- Difference in maximum WSEL due to surge/wave with and without rainfall-driven inland hazard



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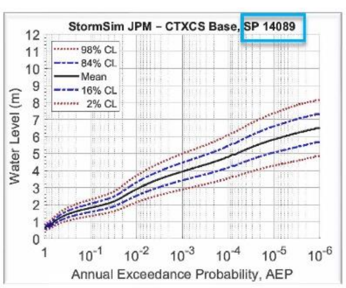
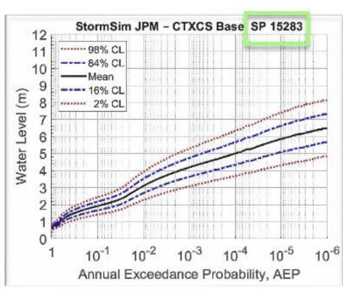
PRELIMINARY HAZARD CURVES

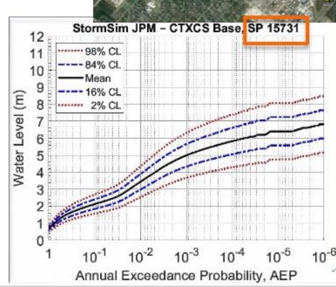
16

Preliminary hazard curves shown for sites near outlet, moving upstream

- 14089, in Sabine Lake
- 15283, near the proposed site at first Horseshoe Bend flow split
- 15731, further upstream







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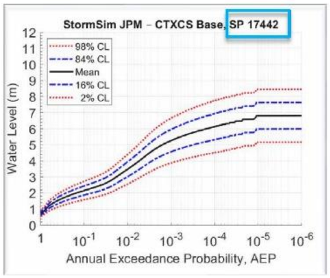
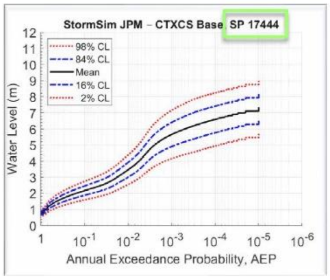
Note: all results are preliminary and currently undergoing QAQC

PRELIMINARY HAZARD CURVES

Preliminary hazard curves shown for upstream sites, near Saltwater Barrier and Outlet of HEC-HMS model





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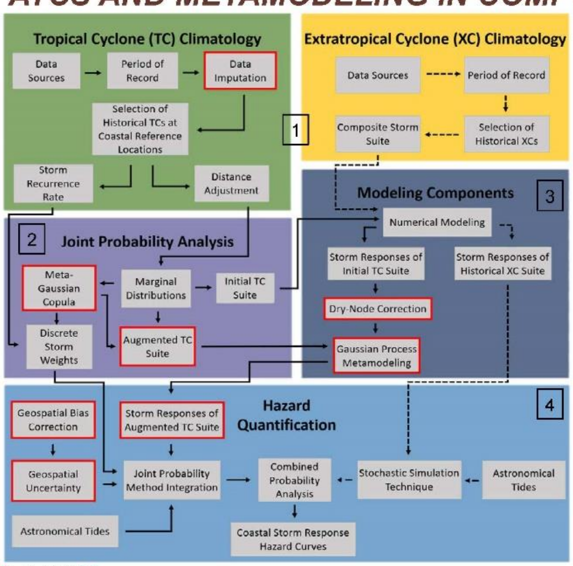
EXPANDING CHS-PCHA WORKFLOW

ATCS AND METAMODELING IN COMPOUND COASTAL HAZARDS



Probabilistic Coastal Hazard Analysis (PCHA)

1. **Storm Climatology Analysis**
   - Processing of historical TC data at points along the coastline (Ex: TC parameters, historical TC tracks)
   - Select suite of historical XCs
2. **Joint Probability Analysis**
   - Develop initial synthetic TC suite (ITCS) for numerical model simulations and assign probability masses
   - **Develop augmented TC suite (ATCS) to expand coverage of parameter and probability space**
3. **Modeling Components**
   - Simulate storms with high-resolution/fidelity numerical models
   - Perform post-processing of data (Dry Node Correction)
   - **Train Gaussian process metamodel (GPM) on ITCS simulations to predict responses for ATCS**
4. **Hazard Quantification**
   - Quantify modeling and measurement uncertainties
   - Quantify storm-induced hazards for TCs and XCs
   - Develop hazard curves describing the magnitude of the hazard as a function of annual exceedance frequencies (AEFs)

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EXPANDING CHS-PCHA - METAMODELS

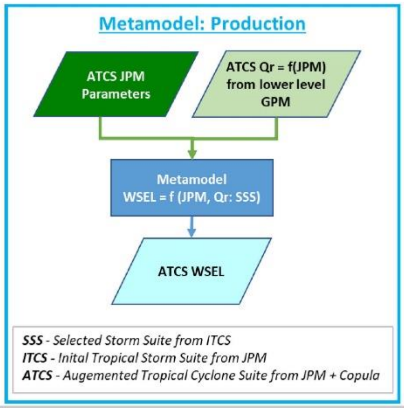
TO COMPOUND COASTAL HAZARDS

Gaussian Process Metamodeling(GPM) Augmented Tropical Cyclone Suites (ATCS)

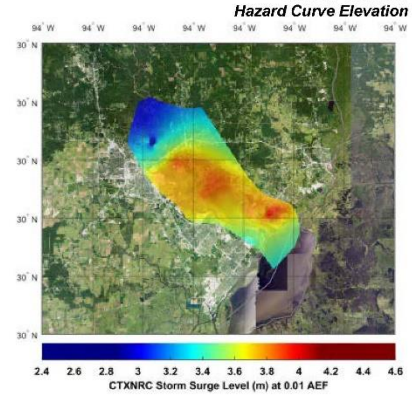
- Increase TC parameter space and probability space resolution of the initial TC suite
- Train a GPM using model simulations of initial TC suite (ITCS, tens to hundreds of storms)
- Apply GPM to estimate responses of ATCS

Compound Application of GPM

- Train GPM with Selected Storm Suite compound rainfall/surge response
- Can incorporate parameters besides JPM parameters (e.g. discharge to characterize random effects of humidity on rainfall)
- GPM using JPM Parameters et al to expand set of WSEL responses



Preliminary Metamodel Run for 0.01 AEF Hazard Curve Elevation



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COMPOUND PROBABILISTIC FLOOD HAZARDS

SUMMARY: NECHES RIVER COMPOUND PILOT

This study demonstrated the feasibility of expanding the USACE CHS JPM-based Probabilistic Coastal Hazard Analysis (PCHA) framework to include compound hazards in the Lower Neches River in Texas in support of an NRC PFHA pilot

- Explicitly incorporated rainfall hazard through a time-dependent spatially-varying parametric TC rainfall model
- Leveraged JPM TC parameterization (typically used for surge modeling) as input for TC rainfall model
- Drove hydrologic, hydraulic and coupled hydrodynamic/wave models using spatially and temporally varying initial and boundary conditions from TC Rainfall, its induced flows, and regional coastal storm responses.
- Quantified concurrent compound hazard characterization in a single workflow
- Testing GPM and higher level PCHA steps to reduce uncertainty in hazard curves

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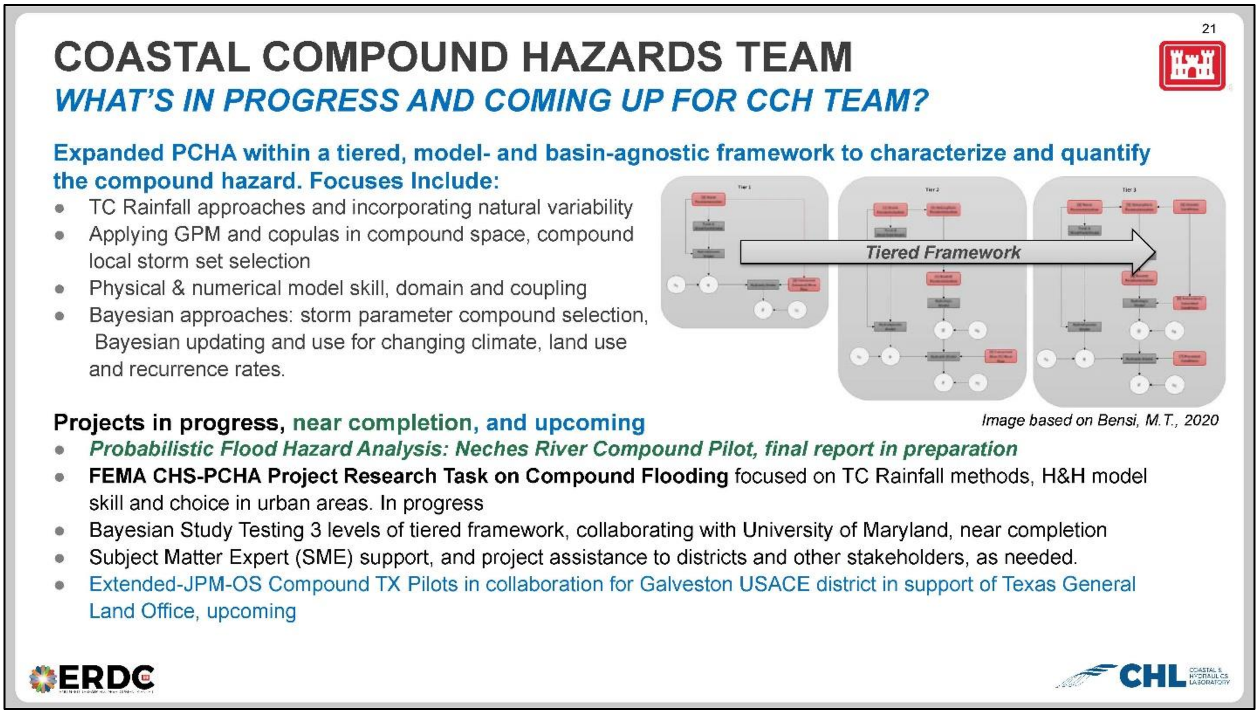
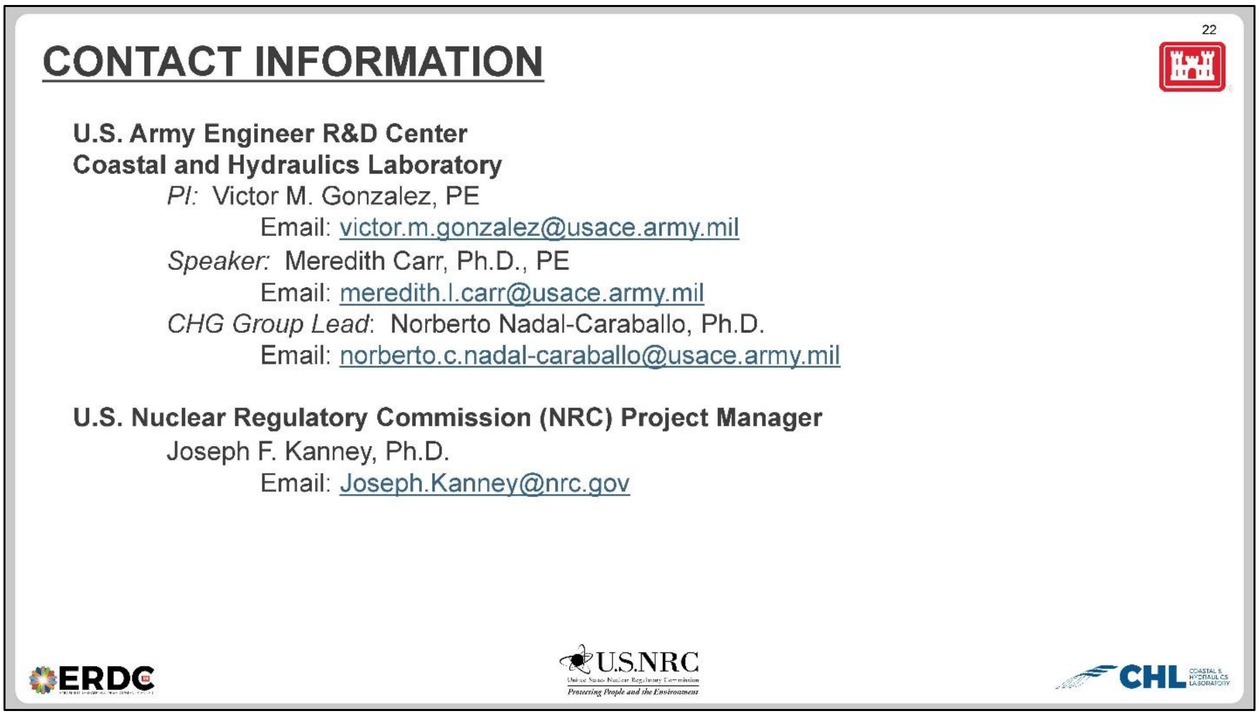




3.6.3.3 Questions and Answers

Question:

When you were combining the HEC-RAS model and introducing the ADCIRC model results, was there any criteria about at which downstream boundary location for to incorporate ADCIRC results?

Answer:

We did two approaches. In one we used the 2D RAS model and in that case, on that downstream boundary with the lake, we used the ADCIRC results from the coastal Texas model that aren't influenced by rain. We saw that the surge was more important in the lower part of the basin and rain was more important upstream so the thought is that that boundary is surge only and we can use those ADCIRC results. But we also looked at using ADCIRC up into that inland flat area. My colleagues modified it to have flow come into ADCIRC at a point where the river goes through a salt-water barrier structure so it's pretty contained. Those were the results I showed you here, where we re-ran those hundred forty-four storms with the specific outflow from the hydrologic basin. In that case the boundary was between the hydrologic model and ADCIRC at that interface. And it was more of a flow boundary.

Question:

When you couple ADCIRC at the boundary, is it just water level that RAS 2D sees? What about the momentum that comes with the storm surge that travels upstream

Answer:

It's currently just the water level.

Question:

How are outlets of streams or rivers affected by sea level treated in the probabilistic flood assessments?

Answer:

There are multiple ways to do it. Here we looked at using it as a downstream boundary that varied with time as the sea level changed through the model runs. But there are other ways, like using it upstream as a flow boundary to a hydrologic model. There're a variety of ways that can be done. If you're talking about sea level change, in some of the work that we've done with the storms, we consider sea level change explicitly. But in this basin, we only have zero sea level rise. But that's available.

Comment:

Joseph Kanney: It occurred to me that the question may have been about tides.

Answer:

So, the way uncertainty is currently done with the PCHA[21] results for the coast is that we have confidence limits, in which the tide is considered as an error. So, it actually increases or decreases the uncertainty at that point.

Question:

You mentioned briefly, in terms of going forward, about being basin agnostic. I'm not sure what you mean. Can you explain that a bit more?

Answer:

[21] Probabilistic Coastal Hazard Analysis

Although I just touched on it briefly, there were a lot of points where we had to use engineering judgement or information about the basin to make decisions about what base flows we would use, how we would vary certain conditions within the basin, etc. That's being done in pilots, but what we'd like to do instead of having that be a judgement every time, where you could get a different answer, is to try to tie those to probability. Instead of picking one thing that has a probability of one, you would apply a distribution to the base flows you put in, or you would apply a distribution to your infiltration parameters. That way you would model those differences and that could be applied to any basin. It could be more consistent with the basin making the decisions for you instead of whoever is running it. Often judgement is still needed and is helpful, but to try to make it so it would work for a large basin or small basin, you would just incorporate those things probabilistically.

Question:

You use the TC[22] rainfall model in this work, and for the region that's an appropriate choice. But as you move, especially up the U.S. east coast, the rainfall is still very important in the flooding, in addition to the surge, but the rainfall is quite a bit different because the storms have typically undergone extratropical transition and it's not a pure TC rainfall event. Have you given any thought about how to handle rainfall for those regions?

Answer:

The probability of the parameters that drive the TC rainfall are varied in this method, but that model essentially gives you one result. So, we're looking at different models we could use and how that would provide uncertainty and natural variability. We're also looking at how one might include just natural variability you'd expect over time. We are looking a lot at what happens once the storm comes on shore because the tracks were developed for storm surge. So, questions of when they come on shore and how you can treat that and also what you do at extratropical transition because the models are for TC are larger issues. A lot of the focus is on getting that driving part correct. A nice thing about the framework is that we can add in parameters that characterize that into the whole framework, especially that second part. We're starting to test that in another study we're working on. But the extratropical transition is tough because not only does it add a lot more parameters to what happens with the rain, but also with the pressure and winds and the speed of the track and so forth.

Question:

Can you discuss a few details of the Copula model?

Answer:

For the next steps of that we're looking at with the GPM[23] and the copula model? The PCHA model takes that JPM[24] workflow and to try to increase that space we develop a set of [storm] suites based on a copula of those parameters. Usually the relationship with the parameters is considered implicit in your selection of storms, but here we actually develop a copula between all those parameters and then use that to create a suite of storms that cover that more of probability space than in those individual storms. Once we have those storms we can take the resulting high-fidelity model and we can train it with the parameters. Then we can say we have these storms for which we know the parameters and the probabilities from that copula, give us an output. But we couldn't run 765,000 different relationships in a high-fidelity model like

[22] Tropical cyclone

[23] Gaussian Process Metamodeling[24] Joint Probability Method

[24] Joint Probability Method

ADCIRC, so we're using those metamodeling skills and we're working on improving them. That was one thing in the work with the University of Maryland that we heard about earlier, where we're looking at those copulas and trying to really make them consistent because this metamodeling is a key element for the compound hazard as we try to cover more space with less storms. If you consider that 660 storms were enough for surge, how many storms would you need to get surge and rain? So, that's really one of the goals and the details of applying it here. We're actually looking at two levels where we use that hydrograph coming into the system to add that random information about the rainfall to expand those storms.

3.6.4 Presentation 3B-4: HEC-RAS Modeling Framework and Lessons Learned from Coastal Flooding PFHA Pilot Study: Coupling and Automation of HEC-HMS and ADCIRC Outputs to 2D HEC-RAS Model Using Python

Authors: Kathleen Harris, Chase Hamilton, Weleska Echevarria-Doyle, Meredith Carr, Victor M. Gonzalez; U.S. Army Corps of Engineers, Engineer Research and Development Center, Coastal and Hydraulics Laboratory

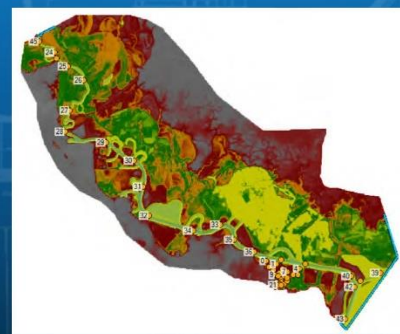
Speaker: Kathleen Harris

The compound flooding impact of combined inland and coastal forcings is a large and growing research area of interest and has implications on damages to vital infrastructure in coastal environments. Complications can easily arise in attempting to couple existing models to simulate the combine effect. A coastal probabilistic flood hazard assessment (PFHA) pilot study was conducted to demonstrate the application of PFHA to external flooding at a hypothetical nuclear power plant location on the Lower Neches River watershed in Texas. This presentation will focus on the modeling framework that was built for the task at hand. Using a python framework, a 2D HEC-RAS model of the Lower Neches River Basin was automated to update boundary conditions, run simulations, and extract and plot results for thousands of hypothetical tropical cyclones (TC). The HEC-RAS model used the HEC-HMS outputs of the TC as the upstream flow boundary condition, the ADCIRC outputs of the corresponding TC as the downstream stage boundary condition, and the rainfall from the same TC within the HEC-RAS 2D domain. Python scripts were created to assign the proper boundary conditions for the TC of interest by altering the HEC-RAS unsteady flow file (.u01) to incorporate the DSS file paths for the TC for the upstream boundary flow and rainfall and writing in the downstream boundary stage from ADCIRC outputs. The model is then run by calling the HEC-RAS executable within the script. Once run, addition python code is used to export the result hdf file to an external location, export results of interest that were saved the HEC-RAS reference points, and plot and save data for accessible viewing. The code then moves on to the next TC, proceeding through the TC numbers provided based on boundary conditions available. The framework was used to run thousands of simulations using various probabilistic inputs and allowed for many lessons learned regarding working with these models and how to automate. Probabilistic results are discussed in other accompanying presentations.

3.6.4.1 Presentation (ADAMS Accession No. ML23177A140)

HEC-RAS MODELING FRAMEWORK AND LESSONS LEARNED FROM COASTAL FLOODING PFHA PILOT STUDY:

COUPLING AND AUTOMATION OF HEC-HMS AND ADCIRC OUTPUTS TO 2D HEC-RAS MODEL USING PYTHON



Presenter: Kathleen E. Harris
(USACE ERDC-CHL)
Chase O. Hamilton, Waleska Echevarria-Doyle, PE,
Meredith L. Carr, PhD, Victor M. Gonzalez, PE
(USACE/ERDC/CHL)

23 March 2023
8th Annual Probabilistic Flood Hazard Assessment Research Workshop

```
hec = win32com.client.Dispatch('RAS630.HECRASController')
hec.Project_Open("path to Neches_SWBtoSabine.prj")
hec.ShowRAS()
hec.Compute_CurrentPlan(None, None, True)
hec.QuitRAS()
```

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A PIECE OF A LARGER PART

3B-3: Probabilistic Coastal Compound Flood Hazard Analysis Pilot Study
Victor M. Gonzalez[1], **Meredith L. Carr***[1], Luke Aucoin[1], T. Chris Massey[1], Ning Lin[2], Dazhi Xi[2], Norberto C. Nadal Caraballo[1], Karlie Wells[1]; [1]U.S. Army Corps of Engineers, Engineer Research and Development Center, Coastal and Hydraulics Laboratory (USACE/ERDC/CHL), [2]Princeton University

Objective: Demonstrate application of Coastal Flooding Probabilistic Flood Hazard Assessment (PFHA) to external flooding at a hypothetical nuclear power plant (NPP) location on the Lower Neches River watershed in Texas.

Characterization of the compound flooding hazard, including storm surge, astronomical tide, waves, rainfall, and coincident riverine flooding, along with associated uncertainties, is necessary to fully address storm risk in coastal settings.

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OBJECTIVE AND OUTLINE

CHL Coastal & Hydraulics Laboratory

Objective:
Incorporate HMS inflows and precipitation into HEC-RAS 2D model, loosely couple downstream boundary to ADCIRC storm surge results, and automate the running of hypothetical tropical cyclones and extraction of results.

Outline:
Model Background
Method
- Notes
- Precipitation
- Hydrology
- Storm Surge
- Automation
- Results

Summary/Lessons Learned

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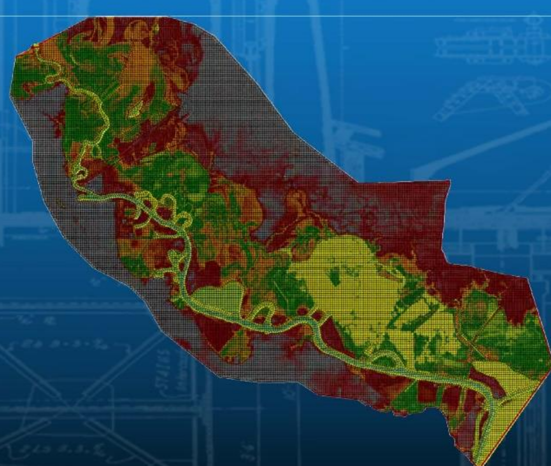
HEC-RAS MODEL

CHL Coastal & Hydraulics Laboratory

HEC-RAS 2D Version 6.3
- Lower Neches Riverine Flooding Analyses (LNRFA), Forth Worth District, Mosser et al. 2019, courtesy SWG

Added precipitation and infiltration
- Gridded, spatially- and temporally-varied tropical cyclone rainfall
- Infiltration model as a reduction in rainfall; parameterized by land use and impervious area



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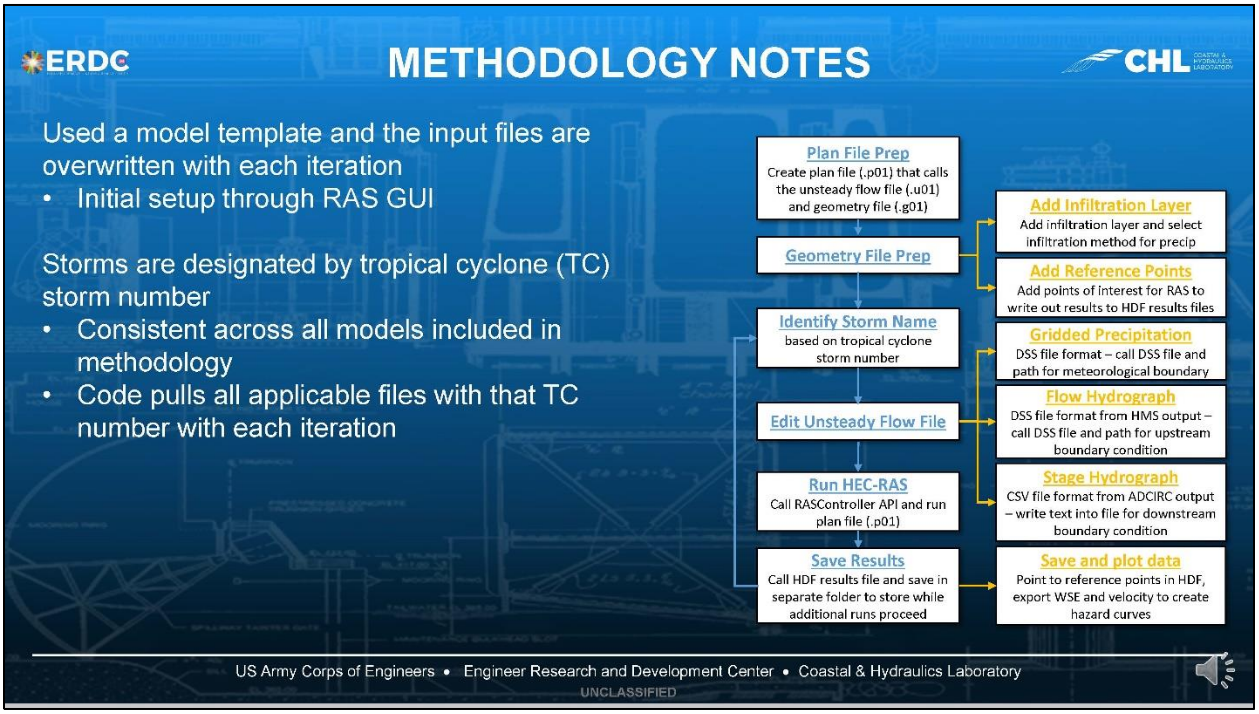

ERDC
METHODOLOGY NOTES
CHL
Used a model template and the input files are overwritten with each iteration
• Initial setup through RAS GUI
Storms are designated by tropical cyclone (TC) storm number
• Consistent across all models included in methodology
• Code pulls all applicable files with that TC number with each iteration
Plan File Prep
Create plan file (.p01) that calls the unsteady flow file (.u01) and geometry file (.g01)
Geometry File Prep
Identify Storm Name
based on tropical cyclone storm number
Edit Unsteady Flow File
Run HEC-RAS
Call RASController API and run plan file (.p01)
Save Results
Call HDF results file and save in separate folder to store while additional runs proceed
Add Infiltration Layer
Add infiltration layer and select infiltration method for precip
Add Reference Points
Add points of interest for RAS to write out results to HDF results files
Gridded Precipitation
DSS file format – call DSS file and path for meteorological boundary
Flow Hydrograph
DSS file format from HMS output – call DSS file and path for upstream boundary condition
Stage Hydrograph
CSV file format from ADCIRC output – write text into file for downstream boundary condition
Save and plot data
Point to reference points in HDF, export WSE and velocity to create hazard curves
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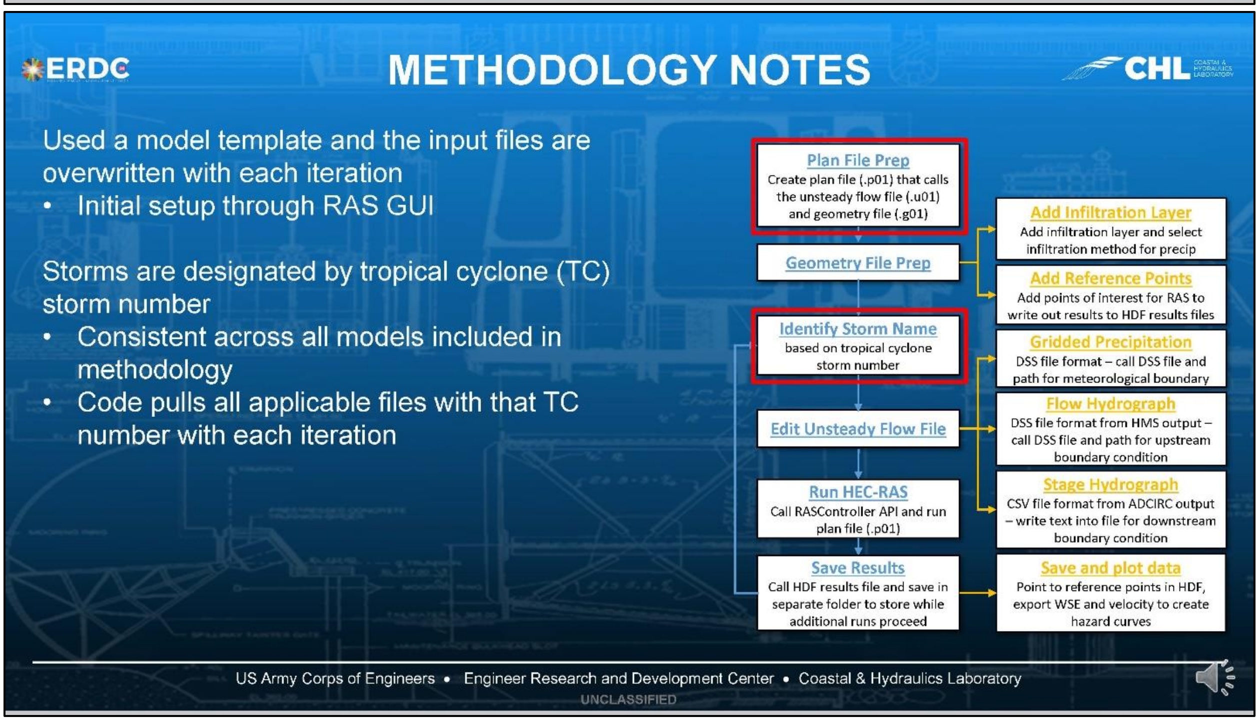

ERDC
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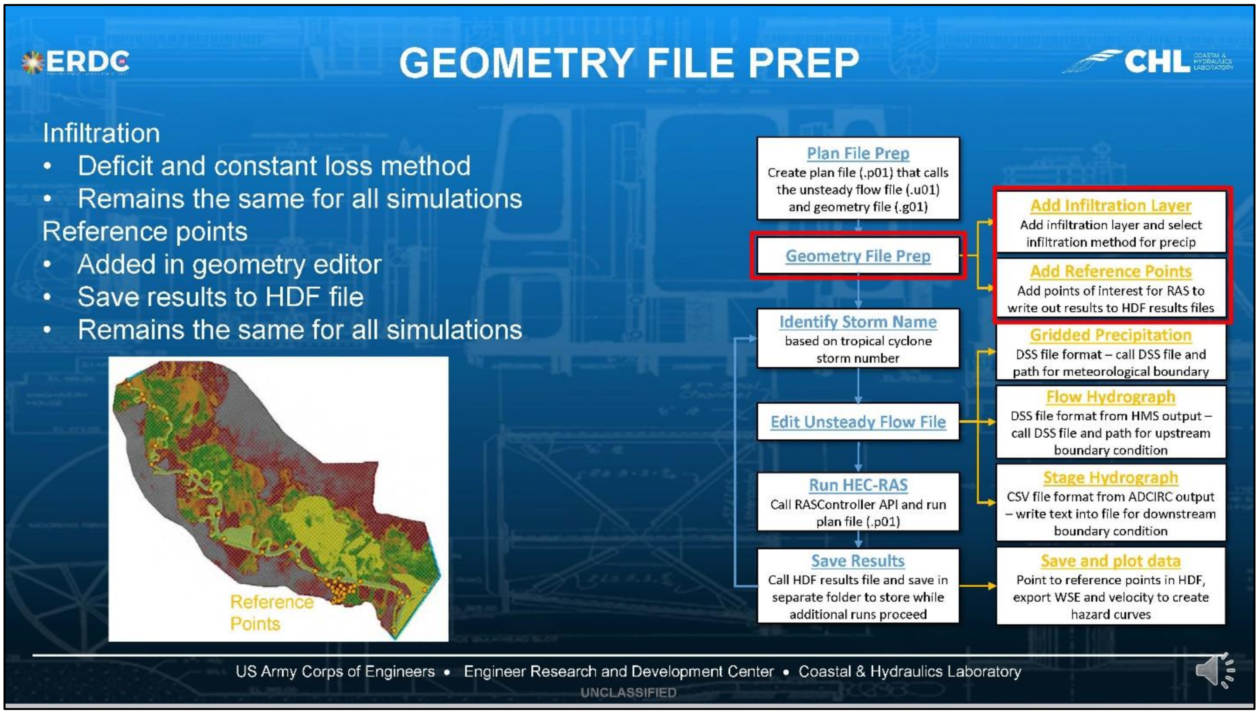
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GEOMETRY FILE PREP
CHL
Infiltration
• Deficit and constant loss method
• Remains the same for all simulations
Reference points
• Added in geometry editor
• Save results to HDF file
• Remains the same for all simulations
Reference Points
Plan File Prep
Create plan file (.p01) that calls the unsteady flow file (.u01) and geometry file (.g01)
Geometry File Prep
Identify Storm Name
based on tropical cyclone storm number
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DSS file format – call DSS file and path for meteorological boundary
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DSS file format from HMS output – call DSS file and path for upstream boundary condition
Stage Hydrograph
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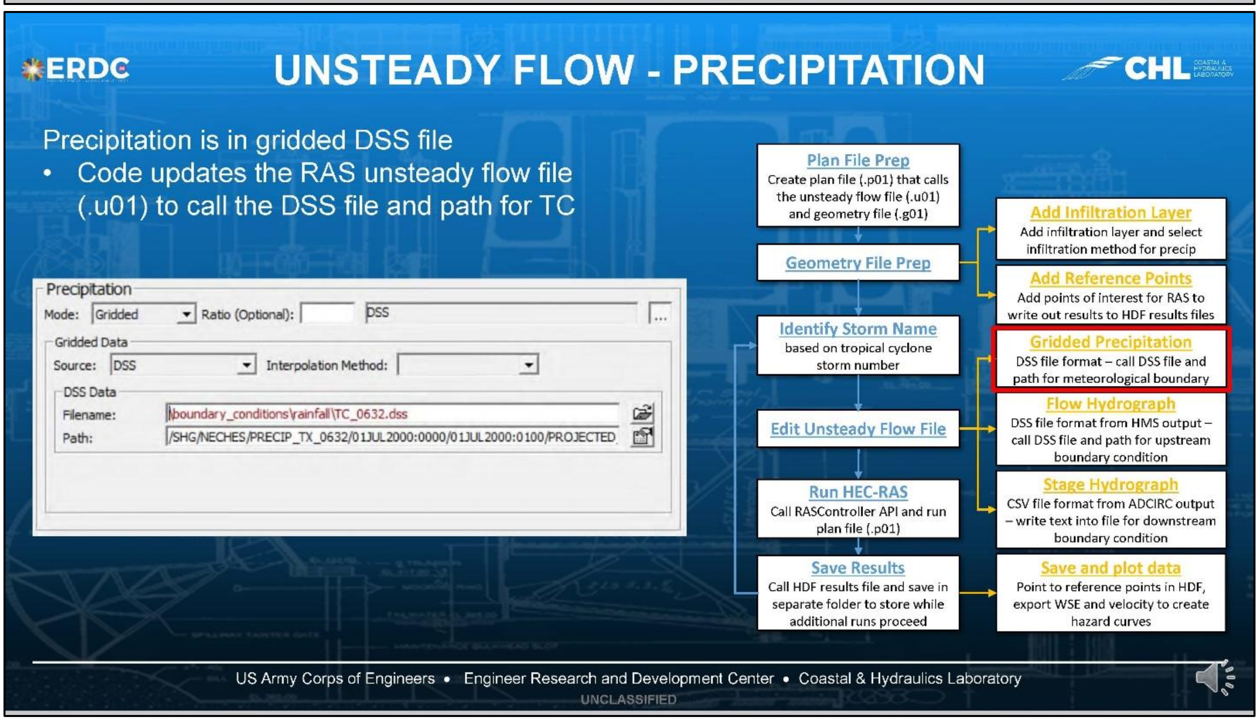
ERDC
UNSTEADY FLOW - PRECIPITATION
CHL
Precipitation is in gridded DSS file
• Code updates the RAS unsteady flow file (.u01) to call the DSS file and path for TC
Precipitation
Mode: Gridded
Ratio (Optional):
DSS
Gridded Data
Source: DSS
Interpolation Method:
DSS Data
Filename: \boundary_conditions\rainfall\TC_0632.dss
Path: /SHG/NECHES/PRECIP_TX_0632/01JUL2000:0000/01JUL2000:0100/PROJECTED
Plan File Prep
Create plan file (.p01) that calls the unsteady flow file (.u01) and geometry file (.g01)
Geometry File Prep
Identify Storm Name
based on tropical cyclone storm number
Edit Unsteady Flow File
Run HEC-RAS
Call RASController API and run plan file (.p01)
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Add Reference Points
Add points of interest for RAS to write out results to HDF results files
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CSV file format from ADCIRC output – write text into file for downstream boundary condition
Save and plot data
Point to reference points in HDF, export WSE and velocity to create hazard curves
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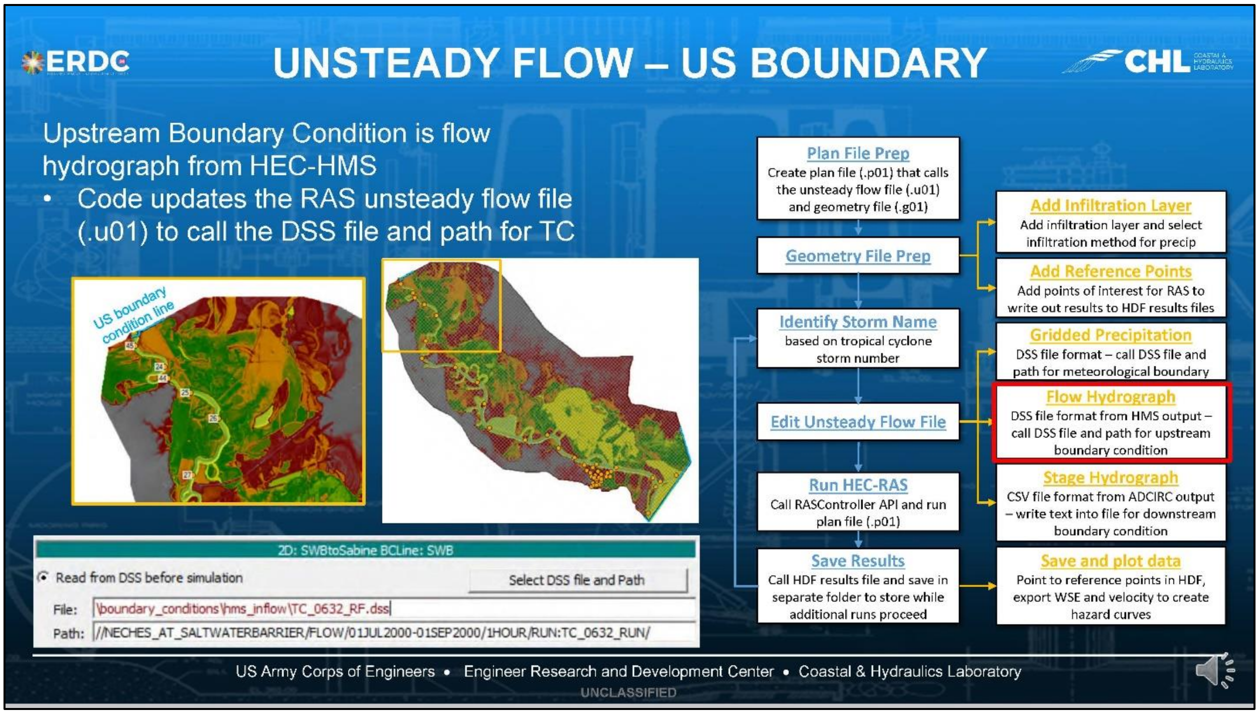
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UNSTEADY FLOW – US BOUNDARY
CHL
Upstream Boundary Condition is flow hydrograph from HEC-HMS
• Code updates the RAS unsteady flow file (.u01) to call the DSS file and path for TC
US boundary condition line
2D: SWBtoSabine BCLine: SWB
Read from DSS before simulation
Select DSS file and Path
File: \boundary_conditions\hms_inflow\TC_0632_RF.dss
Path: //NECHES_AT_SALTWATERBARRIER/FLOW/01JUL2000-01SEP2000/1HOUR/RUN:TC_0632_RUN/
Plan File Prep
Create plan file (.p01) that calls the unsteady flow file (.u01) and geometry file (.g01)
Geometry File Prep
Identify Storm Name
based on tropical cyclone storm number
Edit Unsteady Flow File
Run HEC-RAS
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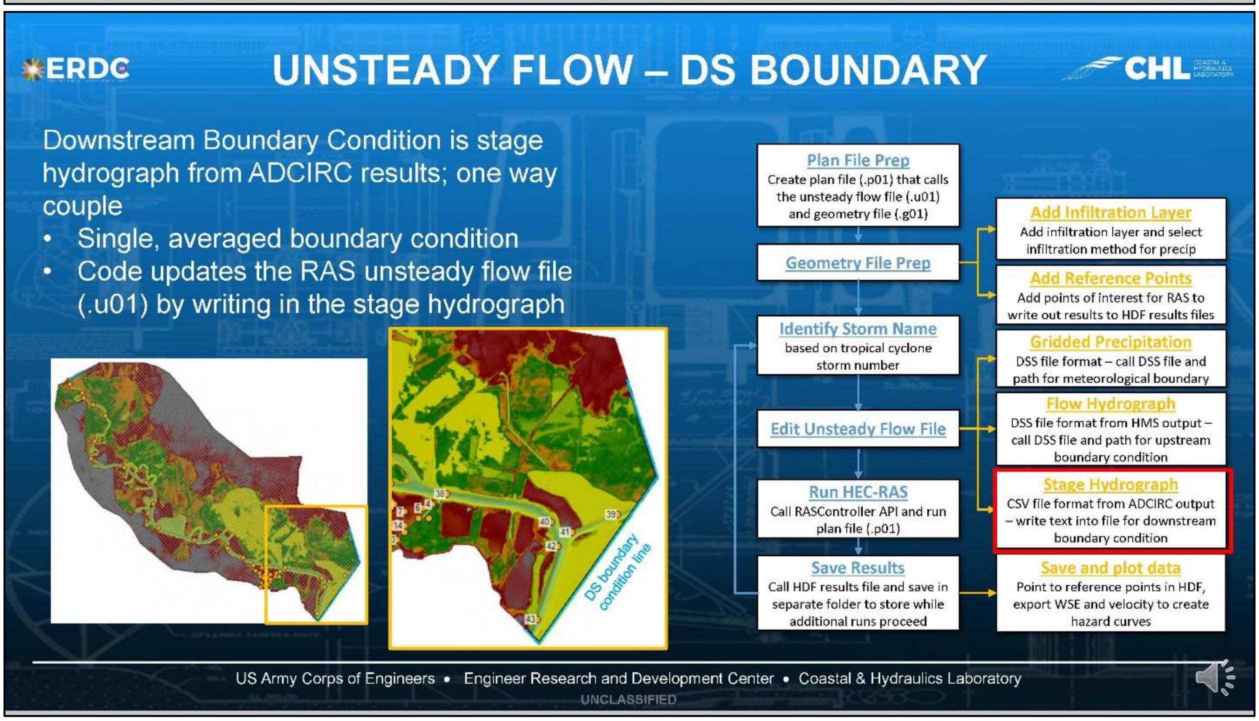
ERDC
UNSTEADY FLOW – DS BOUNDARY
CHL
Downstream Boundary Condition is stage hydrograph from ADCIRC results; one way couple
• Single, averaged boundary condition
• Code updates the RAS unsteady flow file (.u01) by writing in the stage hydrograph
DS boundary condition line
Plan File Prep
Create plan file (.p01) that calls the unsteady flow file (.u01) and geometry file (.g01)
Geometry File Prep
Identify Storm Name
based on tropical cyclone storm number
Edit Unsteady Flow File
Run HEC-RAS
Call RASController API and run plan file (.p01)
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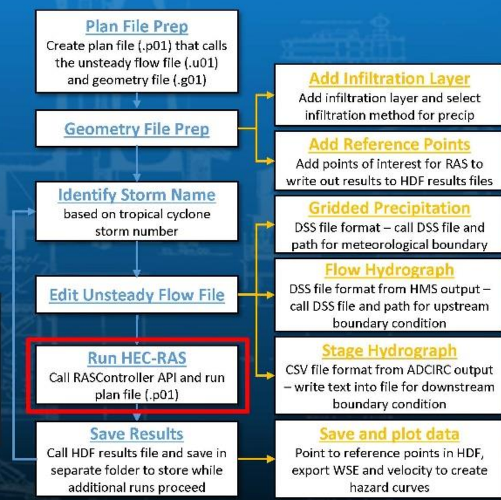
AUTOMATED RUNS

HECRASController is the HEC-RAS API
- VBA
- 1D functionality

Called HEC-RAS client straight from python

Blocking Mode (default) used to allow model to complete simulation before moving on with loop

```
hec = win32com.client.Dispatch('RAS630.HECRASController')
hec.Project_Open("path to Neches_SWBtoSabine.prj")
hec.ShowRAS()
hec.Compute_CurrentPlan(None, None, True)
hec.QuitRAS()
```



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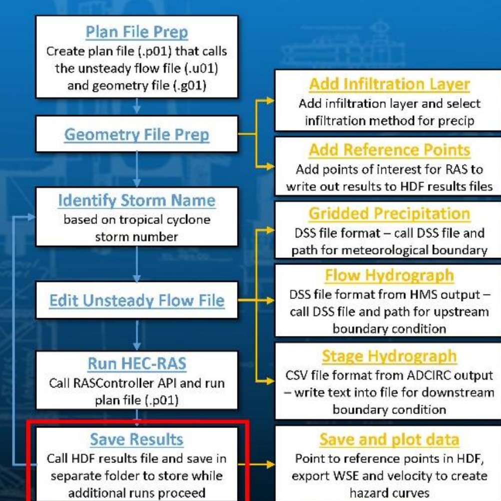
RESULTS

Simple code written to
- save the HDF results file elsewhere to be able to open in RAS Mapper and visualize later
- pull the max WSE and Velocity values from the results
- plot WSE and Velocity at each reference points over time



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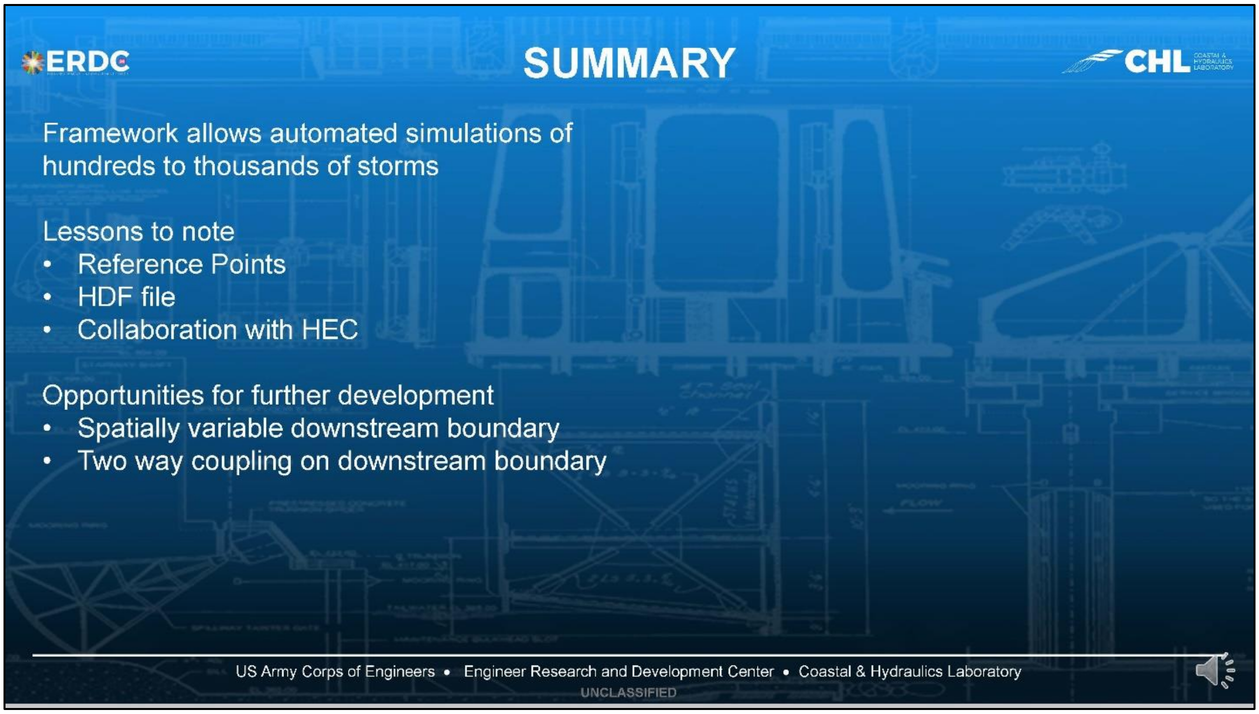
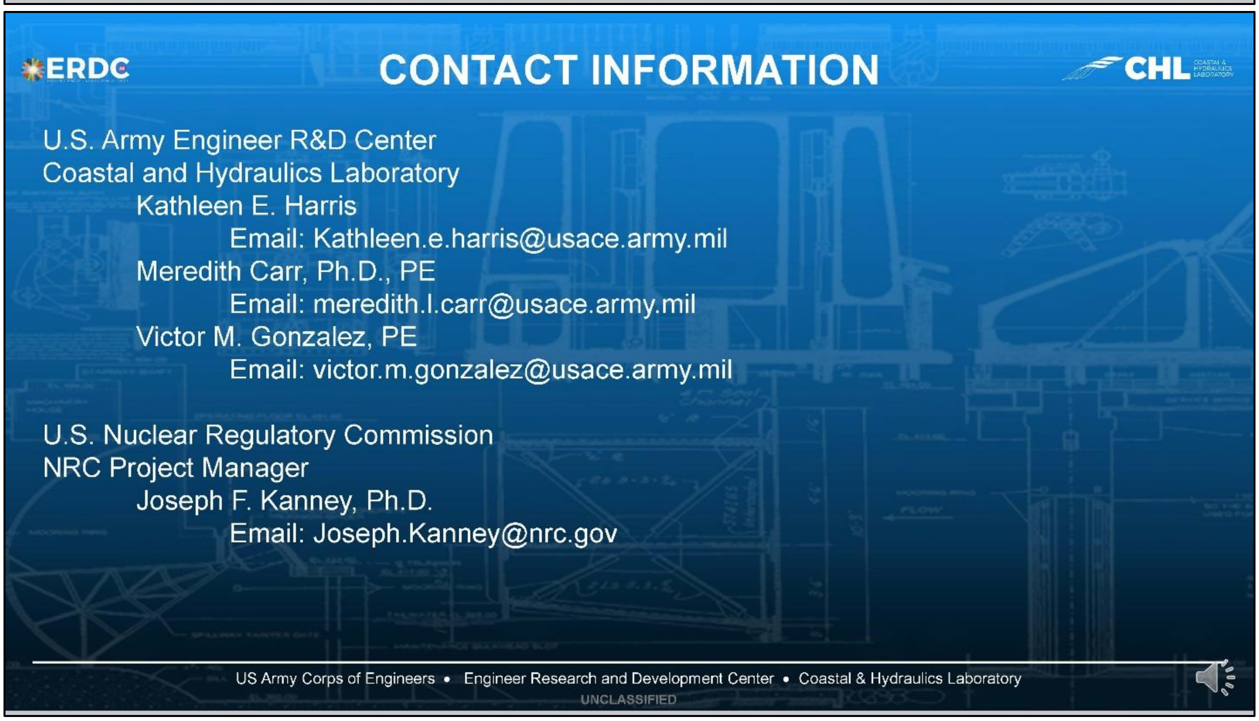




3.6.4.2 Questions and Answers

Question:

Do you know if there are plans to update the HEC-RAS controller to include all the 2D capabilities since everything is kind of going to 2D?

Answer:

That'd be an HEC question. It would be Mark Jensen. He's the RAS controller guy. I don't know if there is as much of a need as there once was because there tends to be work arounds. And with the HDF files, if everything is written out to there, it's more accessible. If you know Mark, then I'd ask him. I think he'd be the point of contact on that one.

Question:

How do you generate the DSS rainfall files from the synthetic storm?

Answer:

Those are provided to me. I think Meredith might be able to answer that a bit better, but they were converted from netCDF to ASCII and then to DSS. Does Meredith want to chime in on that, because I'm not super familiar with it. I think that was Karlie's work, right?

<u>Meredith Carr:</u> One of the co-authors, Karlie Wells, worked through a rather long procedure to make that conversion. Now HEC has posted some tools on their website because HMS now has a way to input this data. We've been working on using those tools but there have been some little steps to try to figure out because HEC-DSS is unique to HEC programs and there's a bit of getting used to using it when you're not a regular user of the system. We're working through that and reaching out to HEC. So, we initially chose a very long convoluted way and are now trying to upgrade what we did.

Question:

Another question is about the stage-hydrograph input. I see in your slides you use CSV files. I think the HEC-RAS model has a limitation of 100 rows for those stage hydrograph boundary condition input. How did you deal with that?

Answer:

We never ran into that limitation. I don't know if that's because it wasn't an issue because we didn't have 100 inputs, but I would think we had more than 100 inputs. Just to be clear, when I was listening back to my presentation, I feel like I wasn't very clear that we didn't use the RAS GUI to input that stuff. I tried to relate what the Python code was doing to what you would do in the RAS GUI just to have that frame of reference, but we weren't actually pasting it in there, so I wanted to be clear on that. The code was actually writing into the .u01 unsteady flow file without accessing the GUI. We didn't run into that limitation, and now I'm questioning, have I seen that limitation before? You can update the number of ordinates as far as how much you paste in. I'm going to just check right now if that's OK. In the unsteady flow editor for inputing the stage-hydrograph there is an option to update the number of ordinates. The one I just looked at was 3,200, so well over 100.

Question:

When you are writing the data into the .u01 unsteady file, there are restrictions that are a hard part when developing your code. For each time step, the value of the stage must be an 8-digit number right? How do you solve that problem?

Answer:

I wouldn't say it is inherently difficult. It is tedious in that you have to go back and check. There was a bit of reverse engineering as far as counting the spaces in the text file and then testing whether RAS recognized it. There was some tedious work to be done there, but it boiled down to counting and then implementing that into the code to paste it every so often.

Comment:

On the question of converting netCDF/GRIB files to HEC-DSS format, HEC has also created HEC-Vortex, a lightweight data processing utility to convert netCDF/GRIB or other formats to HEC-DSS files.

3.6.5 Presentation 3B-5: An Overview of a Multi-Agency Modeling Effort to Quantify Future Conditions in the Great Lakes

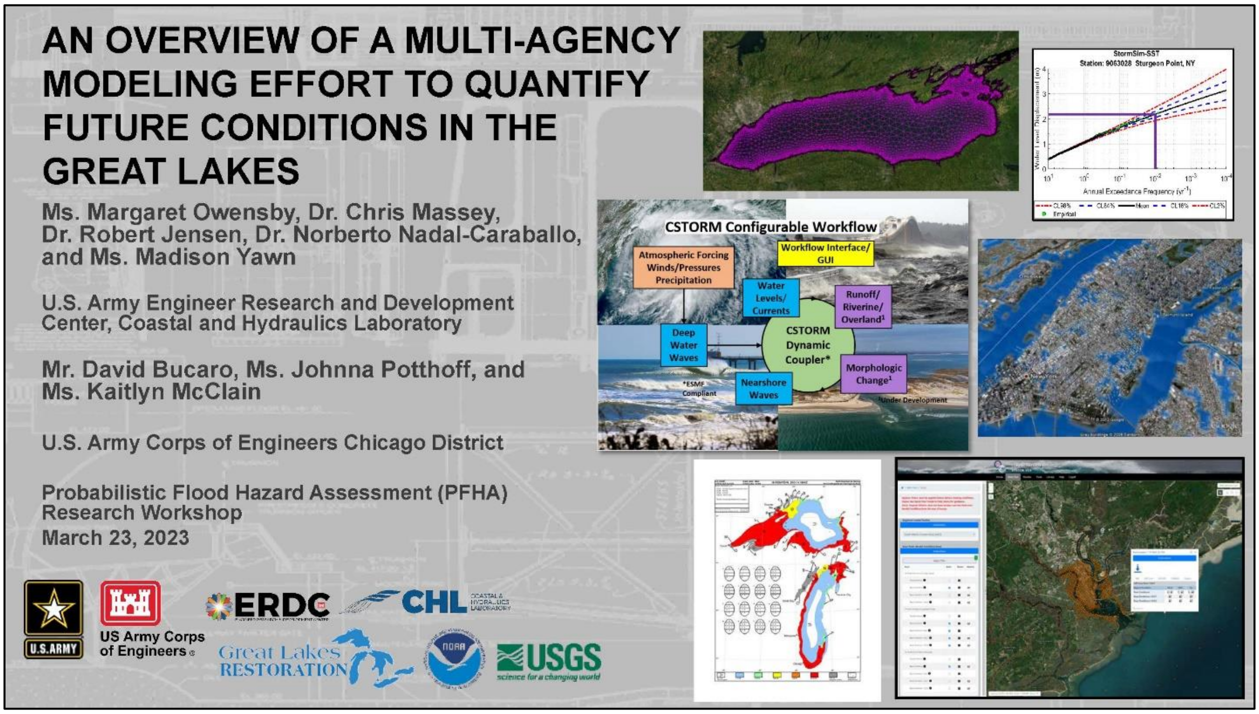
Authors: Margaret Owensby[1], T. Chris Massey[1], Robert Jensen[1], Norberto Nadal-Caraballo[1], Madison Yawn[1], David Bucaro[2], Johnna Potthoff[2], Kaitlyn McClain[2]; [1]U.S. Army Corps of Engineers, Engineer Research and Development Center, Coastal and Hydraulics Laboratory, [2]U.S. Army Corps of Engineers, Chicago District

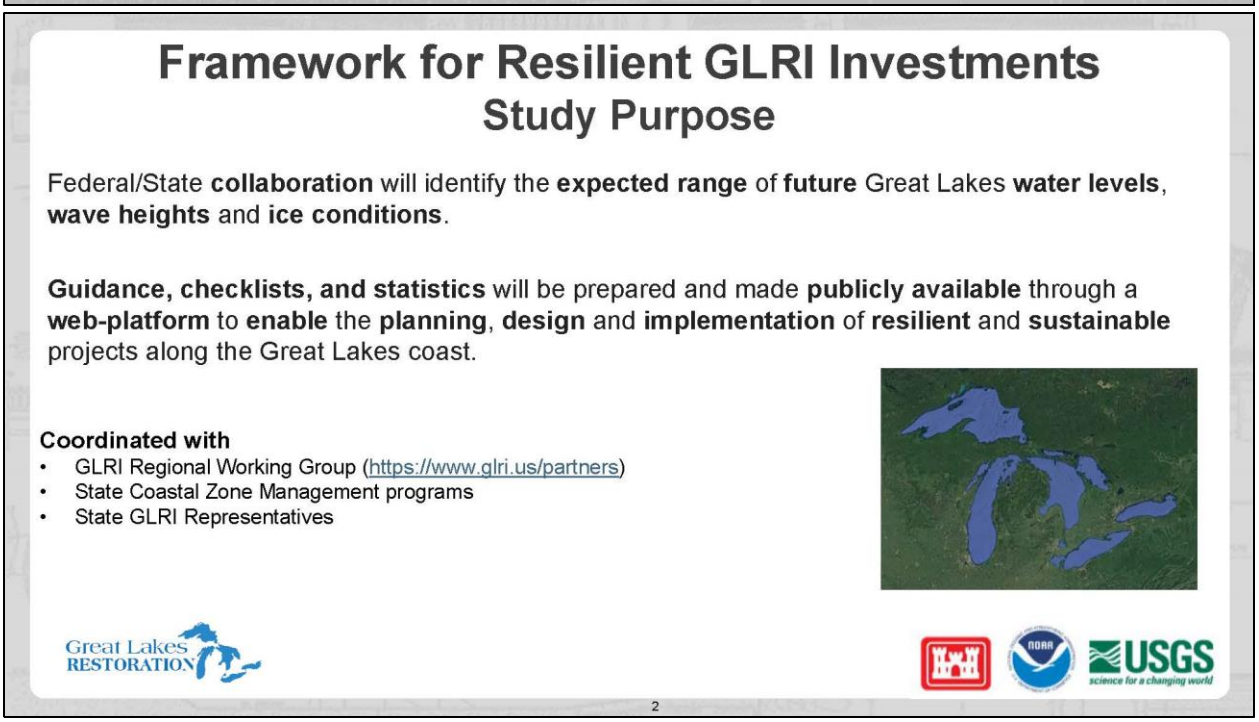
Speaker: Margaret Owensby

3.6.5.1 Abstract

A large, multi-year modeling effort focused on characterizing current and future hydrodynamic conditions in the Great Lakes is being conducted by a multi-agency team comprised of the U.S. Army Corps of Engineers (USACE), the National Oceanic and Atmospheric Administration's Great Lakes Environmental Research Laboratory (NOAA-GLERL), the U.S. Geological Survey (USGS), the Environmental Protection Agency (EPA), the Federal Emergency Management Agency (FEMA), and various state stakeholders. Carried out as part of the Great Lakes Restoration Initiative and prompted by the need to improve planning, design, and implementation of resilient and sustainable projects in this region, this study is designed to identify the expected range of future water levels and wave heights for each of the five Great Lakes along with Lake St. Clair. A distribution of future static lake level conditions is first computed by employing computationally efficient models to account for potential future changes in temperature and precipitation and calculate expected runoff, evapotranspiration, and ice coverage conditions. When a representative set of static lake levels and ice coverage conditions for each lake is determined, coupled ADCIRC and SWAN models are used to generate the resulting surge and wave responses for a suite of historical extreme storm conditions. Probabilistic hazards analysis will then be conducted on model results to calculate the distribution of total water levels and wave heights for each lake for each climate scenario. The resulting statistics will be made publicly available through USACE's Coastal Hazards System and be used to assess flood risk, provide guidance for future projects, and promote coastal resiliency in the region. This presentation provides a general overview of the entire project, including a summary of the methodologies used for storm selection and statistical hazards analysis.

3.6.5.2 *Presentation (ADAMS Accession No. ML23177A141)*





Interagency Collaboration

- Funding Provided By:
  - GLRI (as part of *Action Plan 3, Focus Area 5.2 - Conduct comprehensive science programs and projects*)
  - FEMA
  - EPA
- Routine Quarterly Federal and State Agency Update Meetings
  - Began February 2021
  - Continue through project completion
- Interagency Coordination by GLRI Framework Team
  - Binational Water Quality Agreement, Extended Sub-Committee for Annex 10
  - FEMA Region V
  - GLRI Regional Working Group
  - NOAA Offices of Coastal Management & Oceanic and Atmospheric Research
  - USACE Climate Preparedness and Resilience Planning Center of Expertise
  - EPA, Creating Resilient Water Utilities
  - USGS and NOAA - Great Lakes Water Levels Science Efforts

3

GLRI Framework Scope of Future Scenarios

- Framework will examine range of possible future conditions under changes in temperature and precipitation, not changing storm tracks/types.
- Assumption: Stationarity of weather types and wind events, but they may happen with different static lake level and % ice coverage conditions.
  - Currently, no clear scientific consensus on how storm tracks/types may change.

4

GLRI Framework Interagency Team

USACE Engineer Research and Development Center (USACE-ERDC)

- Range of future conditions development
- Ice cover and wave/surge analysis
- Demonstration vulnerability assessments

NOAA Great Lakes Environmental Research Laboratory (NOAA-GLERL)

- Range of future conditions development
- Lake level modeling
- Ice cover analysis

USGS Woods Hole Coastal and Marine Science Center

- Coastal Change Likelihood

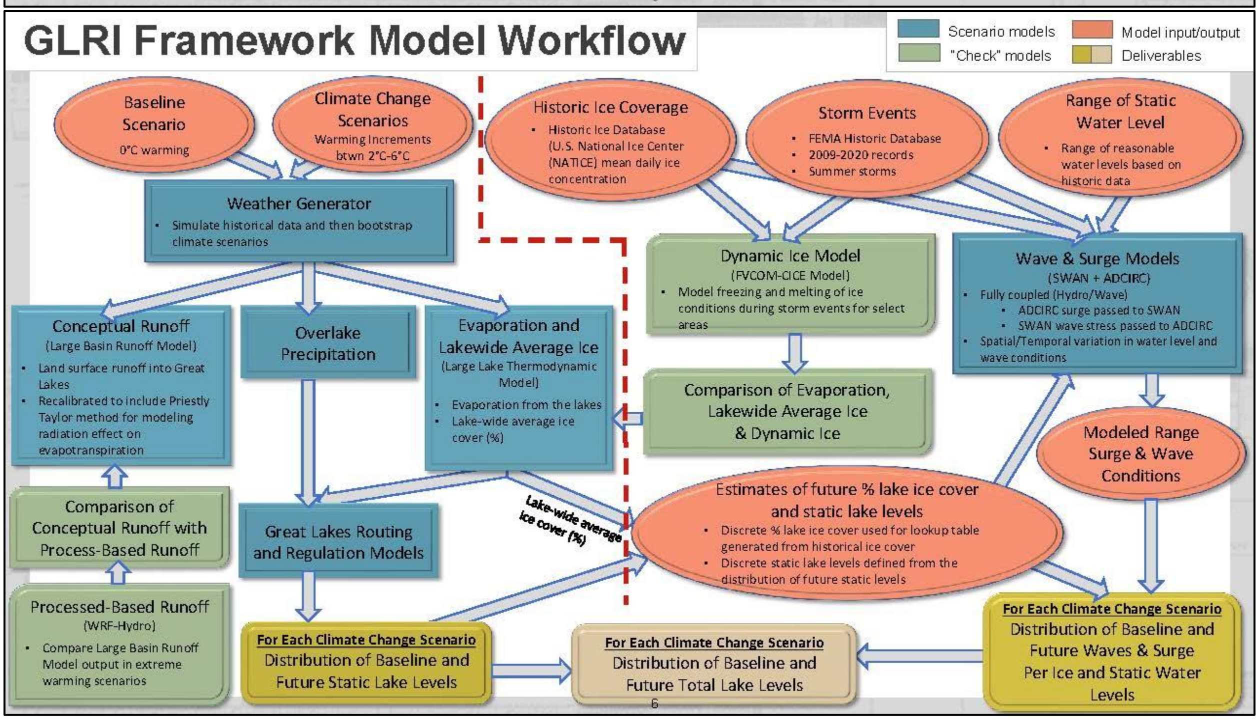
USACE Buffalo, Chicago, Detroit Districts

- Planning and project management
- Lake level modeling
- Design guidance/checklist

Great Lakes RESTORATION

5

GLRI Framework Model Workflow



6

Overview: Weather Generator

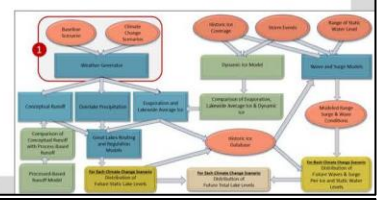
Computationally efficient model

- Statistical algorithm that simulates long series of daily weather data by bootstrapping historical data and then post-processing that data to reflect climate change scenarios

Input: Historical daily time series of precipitation and temperature across Great Lakes watersheds and over each of the Great Lakes. Reanalysis-based daily time series of upper-level atmospheric pressure and incident solar radiation.

Output: Daily precipitation, temperature, and solar radiation data used to drive runoff, evaporation, and net basin supply models

POC: Dr. Scott Steinschneider (Cornell University),
John Kucharski (USACE-ERDC)



Great Lakes RESTORATION

7

Overview: Water Level and Ice Coverage

Computationally efficient models – USACE Lake Level Modeling Framework

- Conceptual runoff, lake evaporation under different climate scenarios, routed to compute water levels
- Lakewide average ice coverage computed by lake evaporation model (used in wave/surge modeling)
- Priestley-Taylor method for computing potential evapotranspiration into the Large Basin Runoff Model

Computationally complex model

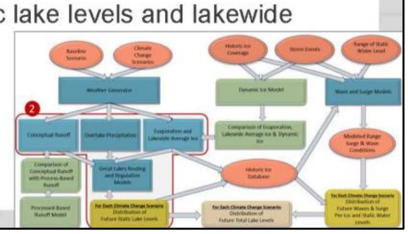
- Extreme warming scenarios
- Compare runoff estimates from computationally efficient models

Input: Output of the Weather Generator

Output: For each climate change scenario, distribution of future static lake levels and lakewide average ice cover

POC: Dr. Lauren Fry (NOAA-GLERL)

USACE Great Lakes Water Resource Management Mission:
https://www.lre.usace.army.mil/Missions/Great-Lakes-Information/

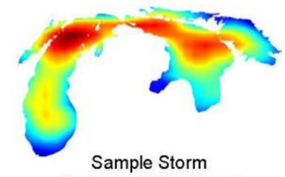


8

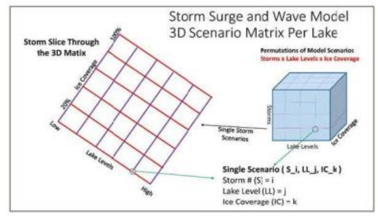
Overview: Surge (ADCIRC) and Waves (SWAN)

Computationally complex models

- ► Computes the spatial/temporal variation of the total water level based on surge and wave estimates
  - Forced by winds (wave) and winds/waves (surge)
  - Affected by ice cover
  - Water Level (surge + wave-setup) added to the lake level for each of the five Great Lakes.



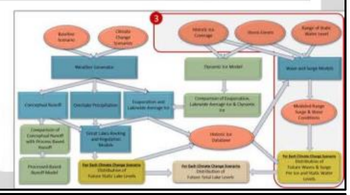
Sample Storm
Maximum Wind Speed



Input:

- ► Bathymetric/topographic data bases for model grid generation
- ► Part 1 (Baseline):
  - Develop list of unique historical extreme storm events for each of the five Great Lakes
  - Wind, pressure, ice concentration fields, and lake level defined for extreme storm events
  - Measurements: waves and water levels for model calibration and evaluation
- ► Part 2 (Production):
  - Set of N_i Storm events for N_j Lake levels and N_k Ice coverages

Production Run Scenarios for Each Lake
$N_{total} = N_i \times N_j \times N_k$



Great Lakes RESTORATION

9

Probabilistic Coastal Hazard Analysis

Extratropical Cyclone (XC) Selection

POT Sample	FSS Development	FSS Hazard Curves	CSS Development	CSS Hazard Curves	Validate CSS
Sample storms from historical datasets at water level gauges using peaks-over-threshold (POT) technique	Eliminate non-wind driven events to create a Full Storm Suite* (FSS) for individual water level gauges	Develop FSS hazard curves (i.e., probability distributions) of storm surge for individual water level gauges	Create multiple Composite Storm Suites (CSS) of varying sizes (i.e., 30, 50, 75, 100 storms) by sampling storms across each FSS	Create hazard curve for each CSS and retain smallest number of storms that match the FSS hazard curves	Validate the CSS by comparing to the FSS water levels for different annual exceedance frequency (AEF) at both tails of the hazard curves

GOAL:

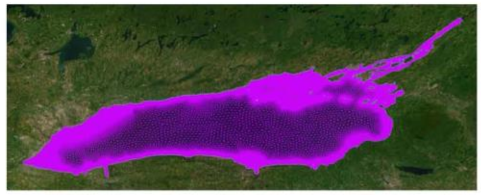
- Develop storm suites including ~180 XC storm events per lake
  - Select storms that describe the full range of the water level hazard across the lake
- Including ~15 summer storm events per lake

USGS science for a changing world

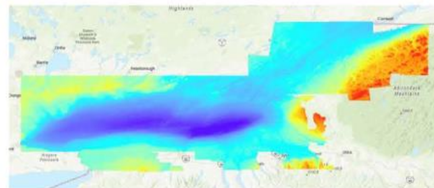
Surge/Wave Model Development – Lake Ontario

The surge/wave models for Lake Ontario are currently in development.

- Meshes constructed using OceanMesh2D, Mesh2D software
- A near-seamless DEM was created for Lake Ontario by the USACE JALBTCX team
- Set of save points developed with stakeholder input
- Calibration/validation being conducted for 8 historical storm events
- Development and calibration/validation process to be repeated for Superior, Michigan/Huron, and Erie (to include St. Clair) – guarantees consistency of approach



- Final mesh resolution ranges from ~ 30 m to 2.5 km
- Mesh contains ~ 840K elements, 427K nodes
- Inland extents to at least 6 m elevation contour (where 0 m is shoreline)



Topo/bathy data sources include:
U.S. Interagency Elevation Inventory, NOAA Digital Coast, USGS National Map Viewer, USACE eHydro

Great Lakes RESTORATION   OceanMesh2D   USGS science for a changing world

11

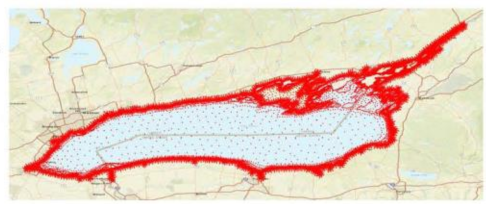
Lake Ontario CHS Save Points

Save points are locations of special interest where model output and statistical results will be made publically available on the Coastal Hazards System.

The Surge/Wave team requested input from stakeholders in order to identify save point locations for Lake Ontario that will best serve the community of practice. This process will be repeated for the other lakes.

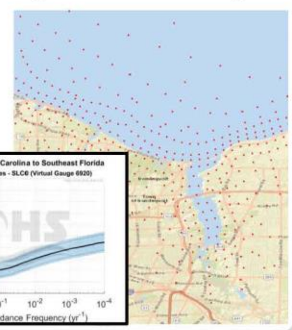
Save points were created at locations of interest to stakeholders, including:

- Ongoing, past, or future project sites
- Nearshore areas (on land) where lake flooding is a concern
- Shoreline areas of interest (e.g. high population density, popular tourist locations, parks, etc.)
- Inside harbors and inlets
- Anywhere else where water level/waves data and statistics would be useful



Final set of save points for which data will be posted to the Coastal Hazards System.

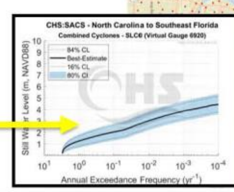
Total number of save points for Lake Ontario: 20,406



What kind of data will be published at each save point?
Downloadable files containing :

- Storm Event Responses
- Water levels & currents peaks and time series
- Significant wave height peaks and time series (with associated periods and directions)

- Statistics
- Annual exceedance frequency values (hazard curves) of water levels and wave heights
- Nonlinear residuals of storm responses
- Storm probabilities



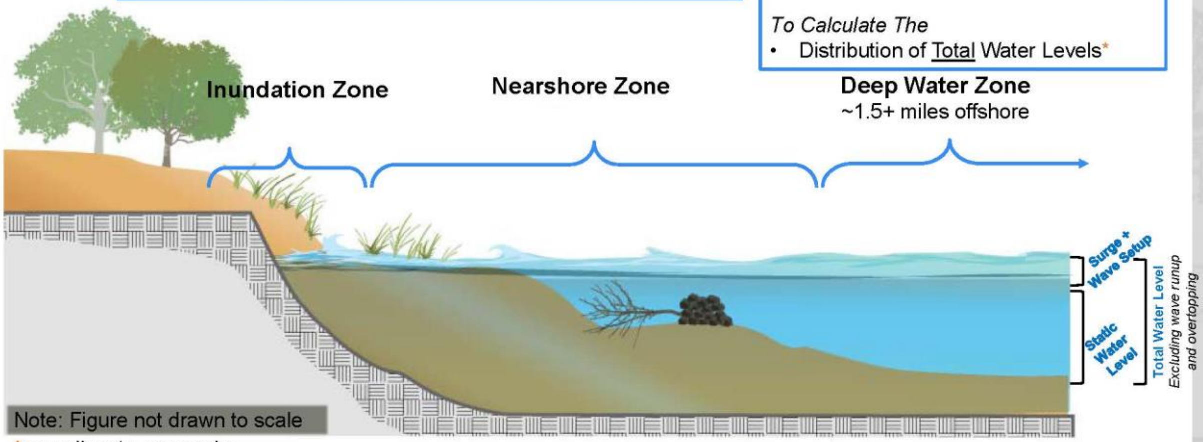
Modeling Deliverables- Surge and Wave Responses

- Time Series consisting of N_i Storm events for N_j Lake levels and N_k Ice coverages at specific locations along the coastline
- Field Estimates consisting of N_i Storm events for N_j Lake levels and N_k Ice coverages defined for the five Great Lakes

- Distribution of Static Water Levels*

And The
- Distribution of Waves & Surge Per Ice and Static Water Levels*

To Calculate The
- Distribution of Total Water Levels*



Note: Figure not drawn to scale

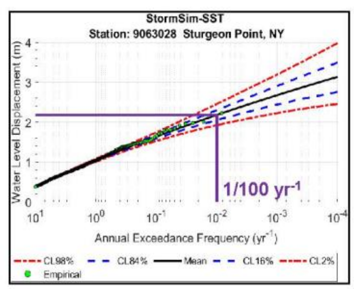
*per climate scenario

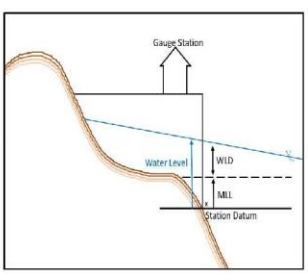
13

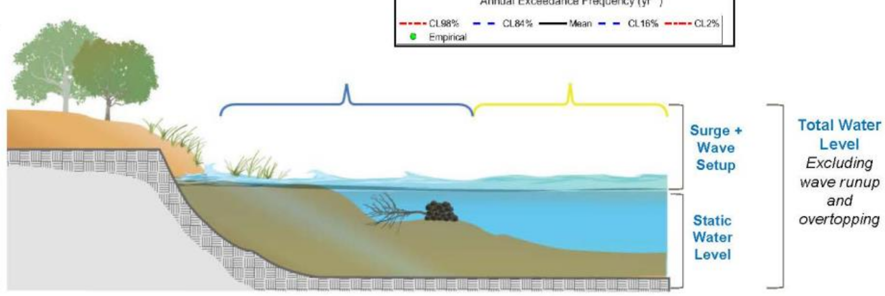
Hazard Estimation For Water Levels

GOAL:

- Estimate hazard by computing water level displacement (WLD)
  - WLD = Water Level – Mean Lake Level (MLL)
  - WLD ➔ surge + wave setup
- Storm surge and seiche events can be represented by WLD
- StormSim-SST
  - Technique for generating the hazard curve of a Peaks-Over-Threshold (POT) sample of WLD values



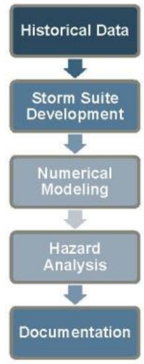




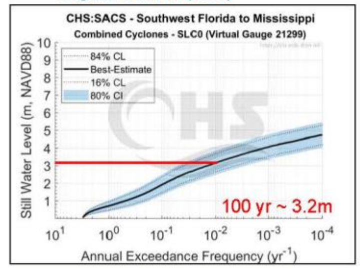
Data Examples

- **Model Simulations: 180 Storms x 10 conditions:**
  1. Lake Level 1 + Ice Coverage 1
     - ADCIRC simulations
     - Wave simulations
     - Hazard Results
  2. Lake Level 1 + Ice Coverage 2
  3. Lake Level 2 + Ice Coverage 1
  4. Lake Level 2 + Ice Coverage 2
  5. Etc…..
- **CSTORM Model Results**
  - Peaks = maximum storm response at each save point
    - Responses: water level, currents, wave height, wave period, etc.
  - Timeseries = time-varying storm responses for entire simulation
    - Responses: water level, currents, wave height, wave period, etc.
- **Statistics Results**
  - Annual exceedance frequency (AEF) data estimated from 1 to 10^{-4} yr^{-1}
    - Water level and wave responses
  - Hazards represented by magnitude and frequency of a storm response

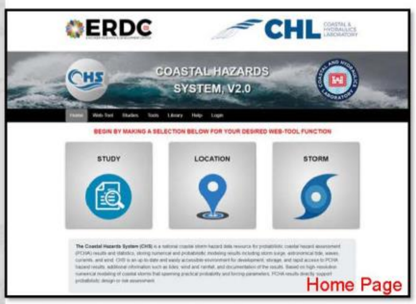
*Meteorological data from the Weather Generator and Lake Level Modeling will be made available to the public through the CHS Library

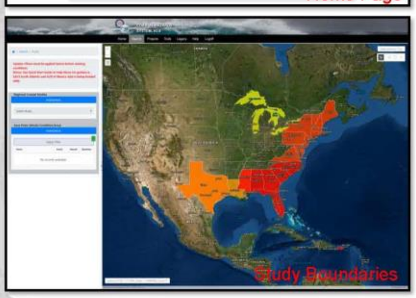


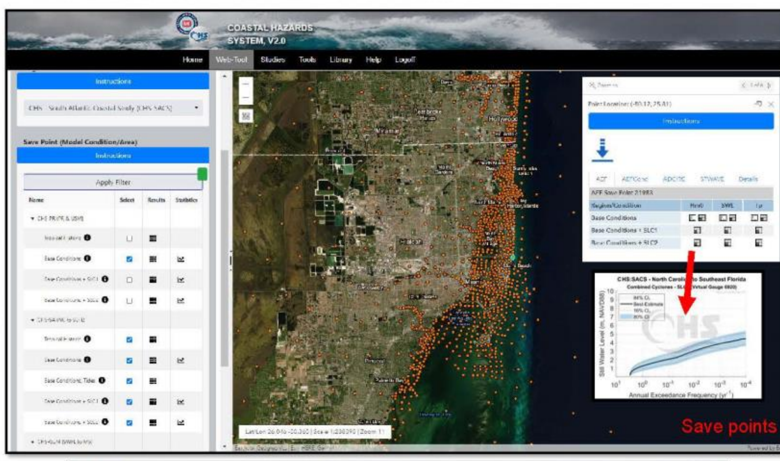
Represent hazard as a function of magnitude and frequency

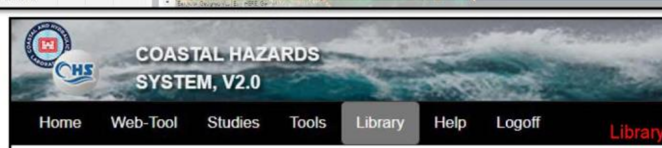


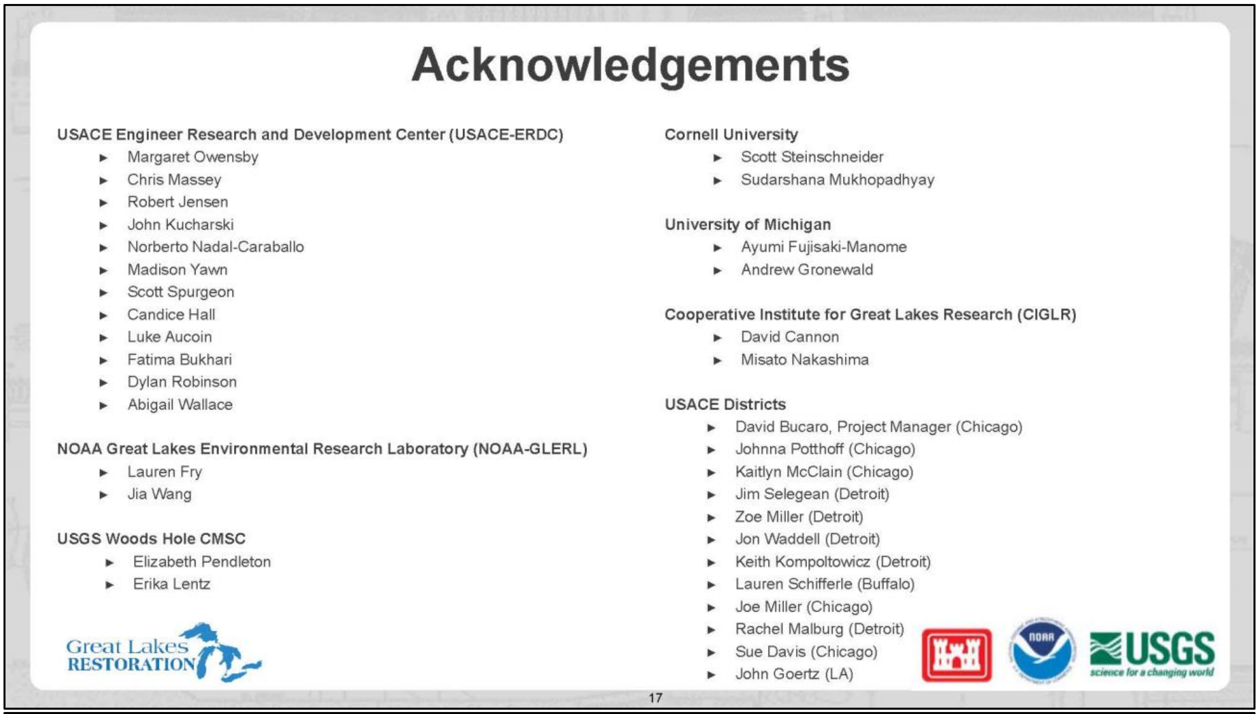
CHS – Website and Webtool https://chs.erdc.dren.mil

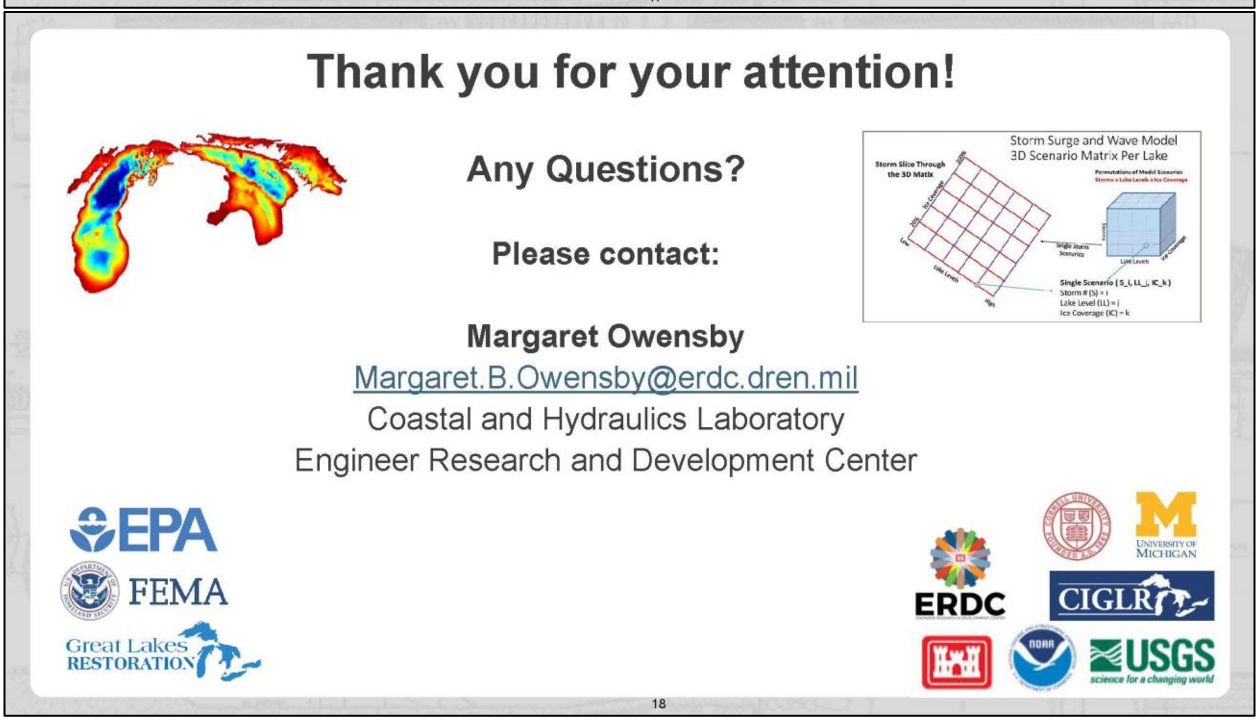












3.6.5.3 Questions and Answers

Question:

If wave runup and overtopping are not included, what is the reason to include the land topography up to 6 meters?

Answer:

We essentially chose the 6-meter mark as the extreme, as the elevation at which we didn't believe any flooding in this area would exceed. That was the main reason for that. We wanted to have a few meters of coverage, in case some water levels got a little bit higher than we anticipated. But like I said, we anticipate that if the flooding got higher than 6 meters, probably impacts on the coast of the Great Lakes would be the least of your problems at that point.

Question:

The model framework looks great. How will the shore change work contributed by Woods Hole is used?

Answer:

Unfortunately, I'm not going to be able to give you a satisfactory answer. I believe that work is going to be conducted in the later stages of the project. So maybe check back with me this time next year and I might be able to give a better answer. But I apologize that I'm not able to give a satisfactory summary of what that team is doing.

Question:

I kept listening for the word seiche in your talk and I didn't hear it and I was also particularly listening for low water hazards associated with seiche. Can you speak to either of those? Are those included in the framework and in some of the issues you might be looking at?

Answer:

We had many discussions about capturing seiche events for this project. I could be mistaken on this, but I believe the consensus was that, for a lot of the conditions that were causing those seiche events, that we were not going to be able to characterize those in our wind and pressure fields. So, there wasn't as much of an emphasis on the seiching events. I could be mistaken on that, but I believe there's not a huge focus on those seiching events in our storm suites.

Question:

You talked about using ADCIRC and SWAN. NOAA has a set of forecast models that they use for the Great Lakes. I believe those are using FVCOM. Are those [NOAA forecast models] going to be leveraged at all in the project?

Answer:

Yes. We've been having discussions with the folks that run the models at NOAA and I believe there is an intention to compare some of our results; test them and compare them with each other to validate our models.

Question:

I know that there's a set of buoys that are put out in the Great Lakes, when they're not iced over. Would those be used to validate the models?

Answer:

I know that we're making use of WIS[25] buoy data in the Great Lakes. I can't remember the comprehensive list of the buoys that we're including, but pretty much any buoy information that

[25] USACE Wave Information Study (wis.erdc.dren.mill/index.html)

we're able to find for those historic events are being included as part of the validation process in our analysis.

3.6.6 Coastal Panel Discussion (Session 3B-6)

Moderator: Joseph Kanney, NRC/RES

Participants:
- Byunghyun Kim, Kyungpook National University, Republic of Korea
- Gorkem Gungor, Zeynep Arslan; Ministry of Energy and Natural Resources, Turkey
- Meredith L. Carr, U.S. Army Corps of Engineers, Engineer Research and Development Center, Coastal and Hydraulics Laboratory (USACE/ERDC/CHL)
- Kathleen Harris, USACE/ERDC/CHL
- Margaret Owensby, USACE/ERDC/CHL

Question:

We've had several presentations on coastal flooding hazards and I think almost all of them in some way or other touched upon the idea that coastal flooding phenomena is really a compound flooding hazard. I think that the days when we would just strictly look at storm surge and be done with it are past. But think I also identified, in many of the talks, that this is not a slam dunk either. There's still a lot of challenges in implementing the compound hazard assessment for coastal situations. So, I'd like each of the presenters to reflect on, from your own experience in a project that you've reported on here or other projects you've worked on, what do you think are the largest challenges. What do you think are the real challenges that we have to address and if you have some ideas for addressing those, whether it be that coupling issue that was discussed by Kathleen or about the rainfall modeling, or getting the different models to communicate. So, any of those topics.

Answer:

<u>Meredith Carr:</u> I think compound is an issue and I think there's a lot of people interested in it. That is very helpful, but I think the biggest challenge is it's crossing disciplines. You're bringing together meteorologists, inland hydrologists, and coastal experts. You're also bringing in people who have the experience in the field, mitigating, and also forecasting. These are very different and you have to find a way to work together and establish language together. We have experts in modeling who are doing that coupling, but we also have smaller basins where it might be something that local stakeholders want to do with their own existing information. So, I think it's important to have a range of options and levels of complexity, but to provide guidance and to also look at the extremes, where we have very sensitive situations like large cities or nuclear power plants. So, I think getting those groups together is both difficult and a challenge. People are excited about it, but it can cause some definite challenges.

<u>Margaret Owensby:</u> Piggybacking off what just Meredith said, for our GLRI[26] project, there are a lot of different agencies involved. One of the reasons why we made the point to include what our definition of total water level is for this study is because we found out, through conversation with our colleagues at some of the different agencies, that just about all of us had a different definition of what total water level was. That's something that we wanted to make sure that we very clearly defined, because the different agencies in many cases have a different vocabulary as to how they describe some of these issues If you can't even speak in the same terms then you're just going to cause more problems.

[26] Great Lakes Interagency Task Force

Byunghyun Kim: To analyze the compound hazard we need many cooperations. We have to analyze the rainfall, the tide, the wave height. We have to calculate all of them to analyze the compound hazard. Although we need time for cooperation, but we have to cooperate.

Gorkem Gungor: I was a bit anxious to make a non-academic presentation, but I can say that for Turkey, for our case, one of the challenges to make the interaction between policymakers and researchers. This was somewhat accomplished in our special plan, in the preparation. But sometimes one stakeholder might be dominant in this interaction, so there are always difficulties and challenges. But we are trying to increase our stakeholder involvement between the policymaker and the regulator and the research and science community in our country.

Kathleen Harris: I don't think I have anything too original to add, but to piggyback on what other people have said, just the inherent difficulty of having so many moving parts and each moving part can affect the other moving parts. So which moving part do you prioritize? There's a lot of judgement that goes into that and complication and computation time. So, I think it's just an inherently difficult problem that everyone's kind of chipping away at, and it's exciting to see each little piece of progress.

Meredith Carr: Just to follow up, we do talk a lot about it as a challenge, but I think the fact that each of these disciplines has gotten to the place they are is why we can start addressing compound. The expertise, the focus, the computer power, and the modeling is why we can actually deal with compound. I think that's part of why, even though it is challenging with a lot of moving parts and sometimes you don't know where to start, it's very exciting and important as well.

Question:

Climate change is on many people's minds. I think, especially for coastal hazards, there's a lot of concern about how climate change may impact coastal hazards, so the question for all the panelists is: In addition to coupling issues between the storm surge and high winds, is there any frameworks under development for the inclusion of the climate change model predictions? If so, what climate change models would be credited, what times frames, what climate change scenarios? What level of complexity would be needed to achieve this? Do we currently have an accepted method for this analysis?

Answer:

Margaret Owensby: I can lead off on this. This is kind of a component of what we're trying to accomplish in our GLRI study. Unfortunately, we're reduced to taking the historic data that we have and kind of bootstrapping for different proposed scenarios. We're trying to use that methodology with the weather generator and the lake level modeling suite to capture what is a possible range of future conditions. Then at a certain point, if you want to get more into the nitty gritty of doing numerical modeling of how that's going to impact coastal flooding, at a certain point you just have to narrow it down, narrow the number of possible scenarios down in some way. So, like I mentioned in my talk, we're basically just trying to choose plausible low, medium, and high values on those lake level and ice condition scenarios to try to cover the whole range of possible values. That's the best way that we had at our disposal to try to characterize future conditions. I'm sure there are much better ways of doing that, but that was kind of the best methodology that we could come up with for the purposes of our study.

Meredith Carr: In terms of the compound work that we've been doing, a lot of the meteorologists we work with, with the rainfall, are leading the effort to deal with the climate change issues. I think, applying it in the whole framework, we need to move forward more beyond scenarios at some point, but right now, most of what we're addressing is in scenario form. Knowing that individually looking at the meteorology we can see more and help us choose those scenarios for the time being until we can incorporate it all together.

Gorkem Gungor: We're mainly a user of the climate modeling results, but I think we should keep in mind the nonstationary impacts and also the possible singular impacts. The models usually go as a continuous process but we should also always keep in mind that there can be singular events, which can move the equilibrium to another position.

Kathleen Harris: Coming at it from a more riverine perspective, there is the Army Corps nonstationarity tool. There's been a push to use that in our projects, and we're starting an effort as part of the streambank stabilization manual we've been updating. Another project I'm on we're looking at compiling the climate change implications for the riverine side. It is so spatially variable on the riverine side, and we're on the front end of this investigation right now for this project. But I think what Meredith had mentioned, with the meteorologists, that seems to be where the uncertainty lies for me. I have the least expertise or confidence in that field, but the idea that one climate model can say that this area is going to be wetter moving forward and this area is going to be drier, and another climate model's results are swapped. It also has to do with organization and runoff and all those variables. I don't think I added any clarity to that, just the idea to look at both the coastal side and the riverine side moving forward and that the nonstationarity tool is a tool that is available on the Army Corps side.

Question:

Did anyone compare hazard curves for the compound event model to the rainfall only model? It seems that, compared to the rainfall only event, the compound event may produce less conservative flood hazards by adding two hazards but multiplying probabilities of two events. Any comments on this issue?

Answer:

Meredith Carr: We have compared those, and it doesn't necessarily mean that for specific return periods or annual frequencies that you will have more, or less. Obviously, there's less events that are compound than are not. But the issue can be that smaller events might give, if you look at them separately, wouldn't seem like as large an event and so that's why it's important to look at them compounded because it's not strictly additive. But yeah, we have compared that. We have tiered models, so we've compared that using bivariate copula analysis. And with this project, we're looking at comparing surge and the surge with rain and trying to see the different impacts and compare that.

Question:

Unfortunately, this question is going to be just directed to our U.S. colleagues. On Tuesday we had Mike Kuperberg, the Director for the U.S. Global Change Research Program, here and he talked about the National Climate Assessments. What information are your various projects pulling from the National Climate Assessments? Is that the correct level of granularity that can be used in projects like this or is it high-level information, but then you still need to do a lot of very detailed modeling by the meteorologists in order to get to information that would be usable as input to your models?

Answer:

Meredith Carr: I think a lot of things that are in the National Climate Assessment (and also you had someone who spoke about billion-dollar disasters), speak more to the concern about compound flooding and the drivers. When I work with folks in the Gulf who are focusing on compound, they don't have a whole lot of tidal difference, so small increases in elevation is an issue. I'll often hear "well we need to get control of the compound because once you add in sea level rise or climate change, we're going to have two issues." So, I think at this point it's very helpful in summarizing the knowledge across fields that can drive both where our focuses are, where stakeholders realize it's an issue and that sort of information. It is general for the models we use, but we can also use if to look at the physical reality of what we might be modeling.

Margaret Owensby: I think that Meredith pretty much summed it up.

3.7 Day 4: Session 4A – Operational Experience

Session Chair: Tom Aird, NRC/RES

3.7.1 Presentation 4A-1: PRA Modeling the FLEX Strategies for External Hazards

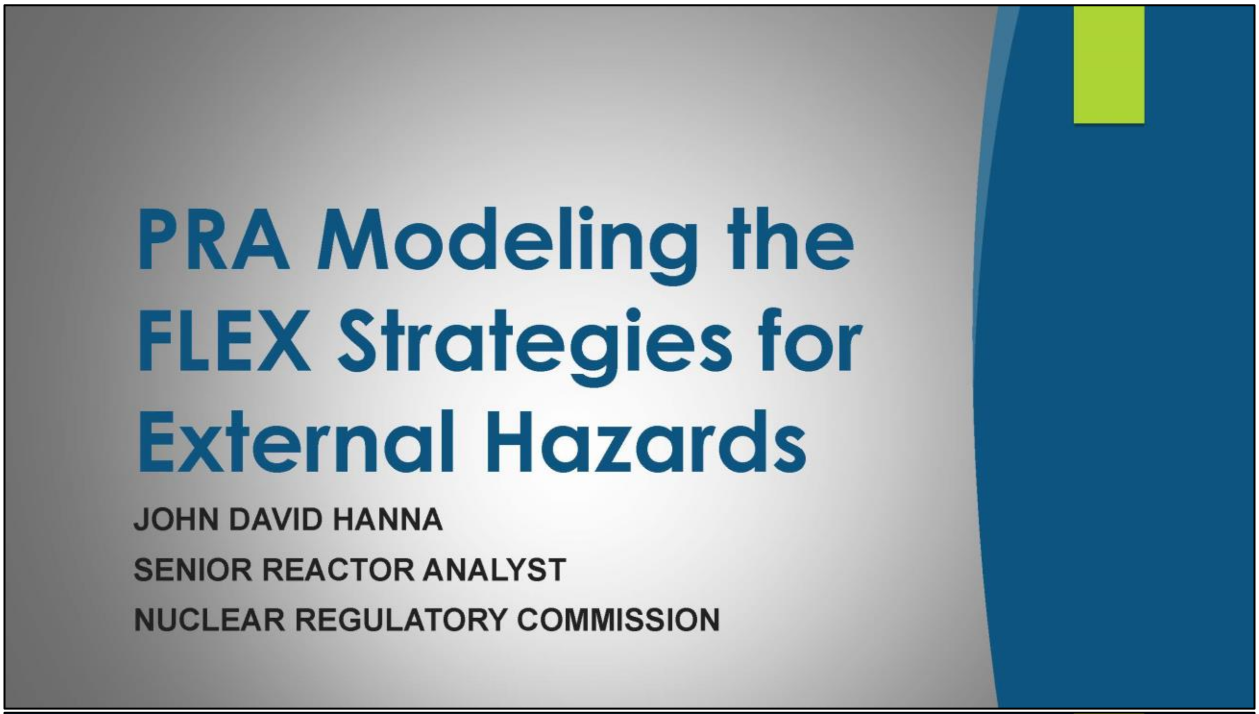
Author: John Hanna, U.S. Nuclear Regulatory Commission, Office of Nuclear Reactor Regulation

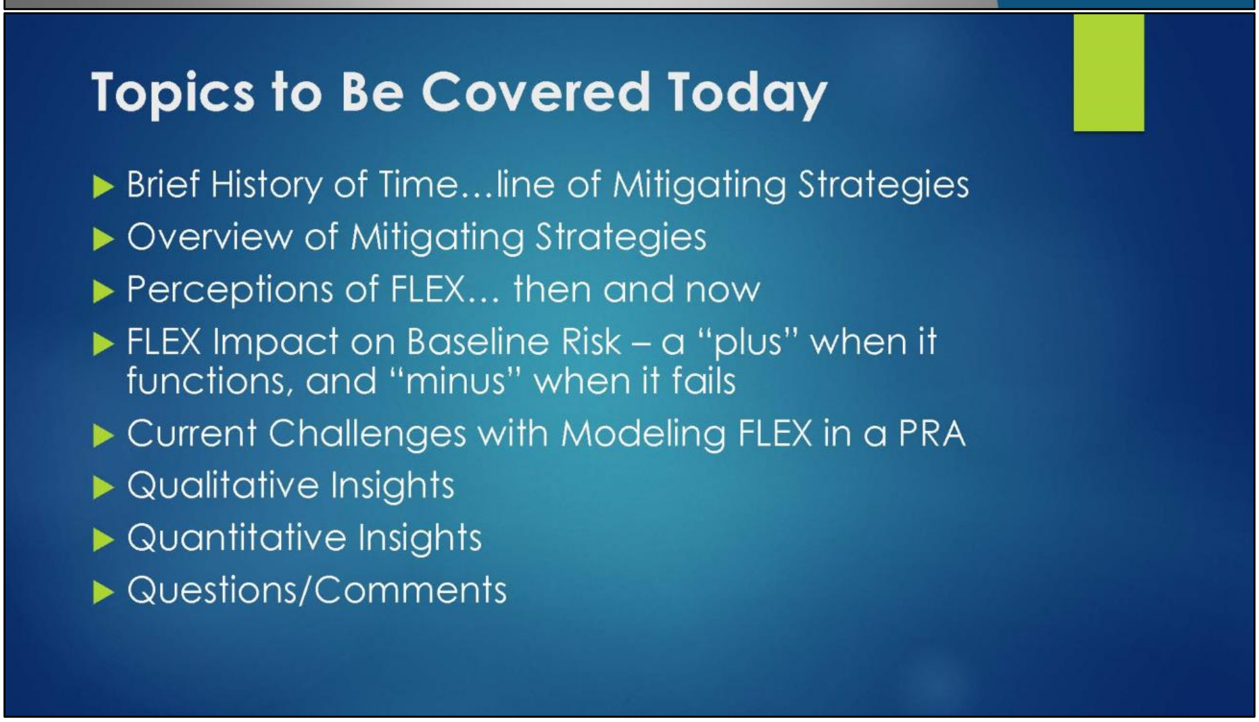
Speaker: John Hanna

3.7.1.1 Abstract

The U.S. Nuclear Regulatory Commission (NRC) maintains a set of Level-1 probabilistic risk assessment (PRA) models, called standardized plant analysis risk (SPAR) models, which are the analytical tools used by the agency to perform risk assessments. Following the events in Japan on March 11, 2011, the NRC issued orders to all operating commercial reactors and required implementation of Mitigating Strategies, commonly known as FLEX. The SPAR models now include the FLEX equipment, strategies, procedures, etc. During this presentation, a brief overview of the Mitigating Strategies will be given, current challenges in modeling FLEX in the PRA will be described, and qualitative and quantitative impacts of the Mitigating Strategies provided.

3.7.1.2 Presentation (ADAMS Accession No. ML23177A142)





What is FLEX? And how did we get here?

- March 11, 2011 – event occurred
- March 12, 2012 – NRC issues orders
- Next few years – licensees develop their "Mitigating Strategies"
- October 6, 2014 – issued TI-191
- October 10, 2017 – issued TI-193
- June 2019 – inspections completed
- Sept. 2019 – Final Rule 10CFR50.155 issued

How did we get here?

- Fukushima showed that our nuclear units though well designed, operated & maintained were vulnerable to large events that can overwhelm Defense-in-Depth, Safety Margins, etc.

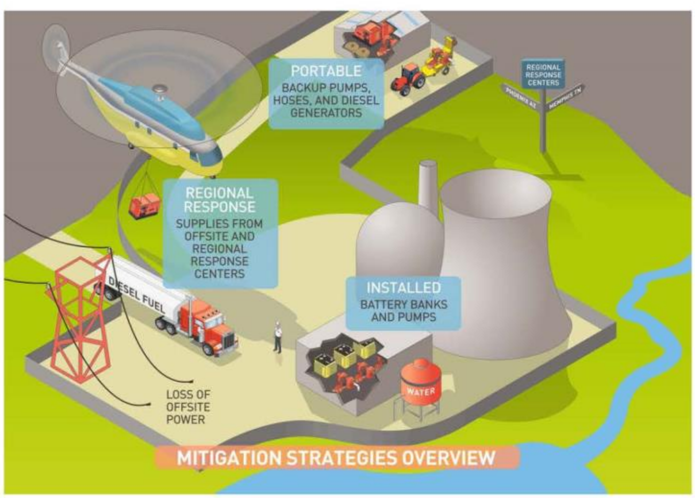
What was +/or is the function of FLEX equipment, i.e., “design basis”?

Original Intent ?

- An extended loss of AC power (ELAP) caused by a large, beyond design basis external event coincident with a Loss of Heat Sink

What it might reasonably be expected to do today?

- “garden variety” LOOP (or even a TRANS) that becomes an ELAP
- additional mitigation for planned maintenance activities
- NOED process for emergent maintenance activities
- outage convenience and improving Defense-in-Depth
- Credited in License Amendment Requests



Mitigating Strategies Overview

Critical Safety Functions

- Core Cooling
- Containment Integrity
- Spent Fuel Pool Cooling

Phase 1 — Phase 2 — Phase 3

T - 0 — ~ 8 hours — ~ 24 hours

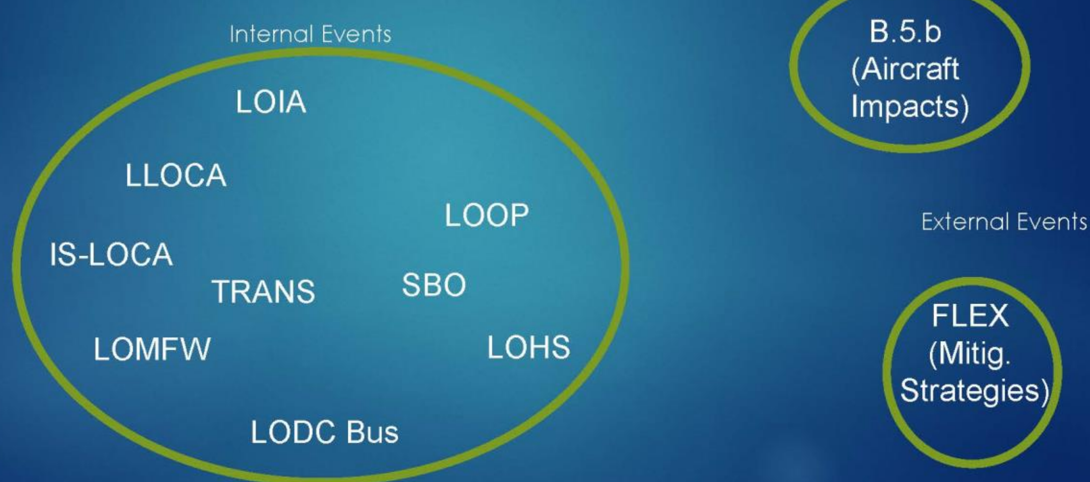

FLEX
FLEX POWER
NORMAL POWER
150 ft. hose lines
FLEX Floating Booster Pumps
FLEX Equipment

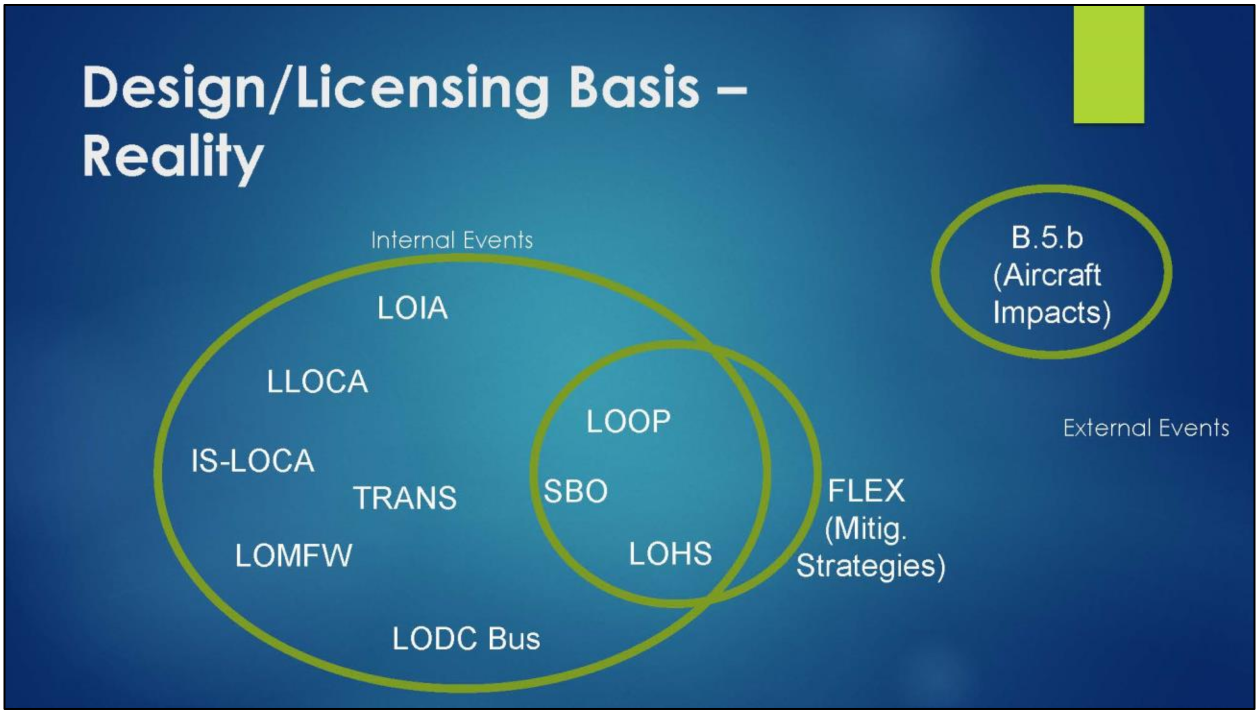

National SAFER locales
1000 Miles
1000 Miles
RRC #2
Phoenix, AZ
RRC #1
Memphis, TN

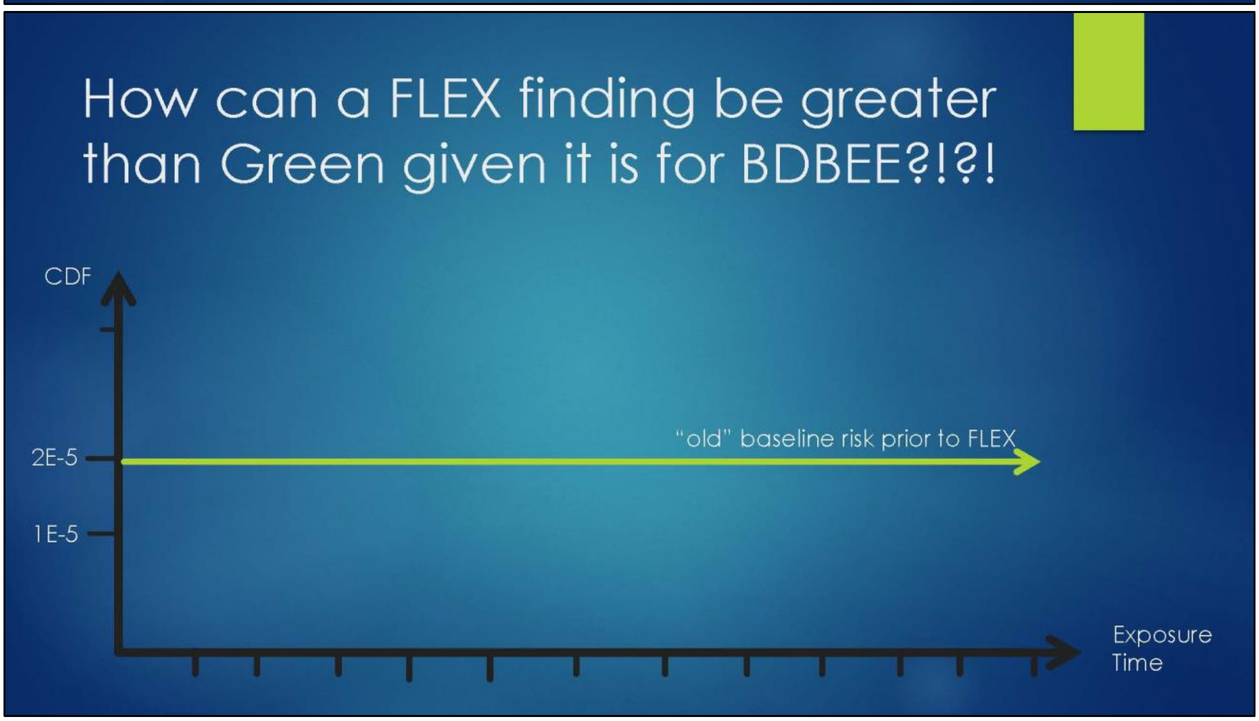
What is the "pedigree" of FLEX equipment?

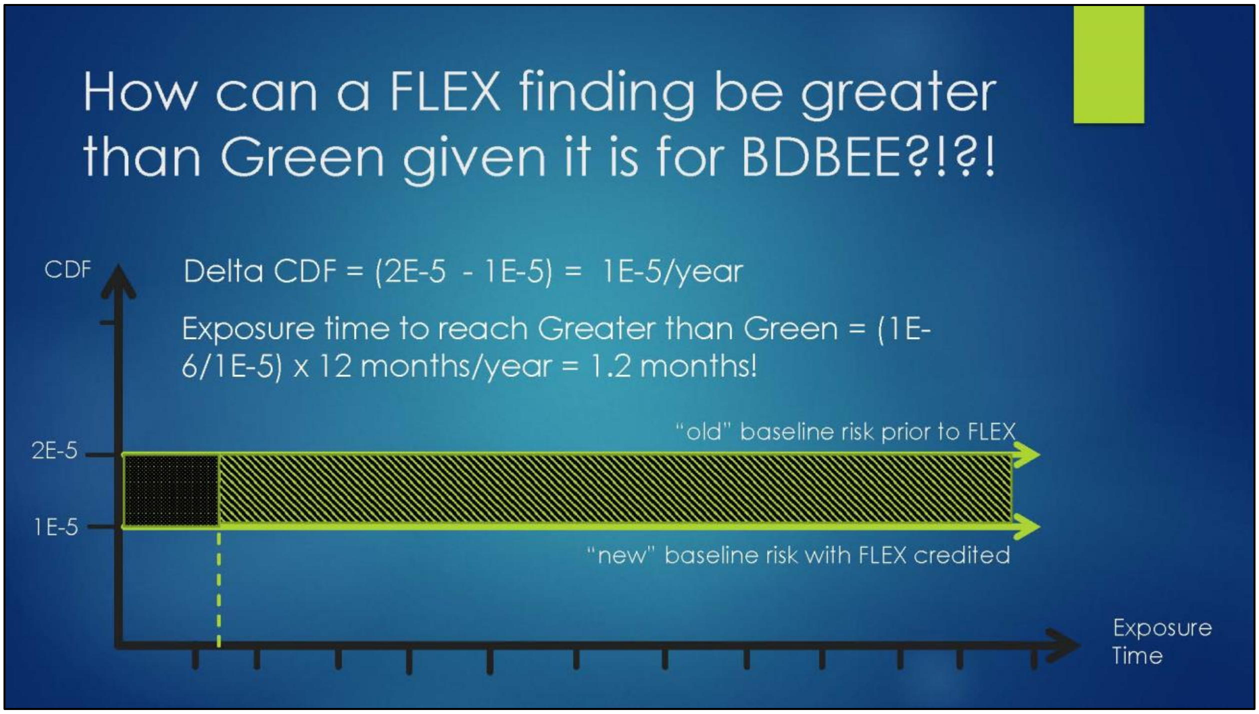
- **Non-Safety Related; Commercial grade, but that doesn't necessarily mean poor reliability**
- **"Beyond design basis" equipment, but potentially (very) risk significant**
- **Initial testing/validation**
- **Long Term Maintenance/Upkeep**

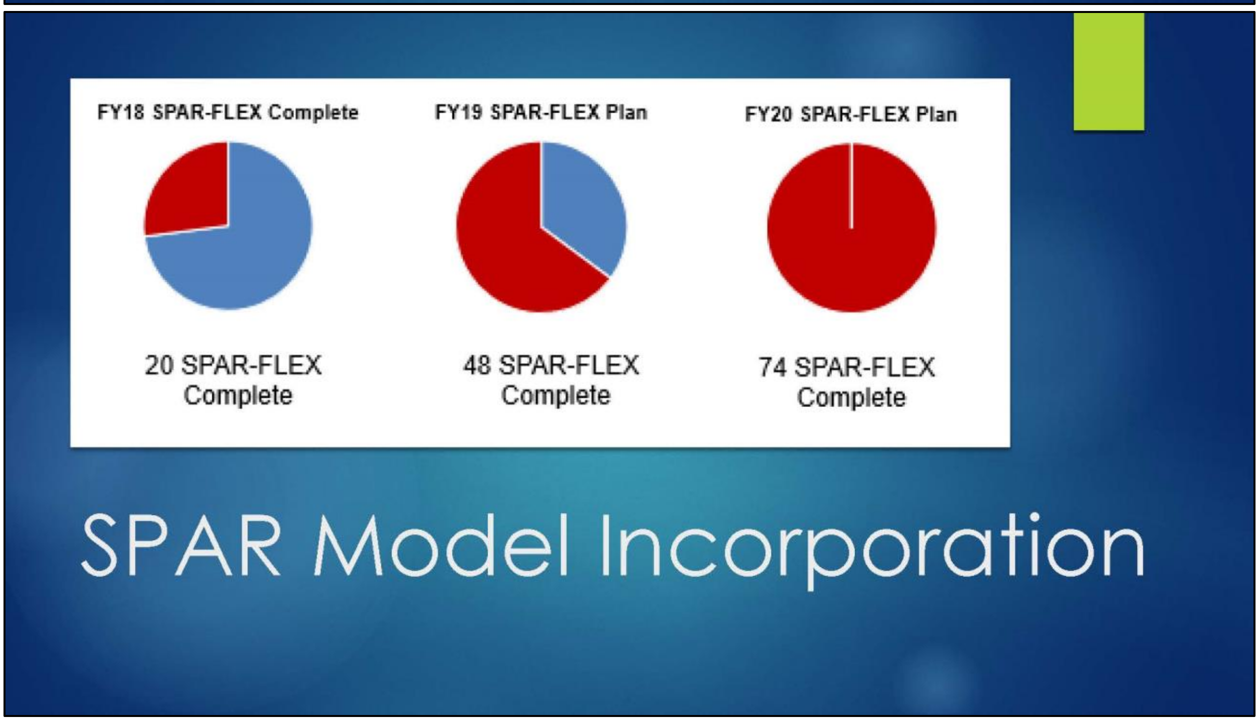
Design/Licensing Basis – Perception




Design/Licensing Basis – Reality
Internal Events
LOIA
LLOCA
IS-LOCA
TRANS
LOMFW
LODC Bus
LOOP
SBO
LOHS
FLEX (Mitig. Strategies)
B.5.b (Aircraft Impacts)
External Events


How can a FLEX finding be greater than Green given it is for BDBEE?!?!
CDF
2E-5
1E-5
"old" baseline risk prior to FLEX
Exposure Time


How can a FLEX finding be greater than Green given it is for BDBEE?!?!
CDF
Delta CDF = (2E-5 - 1E-5) = 1E-5/year
Exposure time to reach Greater than Green = (1E-6/1E-5) x 12 months/year = 1.2 months!
"old" baseline risk prior to FLEX
2E-5
1E-5
"new" baseline risk with FLEX credited
Exposure Time


FY18 SPAR-FLEX Complete
FY19 SPAR-FLEX Plan
FY20 SPAR-FLEX Plan
20 SPAR-FLEX Complete
48 SPAR-FLEX Complete
74 SPAR-FLEX Complete
SPAR Model Incorporation

Recent Issues – Unavailability & Unreliability Values

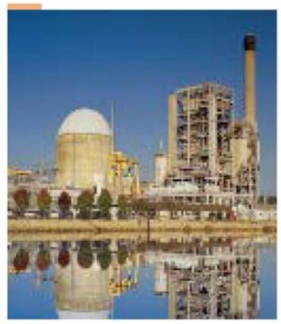
- What values should we assign to these components?
- What are some of the issues/concerns?
  - Overly optimistic values (in the NRC's opinion)
  - Run failures beyond 15 minutes
  - Common Cause failures
  - Limited amount of data & concerns over quality
- What are the "drivers" of FLEX equipment T&M numbers?

Recent Issues – Human Reliability

- How do we assess human reliability with respect to FLEX?
  - Outside of control room
  - Phase 2 is largely based on manual actions
- Expert Elicitation effort – early 2018
  - Good mix of industry & agency staff
  - Mean values & 5% &95% values determined
  - Actions assessed for "sunny day" & BDBEE
  - Results were perceived as too pessimistic
- Recent effort at 2 sites
  - Results are much more plant specific
  - Qualitative as opposed to quantitative values
  - IDHEAS-ECA may be a good approach but there are problems to overcome

Where does FLEX make the most difference? – Qualitative Insights

- **Single unit sites**
- **Fewer EDGs**
- **No crosstie capability at multi-unit sites**
- **Absence of low leakage RCP seals**
- **Small DC batteries**
- **Higher LOOP likelihood**
- **Higher (LOOP/SBO or electrical) risk from internal events**

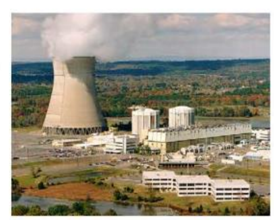


Where does FLEX make the most difference? – Quantitative Insights

	FLEX/Mitigating Strategies OFF		FLEX/Mitigating Strategies ON		Changes	
	Base Case (all initiators)	Base (only LOOP initiators)	Base (all initiators)	Base (only LOOP initiators)	All initiators	Only LOOP initiators
Plant A	5.29E-06	2.61E-06	4.41E-06	1.77E-06	**-17%**	**-32%**
Plant B	1.74E-05	1.34E-06	1.65E-05	5.02E-07	**-5%**	**-63%**

Increasing Credit for FLEX in the PRA Model

Increasing Variation in Plant Design in the PRA Model

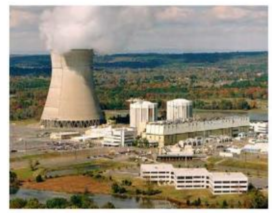


Where does FLEX make the most difference? – Quantitative Insights

		Base Case		
EDG Reliability		**Base Case - Internal + Fire**	**Base Case - Internal + Fire w/ FLEX turned on**	**Percent Change**
	Nominal Model - Out of Box	1.50E-05	1.45E-05	**-3%**
2x worse	Revised Model - New "Reality"	1.59E-05	1.51E-05	**-5%**
	Change	**6%**	**4%**	

Increasing Credit for FLEX in the PRA Model

Increasing Unreliability Values for the 2 EDGs in the PRA Model



Where does FLEX make the most difference? – Quantitative Insights

		Base Case		FLEX Credited			
		Internal & Fire (all sequences)	Internal (only LOOP-WR sequences)	Internal & Fire (all sequences)	Internal (only LOOP-WR sequences)	**Percent Change for Entire Model**	**Percent Change for LOOP-WR sequences only**
national average	**Nominal Model - Out of Box**	2.64E-04	5.87E-06	2.21E-04	3.69E-06	**-16%**	**-37%**
southeast & west	**Revised Model - New "Reality"**	2.58E-04	7.12E-07	2.18E-04	4.26E-07	**-16%**	**-40%**
	Change	-2%	-88%	-1%	-88%		
		Base Case		FLEX Credited			
		Internal & Fire (all sequences)	Internal (only LOOP-WR sequences)	Internal & Fire (all sequences)	Internal (only LOOP-WR sequences)	**Percent Change for Entire Model**	**Percent Change for LOOP-WR sequences only**
national average	**Nominal Model - Out of Box**	2.64E-04	5.87E-06	2.21E-04	3.69E-06	**-16%**	**-37%**
northeast & midwest	**Revised Model - New "Reality"**	2.77E-04	1.96E-05	2.30E-04	1.24E-05	**-17%**	**-37%**
	Change	5%	234%	4%	236%		
	Total "swing" btwn NE & SE	**7%**	**322%**	**5%**	**324%**		

Increasing Credit for FLEX in the PRA Model

Increasing Variation in LOOP frequency in the PRA Model

3.7.1.3 Questions and Answers

Question:

On your about quantitative insights, you mentioned about the difference in design. Is that a difference between a pressurized water reactor (PWR) and a boiling water reactor (BWR)? Is that the main difference?

Answer:

I have to be careful because they are both B&W plants, and we don't have too many B&W plants in the fleet so it may not take much difficulty to figure those out or what they are. But they were similar vintage and of course we're treating the same the S in SPAR model means standardized. So, we're using the same modeling techniques for both plants. So the differences that we are seeing are reflective of the as-built, as-operated plant for plant A and plant B. So yes, it's a good question, and I tried to keep the playing file level, if you will, by selecting two plants of the similar design, similar vintage.

3.7.2 Presentation 4A-2: Failure to Verify Flood Restoration Times at Millstone Unit 2

Author: Dave Werkheiser, U.S. Nuclear Regulatory Commission, Region 1

Speaker: Dave Werkheiser

3.7.2.1 Abstract

During an inspection follow-up to a design basis team inspection, the NRC identified that the apparent time needed to restore from their design basis flooding event (a maximum probable hurricane) was not consistent with their procedure nor the expected inundation and recession time for the flooding event. In addition to a short background, the speaker will discuss the

importance of checking/re-checking the licensee's strategies for extreme weather; questioning the feasibility and/or reliability of a licensee's flood mitigation strategies; and importance of inspectors and analysts working together to assess the practical and theoretical elements when analyzing a challenging scenario.

3.7.2.2 Presentation (ADAMS Accession No. ML23177A143)

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Failure to Verify Flood Restoration Times at Millstone 2

2023 PFHA – Session 4A – Operational Experience

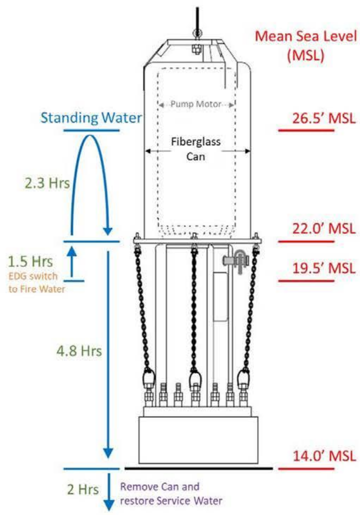
David Werkheiser – Senior Reactor Analyst
USNRC / Region I / Division of Operating Reactor Safety

The Issue(s) - Summary

- 2021 Design Basis Assurance Team Inspection (ref. 1)
  - Using risk insights Team selected CCF of Unit 2 service water strainers as a sample
  - Probable Max Hurricane is the Design Basis Flood event and would exceed Unit 2 intake ground level
  - NRC accepted, during initial licensing, an alternate means to protect a single SW pump
  - The inspectors found that the time needed to restore the service water pump may take more time than was available before the potential loss of the emergency generator
  - NRC documented an Unresolved Item regarding time to a restore service water pump after a max probable flood event (ref. 2).
- 2022 Follow-Up Inspection under PI&R (ref. 3)
  - Licensee developed a white paper and concluded that there more time was needed based on initial design information, but accounting for other variables (post-Fukushima analysis / equipment / actions and non-safety capabilities) there would be success
  - A Green non-cited violation of Design Control (10CFR50 App B Criterion III) (ref. 8)

2023 PFHA - Session 4A 2 U.S.NRC United States Nuclear Regulatory Commission *Protecting People and the Environment*

The Issue - Details



Based on a walkdown of the Unit 2 SW intake area and a procedure review, the team identified an apparent disconnect between the UFSAR description and the implementing procedure. Specifically, the AOP does not direct restoration of the protected SW pump motor until water level recedes to 14 feet, otherwise the intake structure would still be flooded to some degree.

However, the UFSAR description appears to imply that the restoration activities can commence once water level recedes below 22 feet MSL. The apparent disconnect has the potential to extend the coping duration without SW beyond the previously analyzed maximum time of ~4.3 hours. (an additional ~5 hours)

During this period a single EDG would be at reduced loading powering buses and cooled by fire water supplied by on-site tanks. Depending on a number of factors the fire water tanks and/or fuel to the diesel-power fire water pump may be exhausted before SW pump restoration.

Risk Considerations

The finding can not be easily screened in the SDP (IMC 0609 App A, Exhibit 2, Mitigating Systems)

Inspection continued with guidance from SRA to assess the viability of the expressed strategy in the licensee's white paper.

What we considered as Minimum Elements to a Successful PMH strategy as it relates to the finding:

- Timing of SW motor canning (affects transition to single EDG on fire water)
- Capacity of firewater in tanks (including available indications of level / alarms)
- Function of DG firewater pump
- Diesel fuel capacity of the DG firewater pump
- Setting of flow to the firewater-cooled EDG (affects availability of Fire Water duration)
- Timing of SW motor restoration after flood recedes to ground level
- Operator access and response and guidance to support above elements

Other aspects that would be considered:

- Availability of City Water makeup to fire water tanks (MOVs, manual actions, access)
- FLEX equipment support (pre-staged and availability, even without ELAP declared)
- SBO mitigation (DG, availably, access, procedures)

Potential scenarios could be binned as follows considering barriers to success:

- Strategy is success (maintain FW cooling to EDG during PMH event)
- Strategy is unsuccessful, but is recoverable by nearly just-in-time restoration of SW to standby EDG. (short SBO)
- Strategy is unsuccessful, but is recoverable on a longer timeframe (long duration SBO)

Risk Assessment – Data / Assumptions

- Post-Fukushima Flood Assessment (ref. 4 & 5) was significant input since it considered the 10^{-4} vs 10^{-6} storm, and was considered best available. A major factor was the shorter site flood inundation time (5 hrs vs 7 hrs).
- The licensee white paper paralleled the expected strategy docketed in the post-Fukushima response
- Validated timings for operators and assume fire water throttle settings where reasonable and with confidence with NRC Operator Licensing staff support.
- Used success criteria for LOOP event At-Power event tree (RASP Volume 1 and Volume 2, (Section 5)) (ref. 6 & 7) -> Weather-Related LOOP = 1.0
- Emergency Diesel Generators and Service Water was deemed recoverable
- FLEX was not credited, and SBO DG was available with higher failure

Risk Assessment - Conclusions

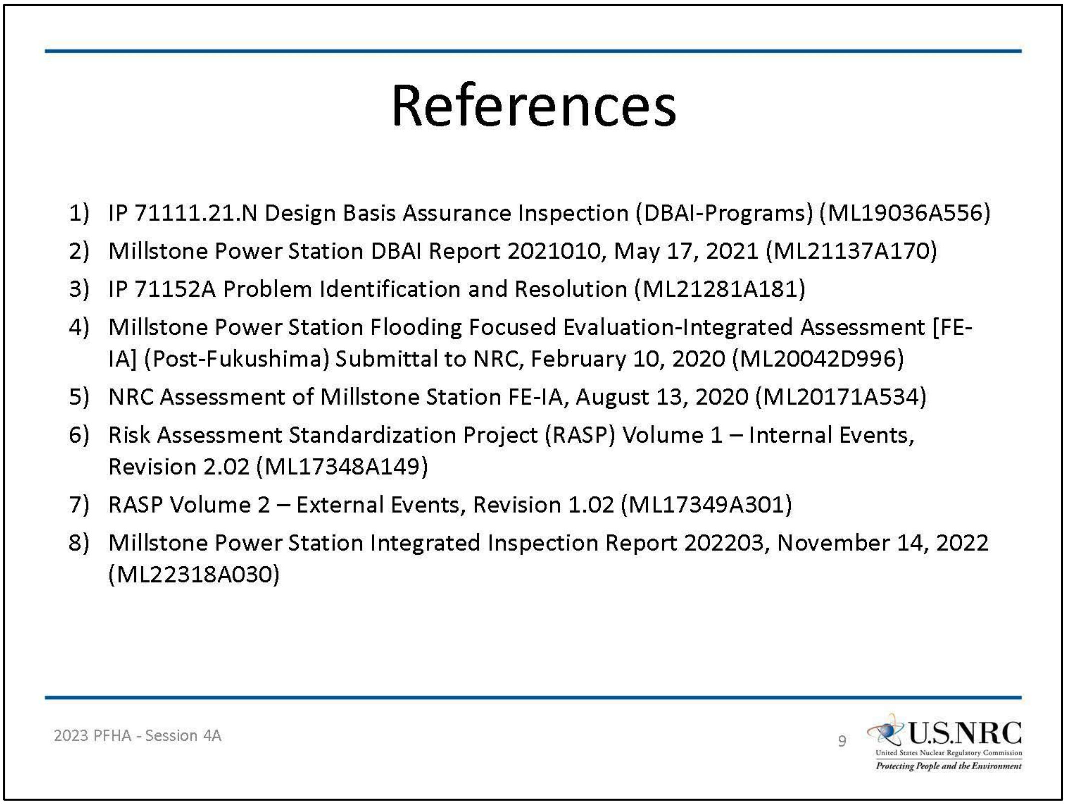
- Estimated delta CDF 2E-7/yr (5% 3E-10, 95% 8E-7)
- The dominant accident sequence -> hurricane event (PMH), loss of offsite power due to high winds, loss of both EDGs and station blackout diesel generator, and failure to recover an EDG, and failure of auxiliary feedwater.
- Considered a bounding estimate and did not account for additional margin afforded by the availability of city water make-up (automatic or manual) to the fire water tanks (extends cooling to the EDG), pre-staged FLEX equipment, and additional resources available from the site during a pre-planned shutdown for a storm event.

Corrective Actions

- Dominion entered the issue into the corrective action program
- Performed a new calculation to determine the additional time it would take the water to recede from El 22.0’ to El 14.0’
- Issued an engineering technical evaluation to resolve discrepancies between the FSAR and operating and maintenance procedures.
- Revised the FSAR and various procedures to maximize the available fire water inventory (extended inventory to 12 hours), and to increase fire pump fuel tank inventory to 12 hours.
- Performed an evaluation to determine the overall plant PMH mitigating strategies impact due to the extended SW pump motor outage (during the postulated weather event)

One NRC

- Support to the Team for sample selection
- Finding screening and processing
- Additional information - what is important and assist in assessing where it may be impactful
- Sharing of information and communication across processes while maintaining in-process (DBAI, PI&R, Site visits,



3.7.2.3 Questions and Answers

Question:

The event that gets us to this issue is a tidal surge from a hurricane, right?

Answer:

That's correct.

Question:

I'm curious because I've had to do this myself for other flooding events. How did you generate the initiating event frequency? We've had a lot of discussion this week about tidal surges, about PMF, about hurricanes and landfall and all that kind of stuff. So how did you generate the frequency? What tools did you use?

Answer:

A lot of the information came from the post Fukushima report [flood hazard reevaluation report]. Since they're coastal plant in the Long Island Sound, this plant was determined to need a integrated assessment. If you just did the original analysis, I don't think it would have passed, so they did this 10^{-4}, 10^{-6} [annual exceedance probability, AEP] storm approach. The original analysis did not take into account wave action. The updated analysis did take into account still water and wave action and it was really more of an integrated approach, what's more probable. Inside there [the flood hazard reevaluation report], gave us those frequencies. So, in our SAPPHIRE models, which is what the NRC uses for the SPAR models, we have bins for different hurricanes and high winds. Bin number 1 for hurricane, was along the line of the 10^{-4}

AEP. We were using that as our event tree, making sure to have proper linkage back to loss of offsite power (LOOP) which we assume was a 1.0 [conditional probability]. So, we used the 10^{-4} storm external event and then 1.0 for a LOOP and we propagated that through. The NRC has guidance documents, the RASP manuals. Volume 2 gives us a little bit of a template to use for external events and that was a very good representative methodology and that's also referenced in our references on the last slide.

Question:

So, you ended up using the probabilistic storm surge assessment that was done for the post-Fukushima flood hazard re-analysis to get that initiating frequency, is that correct?

Answer:

Correct. I think without that there would have been a lot more conversations with headquarters. But because that was a ready-made off-the-shelf activity and some of the work that a lot of staff here have done and the research, that definitely helps us to do this in a timely fashion. And then also, are we open and scrutable for reviews since it's already on the docket.

Question:

What type of information is stored in NRC Safety Portal?

Answer:

Joseph Kanney: You are referring to the Natural Hazards Information Digest (NHID), hosted on the Safety Portal. As part of our probabilistic flood hazard assessment research program, we initially developed what was called the Flood Hazard Information Digest (FHID). This was to support the analysts and folks in NRR who are responding to inspection findings or other events. We collected all of the known information that we have from the FSARs, from any re-analysis, from past events, and collecting that up all into one database. Later, post-Fukushima, we expanded that to other natural hazards. So, currently we have flooding hazards in there, high winds, extreme temperatures, seismic, and that's a resource that is used by NRC staff. It's an internal resource.

3.7.3 Presentation 4A-3: Impact of the 2022 Lake Erie Seiche the Davis-Besse Nuclear Power Station

Authors: Daniel Mills[1], Russ Cassara[1], John Hanna[2]; [1]U.S. Nuclear Regulatory Commission, Davis Bessie Resident Inspector, [2]U.S. Nuclear Regulatory Commission, Office of Nuclear Reactor Regulation

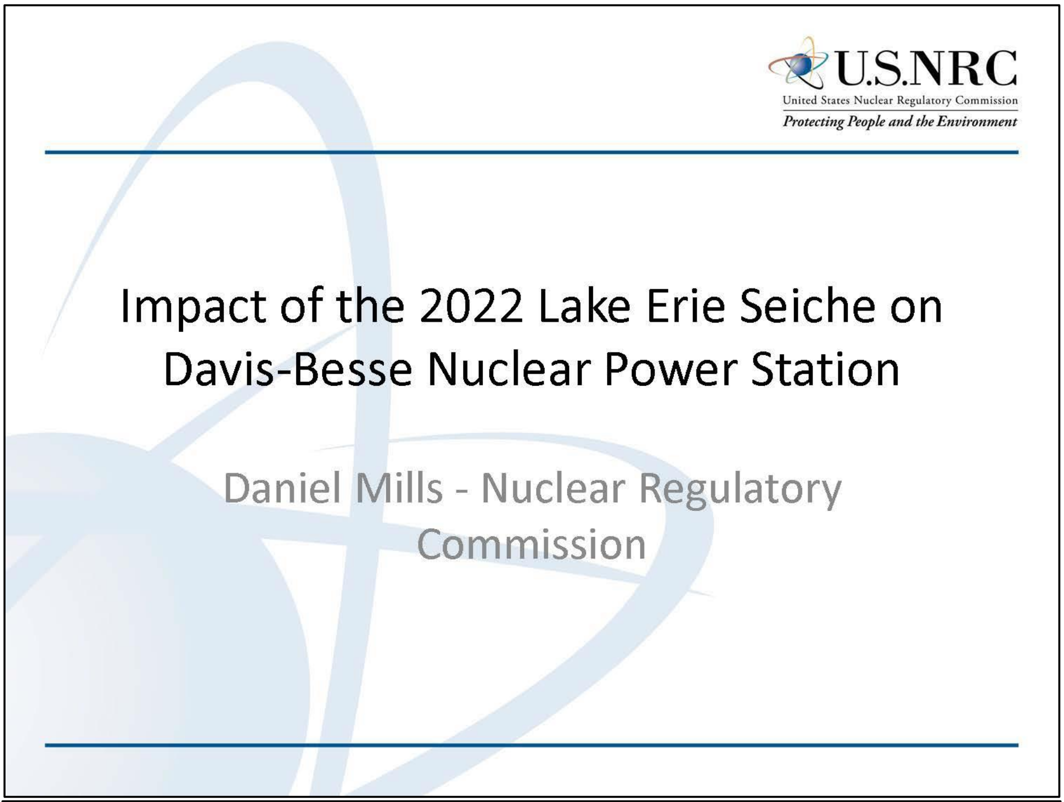
Speaker: Daniel Mills

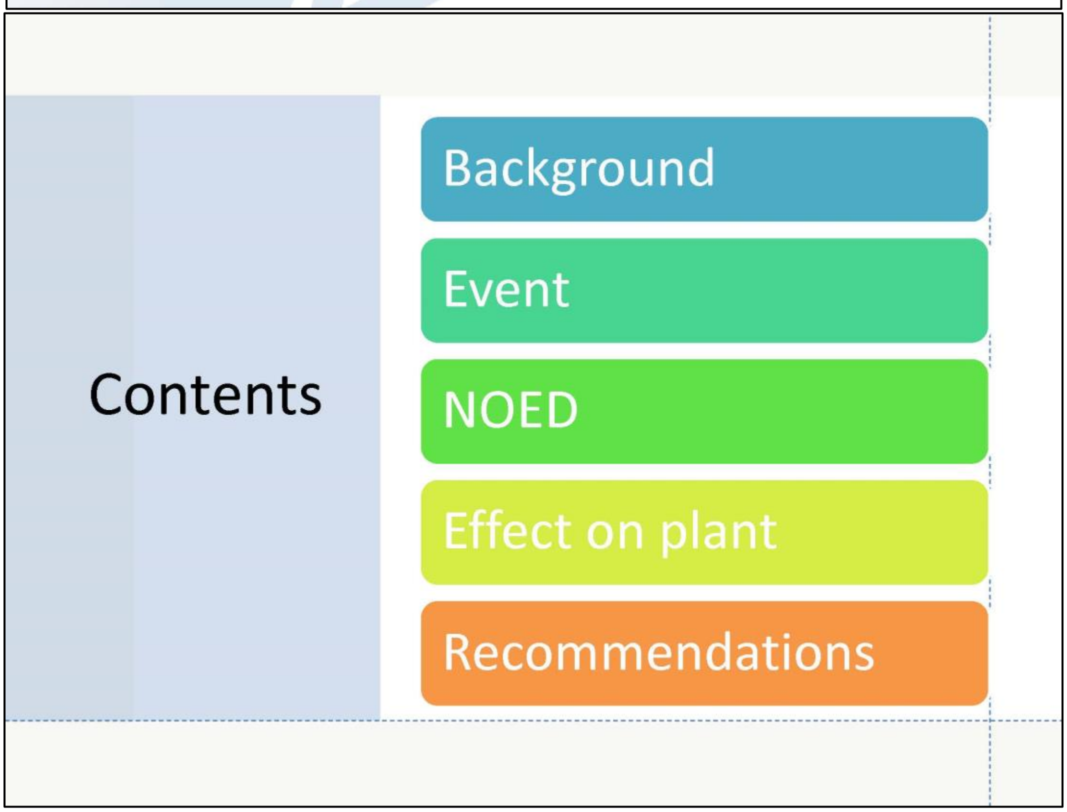
3.7.3.1 Abstract

The Davis-Besse Nuclear Power Station relies on Lake Erie for water to supply its ultimate heat sink. From December 23-25, 2022, Lake Erie experienced a seiche caused by high winds that resulted in historically low water levels at the southwest basin. Because of the low lake level, the Davis-Besse ultimate heat sink dropped below the level required by the plant's technical specifications. After discussion with the licensee and consideration of risk, the NRC granted the plant enforcement discretion to allow continued operation. This presentation discusses the

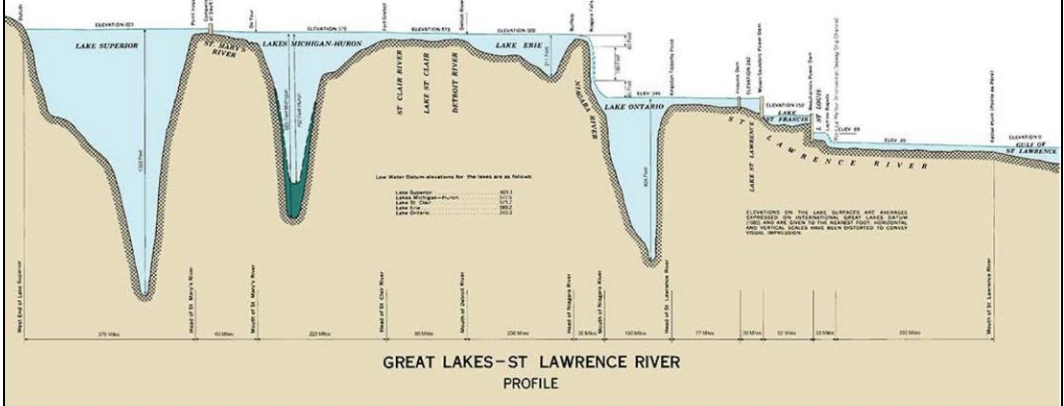
event, its impact on the plant, and the considerations NRC used to grant a Notice of Enforcement Discretion (NOED).

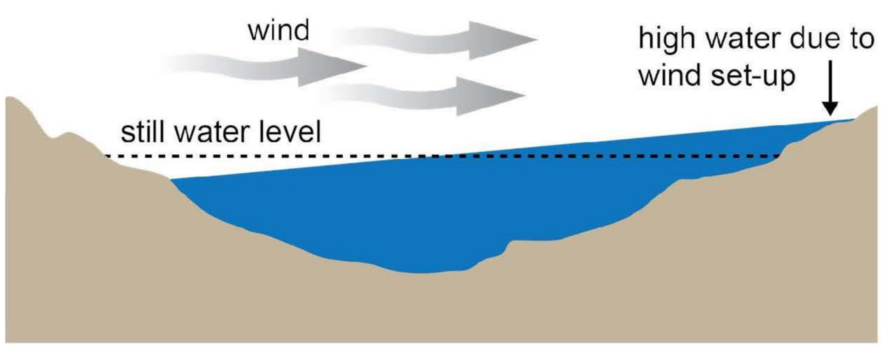
3.7.3.2 Presentation (ADAMS Accession No. ML23177A143)





Background





Wind setup is a local rise in water level caused by wind.

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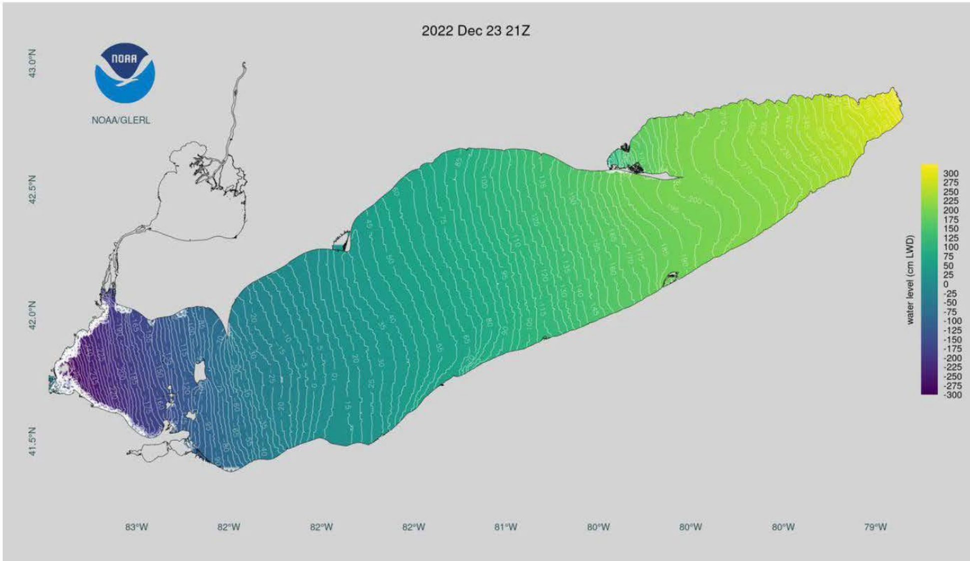

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NOED

- Licensee began informal discussions with SRI on December 22
- TS LCO 3.7.9.A entered at 1412 on 12/23
  - 6 hour shutdown
- Licensee formally requested a NOED on December 23
  - Conference held at 1456 and verbal approval was granted for a 48 hr (total) period of enforcement discretion. The written NOED request followed as required within 2 business days of the verbal request.
  - NRC responded to the written request within two days as required.

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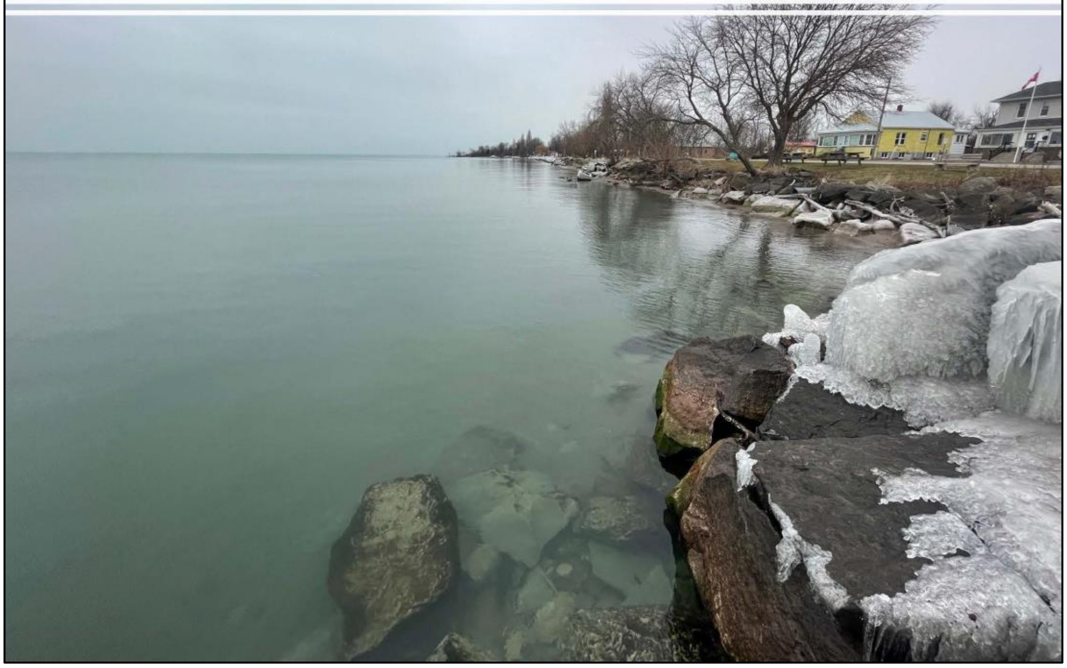
Pelee Island

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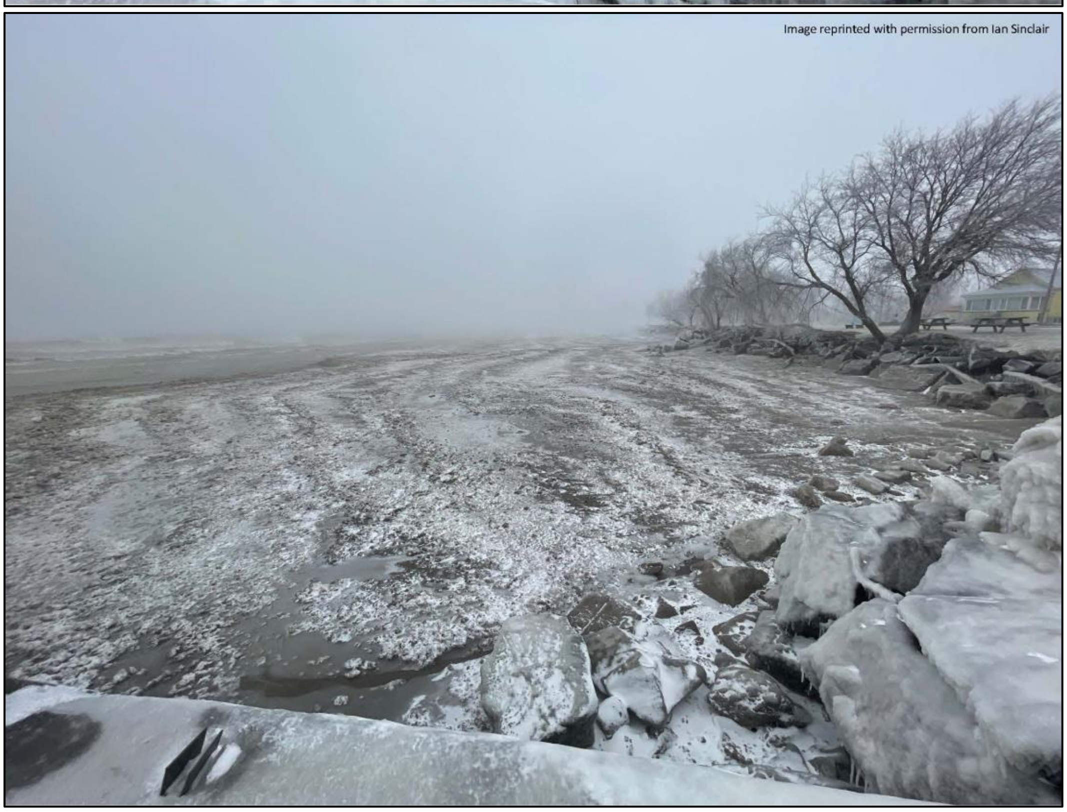
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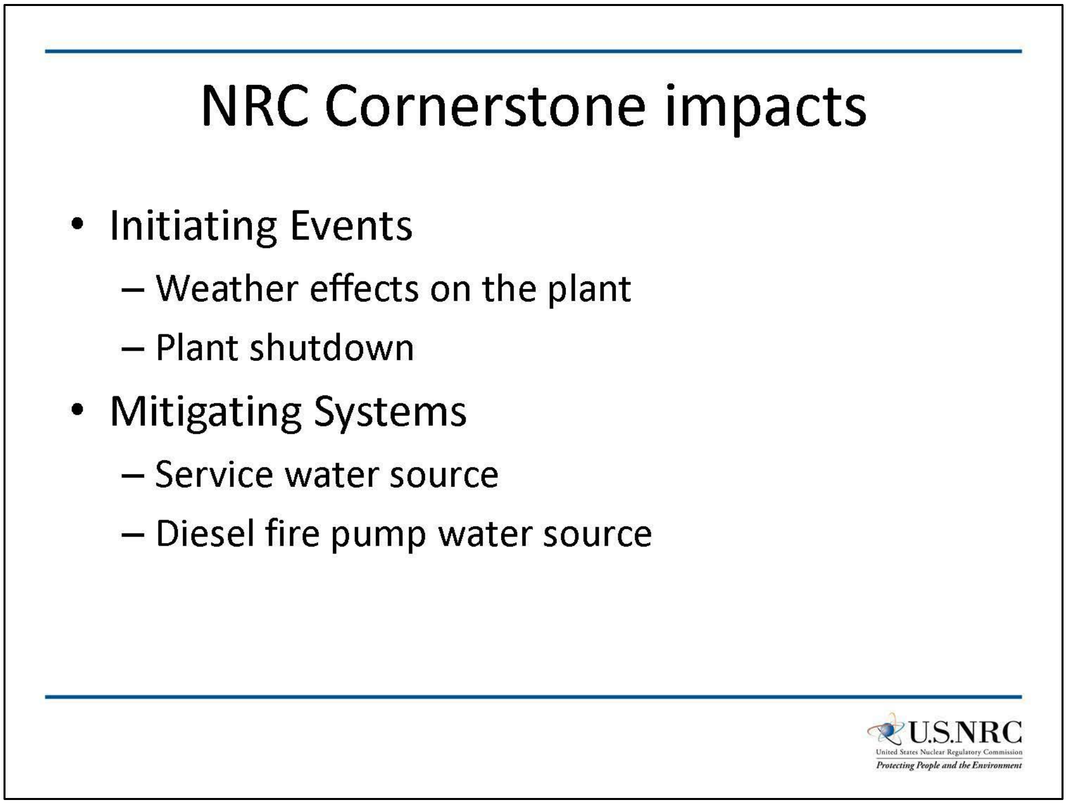


3.7.3.3 Questions and Answers

Question:

How long did it take for water levels to return after the storm?

Answer:

It took on the order of 24 hours.

Question:

When we (hydrologists) estimate the design basis low water levels, we sometimes use average 1-day or 7-day low water levels for rivers and lakes as design basis. Do you think these average estimates, instead of instantaneous water levels, are reasonably conservative for emergency plant operations?

Answer:

In this case, the technical specification requirement for Davis Bessie is an intake forebay level 562 feet. However, the safety analysis supports safe shutdown under most limiting conditions, which would be during summer when the ambient temperatures are elevated and water temperatures are also elevated at an intake forebay level of 560 feet. That's the level at which the intake canal and the lake decouple. So, the plant design is likely conservative enough. I think those numbers are based on the 100-year low water level, which if memory serves, was in the 1930s and I think it was lower than this event. But this event was one of the top 10 most significant wind-driven seiche events on Lake Erie.

Question:

Is Lake Erie the Ultimate Heat Sink (UHS) or does the station utilize a separate pond or an underwater dam to create their UHS?

Answer:

The intake canal and intake forebay is the ultimate heat sink. The lake supplies that ultimate heat sink. The intake canal and intake forebay is designed to hold sufficient amount of water volume to allow plant shutdown and plant cooldown from 560 feet water level while decoupled from the lake itself.

Question:

Was there an EAL[27] Declaration for this?

Answer:

There was not. There was no emergency declaration for this.

Question:

Please discuss the content of NOED[28]. Did it include a risk analysis? Was it quantitative or qualitative?

Answer:

There were discussions starting on the 22nd, the day before this event occurred, based on weather forecasts and that included regional risk analysts and risk analysts at headquarters as well. The NOED itself included a discussion of the risk profile related to the ability of the plant to affect a safe shutdown and the ability to remain shut down and cooled down, if the event were to worsen and become a prolonged drop in the lake water level.

3.7.4 Session 4A-4. Operational Experience Panel Discussion

Moderator: Joseph Kanney, NRC/RES

Participants:
- John Hanna, NRC/Region 3
- Dave Werkheiser, NRC/Region 1
- Daniel Mills, NRC/Region 3

Question:

John Hanna: Dave and Daniel, what are you seeing with respect to how licensees treat FLEX equipment. We've touched on FLEX in all three of these presentations, the mitigating strategies. What are you seeing out in the field? How are licensees treating the FLEX equipment, the procedures, and the training. Is the equipment being treated as important when issues come up? Are they being treated under the corrective action program? Are failures taken seriously?

Answer:

[27] Emergency Action Level

[28] Notice of Enforcement Discretion

Dave Werkheiser: Being the SRA[29] for Region I, I tend to see the plants for the northeast United States. We see, at least over the last number of years, as licensees are putting FLEX into their PRA models, they see the benefits. They see the impact on the risk. The pedigree is what it is right, but they'll start to treat the model much more with respect. The thing that is interesting is, the majority of them that do incorporate FLEX but just keep them in their shelters, you'll see that they'll just stick to what's the minimum required, for maintenance. They'll still go into corrective action program, just so they can stay ahead of that. But if any of those pieces or parts are functions that are permanently installed in the plant, that they partially credit (in this Millstone case there was a subset of FLEX equipment that was permanently installed or pre-staged), in the procedures they recognized that impact for maintenance and review and corrective action program. And that training, at least what we found throughout our reviews, are much more refined and consistent with things we see that are stage-related or very important to safety.

Daniel Mills: At Davis Besse, there is a somewhat unique FLEX approach, which includes a permanently installed diesel-driven, what they call, emergency feedwater pump. It allows them to take credit for a significant risk reduction. It includes its own facility with its own diesel fuel source, its own water source, and can inject into both or either of the steam generators. It is a backup essentially for the turbine-driven auxiliary feed pumps, which are very risk significant pieces of equipment. So that piece of equipment in the facility is essentially treated by the licensee as another safety-related piece of equipment. They have what they call their FLEX specs which are modeled on their technical specifications and include periodic surveillances. In general, that piece of equipment and the facility it's in are treated as a very risk significant piece of plant equipment. Half of their portable equipment is stored in that facility, which is a hardened concrete bunker-type facility. It is treated as is normal for the industry, which is those pieces of equipment are run on scheduled periodic surveillance schedules and in general that equipment is well cared for. From what we've seen, at least at Davis Besse, the FLEX approach is trained on and is well understood by plant staff and especially operations.

Question:

John Hanna: Correct me if I'm wrong, but that FLEX equipment that you described in that hardened structure, which is part of the Phase 2 strategy, is also paying significant dividends for their fire risk, right? That's also helping out for internal events but also for fire risk as well in their CDF[30], right?

Answer:

Daniel Mills: That's correct. In fact, part of their transition to NFPA 805[31] was the construction of and installation of this facility and the emergency feedwater pump.

Question:

(to Jon Hanna) I'm very interested in your results considering the FLEX model. If possible, can you explain a little bit regarding the event tree model considering the FLEX system?

Answer:

John Hanna: The way we handled that modeling is shown in the prior slide, where you had that Venn diagram[32]. It was not as hard as you might think. In this slide you can see loss of offsite

[29] Senior Reactor Analyst

[30] (estimated) core damage frequency

[31] National Fire Protection Association Standard 805.

[32] Referring to slide 10 in presentation 4A-1.

power (LOOP), station blackout, which is essentially just a loss of offsite power without any diesels, and loss of heat sink. Those were already existing in our SPAR models in SAPHIRE, so adding FLEX was not that difficult. It was just adding additional branches, so when you got to the event trees for LOOP, that then transitioned to station blackout. Take those station blackout trees and just add several fault trees to then give you a chance for success. So, just putting yourself in the shoes of the operators. The loss of offsite power happens for whatever reason, and the diesels don't start. Within a fairly short amount of time they have to decide whether or not to go into the declare extended loss of AC power (ELAP) and start implementing the FLEX strategies. Then you just add on a fault tree for the FLEX equipment, whether it be for secondary heat removal, primary injection, spent fuel pool makeup, whatever the strategies are. It's fairly simple to add that on, and Idaho did that for us for all the SPAR models.

Dave Werkheiser: You'll see that fault tree and where those functions are success, just like John said. That functional element in the event tree we can go down and that fault tree, which may have the safety-related components, as the FLEX equipment, directly linked into the full-power internal events.

Question:

How could you calculate the failure probability of the FLEX system?

Answer:

John Hanna: Initially, we really didn't have very much information. This equipment was installed in the last few years and it was only tested either monthly or quarterly depending on the type of equipment. We didn't have a lot of data. So, if we had a portable emergency DC generator, a 480-volt or a 4160 portable diesel generator, we just used the numbers for fail-to-start, fail-to-run, test and maintenance on availability for the installed in-plant equipment. We knew that wasn't really a great approximation, but it was a good starting point. We could at least start with that. Your question is a good one, because now with the new PWR owners group data that has been shared with the agency, we now have a better estimate of what the availability/reliability is, and it is not as good as the installed, in-plant equipment.

Dave Werkheiser: Just to add on what John was saying, that FLEX equipment, because there's a lot of uncertainty for that, as analysts, we multiply that by 3, or some factor, mostly 3. Because that failure probability is taken from historical operating experience for safety related equipment, which has a maintenance, and a training, a pedigree that goes along with that. So, to offset the uncertainty, we would turn on our FLEX, and then we would multiply those FLEX hardware equipment times 3, along with human error probabilities. We'd make adjustments to that. Like what John was saying, we had gotten information from industry in 2020 and we're starting to incorporate that into our FLEX and those failure probabilities tend to be higher than our factor of 3. So, we've been doing some sensitivities with regard to that, so we're starting to use the licensees' failure information.

John Hanna: It's worth noting the industry has been working with the agency in a very cooperative, collaborative kind of way. For example, we've identified that there's been issues with the batteries on some of the portable equipment so the industry and NEI[33] has taken that on and is doing something to address those hardware issues and improving the availability/reliability of that equipment. So, some kudos to the industry for working with us in a collaborative kind of way to make sure that sure that FLEX is reliable as it can be.

[33] Nuclear Energy Institute

Question:

I recall that FLEX only needs to be trained or demonstrated on a multi-year timeline, right? And did you say that some of the sites are doing that more frequently and is that able to inform the reliability of the overall strategies?

Answer:

John Hanna: Maybe you could clarify the first part of the question about on a multi-year?

Question:

I could be completely misremembering, but I thought that the requirement to go through the FLEX procedures, wasn't on a monthly or quarterly like the equipment. It was a longer timeframe, and I might be wrong.

Answer:

John Hanna: This is all spelled out in an NEI document, which I don't remember the number of off the top of my head. But that NEI document explains which type of components you should test monthly and which components you test quarterly. Then as far as the training, I believe that the job performance measures, for example, for the operators, is on a re-qual basis, so however often the reactor operators and senior reactor operators are getting qualified or re-qualified. That's part of their testing and training program. So, it might be only every two years, for example, but that's as frequently as they train on all their emergency operating procedures.

Dave Werkheiser: You'll find that the plants that are just using the FLEX equipment for FLEX, not incorporated into any other type of operating procedure, will tend to stay with the NEI guidance, along with the facility implementation plan (FIP). For the plants that are starting to realize the benefits of that particular device from a risk perspective for whatever event they can credit that, you will see probably more training, more maintenance because that snaps into their normal pedigree, their frequency. They just put it right into the regular program. So, you start to see as they use it more, and they incorporate it more, there's more training, and there's more maintenance. That's just starting to become the norm. But there's still a group that says that FLEX is great, we had to do it. It's there and we're just doing the minimum required. Then there's plants that really see that benefit and they are really taking more care of it and doing more training. So, it really depends.

Comments:

Joseph Kanney: There are a couple of references to some documents in the chat: PWROG-18042-NP Revision 1, FLEX Equipment Data Collection and Analysis.

John Hanna: Yes, that's the data that we were talking to earlier.

Dave Werkheiser: That's the owners group information for the failure data; we are in the process of incorporating that into our SPAR models.

Joseph Kanney: The chat also mentions that the NEI document is NEI 12-06.

3.8 Day 4: Session 4B – Wrapping Up

Session Chair: Tom Aird, NRC/RES

3.8.1 Presentation 4B-1: On Fuzzy-Systems Modeling of Ponded Infiltration, as Analogue to Flooding, in Fractured-Porous Subsurface Media

Author: Boris Faybishenko; Lawrence Berkeley National Laboratory

Speaker: Boris Faybishenko

3.8.1.1 Abstract

The goals of the presentation are to illustrate (1) the application of ponded infiltration tests as a physical analogue for understanding water and contaminant transport phenomena under flooding conditions, and (2) the use of fuzzy soft computing as a suitable technique for numerical modeling of unsaturated-saturated subsurface media, using uncertain field-based information. Fuzzy logic is generally a form of artificial intelligence (AI) software and is considered a subset of AI.

The presentation will include an overview of the design and the results of observations obtained during a series of ponded infiltration tests conducted in fractured basalt in Idaho at the Radioactive Waste Management Complex (Large Scale Infiltration Test), Box Canyon (Meso-Scale infiltration test), and Half-Hells Acre (Small-Scale field test) sites. These results will first be used to demonstrate the complexity of the geometry and physics of flow and transport through fracture-porous media, followed by the analysis of three types of uncertainty representation for modeling of subsurface heterogeneous media: (a) randomness (random fluctuations are described using traditional probabilistic models), (b) fuzziness (using imprecise, subjective, linguistic, or expert-specified information), and (c) fuzzy randomness (incomplete, fragmentary objective, data-based, randomly fluctuating information, which can also be dubious or imprecise). Hydrogeological flooding predictions are subject to two main types of uncertainties: aleatoric uncertainty—mainly caused by subsurface heterogeneities and variability; assessing such variability is subject to ambiguity, vagueness, imprecision, ignorance, etc., and (b) epistemic uncertainty—caused by selection of different conceptual and simulation models and their parameters, involved in hydrogeological modeling.

The application of the fuzzy system approach will be demonstrated using calculations of the fuzzy regression and a fuzzy C-means clustering for the water travel time, based on the results of ponded infiltration tests, fuzzy number presentation of the water flux and hydraulic conductivity of fractured rock, and the fuzzy evaluation of the groundwater recharge as criteria for the assessment of groundwater vulnerability.

3.8.1.2 Presentation (ADAMS Accession No. ML23177A145)

On Fuzzy-Systems Modeling of Ponded Infiltration, as Analogue to Flooding, in Fractured-Porous Subsurface Media

8th Annual NRC Probabilistic Flood Hazard Assessment (PFHA) Research Workshop

Boris Faybishenko
Lawrence Berkeley National Laboratory, Berkeley, CA

March 24, 2023

Goals

1. Illustrate the application of ponded infiltration tests as a physical analogue for understanding water and contaminant transport phenomena under flooding conditions

Small-Scale field test

Hell's Half Acre Research Site
1997-1999

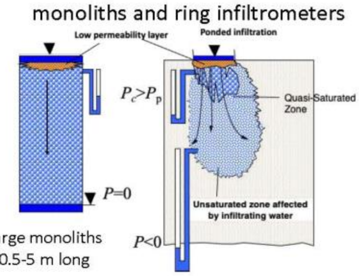
Meso-Scale field test

Box Canyon Analog Site
1995-1999

Large-Scale field test

Large Scale Infiltration Test at
RMWC - 1994

Confined and unconfined monoliths and ring infiltrometers

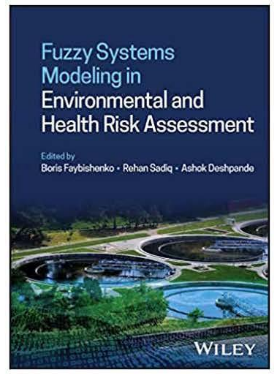


Large monoliths
0.5-5 m long

Goals

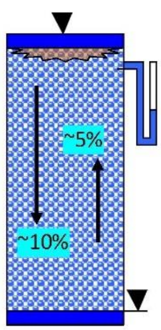
2. Illustrate the use of fuzzy (soft) systems modeling to describe the results of field observations, taking into account the uncertainty of field-based information.

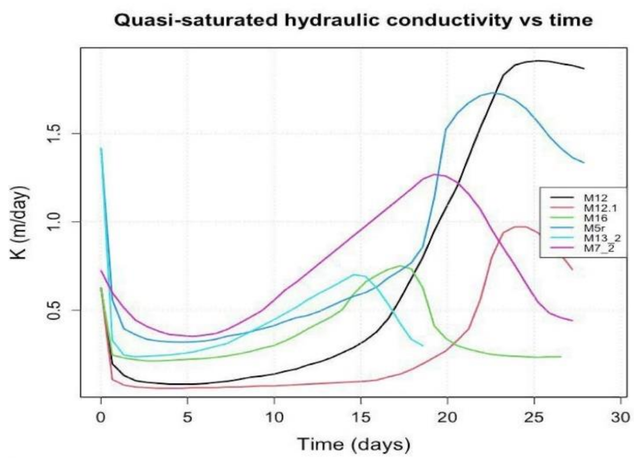
- Introduce the idea of fuzziness and possibility theory
- Examples of fuzzy analysis of ponded infiltration tests.



Temporal dynamics of flow rate and hydraulic conductivity depends on the volume of remaining entrapped air in porous media

The largest volume of remaining entrapped air is under conditions of ponded infiltration

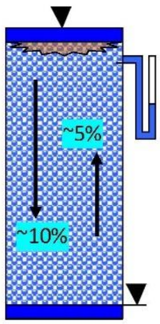


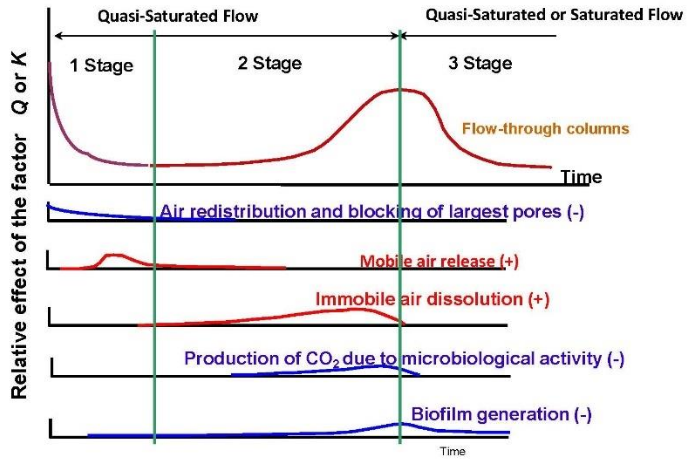


- Faybishenko, B., Hydraulic behavior of quasi-saturated soils in the presence of entrapped air: Laboratory experiments. *Water Resour. Res.*, 1995, 31, 2421-2435.
- Faybishenko, B., Comparison of laboratory and field methods for determining quasi-saturated hydraulic conductivity of soils, *Characterization and Measurement of the Hydraulic Properties of Unsaturated Porous Media*, 279-292, 1999.

Temporal Dynamics of Flow Rate and Hydraulic Conductivity Depends on the Volume of Remaining Entrapped Air

The largest volume of remaining entrapped air is under conditions of ponded infiltration





- Faybishenko, B., Hydraulic behavior of quasi-saturated soils in the presence of entrapped air: Laboratory experiments. *Water Resour. Res.*, 1995, 31, 2421-2435.
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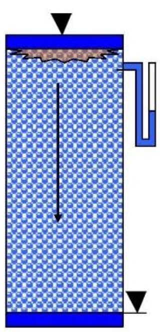
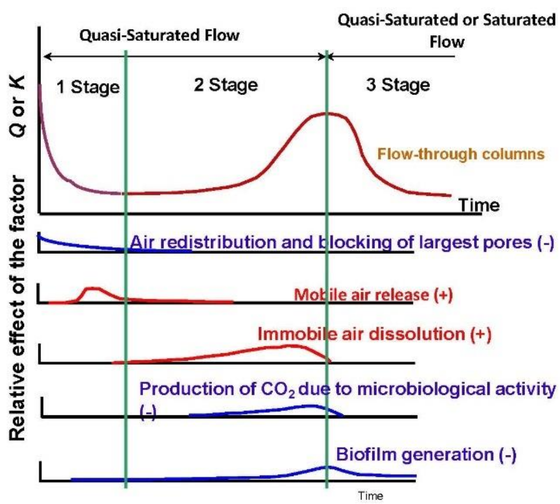
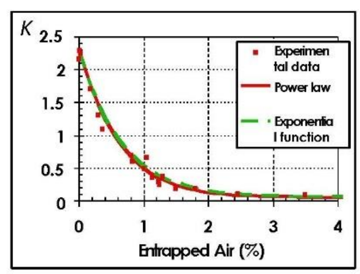
Temporal Dynamics of Flow Rate and Hydraulic Conductivity Depends on the Volume of Remaining Entrapped Air



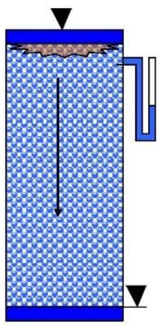


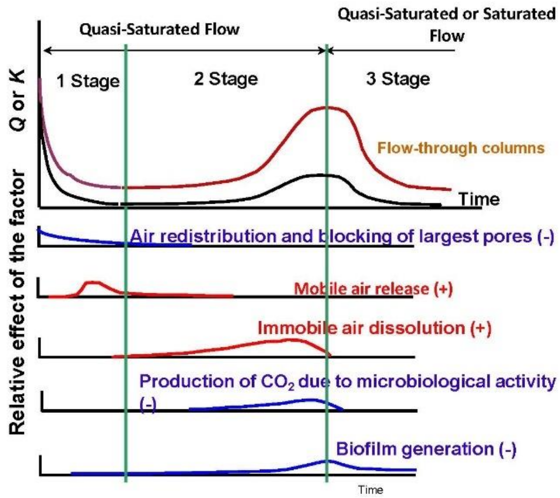


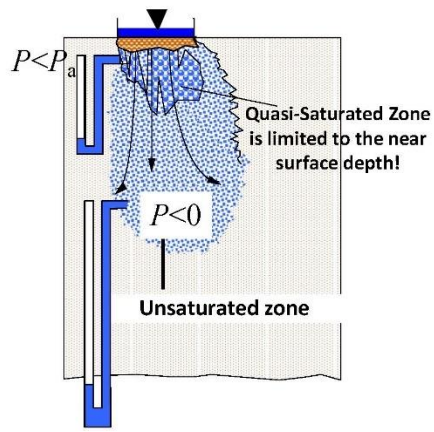
$$K(\mu) = K_o + (K_s - K_o)\exp(-\alpha\mu)$$

$$K(\mu) = K_o + K_s[1 - \frac{\mu}{\theta_s - \theta_r}]^n$$

Temporal Dynamics of Flow Rate and Hydraulic Conductivity Depends on the Volume of Remaining Entrapped Air

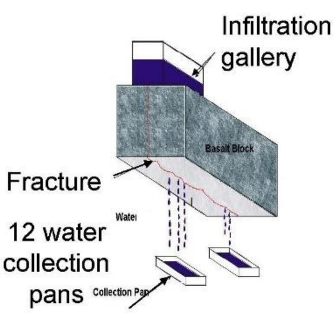


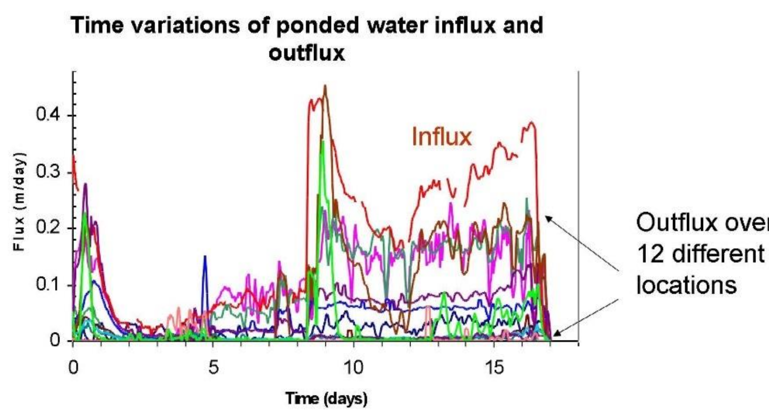




Evidence of spatial and temporal instabilities in water flow:

Small-Scale (1 m) Hell's Half Acre ponded infiltration test (Idaho)

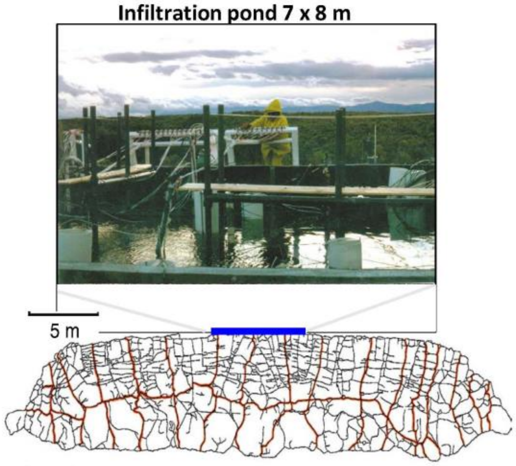




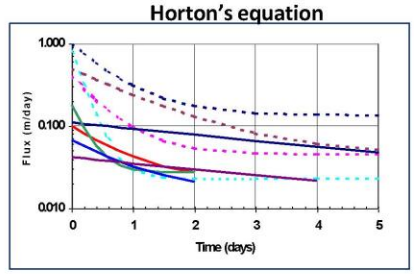
Podgorney, R., T. Wood, B. Faybishenko, and T. Stoops, Spatial and temporal instabilities in water flow through variably saturated fractured basalt on a one-meter scale, Geophysical Monograph No. 122, "Dynamics of Fluids in Fractured Rock," pp. 129-146, 2000.

Evidence of spatial and temporal instabilities in water flow:
Intermediate-Scale Ponded Infiltration, Box Canyon, Idaho

Infiltration pond 7 x 8 m



Ponded water influx vs. time can be described by Horton's equation



$$q = i_f t + (1/'3)(i_o - i_f)[1 - \exp('3\,t)]$$

B.Faybishenko et al., Conceptual model of the geometry and physics of water flow in a fractured basalt vadose zone. *Water Resour. Research*, 2000.

Evidence of spatial and temporal instabilities in water flow:
Intermediate-Scale Ponded Infiltration, Box Canyon, Idaho

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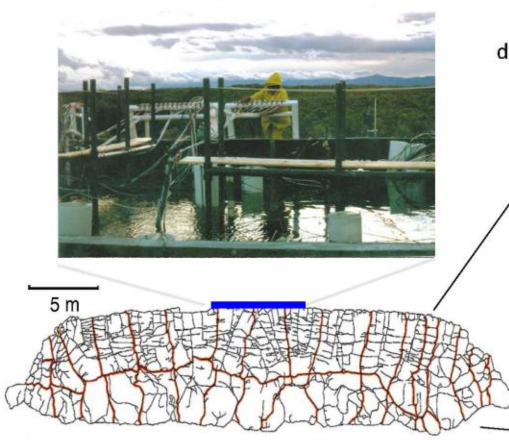
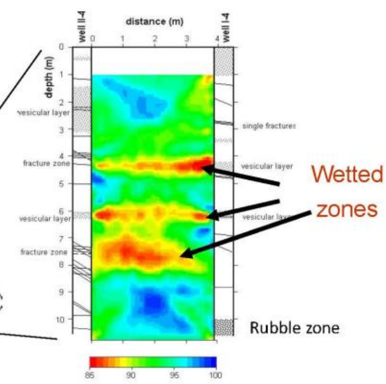


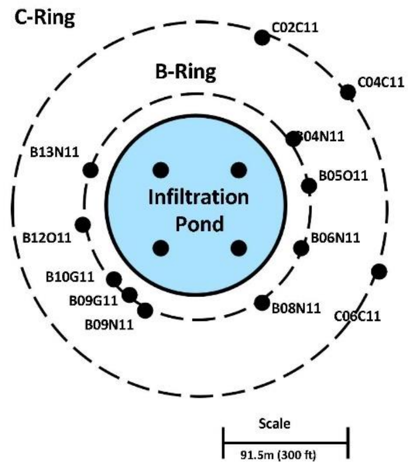
Ground penetrating radar velocity tomographs demonstrate wetted zones, but are unable to detect individual flow-through fractures

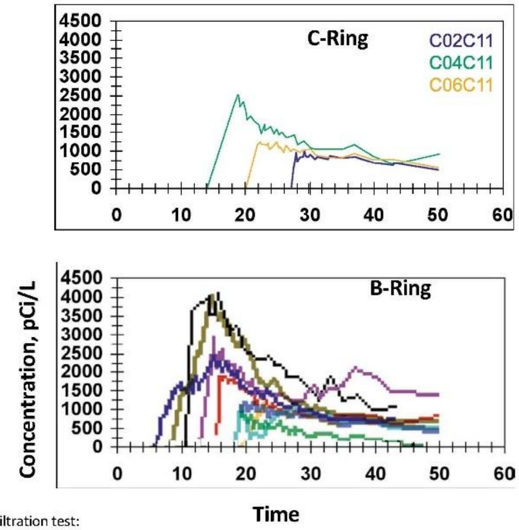


B.Faybishenko et al., Conceptual model of the geometry and physics of water flow in a fractured basalt vadose zone. *Water Resour. Research*, 2000.

Evidence of spatial and temporal instabilities in water flow:

Large Scale Infiltration Test at the RWMC, Idaho

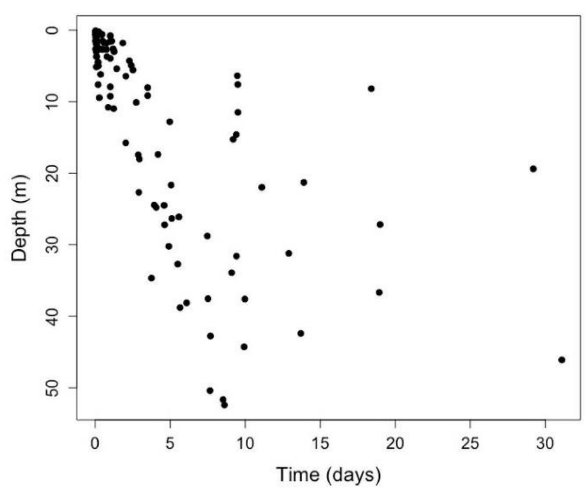




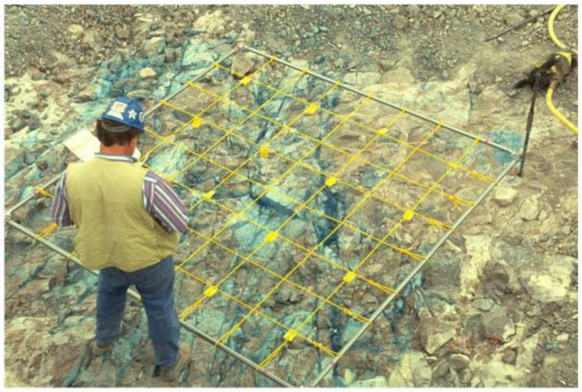
Se-75 Breakthrough Curves

Newman, M.E. and Dunnivant, F.M., Results from the large-scale aquifer pumping and infiltration test: transport of tracers through fractured media, INEL-95/146 ER-WAG7–77, 1995.
Wood, T.R. and Norrell, G.T., Integrated large-scale aquifer pumping and infiltration tests: groundwater pathways OU 7–06: summary report, INEL-96/0256, 1996.

Summary of the Water Travel Time vs. Depth from Three Field Ponded Infiltration Tests in Fractured Basalt



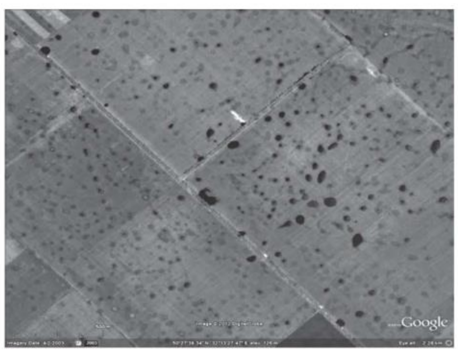
Land surface heterogeneity is one of the primary reasons of preferential water flow and transport under flooding



Photograph of the sparse area of fractures and tracer distribution that were mapped at the Infiltration Test Site at Fran Ridge

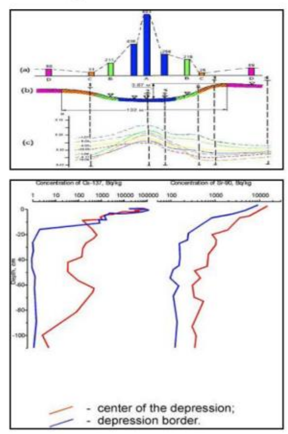
(Nicholl, M.J. and Glass, R.J. 2002. Field Investigation of Flow Processes Associated with Infiltration into an Initially Dry Fracture Network at Fran Ridge, Yucca Mountain, Nevada: A Photo Essay and Data Summary. SAND2002-1369. Albuquerque, New Mexico: Sandia National Laboratories. ACC: MOL.20031124.0211.)

Land surface heterogeneity is one of the primary reasons of preferential water flow and transport under flooding



Ukraine, Chernigiv oblast, Yablunivka, 18 km SW from Pryluki (East from Chernobyl Exclusion Zone).

Shestopalov V. et al., Groundwater Vulnerability, Chernobyl Nuclear Disaster, 2014



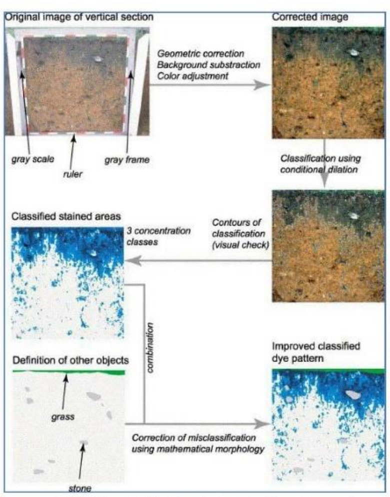
^{137}Cs and ^{90}Sr distribution with depth Veresok site (Shestopalov, 2009)

- Accumulation of radionuclides in local topographic depressions:
  - Accelerated transport of radionuclides from the surface toward groundwater in sandy soil, or
  - Build up of contaminants in clayey soils

Hydrogeological flooding predictions are subject to two main types of uncertainties

- *Aleatoric* uncertainty—mainly caused by subsurface heterogeneities and variability; assessing such variability is subject to ambiguity, vagueness, imprecision, ignorance, etc.
- *Epistemic* uncertainty—caused by selection of different conceptual and simulation models and their parameters, involved in hydrogeological modeling.

Do we have sufficient information to construct reliable deterministic or stochastic models to predict complex flow and transport processes through fracture-porous media?



Source: M.Weiler, H.Fluhler Inferring flow types from dye patterns in macroporous soils, *Geoderma* 120 (2004) 137 – 153. doi:10.1016/j.geoderma.2003.08.014

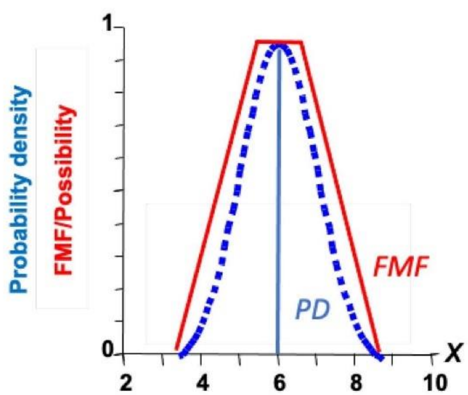
- Nonlinear and nonstationary processes and a combination of feedback and feedforward phenomena in highly heterogeneous subsurface media
- Rapid flow or bypass phenomena through large fractures
- Small changes in initial and boundary conditions cause unrepeatability of flow dynamics in successive ponded infiltration events and significant nonstationarity of measured flow and transport parameters

Uncertainty is inherently involved in characterization of complex subsurface media

- Vague delineation of subsurface heterogeneities and preferential flow paths due to sparse data collection.
- Ambiguity is commonly present in characterization of a subsurface system, types of measurements, and models applied.
- The subsurface fractured-porous media falls under the category of a fuzzy system.

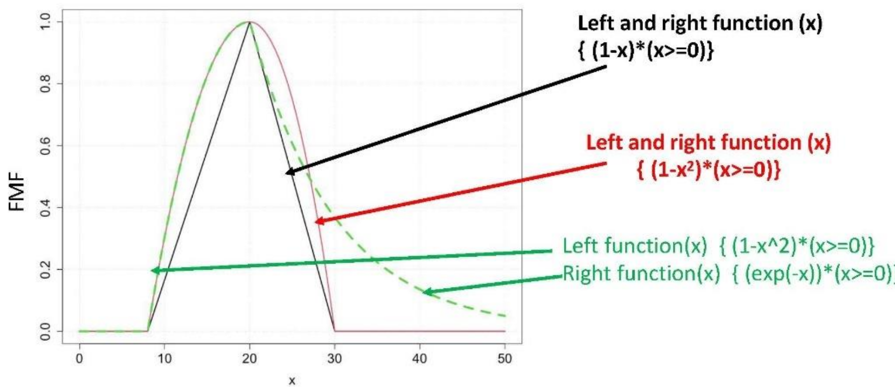
The degree to which a soil layer is more heterogeneous is a fuzzy characteristic

Fuzzy Number is Defined as the Possibility Distribution Function



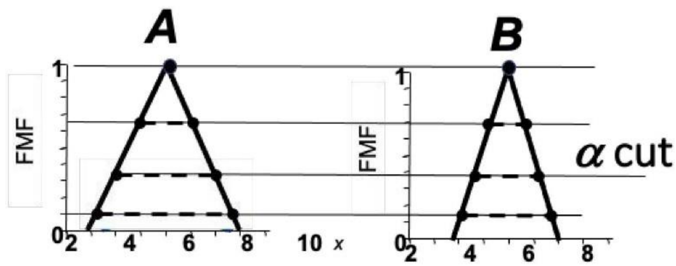
- A fuzzy number is a quantity whose value is imprecise, rather than exact as is the case with "ordinary" (single-valued) numbers.
- A fuzzy number can be thought of as a function whose domain is a specified set real numbers.
- **FMF bounds a probability distribution**

Examples of fuzzy numbers



R package: Calculator.LR.FNs}

Fuzzy calculus is based on the principles of Interval Analysis



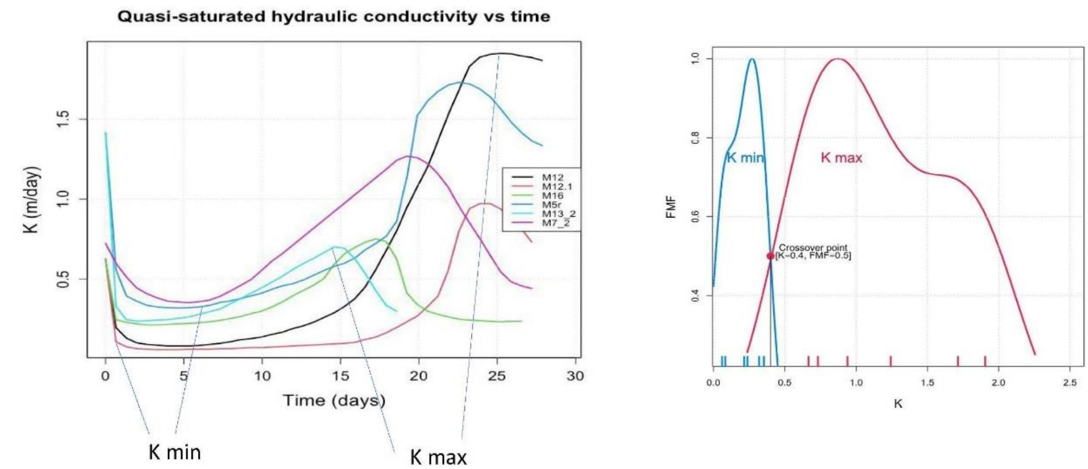
A = [a,b], B=[c,d], where a≤b and c≤d

[a,b] + [c,d] = [a+c, b+d]

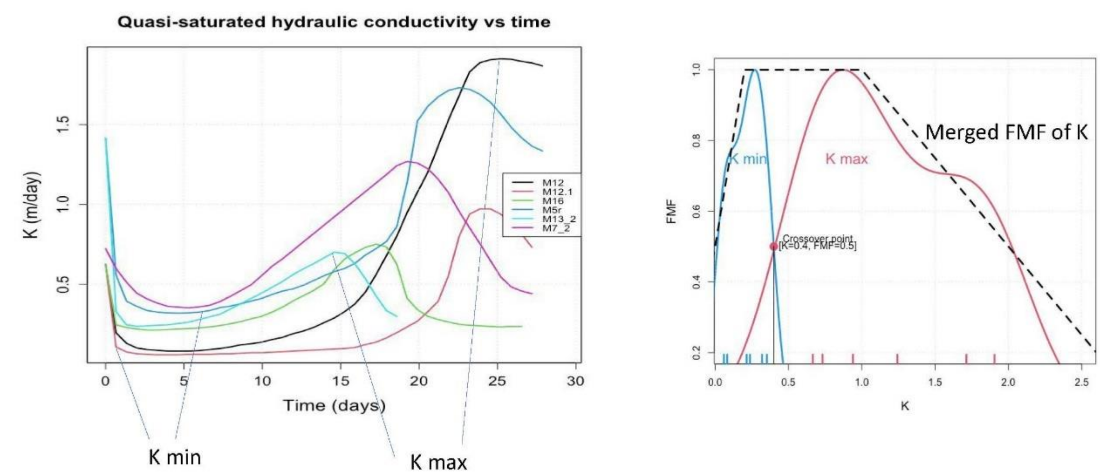
[a,b] - [c,d] = [a-d, b-c]

[a,b] · [c,d] = [min(ac, ad, bc, bd), max(ac, ad, bc, bd)]

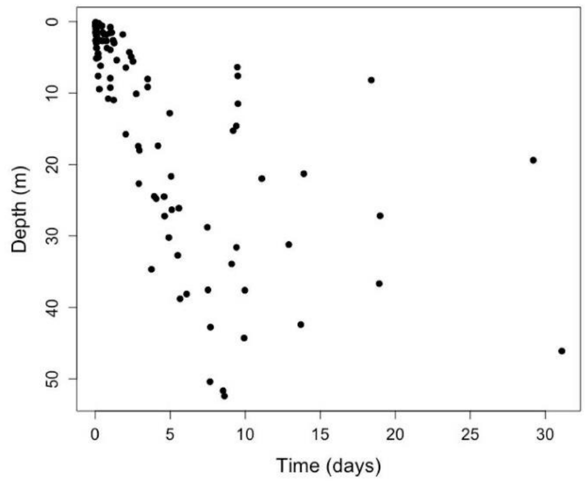
Interpretation of ranges of hydraulic conductivity using fuzzy numbers



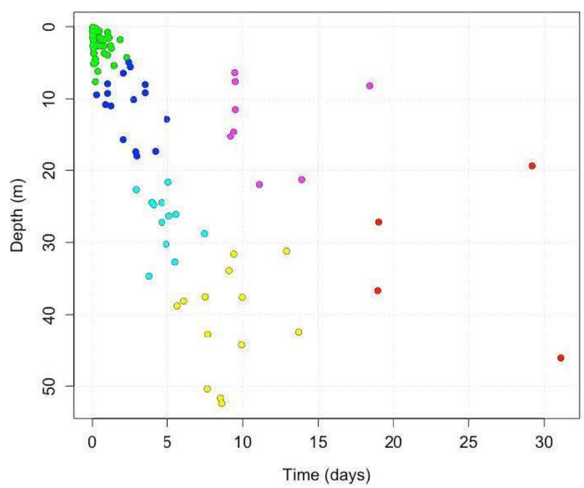
Interpretation of ranges of hydraulic conductivity using fuzzy numbers based on the normalization of the PDF



Summary of the Water Travel Time vs. Depth from Three Field Ponded Infiltration Tests in Fractured Basalt

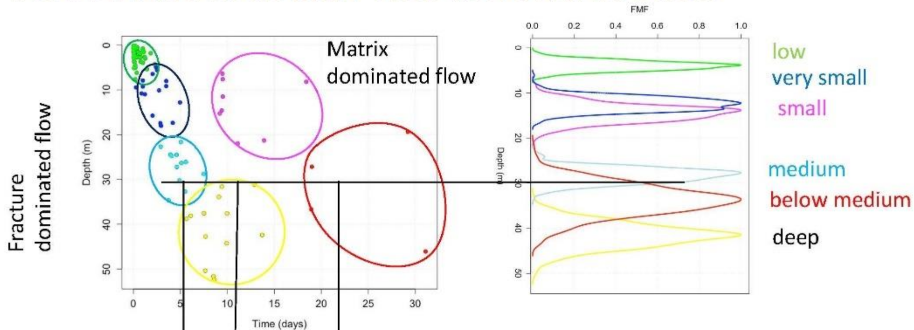


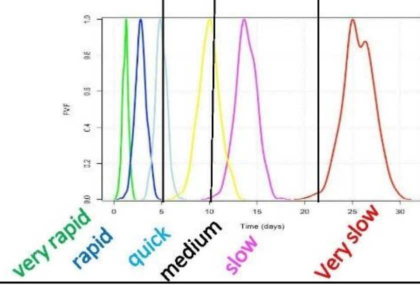
Fuzzy C-means Clustering of Water Travel Time vs. Depth from Three Field Ponded Infiltration Tests in Fractured Basalt



Fuzzy C-means clustering is used to partition a collection of numerical data into a series of overlapping clusters. The degrees of belongingness are interpreted as fuzzy membership values.

Fuzzy C-means Clustering of Water Travel Time vs. Depth from Three Field Ponded Infiltration Tests in Fractured Basalt

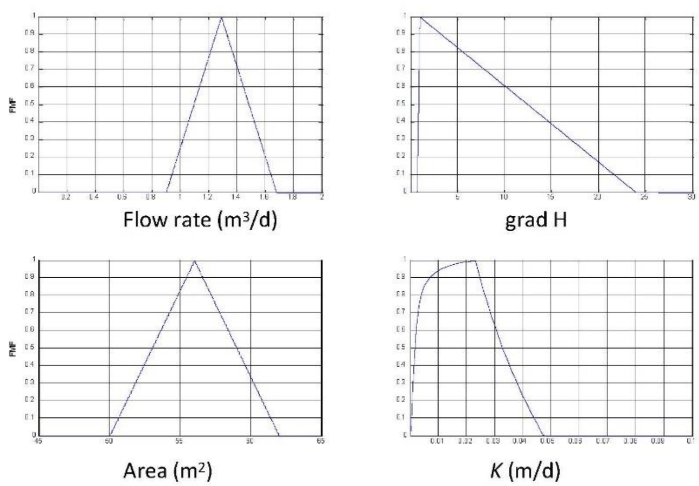




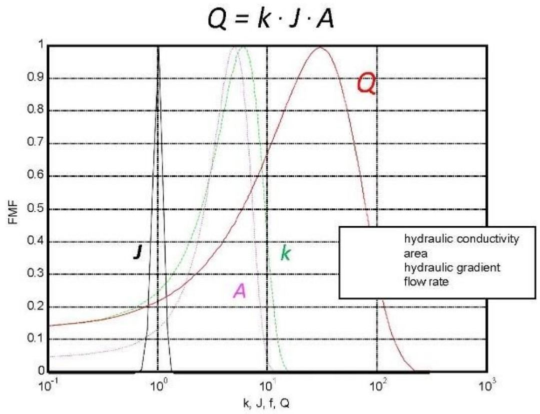
- Membership functions (FMF) are used to define how each depth is mapped to a membership value of time (or degree of membership) between 0 and 1.
- FMFs are foundation of fuzzy logic and are used to define a set of *if-then* rules

Using Fuzzy Darcy's Law to calculate the fuzzy hydraulic conductivity

$$Q = \underset{\sim}{K} \times \underset{\sim}{gradH} \times \underset{\sim}{Area}$$



Calculations of fuzzy flux from Fuzzy Darcy's law



hydraulic conductivity

k **= gaussmf (x, [3 6])**

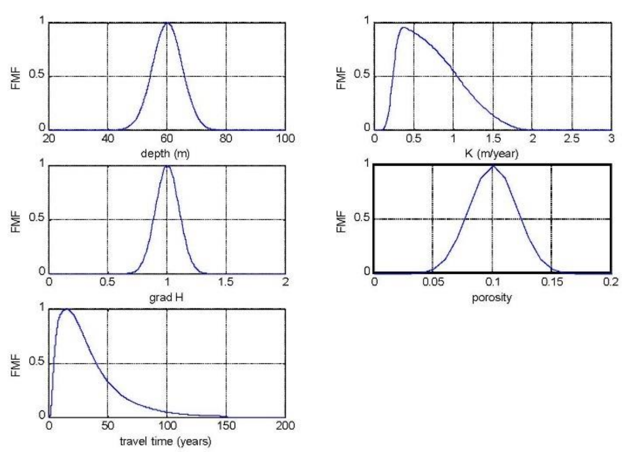
area of flow

A **= gaussmf (x, [2 5])**

hydraulic gradient

J **= gaussmf (x, [.1 1])**

Calculation of fuzzy water travel time



Fuzzy Calculus:

Advantages

- Requires little data for uncertainty calculations
- Fast and easy to compute
- Doesn't require information about correlations
- Conservative, but not hyperconservative
- FMFs don't have to be precise
- No assumptions about correlations
- Fast and convenient software

Disadvantages

- α-levels may not be comparable for different variables
- Can't use correlations to constrain answers
- Not conservative against all possible dependencies
- Large databases can make calculations cumbersome

Summary and conclusions

- Ponded infiltration tests are physical models/analogues to study land surface flooding,
- We don't have sufficient information to characterize multiple factors and subsurface processes,
- Incorporation of fuzzy logic into hydrogeological predictions may provide significant payoff for solving problems which are characterized by imprecise, vague, and ambiguous information.

Examples of prospective applications

- Simulations using fuzzy ordinary and partial differential equations for hydrological predictions,
- Management of water resources, decision making, and risk analysis,
- Spatio-temporal analysis of climatic data.

3.8.1.3 Questions and Answers

Question:

In the research that you've been doing, you've been looking at preferential flow due to fractures, but at nuclear power plant sites, there's a lot of preferential flow, due to the way that backfill is placed around things. If you have underground pipes, and when you compact the excavation around that pipe, there's still going to be preferential flow. When you're trying to compact up against buildings, there'll be preferential flow. So there's a lot of preferential flow around the site. Would the fuzzy calculus application be applicable to that kind of preferential flow as well?

Answer:

It is a common feature of preferential flow along the underground infrastructure along the pipes. I believe that this approach can help to assess this type of preferential flow based on our approximate knowledge about the location of pipes. Because we cannot build conventional deterministic or stochastic models to describe this type of preferential flow, fuzzy logic will provide significant improvement and will provide the assessment of this type of water penetration. I believe so that it will work.

3.8.2 Presentation 4B-2: Probabilistic Flood Hazard Assessment for Local Intense Precipitation at Nuclear Power Plant Sites – A Pilot Study

Author: Rajiv Prasad[1], Arun Veeramany[1], Rajesh K. Singh[1], Joseph Kanney[2]; [1]Pacific Northwest National Laboratory, [2]U.S. Nuclear Regulatory Commission

Speaker: Rajiv Prasad

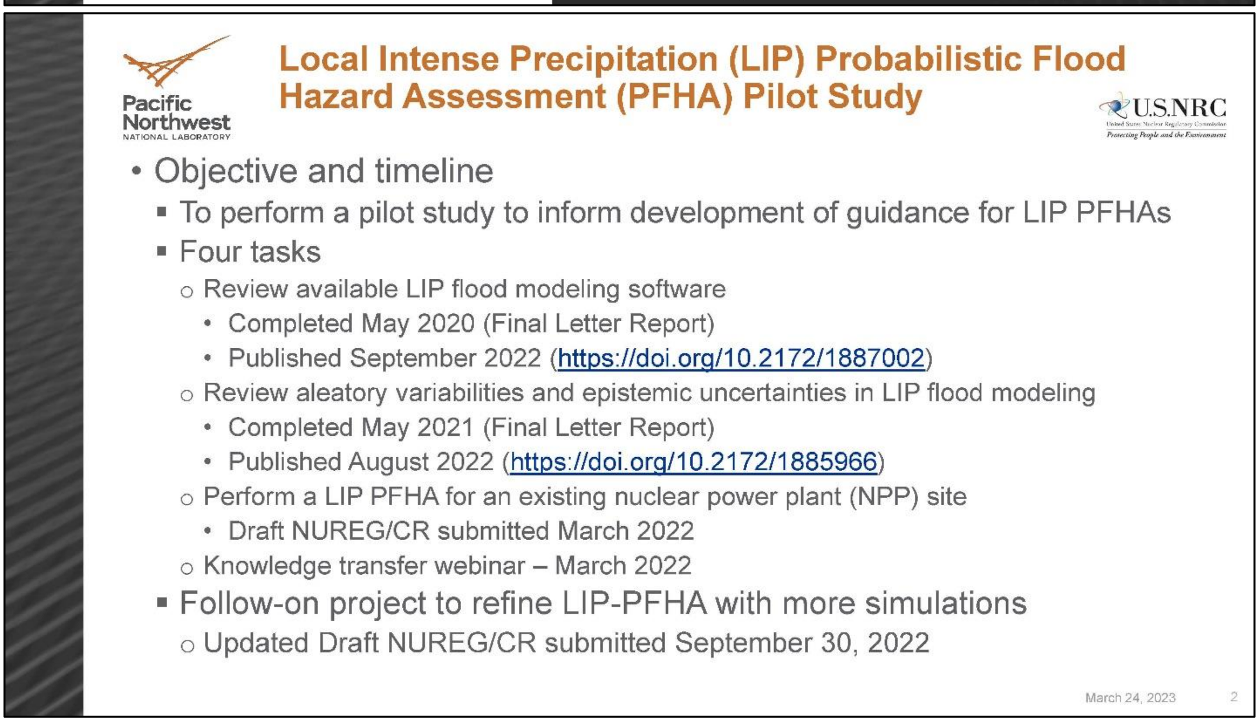
3.8.2.1 Abstract

While nuclear power plants (NPP) in the United States provide approximately 19 percent of the nation's energy production, they are also critical infrastructure that are threatened by extreme hydrological events. We describe a methodology to perform probabilistic flood hazard assessments (PFHAs) from local intense precipitation (LIP) for NPP sites. A pilot study was performed at an existing NPP to develop the methodology and obtain insights that can help improve safety. The methodology leverages statistical properties of hydrological inputs and parameters with a deterministic, dynamic hydraulic model to probabilistically estimate flood hazards.

The LIP PFHA was performed using the selected NPP's existing LIP flood model developed to support post-Fukushima flood re-evaluation. A set of sensitivity analyses was performed to understand the sensitivity of the flood model predictions to inputs, model parameters, and site configuration. The LIP PFHA methodology used a stratified sampling approach for the aleatory variables (i.e., precipitation depth and associated storm characteristics). The scope of this study did not include performing a site-specific, precipitation-frequency analysis. Instead, probabilistic precipitation characteristics were obtained from the National Oceanic and Atmospheric Administration Precipitation Frequency Data Server. The epistemic variable (i.e., Manning's roughness coefficient multiplier) was sampled from a uniform, discrete distribution covering a reasonable range of values.

The LIP flood model simulations were performed in FLO-2D™, a two-dimensional flood routing model using the Pacific Northwest National Laboratory high-performance computing cluster. The predicted flood parameters were post-processed to create flood hazard curves at selected locations important to safety of the NPP. The pilot study shows that existing NPP site flood models can be leveraged to perform LIP PFHAs using a statistical-dynamical approach. However, it is recommended that site-specific, precipitation-frequency analyses be used to support these PFHAs.

3.8.2.2 Presentation (ADAMS Accession No. ML23177A146)



LIP PFHA Pilot Study: Task 3
LIP PFHA at an existing NPP site

- Task 3: Perform a LIP PFHA at an existing NPP site that has multiple units
  - Site selection
  - Model acquisition
  - Data collection
  - Sensitivity analysis
  - PFHA computations
  - Hazard curve creation

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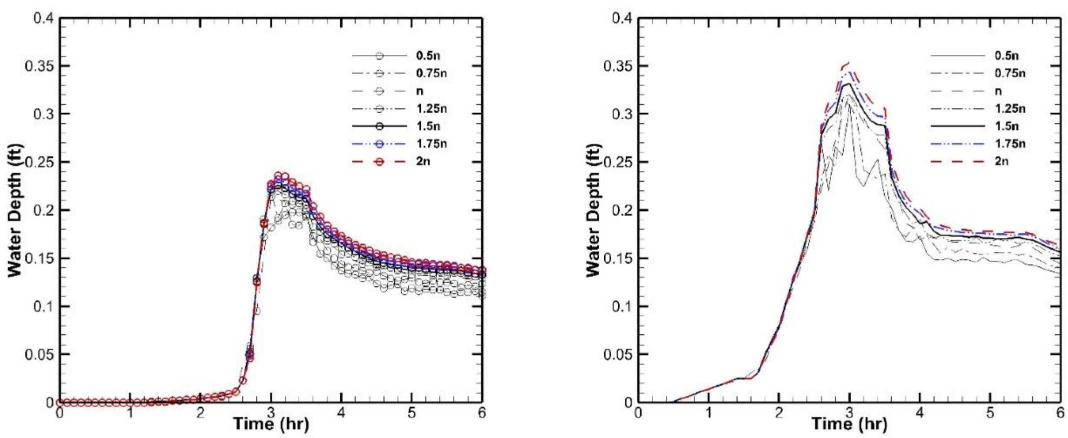
LIP PFHA Pilot Study: Task 3
Sensitivity Analysis – Manning's roughness coefficient



Grid Cell 1

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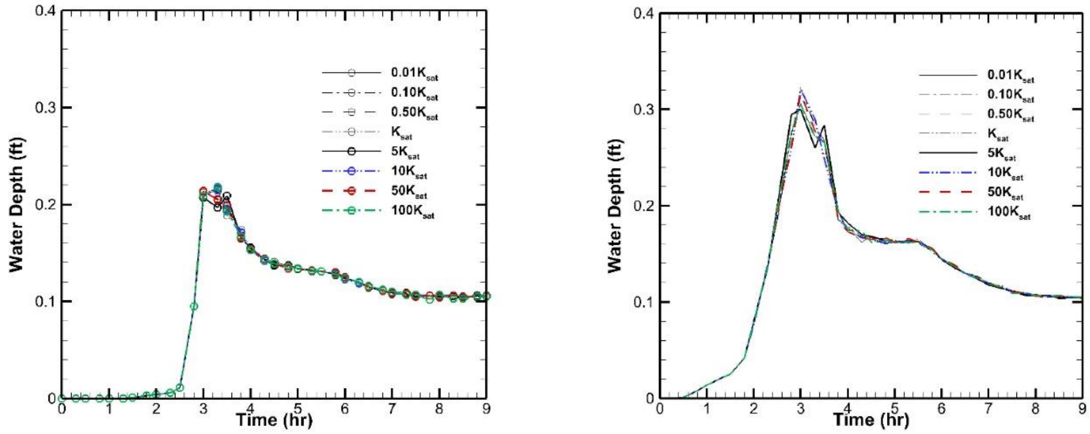
LIP PFHA Pilot Study: Task 3
Sensitivity Analysis – effective hydraulic conductivity



Grid Cell 1

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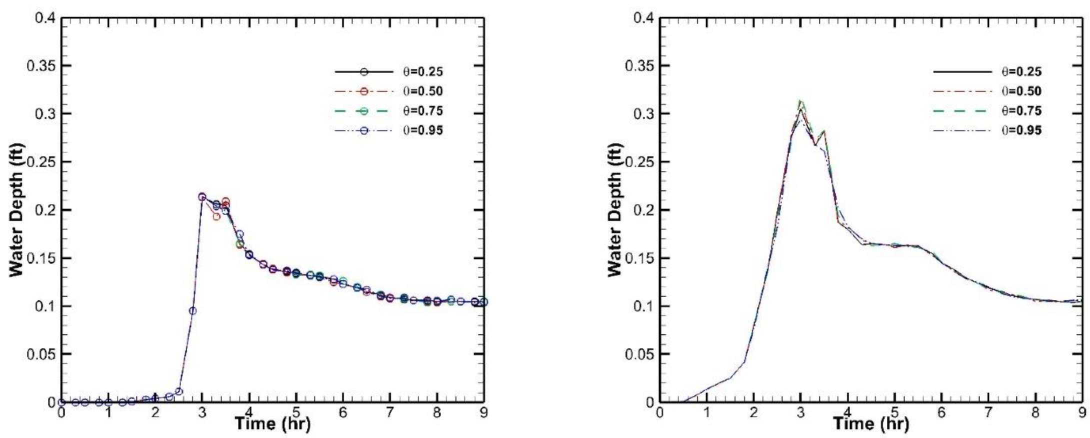
LIP PFHA Pilot Study: Task 3
Sensitivity Analysis – initial soil moisture content



Grid Cell 1

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LIP PFHA Pilot Study: Task 3
Sensitivity Analysis – storm duration and temporal distribution

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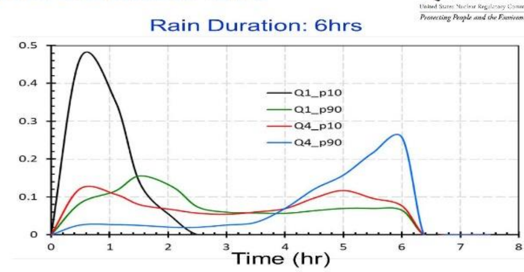
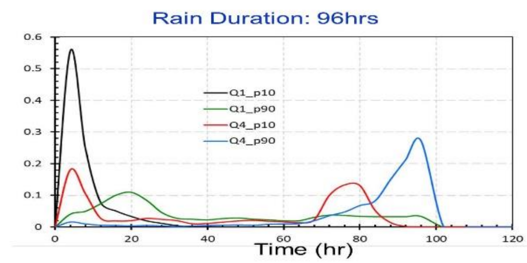
Duration	Percentage			
	First Quartile	Second Quartile	Third Quartile	Fourth Quartile
6 hr	52	23	16	9
12 hr	51	22	17	10
24 hr	50	19	17	14
96 hr	53	19	14	14





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LIP PFHA Pilot Study: Task 3
Precipitation input – storm total depth

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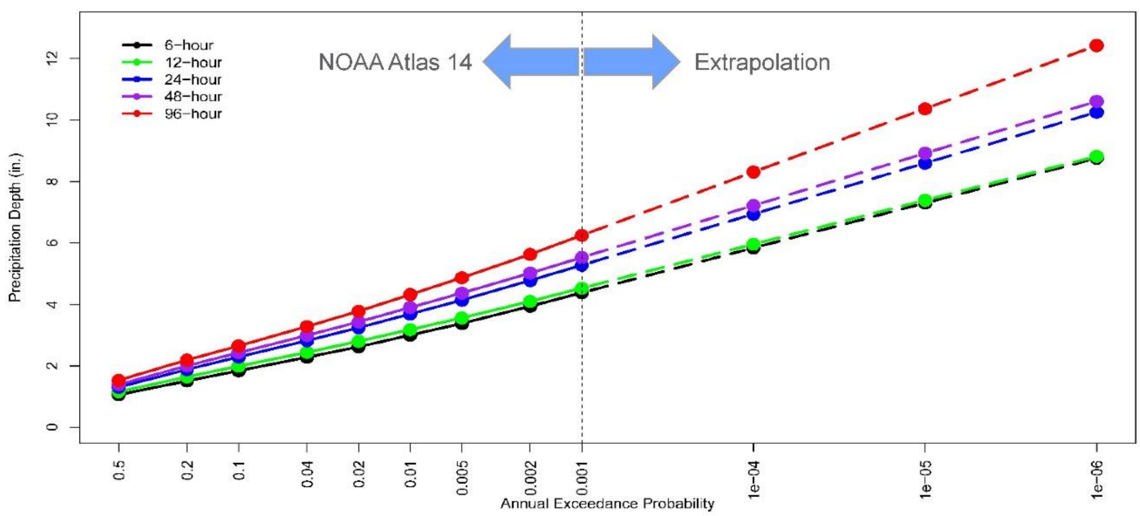
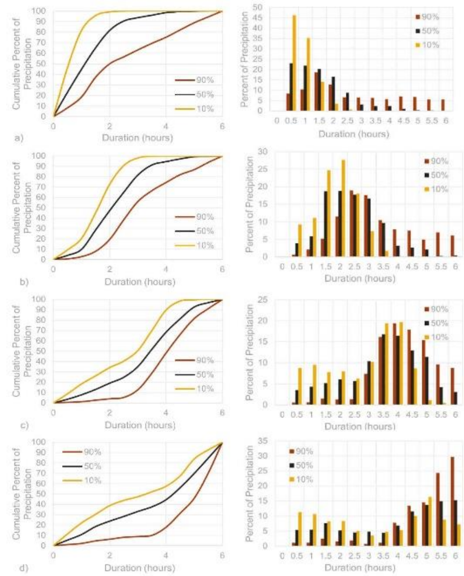


LIP PFHA Pilot Study: Task 3
Precipitation input – storm creation

Duration	Percentage			
	First Quartile	Second Quartile	Third Quartile	Fourth Quartile
6 hr	52	23	16	9
12 hr	51	22	17	10
24 hr	50	19	17	14
96 hr	53	19	14	14

- Storm creation
  - Four durations: 6, 12, 24, and 48 h
  - Maintain relative quartile frequency
  - Three percentiles of storm temporal distributions: 10, 50, 90



PFHA methodology

- Annual exceedance probability (AEP) for a flood hazard

$$P(\boldsymbol{Z} > \boldsymbol{z}) = 1 - P(\boldsymbol{Z} \leq \boldsymbol{z}) = 1 - F(\boldsymbol{z}) = \int_{\boldsymbol{z}}^{\infty} f(\boldsymbol{u})d\boldsymbol{u}$$

A flood hazard

A particular magnitude of the flood hazard

The cumulative distribution function for the flood hazard

$$\boldsymbol{Z} = T[G(\boldsymbol{I}, \boldsymbol{\Theta}, \boldsymbol{\Phi})]$$

$\boldsymbol{Z}$ = the set of flood hazards,
G = the flood simulation model,
$\boldsymbol{I}$ = the set of hydrometeorologic input variables,
$\boldsymbol{\Theta}$ = the set of the model parameters,
$\boldsymbol{\Phi}$ = the set of initial and boundary conditions, and
T = any further transformations or analyses needed to estimate the flood hazards from the simulated flood parameters.

PFHA methodology

- AEP

$$P(Z > z) = \int_{\{I,\Phi,\Theta:\,T[G(I,\Phi,\Theta)]>z\}} \overbrace{f(I,\Phi,\Theta)}^{\text{Joint PDF of }(I,\Phi,\Theta)}\, dI\, d\Phi\, d\Theta$$

multi-dimensional integration is taken over this set of (I, Φ, Θ)

- Numerical integration for $P(Z > z)$

$$\hat{P}(z) = \frac{1}{N}\sum_{i=1}^{N} H(z_i - z)$$

$H(z_i - z) = 1$ for $z_i = T[G(I_i, \Phi_i, \Theta_i)] > z$, and $H(z_i - z) = 0$ otherwise

PFHA methodology

- Numerical integration for $P(Z > z)$ for very low AEPs
- Stratified sampling approach
  - Desired range of AEPs divided into several strata
  - Numerical integration must account for strata and number of samples drawn from each stratum; Total Probability Theorem is applied and the estimator for the exceedance probability becomes

$$P(Z > z) = \sum_{j=1}^{M} P(Z > z|S_j)\, p(S_j)$$

where M is the number of strata and S_j is the probability associated with the jth stratum.

PFHA methodology

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U.S.NRC

- Strata used to sample precipitation depths
- A total of 8,832 simulations
  - 4 storm durations ×
    3 storm temporal distribution percentiles ×
    23 storm precipitation depth strata ×
    8 storm precipitation depths per stratum ×
    4 Manning's roughness coefficients

Stratum Number S_j	AEP range	Probability $p(S_j)$
1	$5.0\times10^{-1} - 3.0\times10^{-1}$	2.0×10^{-1}
2	$3.0\times10^{-1} - 1.7\times10^{-1}$	1.3×10^{-1}
3	$1.7\times10^{-1} - 1.0\times10^{-1}$	7.0×10^{-2}
4	$1.0\times10^{-1} - 5.5\times10^{-2}$	4.5×10^{-2}
5	$5.5\times10^{-2} - 3.0\times10^{-2}$	2.5×10^{-2}
6	$3.0\times10^{-2} - 1.7\times10^{-2}$	1.3×10^{-2}
7	$1.7\times10^{-2} - 1.0\times10^{-2}$	7.0×10^{-3}
8	$1.0\times10^{-2} - 5.5\times10^{-3}$	4.5×10^{-3}
9	$5.5\times10^{-3} - 3.0\times10^{-3}$	2.5×10^{-3}
10	$3.0\times10^{-3} - 1.7\times10^{-3}$	1.3×10^{-3}
11	$1.7\times10^{-3} - 1.0\times10^{-3}$	7.0×10^{-4}
12	$1.0\times10^{-3} - 5.5\times10^{-4}$	4.5×10^{-4}
13	$5.5\times10^{-4} - 3.0\times10^{-4}$	2.5×10^{-4}
14	$3.0\times10^{-4} - 1.7\times10^{-4}$	1.3×10^{-4}
15	$1.7\times10^{-4} - 1.0\times10^{-4}$	7.0×10^{-5}
16	$1.0\times10^{-4} - 5.5\times10^{-5}$	4.5×10^{-5}
17	$5.5\times10^{-5} - 3.0\times10^{-5}$	2.5×10^{-5}
18	$3.0\times10^{-5} - 1.7\times10^{-5}$	1.3×10^{-5}
19	$1.7\times10^{-5} - 1.0\times10^{-5}$	7.0×10^{-6}
20	$1.0\times10^{-5} - 5.5\times10^{-6}$	4.5×10^{-6}
21	$5.5\times10^{-6} - 3.0\times10^{-6}$	2.5×10^{-5}
22	$3.0\times10^{-6} - 1.7\times10^{-6}$	1.3×10^{-6}
23	$1.7\times10^{-6} - 1.0\times10^{-6}$	7.0×10^{-7}

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Sampling Strata

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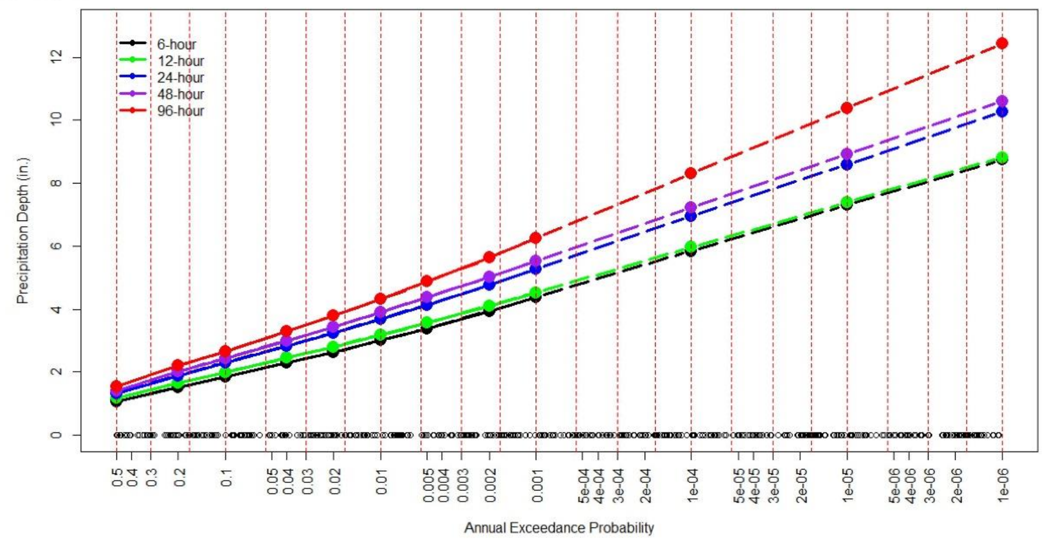

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PFHA simulations

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- FLO-2D was run on PNNL's high-performance compute cluster
  - Linux
    - Native Linux version of FLO-2D is not available
    - Used Wine Windows emulator
  - Multiple compute nodes were employed (frequently 60-100 nodes concurrently)
    - 24 processing cores per node, 1.2-3.1 GHz clock speed, 62 GB random access memory
  - Each simulation was independent
  - Approximately 1.3 million CPU hours
- Hazard curves
  - Flood depth
  - Flood velocity
  - Flood depth × flood velocity
  - Flood duration (duration for which flood depth exceeds 0.1 ft during a simulation)

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PFHA results

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- Hazard curves were created at multiple selected grid cells
  - mostly adjacent to and in similar locations with respect to each unit's SSCs
  - At the selected locations of interest
    - More than half showed maximum flood depth smaller than 0.1 ft
    - At such small depths, model solutions may be affected by inaccuracies and uncertainties in terrain elevation data
    - At some grid cells, counterintuitive flow dynamics were observed
  - Recommendation
    - Carefully interpret model results at locations of very shallow flood depths

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Results – flood depth hazard curve (adjacent to diesel generator building)

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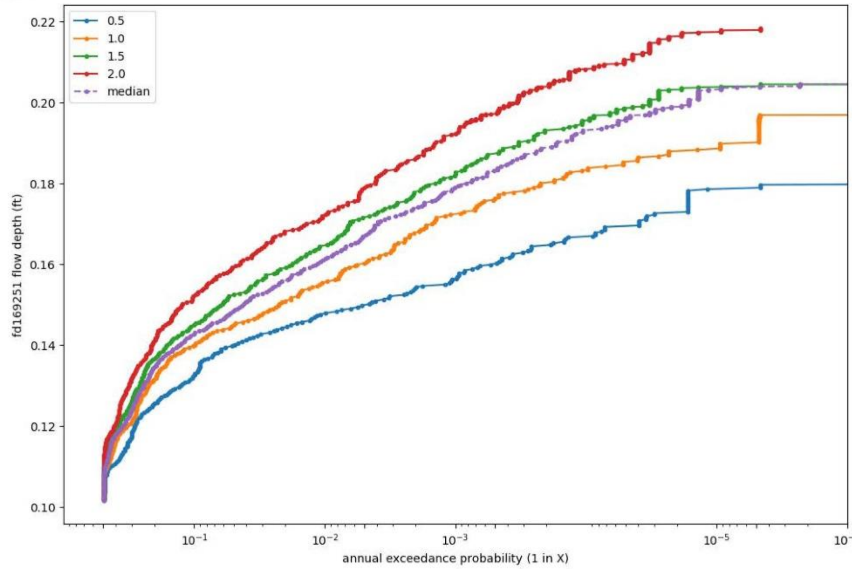

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Results – flood velocity hazard curve (adjacent to diesel generator building)

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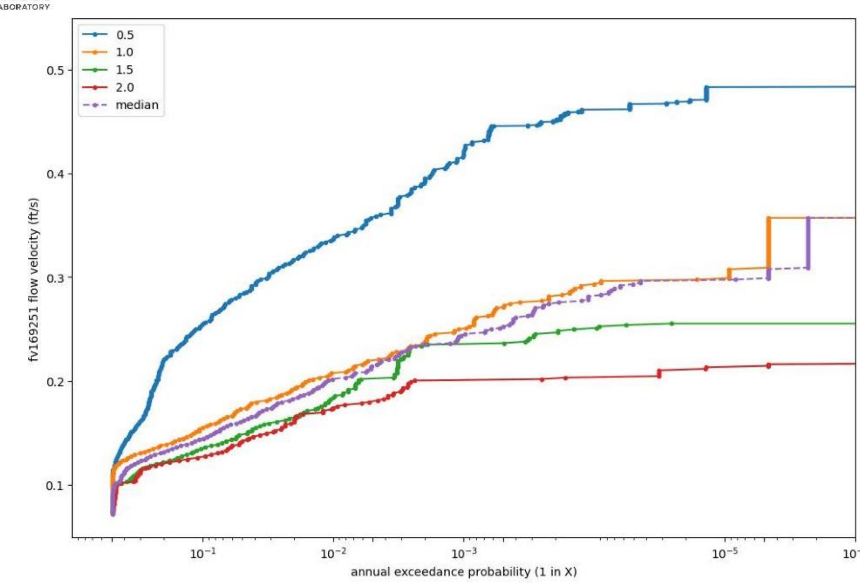

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Results – flood depth × flood velocity hazard curve (adjacent to diesel generator building)

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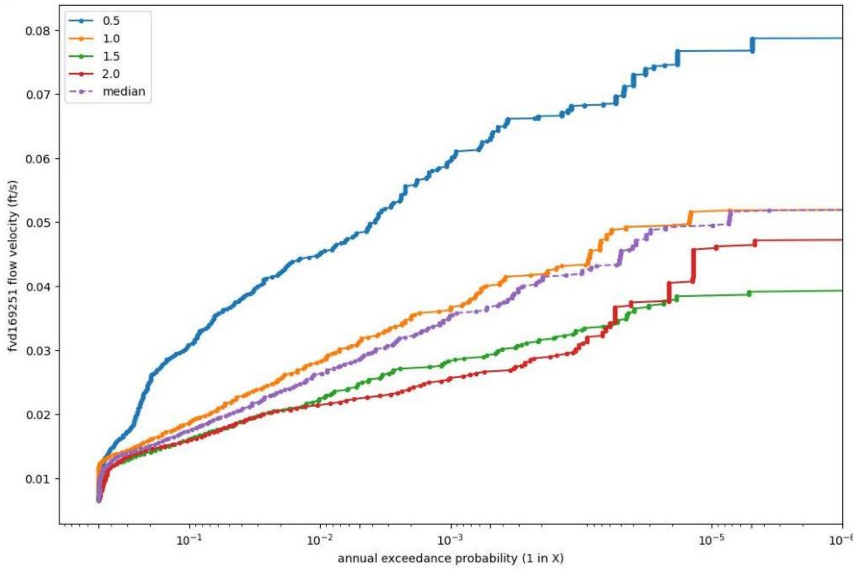

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Results – flood duration hazard curve (adjacent to diesel generator building)

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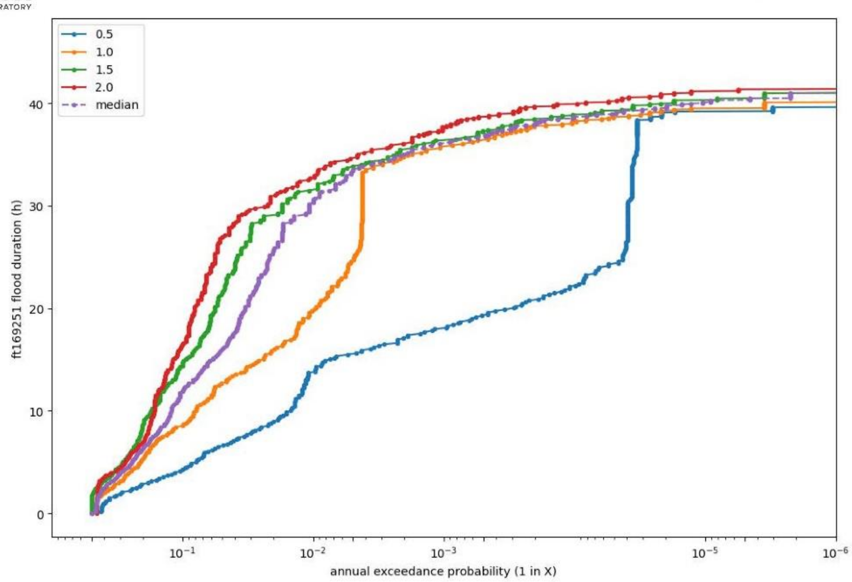

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Counterintuitive results – flood depth (adjacent to containment building)

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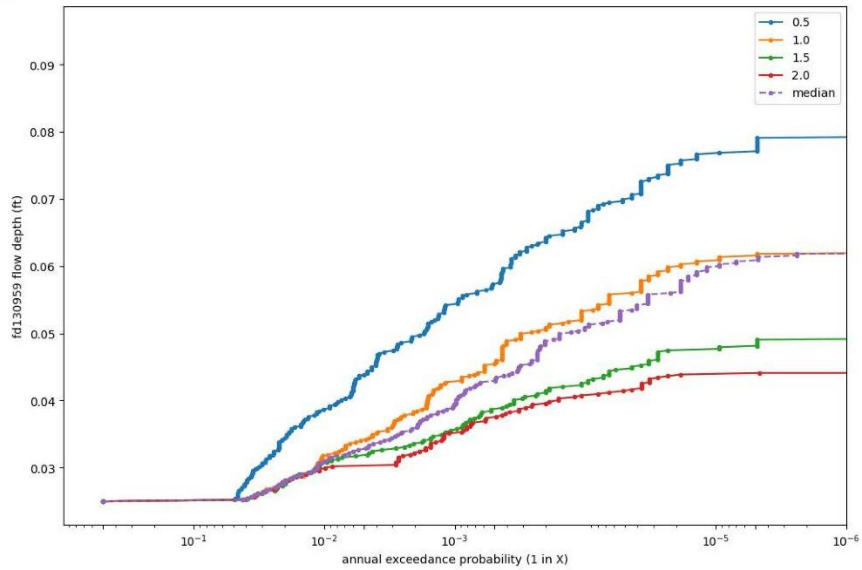

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Counterintuitive results – flood velocity (adjacent to containment building)

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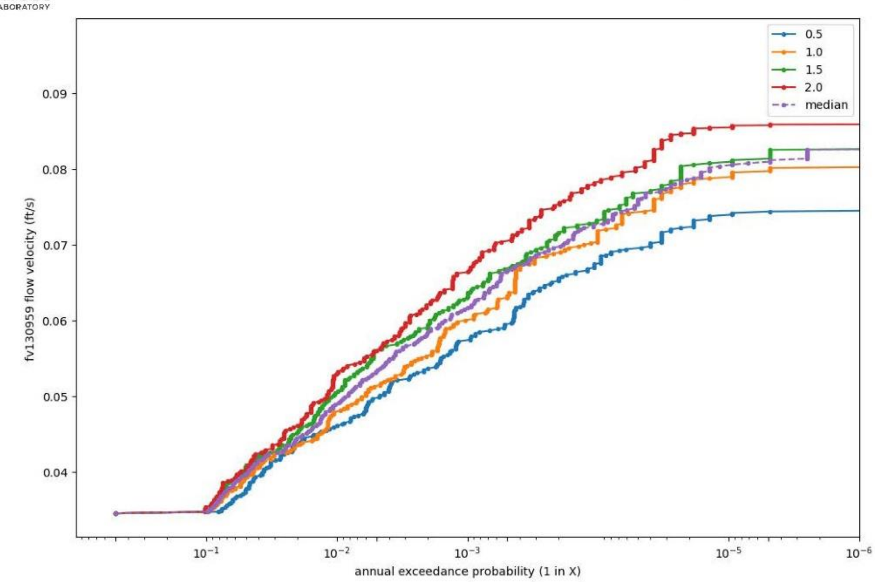

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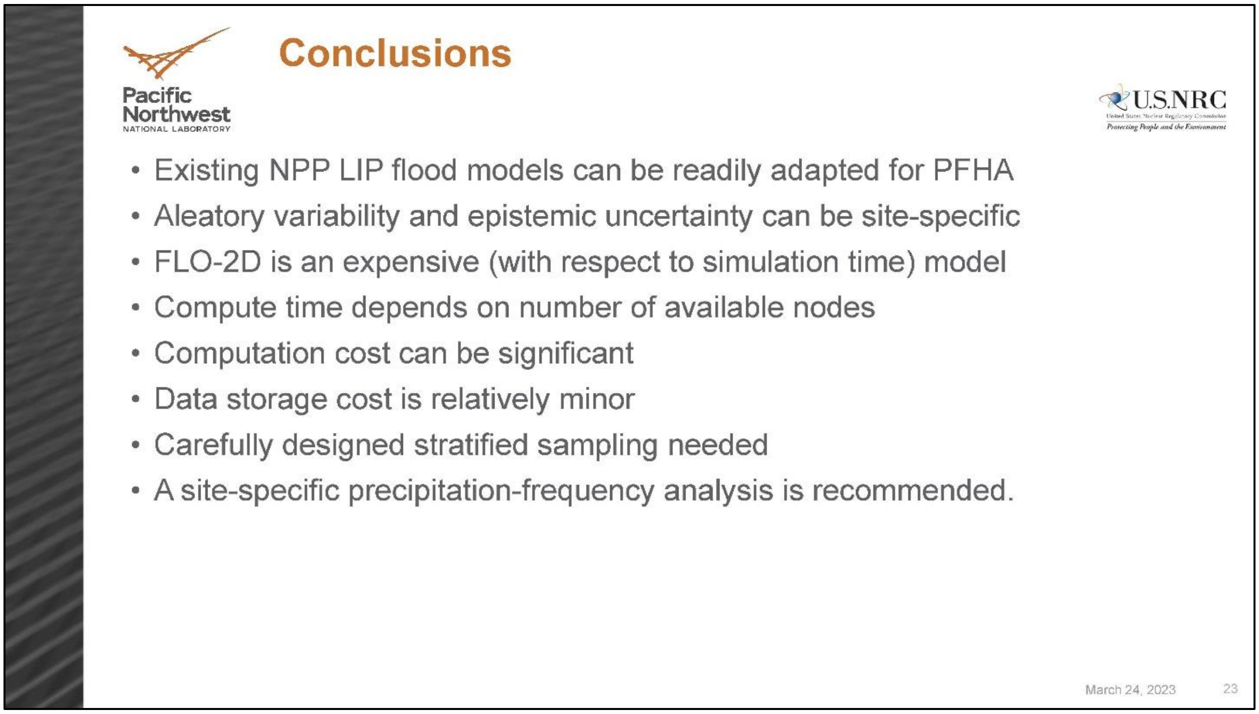
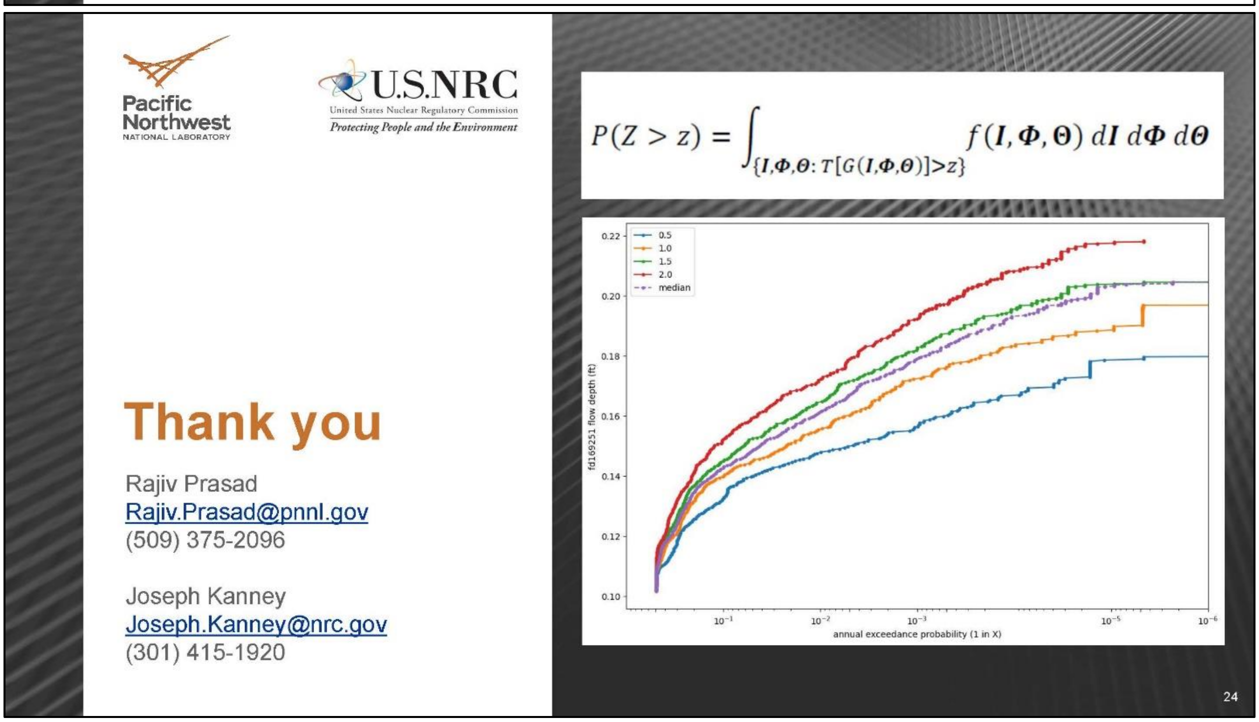




3.8.2.3 Questions and Answers

Rajiv Prasad was not available for the Q&A, so Joseph Kanney (NRC Project Manager) fielded the questions.

Question:

You calculated flood velocity and also flooding depth times and velocity. Can you explain the reason why you used the flood velocity and also flood depth times the flood velocity for the intensity measure?

Answer:

Joseph Kanney: We wanted to provide information that would be useful for assessing any impacts or consequences, and that will depend upon the structure, system, or component that you're looking at specifically. In some cases, say for example, a pump or a piece of electrical equipment, then the flood depth is what you'd be interested in. If it gets wet, it's gone. In other cases, say for example, a structural element, you may be interested in the dynamic forces on that structure that would allow you to estimate whether that structure might fail. So that might be one reason for using the velocity, so you can get the dynamic forces. Then for depth times velocity, that would be interesting in the case where the plant flood response procedure has people actually going out and doing something, maybe put some flood protection feature in place, or turn a valve, or do something when there is actually water on the site. The ability of a person to either stand or walk, is related to that depth times velocity.

Question:

I'm not very familiar with FLO-2D, what is the region of the hazard that's being taken, like when you get the hazard curves, is it for a particular area, and can you change that area?

Answer:

Joseph Kanney: FLO-2D is a finite difference model, so basically it would apply a uniform grid to the entire domain that you are trying to model and for local intense precipitation you'd typically be looking at the power block maybe some other regions close by. Maybe if you are interested, say, in the switch yard you might expand it out. So that would typically be the domain that you are looking at in terms of a local intense precipitation analysis. FLO-2D just applies a uniform finite difference grid so then for each cell you are going to get the results: the depth, velocity, whatever, at each cell. Then you'd go in and look at the cell that's located near the SSC that you are interested in.

Question:

Can you put that site in relation to the water source, in the case of a coastal area, and get that information?

Answer:

Joseph Kanney: Yes, you can do that. In some cases, you might want to do that even for a local intense precipitation analysis if there is, for example, a nearby water body, where the water level could be coming up in that water body such that the outlet of some drainage feature would be affected and you could have backwater coming on to the site. At this particular site, we didn't have any of those features, but you could easily envision a site where you might need to do that.

Question:

In LIP modelling is there any difference between directly inputting rainfall data and calculating runoff and inputting it as a boundary condition?

Answer:

Joseph Kanney: Again, you may have an adjacent water body. Or in some instances, you could have an adjacent area where there is water moving onto the site from the LIP event. In that case, you would need to account for that in terms of a boundary condition. But absent those sorts of features, you'd just be applying the rainfall right onto the site. But always you want to move your boundaries out far enough that it's not impacting your solution obviously.

Question:

I may have missed this but so, your Z is that Z per rainfall duration? Or is it Z integrating over possible rainfall durations? Like is it a Z-1-hour?

Answer:

Joseph Kanney: No because we do multiple durations. So, the hazard curve should be integrating over the different durations that we used.

Question:

OK, so I totally may have missed this and if it's in the report, you can tell me to look. So, how did rate the relative frequencies of those different durations, and then the fact that they are embedded within each other?

Answer:

Joseph Kanney: We did discuss that in the report, and I can't remember exactly what the correct answer is, so I'll get back to you on that.

3.8.3 Presentation 4B-3: Research Activities on Extreme External Hazard Risk Assessment of Korean NPP

Author: Minkyu Kim, Daegi, Hahm; Korea Atomic Energy Research Institute (KAERI)

Speaker: Minkyu Kim

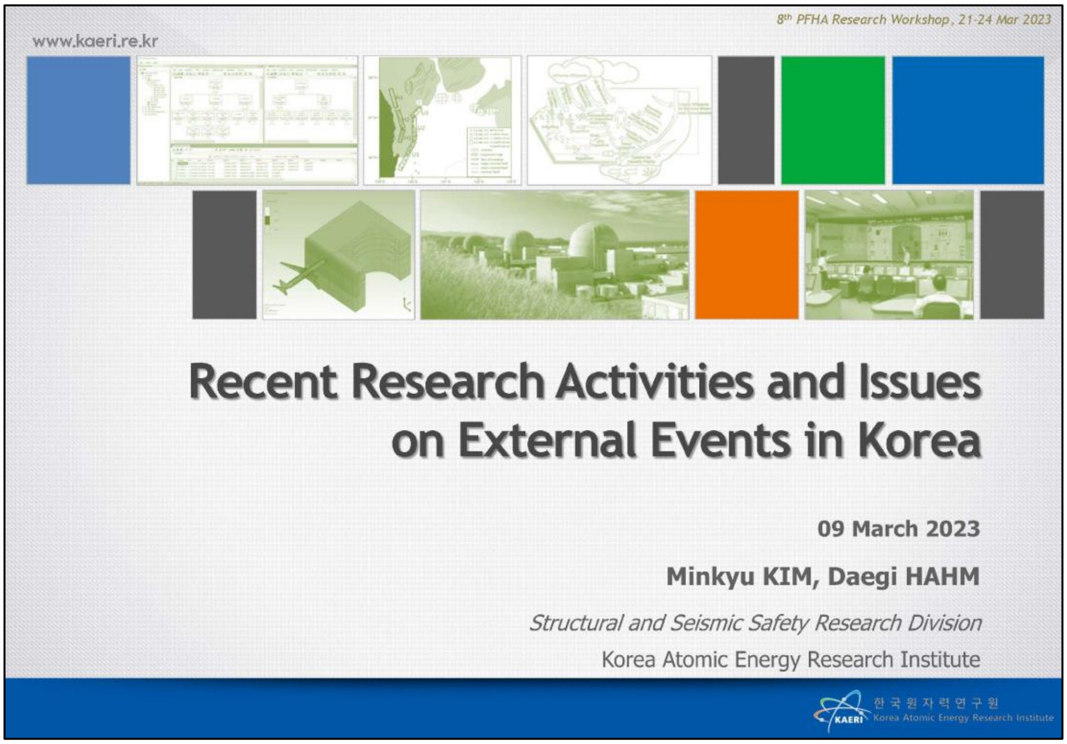
3.8.3.1 Abstract

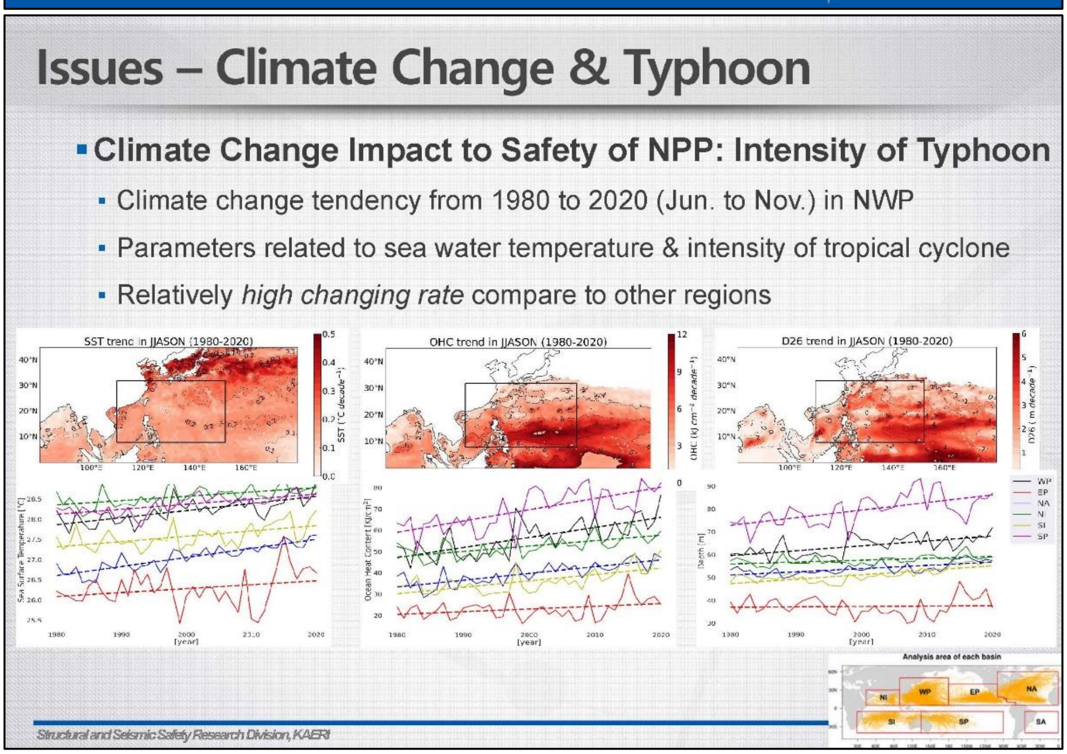
Global climate change is currently underway, and it has already reached an irreversible level, and Korea is already affected by it. Nuclear power is being suggested as a very good alternative to reducing the rate of climate change, but reducing carbon emissions by dramatically increasing the amount of nuclear power plants is not possible in the short term. In reality, it is more urgent to secure the safety of nuclear power plants from the effects of external disasters, which are increasing in intensity and frequency due to climate change. For this reason, the Korean government launched a five-year research program to improve the safety of operating nuclear power plants in 2022. The project is led by the Korea Atomic Energy Research Institute, with seven universities and three companies participating.

This research program is constructed into three parts. The first topic is an extreme/combined external hazard assessment, the second topic is a risk assessment of NPP and safety-related infrastructure systems and the last topic is the safety enhancement for operating NPPs in Korea regarding the extreme/external hazard considering climate change. For performing the external hazard assessment, we will develop the simulation and hazard assessment methods for extreme/combined external events. For performing a risk assessment of NPP against extreme/external hazards, we will develop a fragility assessment method and probabilistic safety assessment method for external hazards. For the development of safety enhancement against

the external hazard, we will develop an optimal risk mitigation and management strategy based on hazard progress scenarios and SSCs safety enhancement methods and demonstration technology.

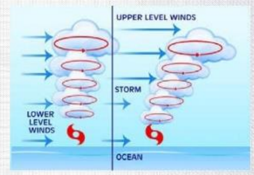
3.8.3.2 Presentation (ADAMS Accession No. ML23177A147)

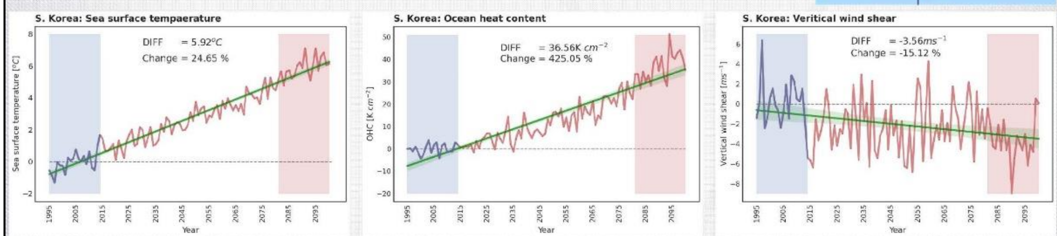




Issues – Climate Change & Typhoon

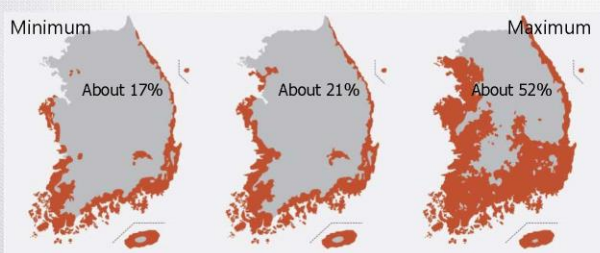
- **Past & Future Projection**
  - Future projection of climate change indices based on SSP5-8.5
  - Difference between [1995-2014] and [2081-2100]
  - *All Changes* of climate parameters are *favorable* to tropical cyclone (Typhoon):
    - Ocean: Increase of SST, OHC, D26
    - Atmosphere: Decrease of VWS, VOR





Issues – Typhoon & NPPs in Korea

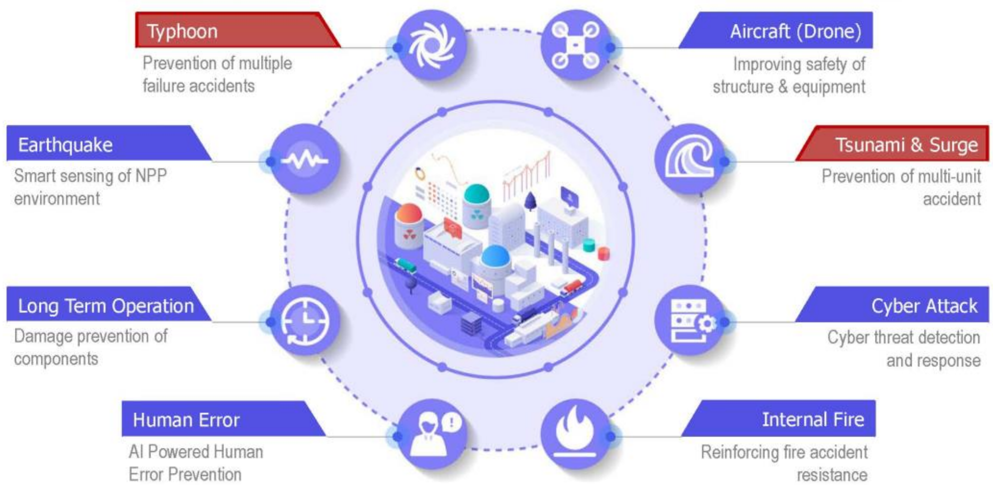
- **Typhoon: Threat of safety of NPPs**
  - Increase of typhoon intensity will affect to the safety of Korean NPPs.
  - In 2020, 4 NPPs automatically tripped by typhoon Maysak and Heishen
    - Salt spray impacts to power transmission equipment: circuit breakers operation
    - Not caused by typical hazards caused by typhoon
    - Seriously aware the danger of meteorological hazards and climate change



Expected subtropical zone of South Korea 2100 (%)

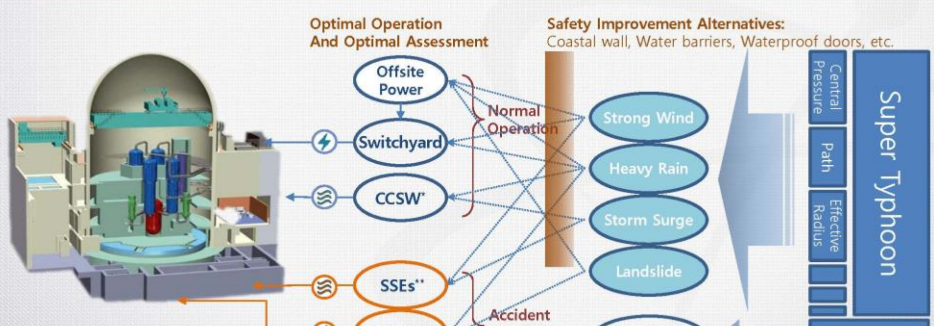
Issues – Typhoon & NPPs in Korea

- 8 Major Issues Threaten the Safety of NPPs (2021)



Activities – Researches on External Events

Objective	Safety Enhancement of NPPs against Extreme/Combined External Hazard
Overview	• Duration: 5-year research project from 2022 to 2026 • Focused on Extreme External Natural Hazard – Climate Change • Focused on Combined Natural Hazard – Heavy Rain, Storm Surge, Strong Wind, etc. • Development of a technology for accident preparedness and management against extreme/combined external natural hazard



*CCSW: Component Cooling Sea Water
**SSEs: Safe Shutdown Equipments
***MACST: Multiple Barrier Accident Cooling Strategy

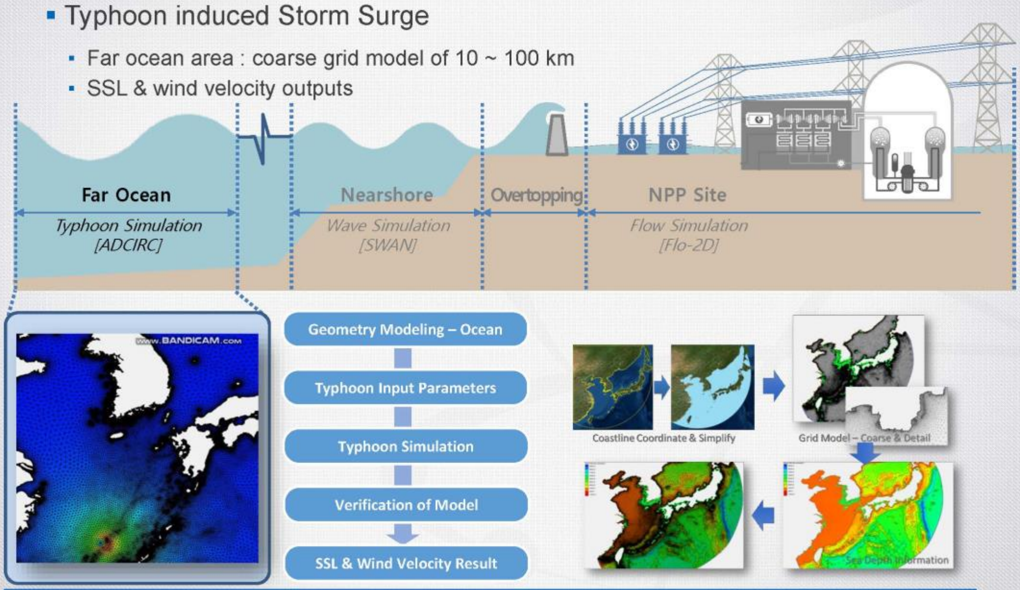
Activities – Researches on External Events

- **Project contains:**
  - **Extreme/combined External Hazard Assessment**
    - **[Project 1]** Simulation and hazard assessment methods for extreme/combined external events
  - **Risk Assessment of NPP and Safety-related Infrastructure Systems**
    - **[Project 2]** Fragility assessment method
    - **[Project 3]** Probabilistic safety assessment method
  - **Safety Enhancement**
    - **[Project 4]** Optimal risk mitigation and management strategy based on hazard progress plant response scenarios
    - **[Project 5]** SSCs Safety enhancement methods and demonstration technology
- **Joint Research Group & Budget**
  - **1 Institute / 7 Universities / 3 Engineering Companies**
  - **$ 20M / 5 years**

Research Area	Institute	University	Industry
Structural Engineering	○	1	1
Reliability Engineering	○	1	
Coastal Engineering		1	2
Wind Engineering		1	
Hydrological Engineering	○	1	
Meteorological Science		1	
Nuclear System Engineering	○	1	

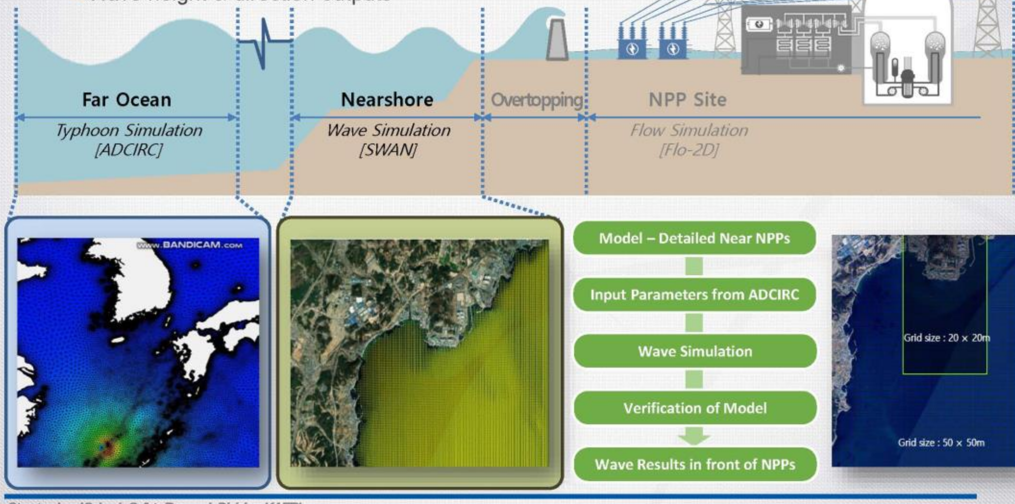
Activities – Simulation of External Events

- Typhoon induced Storm Surge
  - Far ocean area : coarse grid model of 10 ~ 100 km
  - SSL & wind velocity outputs



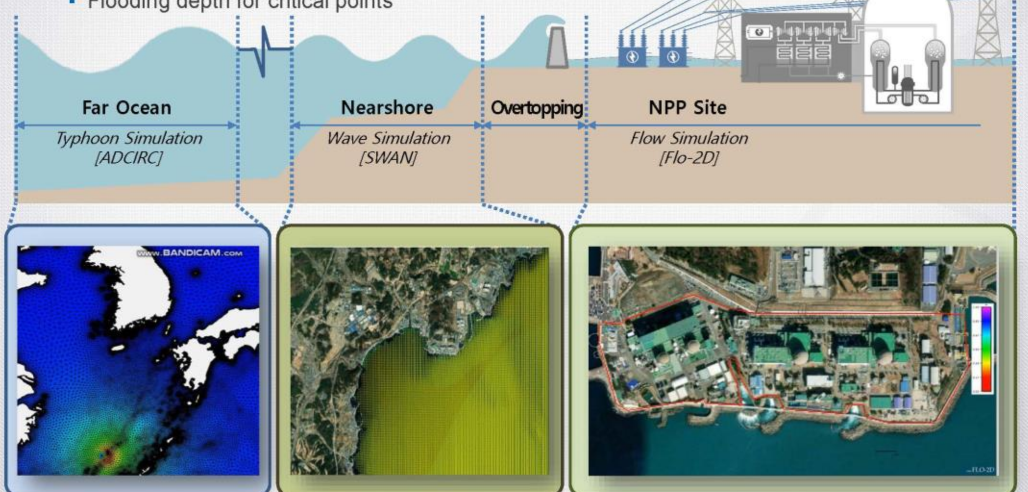
Activities – Simulation of External Events

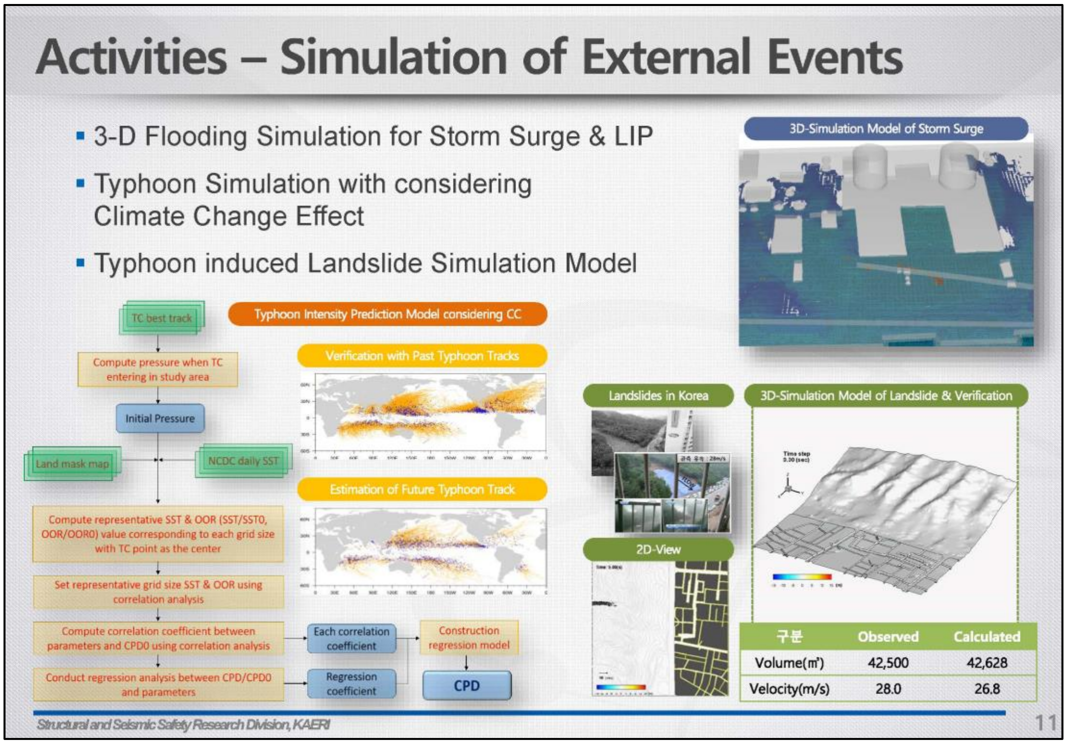
- Typhoon induced Storm Surge
  - Nearshore area : midsize grid model of 20 ~ 50 m
  - Wave height & direction outputs

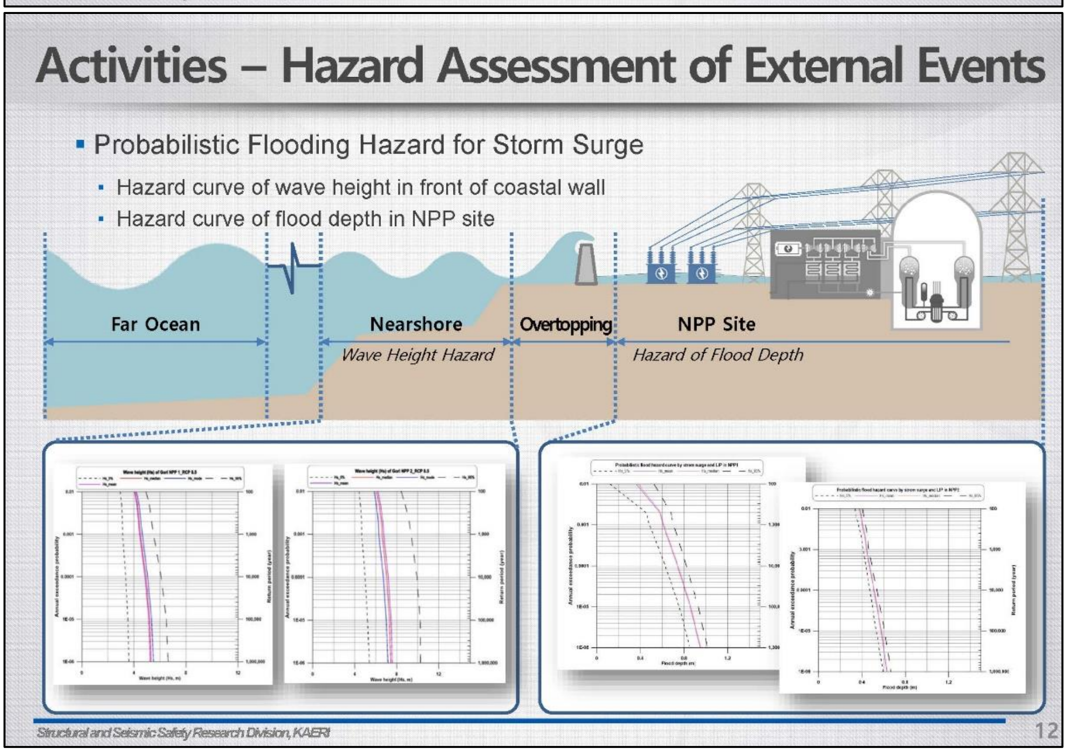


Activities – Simulation of External Events

- Typhoon induced Storm Surge
  - Inside NPP site : detailed grid model of 3.0 x 3.0 m
  - Flooding depth for critical points




Activities – Simulation of External Events
3-D Flooding Simulation for Storm Surge & LIP
Typhoon Simulation with considering Climate Change Effect
Typhoon induced Landslide Simulation Model
3D-Simulation Model of Storm Surge
TC best track
Typhoon Intensity Prediction Model considering CC
Compute pressure when TC entering in study area
Verification with Past Typhoon Tracks
Initial Pressure
Land mask map
NCDC daily SST
Estimation of Future Typhoon Track
Compute representative SST & OOR (SST/SST0, OOR/OOR0) value corresponding to each grid size with TC point as the center
Set representative grid size SST & OOR using correlation analysis
Compute correlation coefficient between parameters and CPD0 using correlation analysis
Each correlation coefficient
Construction regression model
Conduct regression analysis between CPD/CPD0 and parameters
Regression coefficient
CPD
Landslides in Korea
2D-View
3D-Simulation Model of Landslide & Verification
구분 | Observed | Calculated
Volume(m³) | 42,500 | 42,628
Velocity(m/s) | 28.0 | 26.8
Structural and Seismic Safety Research Division, KAERI
11


Activities – Hazard Assessment of External Events
Probabilistic Flooding Hazard for Storm Surge
Hazard curve of wave height in front of coastal wall
Hazard curve of flood depth in NPP site
Far Ocean
Nearshore
Wave Height Hazard
Overtopping
NPP Site
Hazard of Flood Depth
Structural and Seismic Safety Research Division, KAERI
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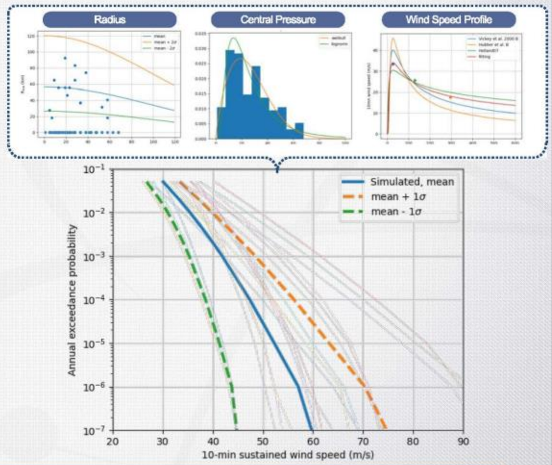
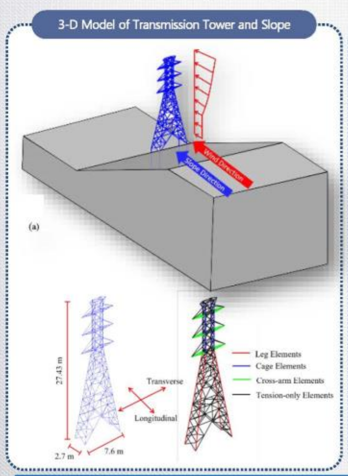
Activities – Hazard Assessment of External Events

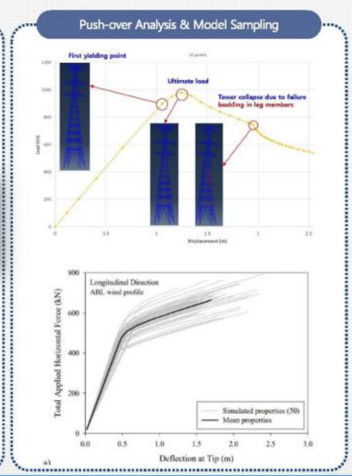
- Probabilistic High Wind Hazard for Network Risk Assessment
  - For network reliability analysis of power transmission system around NPPs
  - Automatic generation of PHWH curve at the location of transmission tower
  - Using typhoon parameters

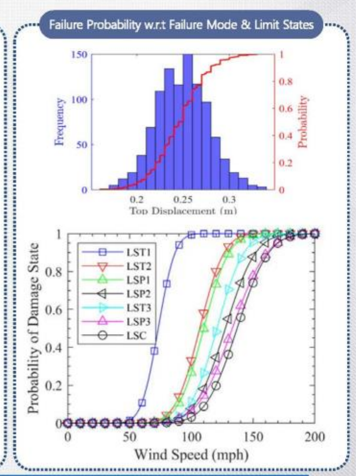


Activities – Fragility Assessment against EE

- Fragility Assessment of Transmission Tower
  - Coupled model for transmission tower, foundation, and slope
  - Considering various failure modes & limit states

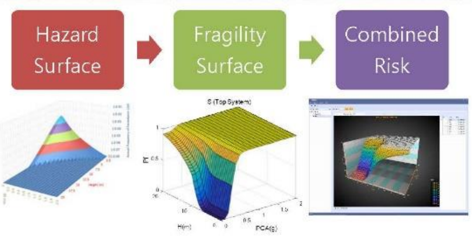




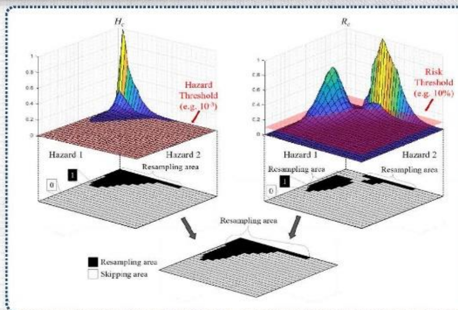


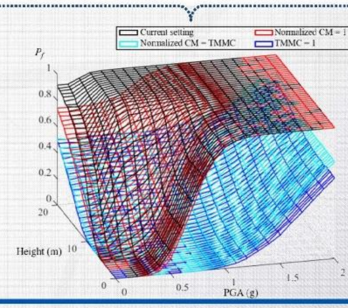
Activities – Risk Assessment & Optimization

- Improvement of COHRISK
  - Developed risk assessment s/w for CoH: COHRISK (2019)
  - For general cases of CoH: Consequential, co-occurrence and independent cases
  - Improved algorithm for multi-dimensional multi-objective multi-variable optimization problem



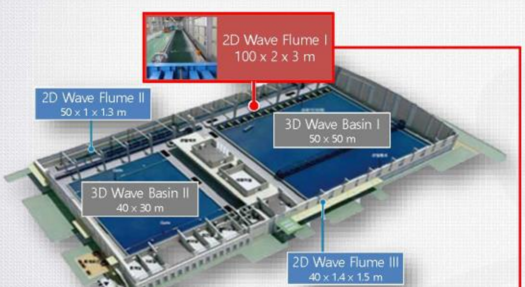
Improvement of probabilistic risk assessment software for extreme/combined natural hazards

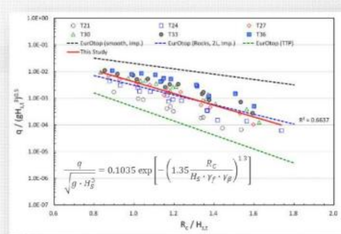


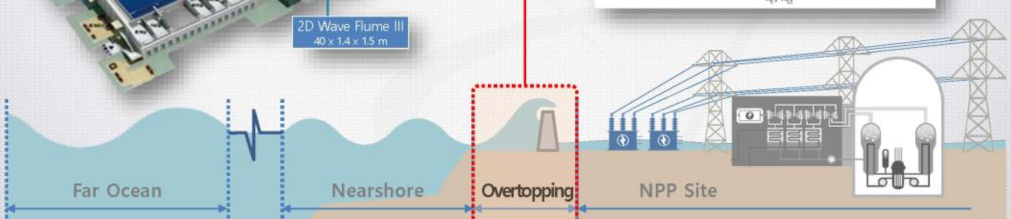


Activities – Experimental Studies

- Estimation of Overtopping Discharge using 2-D Wave Flume
  - Biggest ocean simulation facility in Korea
  - Developing empirical model to estimate overtopping discharge amount during storm surge

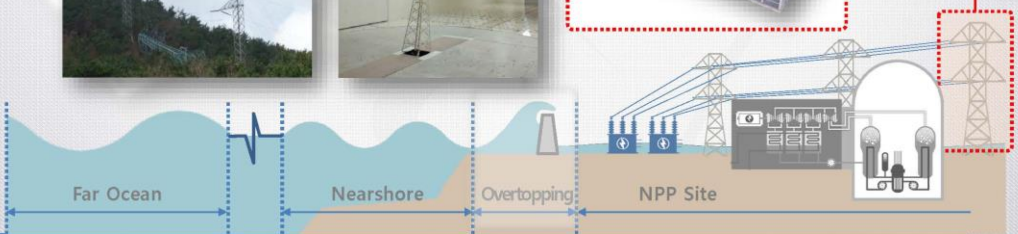






Activities – Experimental Studies

- Estimation of Overtopping Discharge using 2-D Wave Flume
- Wind Load Assessment & Fragility Assessment of Transmission Tower
  - Biggest wind tunnel and outdoor wind generator facility in Korea
  - Measuring aerodynamic coefficient according to horizontal wind angle



Summary

- **ISSUES: CLIMATE CHANGE favorable to increase of intensity of TYPHOON**
  - Not only ocean related indices but also atmosphere indices
  - The latitudes of super typhoon origins are gradually moving north.
- **ACTIVITIES: Projects to IMPROVE SAFETY against extreme external hazards**
  - Joint research group of total 11 research teams
  - Focused on:
    - Simulation models – including climate change effect
    - Probabilistic hazard assessments
    - Fragility assessment
    - Probabilistic risk assessment & optimization
    - Experimental studies – verification & demonstration
  - Very challenging because:
    - Integration of results produced by various research area
    - Incorporation of new research topics – climate change, combination of external hazards

3.8.3.3 Questions and Answers

Question:

It was interesting to see the part about the landslide modeling. As a preliminary to that, have you done any sort of screening to decide which sites might need that type of modeling? Or would you just plan to do that modeling at every site?

Answer:

We already decided a target site of one nuclear power plant because actually it is impossible to perform the modeling for all of the nuclear power plant sites. But anyway, Korea has a lot of mountains, so it is very difficult to find some flat land, so all nuclear power plants are located near very sharp slopes so it is important, one of the important issues for Korea.

Comment:

On the slide that showed how certain typhoon features would change under climate change, I noticed that, at least for the Pacific, the projections that you are using are showing that wind shear is expected to decrease. That was very interesting because, at least from the studies that I'm familiar with in the North Atlantic, climatologists expect the vertical wind shear in the North Atlantic to increase with climate change. It basically introduces a fair amount of uncertainty in terms of North Atlantic tropical cyclones because the sea surface temperature is increasing, but the wind shear is also increasing and how those two factors will compete with each other introduces a lot of uncertainty.

Question:

Regarding the fragility of the electrical towers, would you also want to include not just damage to the tower due the wind, but also debris hitting the tower or maybe debris hitting the wires.

Maybe the tower may remain in-tact, but the wires could be damaged by debris associated with the storm.

Answer:

Yes, wind-blown debris is one of the very important issues for the nuclear power plant, not just for the transmission tower. During the first three years, the first phase, we plan to develop this kind of high-wind fragility. But after that last two years we are going to consider the wind-blown missile for the transmission tower and, moreover, the turbine buildings. It's relatively weaker than the auxiliary building and the containment building. We are planning to perform those simulations and also test.

Question:

I assume since all of the Korean plants are located on the coast, that typhoon winds would dominate over any other types of wind events like tornadoes or straight-line winds. Is that correct?

Answer:

Yes. In Korea, we can say there is no tornado at all. We only have typhoons. So, the high winds sources maybe, more than 90%, is from the typhoons in Korea.

3.8.4 Presentation 4B-4: External Flooding PRA Guidance

Authors: Marko Randelovic[1], Raymond Schneider[2]; [1]Electric Power Research Institute, [2]Westinghouse Company

Speakers: Marko Randelovic, Raymond Schneider

3.8.4.1 Abstract

EPRI is currently developing guidance for performing an external flood PRA for use in the nuclear industry. The guidance establishes a structured framework for treating the spectrum of external flood hazards and provides background materials and examples for the PRA analyst to use. Specifically, the project aids the PRA analyst in:

1. Defining and characterizing the external flood hazard, considering event and plant-specific issues.
2. Estimating external flood hazard frequencies.
3. Developing external flood fragility curves for flood significant Systems, Structures, and Components (SSCs).
4. Preparing an external flood event tree, including consideration of actions preparing the plant for the flood, mitigating the flood hazard, and responding to random and flood-induced failures of initial flood mitigation strategies.

Guidance is being developed to be consistent with expected requirements of the ASME/ANS PRA Standard. To facilitate understanding simple hypothetical example applications illustrate the interface with the probabilistic flood hazard assessment (PFHA), parsing the flood analysis to characteristic event frequencies and the development of various PRA flood event trees and overall quantification overall process. This guidance also includes a potential screening approach for the flood related combined/correlated hazards.

3.8.4.2 Presentation (ADAMS Accession No. ML23177A148)

External Flooding Guidance For Probabilistic Risk Assessment

8th Annual Probabilistic Flood Hazard Assessment Workshop

Marko Randelovic – Project Manager, EPRI
Ray Schneider, Fellow Engineer, Westinghouse

March 24, 2023

www.epri.com

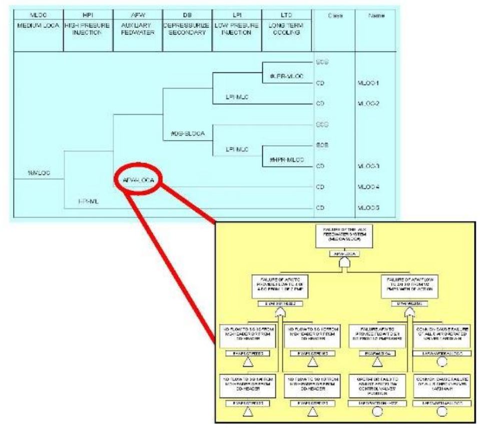
Background

- The EPRI External Flooding PRA Guidance (3002023808) provides state-of the art framework for the development of the external flooding PRAs.
- Report includes guidance for the PRA analyst to
  - collect relevant hazard information and
  - Interface relevant hazard information with PRA models reflecting plant unique features
- This presentation emphasizes the importance of the characterization of the external flood hazard and the interface with the PRA analysis.
  - External flood hazard characterization considers hydrology, meteorology and/or hydrodynamics
  - For the purpose of the PRA, only some features/variables (input/outputs) of the flood characterization effort are explicitly used to develop and quantify the PRA model

2 www.epri.com

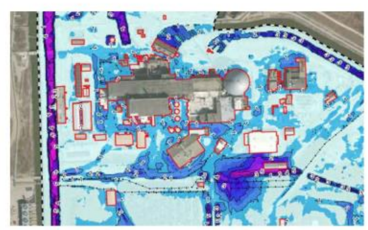
External Flood Guidance for Probabilistic Risk Assessment Issued in 2022

- Guidance provides a structured roadmap for performing an External Flood PRA (XFPRA) consistent with the ASME/ANS PRA Standard.
- Includes guidance for:
  - Defining and characterizing the external flood hazard
  - Identifying flood induced failure modes
  - Developing external flood fragility curves for flood significant Systems, Structures, and Components (SSCs).
  - Preparing and quantifying a PRA external flood event tree.
- Guidance is focused for the PRA analyst



External Flood Guidance for Probabilistic Risk Assessment

- Guidance supports using the baseline internal events and internal flood PRAs as basis for developing relevant flood-induced failures for the External Flood PRA.
- Where available and appropriate national and international documents and methods are identified to support both:
  - Probabilistic flood hazard analysis (PFHA)
  - Fragility assessments
- Methodology was developed in collaboration with EDF



External Flood PRA Process

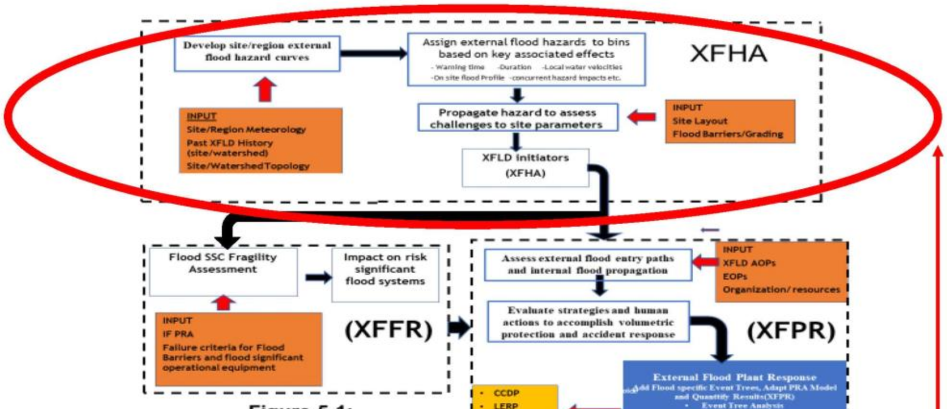


Figure 5-1: Overview of an External Flood PRA

Focus of today's presentation is the role of the PFHA analysts in characterizing the external flood hazard and the interface with the PRA analyst.

XFHA: Characterization of the External Flood Hazard

- External Flood Hazard Characterization
  - Hazard characterization is a foundation for the PRA model.
  - More complete hazard characterization facilitates a more realistic treatment of the impact of the hazard on the PRA.
  - Hazard characterization consists of subdividing the external flood hazard into a complete set of external flood initiating events with sufficient detail for propagation into the PRA model.
  - Hazard scenarios may be represented by
    - Probability of occurrence
    - Transient flood level profiles
    - Potential concurrent associated effects (wind velocities, lightning potential, etc.)
  - Characterization includes consideration of uncertainties in temporal features, flood elevations and presence and severity of associated effects.

XFHA: Characterization of the External Flood Hazard Informs Fragility Analysis

- External Flood Characterization such as flood level, timing and associated effects (e.g., high winds, etc.) informs the PRA fragility analysis through:
  - Characterizing flood related challenges to flood significant SSCs including
    - permanent/temporary barriers
    - pumps or other powered components

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XFHA: Characterization of the External Flood Hazard Informs Human Reliability Analyses

- External Flood scenario Characterization informs:

  Human Reliability Analysis and Plant Response Quantification through:
  - Warning time
  - Site conditions during site preparations
  - Site conditions during flood response and mitigation
    - Examples :
      - Impact of high winds on actions taken outdoors
      - Lightning related impacts on human actions

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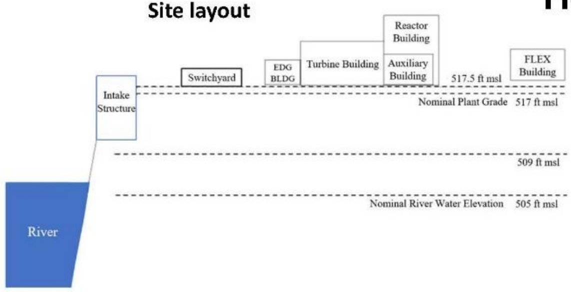
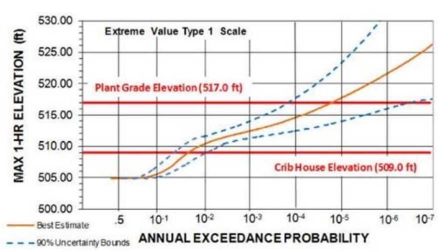
Example Applications

- Guidance document includes simplified hypothetical example external flood PRAs.
  - Local Intense Precipitation
  - Riverine Flood
  - Storm Surge Hazard
- Each selected external flood PRA example illustrates a unique inter-relationships between the hazard features and the PRA model molding the plant response.

Example Illustration: Hazard Characterization of the Riverine Flood

Site layout





Hypothetical Flood Hazard Frequency Curve

Hazard Curve developed with stochastic event frequency model. Characterization includes:

- Development of hazard frequency curve
- Identifying flood levels
- Identifying flood profile and warning times
- Identifying associated effects
  - Wind speeds

Information collected during hazard characterization supports the disaggregation of flood hazard curves into a set of scenarios with unique features.

Example: Riverine Flood
Partial Summary of River Flood Scenarios

XFLD-ID	Range of Flood Elevation (H)	Mean Initiating Event Frequency @ Midpoint Elevation	Lower Bound (0.05 confidence limit) Exceedance Frequency	Mean Exceedance Frequency	Upper Bound (0.95 confidence limit) Exceedance Frequency	River Rise Time 509-517 (hr) Median Rate of River Rise (ft/hr)
	ft	Per Year	Per Year	Per Year	Per Year	[LB, Median, UB]
XFLD-01	517-518	5.00E-06	5.00E-07	1.50E-05	1.10E-04	Rate of rise =0.75
XFLD-02	518-519	4.00E-06	1.00E-07	1.00E-05	9.00E-05	Rate of rise =0.75
XFLD-03	519-520	2.00E-06	1.00E-08	6.00E-06	8.00E-05	Rate of rise =0.75
XFLD-04	520-521	2.00E-06	5.00E-09	4.00E-06	6.00E-05	Rate of rise =0.75
XFLD-05	521-522	1.00E-06	2.00E-09	2.00E-06	3.00E-05	Rate of rise =0.75
XFLD-06	522-523	3.00E-07	1.00E-09	1.00E-06	2.00E-05	Rate of rise =0.75
XFLD-07	523-524	2.00E-07	8.00E-10	7.00E-07	1.50E-05	Rate of rise =0.60
XFLD-08	524-525	3.00E-07	5.00E-10	5.00E-07	1.00E-05	Rate of rise =0.50
XFLD-09	525-530	1.90E-07	3.00E-10	2.00E-07	8.00E-06	Rate of rise =0.10
XFLD-10	>530	1.00E-08	1.00E-10	1.00E-08	2.00E-06	Rate of rise =0.01

- Flood hazard characterized by two initiating event groups, each with 10 scenarios. Scenarios divided based on peak flood elevation.
- Initiating event groups are divided based short and long warning times.
- Warning time and flood elevation were selected as significant flood hazard features for modeling.

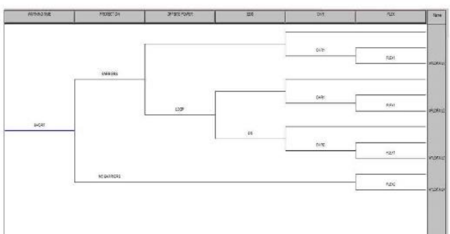
Example: Riverine Flood
Fragility Analysis Considerations

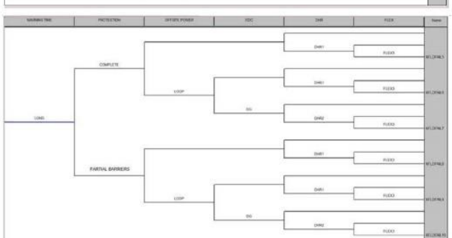
- Fragility analysis primarily affected by type of barrier, warning time and flood level.
- Assumptions for hypothetical simplified examples:
  - Permanent barriers assumed to fail on overtopping. These barriers were not considered to be subject to leakage or hydrostatic /hydrodynamic failures.
  - Fragility of temporary barriers are affected by installation effectiveness. To simplify the assessment, temporary barriers were assumed to fail for flood events with short warning times and fail due to overtopping for long warning time scenarios.

Example: Riverine Flood Human Reliability Analysis Considerations

- Human Reliability Analysis (HRA) considers hazard characteristics that affect timing factors for actions, and other human reliability shaping factors
- Timing factors include:
  - Warning time
  - Flood profile /rise time
    - Factors impacting available time for protective and mitigation actions
- External Flood Associated factors that may degrade performance of preparatory or mitigation actions are primarily focused on outdoor actions. These associated effects include:
  - Adverse winds (as they may impact movement on site, maintenance activities, communications, etc.)
  - Flood levels (as they may impact movement on site and task feasibility, etc.)
  - Flow rates (as they may impact movement on site and task feasibility, etc.)

Example: Riverine Flood Plant Response


Short Warning Time Event Tree


Long Warning Time Event Tree

- Plant response model integrates fragility and human reliability models in an event tree structure. Event tree includes:
  - Protection (Barrier Installation)
  - Offsite Power
  - EDGs
  - Decay heat removal
  - FLEX Strategies
- Short warning times increase probability of failure of critical temporary flood barriers and greater probability for failure of FLEX recoveries.
- Long warning time scenarios consider temporary barriers at a minimum will be partially installed. Probability for FLEX actions considers additional time for FLEX setup strategies.

Example: Riverine Flood Quantification

- Quantification involves propagation of flood hazard scenarios, including associated effects and conditional probabilities for each scenario considered into the plant response model.

Peak Flood Elevation (ft)	River Flood Mean Flood Frequency (per year)	Conditional Core Damage Probability (CCDF)	River Flood CDF (per year)
518	5.00E-06	1.25E-06	6.25E-12
519	4.00E-06	1.69E-04	6.76E-10
521	4.00E-06	4.77E-02	1.91E-07
525	1.80E-06	5.70E-01	1.02 E-06
>525	2.00E-07	1	2.00E-07
Total			1.41E-06

- For this example, core damage driven by lower frequency flood events.

Hazard Characterization Insights and Takeaways

- The capability of the PRA is supported by scope and extent of detail included in the hazard characterization.
  - External flood hazard characterization is more than an inundation assessment.
- Hazard characterization conservatisms and the level of detail can limit the scope and capability of the PRA.
- Understanding the intended use of the hazard characterization is important.
- Consideration of associated effects can provide more realistic risk assessments
- Realistic PRA modeling, supported by the appropriate hazard analysis, provides realistic flooding insights which can be used to improve mitigation strategies.

Summary

- PFHA analysis and associated information generated to characterize the hazard, has an important role in developing an appropriate external flood PRA model.
- To effectively accomplish this role the PFHA analyst and PRA analyst should understand their respective scopes and how hazard information is developed and applied.
- EPRI External Flooding PRA Guidance provides a framework for the external flooding risk assessments
  - https://www.epri.com/research/products/000000003002023808

Major 2023 Project Activities

- Future activities focused on providing training with insights into the use of the EPRI External Flood Guidance document

- Establishing External Flooding best practices based on lessons learned from past flood events.
  - EPRI document to be published sometimes Q4 of 2023

Lessons Learned from Preparing for and Coping with Severe Flood Hazards

- Develops insights from Fort Calhoun Station Missouri River flood and other selected industry international flood events.
- Issues to consider include:
  - The importance of considering warning times
  - Role of procedures
  - Organizational, staffing and resource management considerations
  - Preparing for external flood events at shutdown
  - Role of temporary barriers and flood mitigation strategies
  - Fragility considerations for active and passive components

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Lessons Learned from Preparing for and Coping with Severe Flood Hazards(continued)

- Utilities with may use the insights to:
  - Review plant hazards and flood defenses
  - Evaluate mitigation strategies for off-normal plant states
  - Identify efficient and effective actions that reduce external flood risks
  - identify time available for flood significant actions
  - Identify the importance of preparatory as well as mitigation procedures
- EPRI is always interested in having industry participation and collaboration
  - If you are interested in participating in this task, contact Marko Randelovic (mrandelovic@epri.com)
  - EPRI document to be published ~ Q4 of 2023

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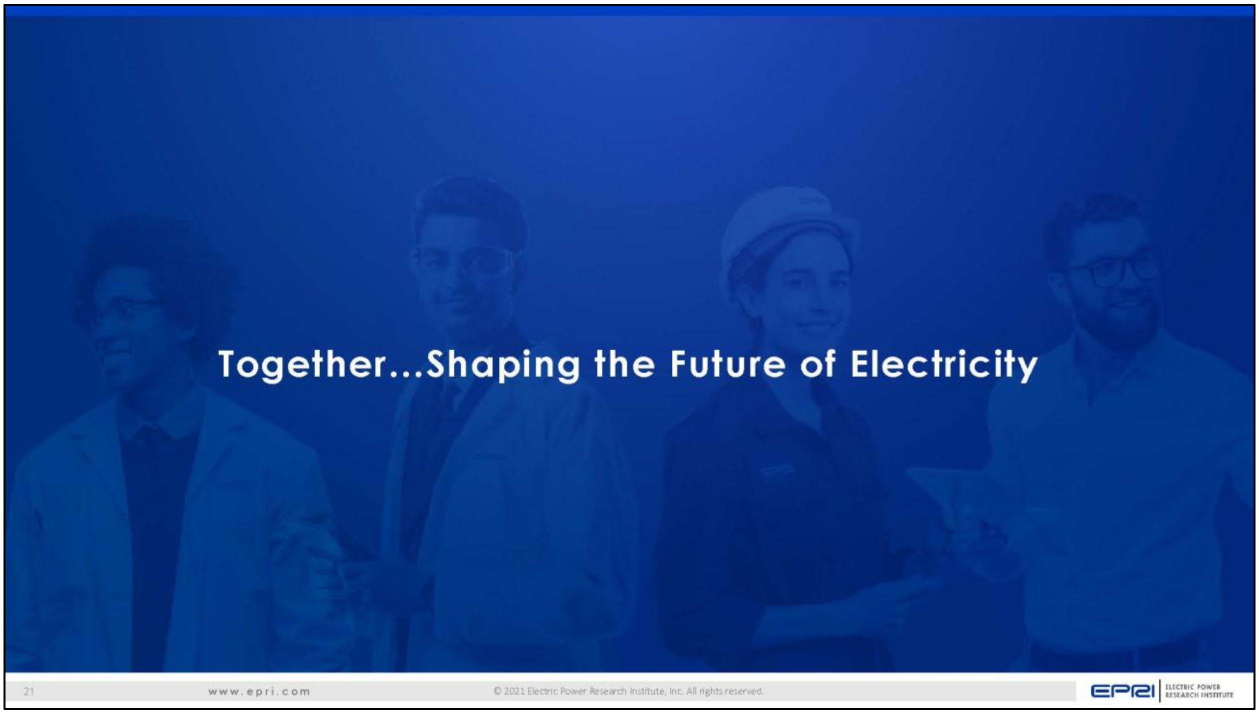


3.8.4.3 Questions and Answers

Question:

You mentioned at the very start that you included international perspectives in the guidance document. Could you describe, briefly, where did that international experience and perspective have the most effect?

Answer:

Marko Randelovic: It has the effect in terms of the implementation and integration of all of the different elements. How do we develop the scenarios? How do we quantify different elements?

Ray Schneider: It also helped in the hazard characterization. We looked at other methods that were done by other countries in how they calculate that hazard and how they include wind-related effects and stuff like that. It was most important in understanding how they basically analyzed the hazard and that would be my take-away from this.

Comment:

Joseph Kanney: Thank you for this presentation. I think this a very important topic. I think effective communication and cooperation between the hazard analysts and the PRA experts is really crucial to having a good product at the end that really helps us develop the appropriate risk insights.

3.8.5 Presentation 4B-5: A Proposal for Paradigm Shift in Hydrological Ensemble Predictions: From Parameter Inference to Probabilistic Error Estimation

Authors: Vinh Ngoc Tran[1], Valeriy Y. Ivanov[1], Donghui Xu[1], Jongho Kim[2]; [1]University of Michigan, [2]University of Ulsan, South Korea

Speakers: Valeriy Y. Ivanov

3.8.5.1 Abstract

Although the application of sophisticated hydrologic-hydrodynamic models (HHM) to flood forecasting has grown significantly over the last decade, it has remained limited due to the inherent computational burden and data-model uncertainties. We present a novel modeling framework that has the potential to address these issues by combining the advantages of three modeling techniques: HHM, surrogate, and machine learning (ML). Specifically, a comprehensive HHM can integrate a large amount of watershed information and knowledge-based parameter assumptions to provide physics-informed predictions. Surrogate modeling can resolve the computational burden of a high-fidelity HHM, opening the opportunities for uncertainty quantification, sensitivity analysis, and applications in real-time. By combining HHM-surrogate model simulation outputs with observations, the potential of ML approach can be explored to create a novel probabilistic framework capable of forecasting an ensemble of HHM-surrogate errors that include both aleatory and epistemic uncertainties. Overall, the proposed framework advocates practical utility of first-principles, high-fidelity models for flood-forecasting, with surrogate and ML modeling aiding real-time applications and uncertainty quantification.

3.8.5.2 Presentation (ADAMS Accession No. ML23177A149)

A Proposal for a Paradigm Shift in Hydrological Ensemble Predictions: From Parameter Inference to Probabilistic Error Estimation

Vinh Ngoc Tran*[1], **Valeriy Y. Ivanov**[1], Donghui Xu[1,2], Jongho Kim[3], Dan Wright[4], Khachik Sargsyan[5]

[1] University of Michigan (USA)
[2]Pacific Northwest National Lab, DoE (USA)
[3]Ulsan University (South Korea)
[4]University of Wisconsin - Madison
[5]Sandia National Labs, DoE (USA)

CIVIL & ENVIRONMENTAL ENGINEERING
UNIVERSITY OF MICHIGAN

Outline

1. Resolving flooding dynamics at **"human" spatial scales (10^0~10^2 m)**: pluvial floods

2. Uncertainty quantification for high spatial resolution flooding simulation (and real-time)

3. Probabilistic **error estimation** to address accuracy of **streamflow** prediction

FLOODS

Photo: David Coates/Detroit News | louisianahelicam.com | Robert Gauthier/*Getty Images*

- Flooding in densely populated areas is **the costliest natural hazard of all weather-related events**[1]
  - $662 billion between 1995-2015[1]
- People in flood path will **double – from one to two billion within two generations**[2]

Fluvial flooding: rivers or streams rise out of their banks in response to precipitation[3]

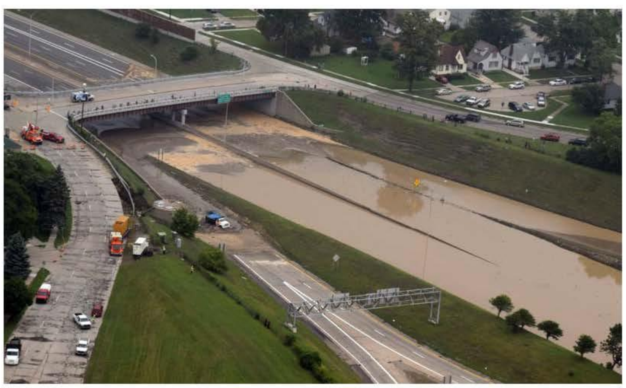
Pluvial flooding: intense precipitation exceeds the rate of natural and engineered drainage[4]

Groundwater flooding: when the water table rises above the land surface[5]

Coastal flooding: result from high tide conditions and storm surge[6]

1. CRED, U., 2015. United Nations, Geneva
2. De Groeve et al., 2015. Bulletin of the AMS, 96(5).
3. Kundzewicz et al., 2010. Mitigation and Adaptation Strategies for Global Change
4. Rosenzweig et al., 2018. Water, 5(6).
5. Macdonald et al., 2012. J. Flood Risk Manag., 5(1).
6. Rosenzweig et al., 2021. Earth's Future.

Pluvial Floods



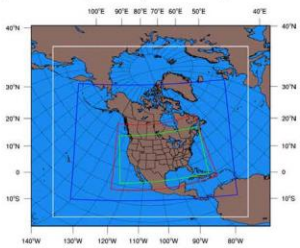
Interstate 696, 12 August 2014, one day after several inches of rain (*AP Photo/Carlos Osorio*).

Interstate 75 in Detroit, on 26, 2021. A Detroit-area water service provider denied flooding claims based on an independent review that found the flooding was due to the amount of rainfall and not a defect in its collection system. *(Max Ortiz/Detroit News via AP, File)*

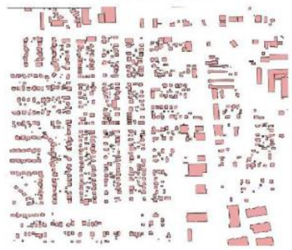
Prediction: Are Key Ingredients There?

DATA

Precipitation: *High-Resolution Rapid Refresh* forecast product (HRRR; 1-hour, 3 km resolution)[1]



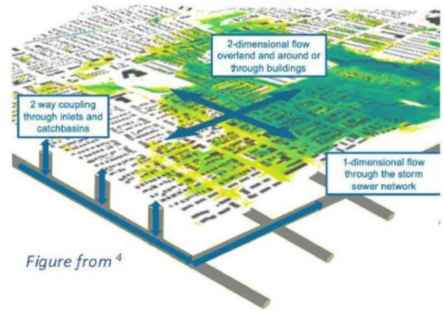
Urban layout



Cal/Val data

Review "*… highlighted the need for additional (ambitious) experimental efforts to support the development and validation of more realistic computational models of urban floods*"[2]

MODELS

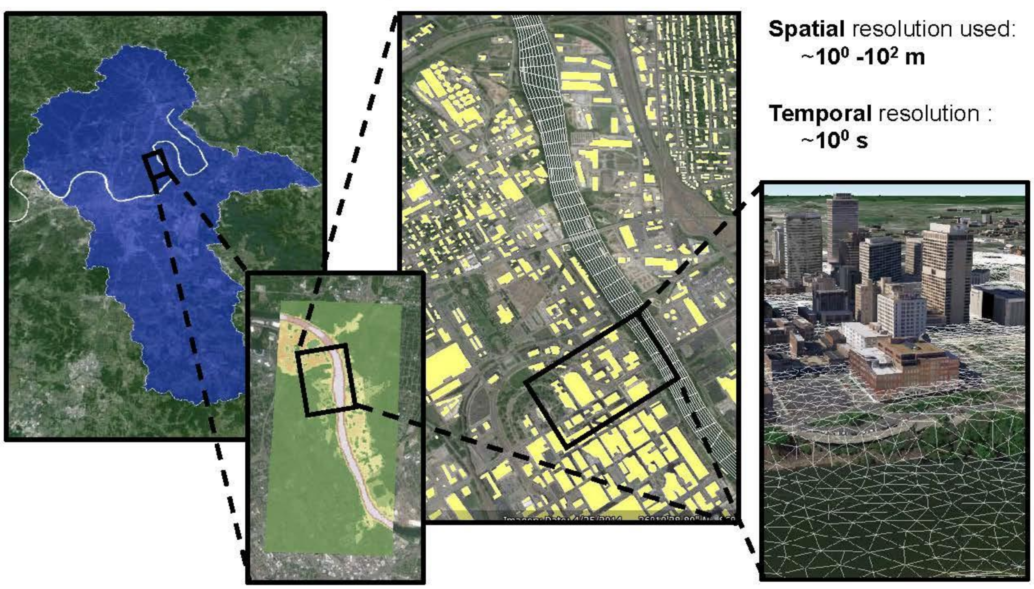


Review "*… since the 1970s, there have been vast improvements in flood inundation modelling.*"[3]

Review "*… While … high-skill models for coastal and fluvial flooding are available for research and practice…, models for pluvial and groundwater flooding remain in early stages of development.*"[4]

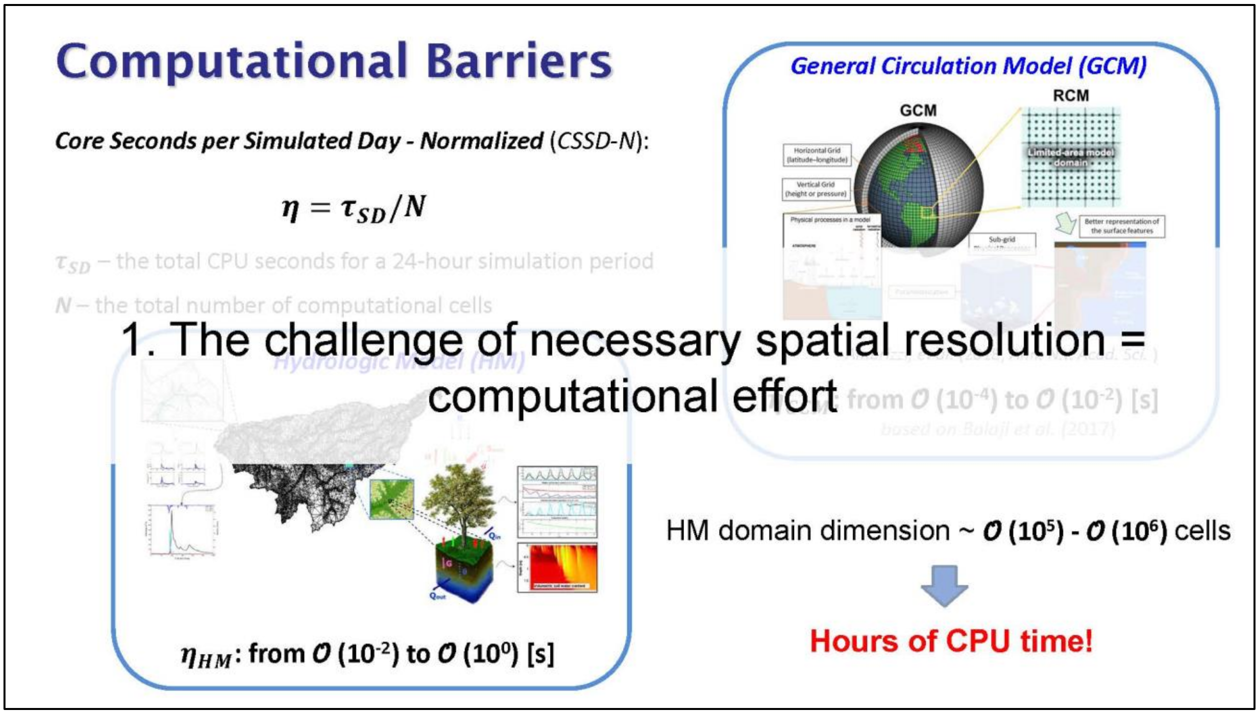
1. *Benjamin et al, 2016. Monthly Weather Review, 144(4).*
2. *Mignot et al. (2019). J. Hydrol., 568.*
3. *Tang et al. 2017. Environmental Modelling & Software, 90.*
4. *Rozenzweig et al., 2021. Earth's Future*

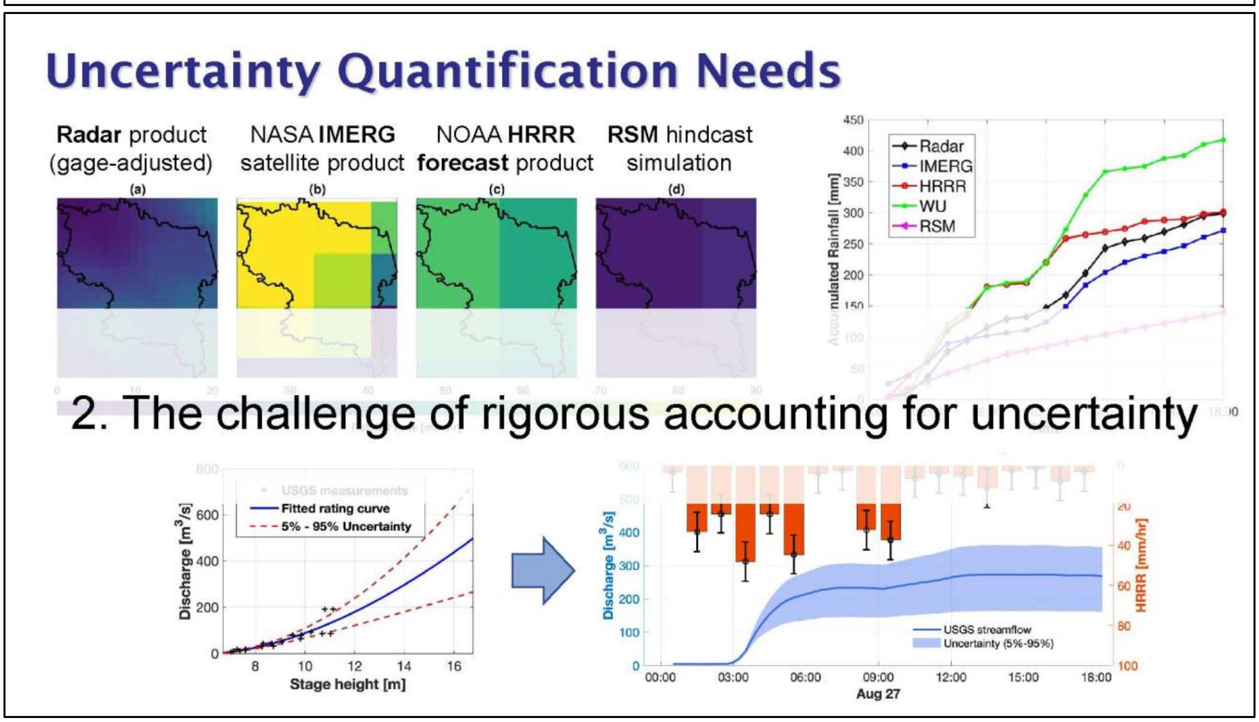
High-fidelity Modeling Example: Nashville 2010 Flood



Spatial resolution used: ~10^0 - 10^2 m

Temporal resolution : ~10^0 s


Computational Barriers
Core Seconds per Simulated Day - Normalized (CSSD-N):
η = τSD/N
τSD – the total CPU seconds for a 24-hour simulation period
N – the total number of computational cells
General Circulation Model (GCM)
GCM
RCM
1. The challenge of necessary spatial resolution = computational effort
from O (10-4) to O (10-2) [s]
based on Balaji et al. (2017)
Hydrologic Model (HM)
HM domain dimension ~ O (105) - O (106) cells
Hours of CPU time!
ηHM: from O (10-2) to O (100) [s]


Uncertainty Quantification Needs
Radar product (gage-adjusted)
NASA IMERG satellite product
NOAA HRRR forecast product
RSM hindcast simulation
(a)
(b)
(c)
(d)
Radar
IMERG
HRRR
WU
RSM
Accumulated Rainfall [mm]
2. The challenge of rigorous accounting for uncertainty
USGS measurements
Fitted rating curve
5% - 95% Uncertainty
Discharge [m3/s]
Stage height [m]
Discharge [m3/s]
HRRR [mm/hr]
USGS streamflow
Uncertainty (5%-95%)
Aug 27

Urban Flooding: Challenge of Scale & Uncertainty

- **Useful spatial** scale: **~10^0 -10^2 m** → city-scale flooding: **~10^6** cells
- **Event time** scale: **~10^0 – 10^1** day
- **Uncertainty**: precipitation, surface conditions, model parameters (and the model itself!)

Model	Simulation time for 24-hour event	Uncertainty Quantification with 10,000 simulations
tRIBS-OFM	52 [hours]	520,000 [hours] ≈ **60 [years]**
tRIBS-OFM parallel model	3 [hours] with 30 CPUs	30,000 [hours] ≈ **3.5 [years]**

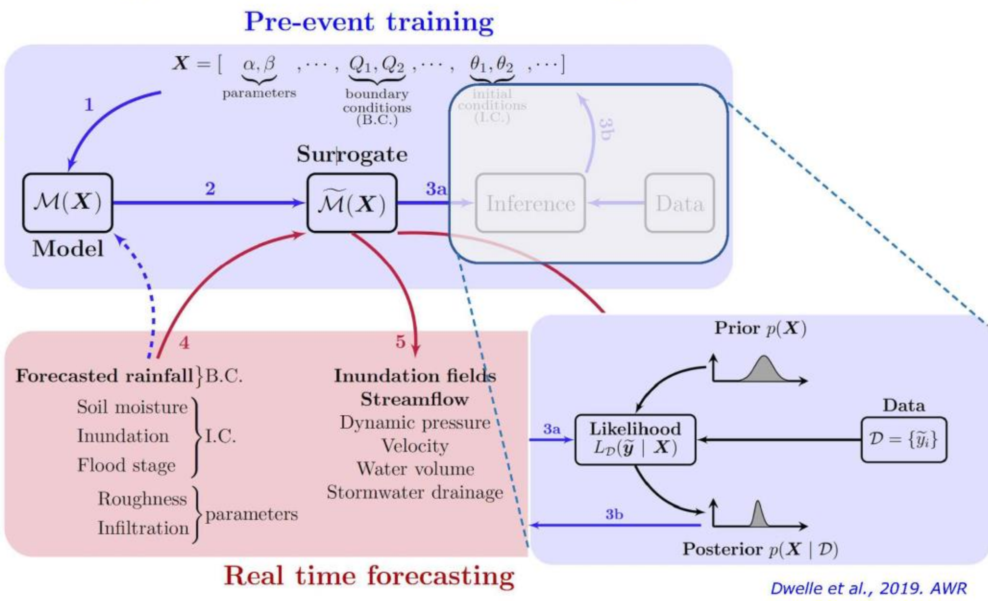
Real-time and/or uncertainty-informed assessment: computationally impossible (or impractical)

Urban Flooding: Physics and Surrogates

Xiu and Karniadakis, 2002. SIAM J. Scientific Computing

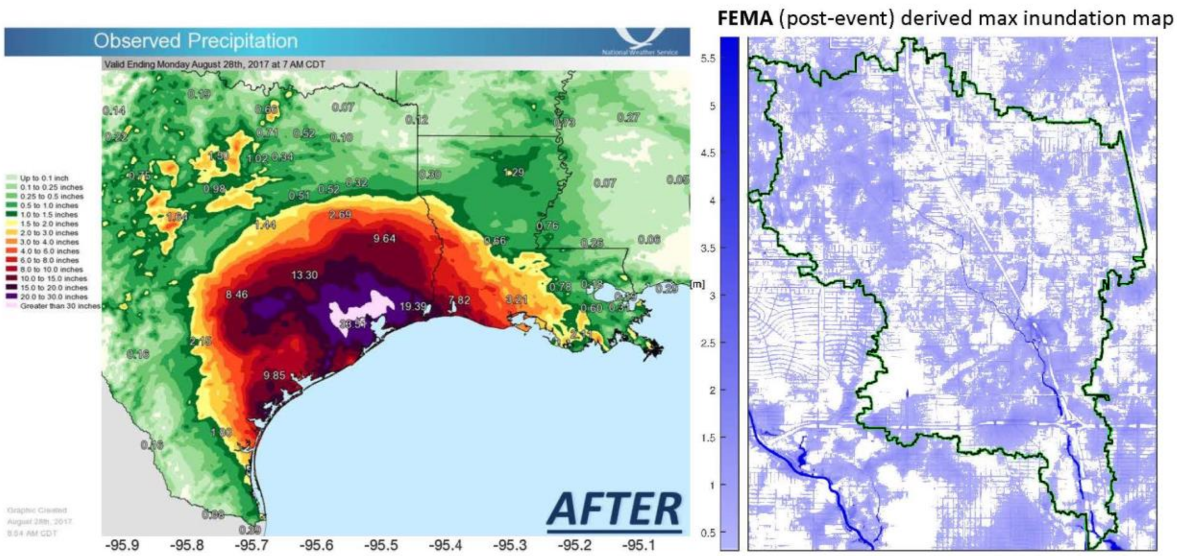
Najm, 2009. Ann. Rev. Fluid Mechanics

Sargsyan et al., 2014. Int. J. Uncertainty Quant.

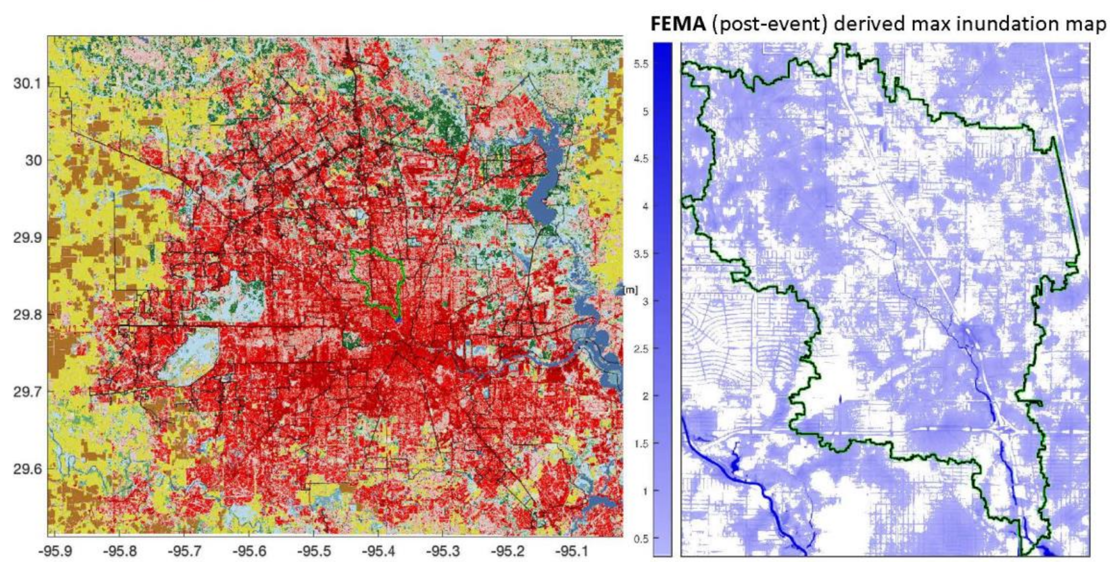


Dwelle et al., 2019. AWR

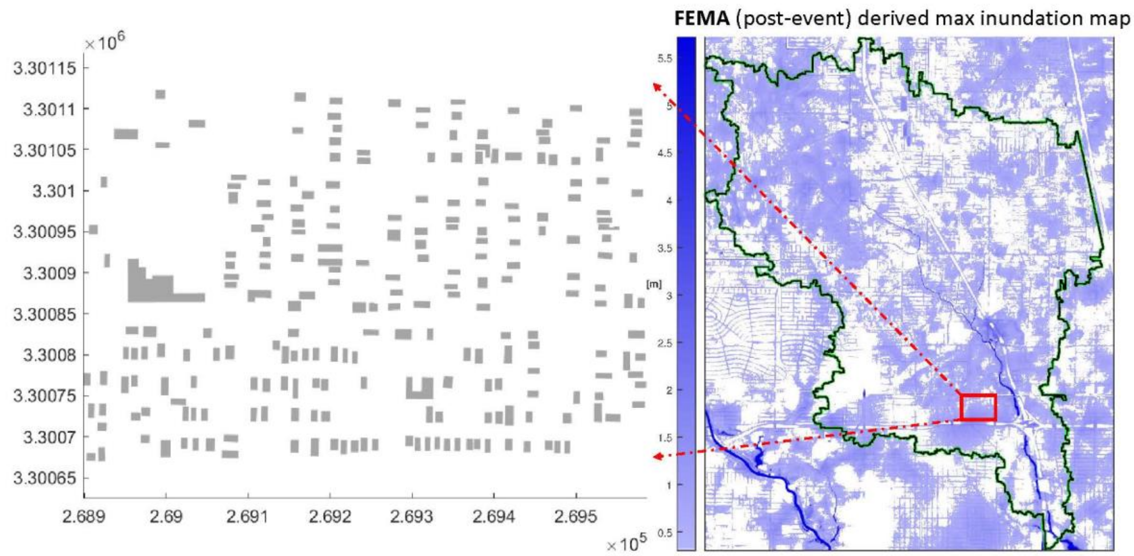
Case Study: Houston 2017 Harvey Event



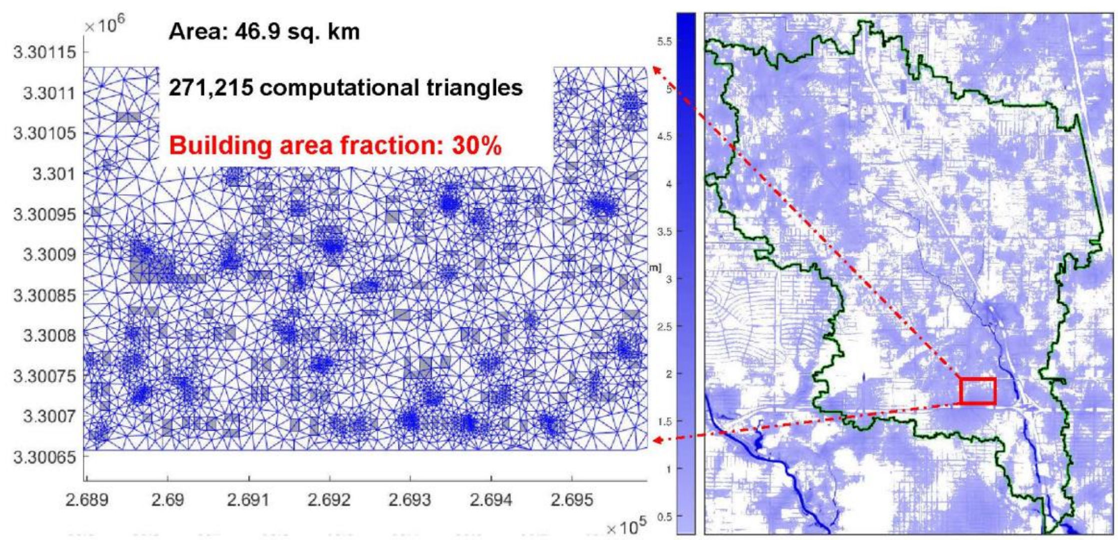
Case Study: Houston 2017 Harvey Event



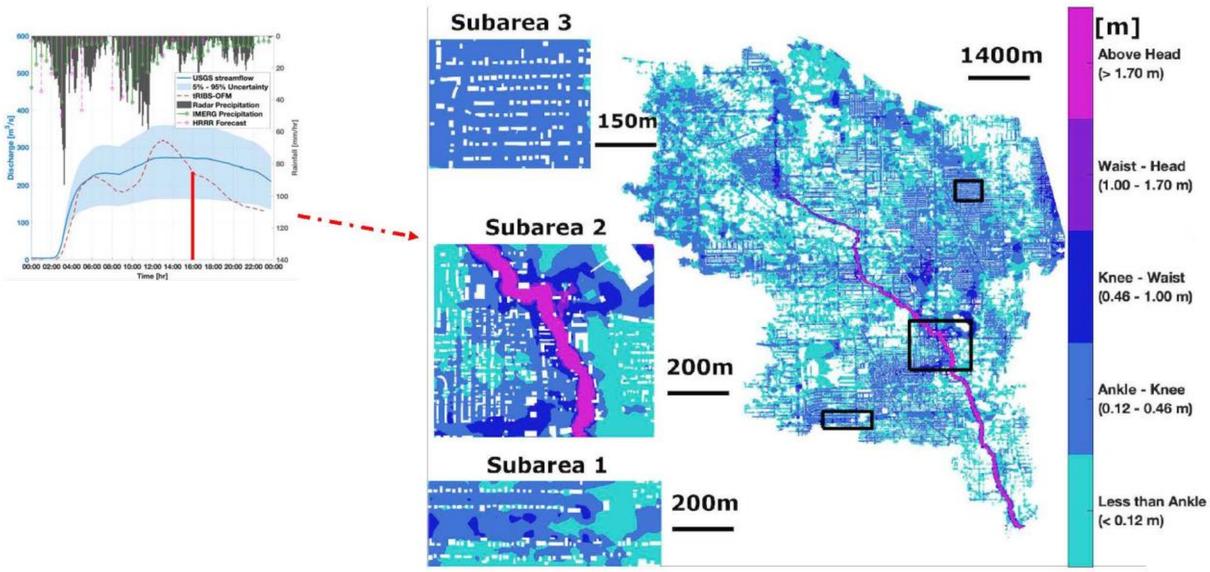
Case Study: Houston 2017 Harvey Event



Case Study: Houston 2017 Harvey Event



High-Fidelity Simulation: tRIBS-OFM



Ivanov et al. (2021), GRL, Breaking Down the Computational Barriers to Real-Time Urban Flood Forecasting

Uncertainty Quantification Framework

Pre-event training

We train the surrogate model with inputs of <u>uncorrelated</u> rainfall pulses:

Rainfall intensity ~ $\boldsymbol{U}(0, 50)$ [mm/hour]

Forecasted rainfall }B.C.

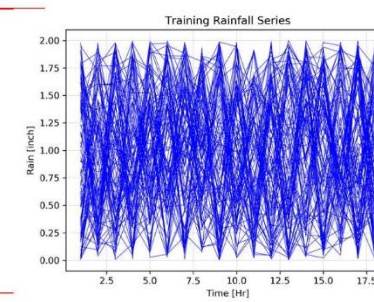
Soil moisture
Inundation } I.C.
Flood stage

Roughness
Infiltration } parameters

Inundation fields
Streamflow
Dynamic pressure
Velocity
Water volume
Stormwater drainage

Sensitivity analysis

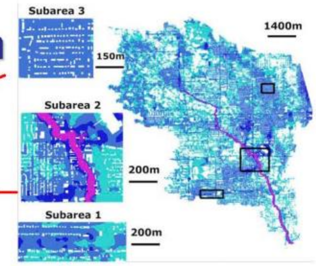
Real time forecasting



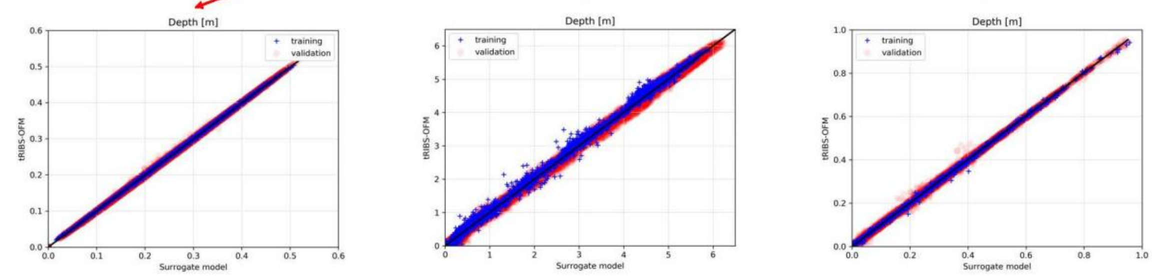
The goal of PCE model training is to solve for the **coefficients** $\mathbf{c_i}$ and store them as a PCE coefficient array for a given *quantity of interest* (***QoI***)

Ivanov et al. (2021), GRL, Breaking Down the Computational Barriers to Real-Time Urban Flood Forecasting

Surrogate Model Performance: Inundation



Water depth at hour 16 for the three Subareas



Ivanov et al. (2021), GRL, Breaking Down the Computational Barriers to Real-Time Urban Flood Forecasting

Surrogate Model "Forecast": Inundation

HIGH-FIDELITY MODEL (tRIBS-OFM)

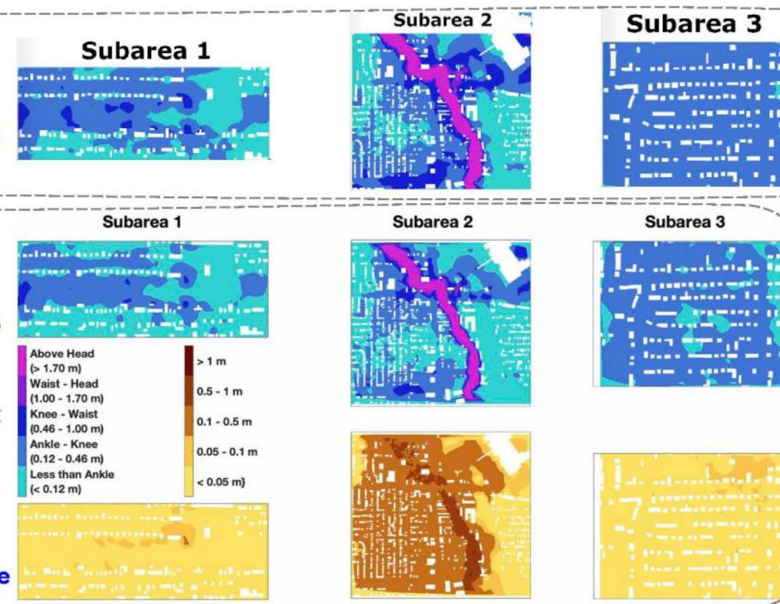
Single simulation

SURROGATE MODELS
7,057 cells = QoIs

Posterior 50%

Precipitation is uncertain: 10,000 realizations

Posterior 5%-95% range



Computational Performance

Model	Simulation time for 24-hour event	Uncertainty Quantification with 10,000 simulations
tRIBS-OFM	52 [hours]	520,000 [hours] ≈ **60 [years]**
tRIBS-OFM parallel model	3 [hours] with 30 CPUs	30,000 [hours] ≈ **3.5 [years]**
PCE-based surrogate model	10^{-7} [hours]	10^{-3} [hours] ≈ **3.6 seconds**

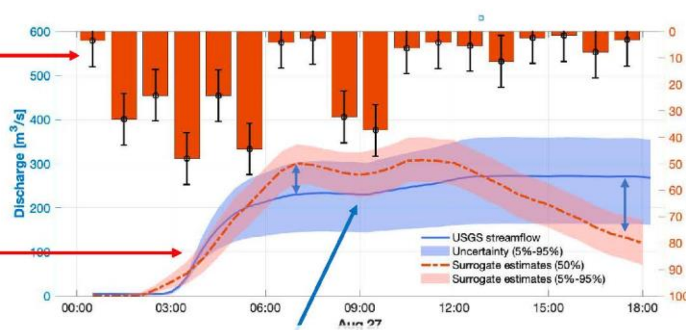
The reduction of computational cost for a QoI surrogate model is by **up to 7 orders of magnitude**

Ivanov et al. (2021), GRL, Breaking Down the Computational Barriers to Real-Time Urban Flood Forecasting

Surrogate Model "Forecast": Outlet Discharge

Precipitation is treated as uncertain: 10,000 series

Outlet discharge is "forecasted" at hour 0 using uncertain rainfall (18-hour lead forecast)

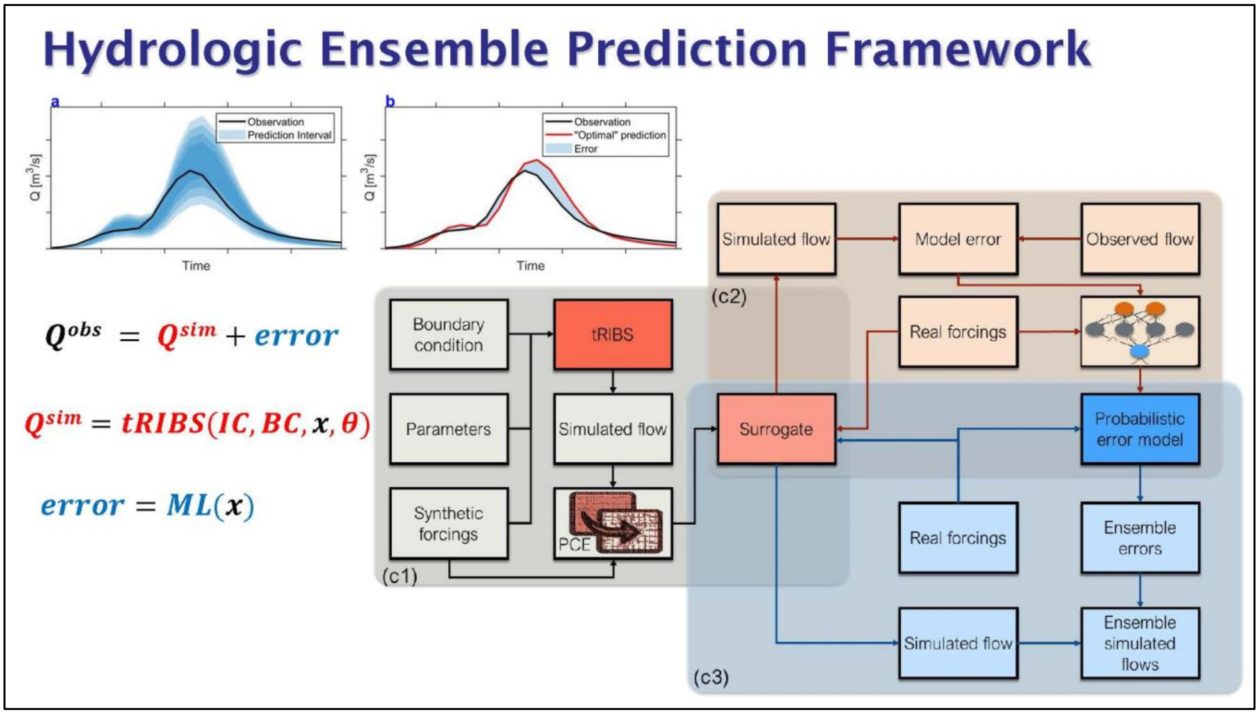


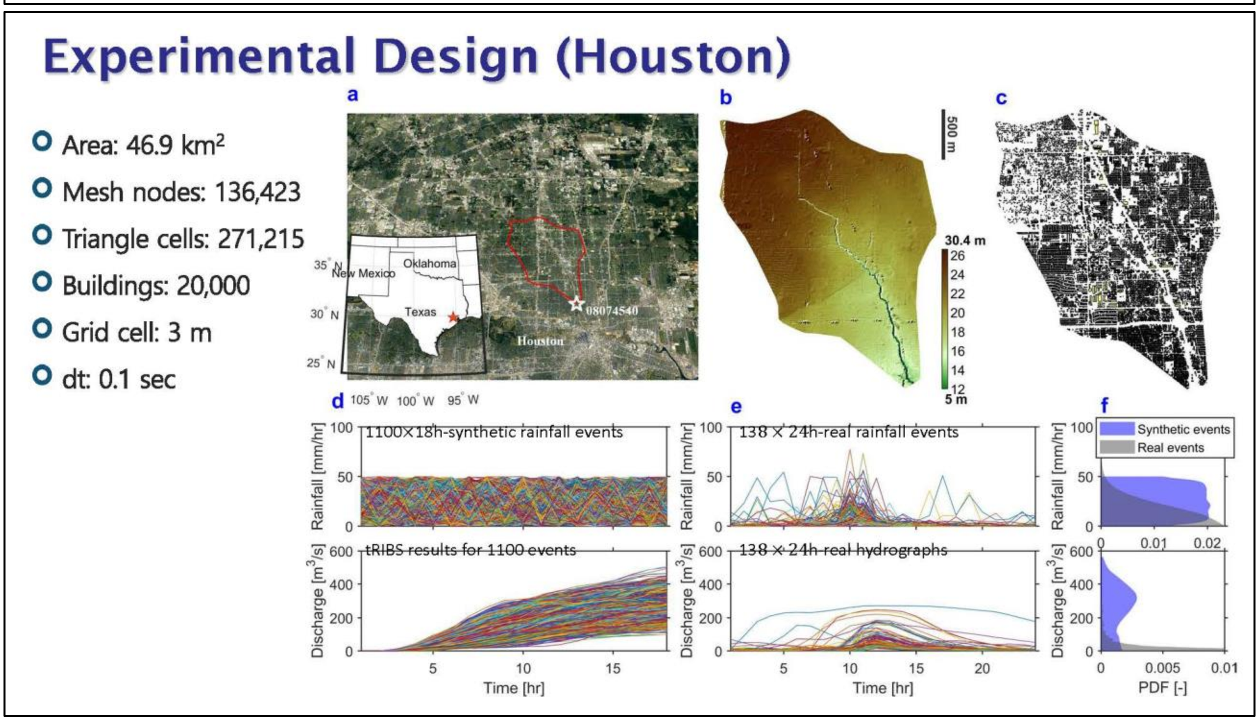
Outlet discharge "observations" with

3. The challenge of variable predictive accuracy

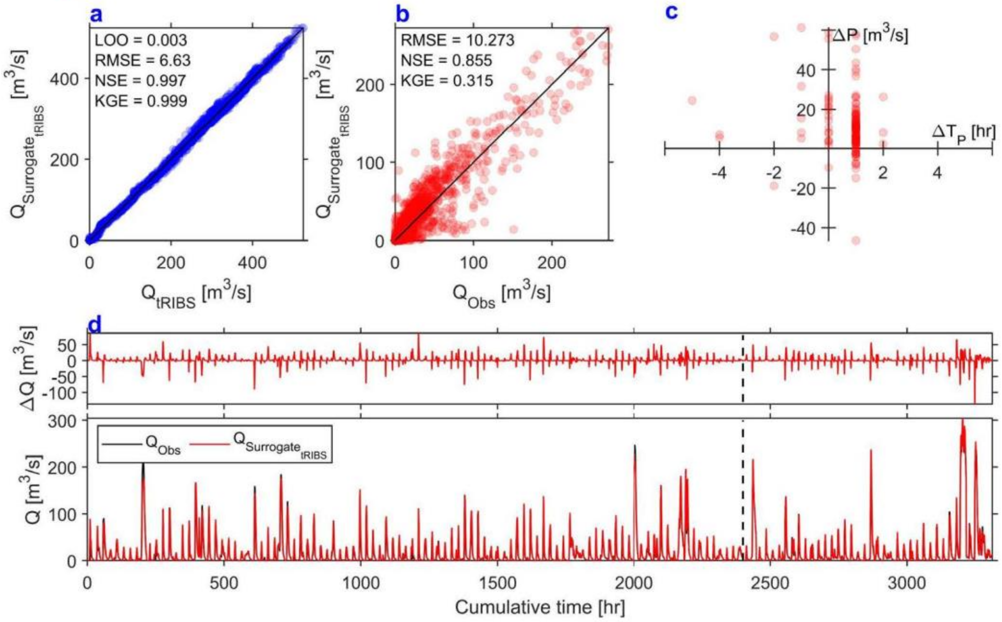
relationship)

Ivanov et al. (2021), GRL, Breaking Down the Computational Barriers to Real-Time Urban Flood Forecasting

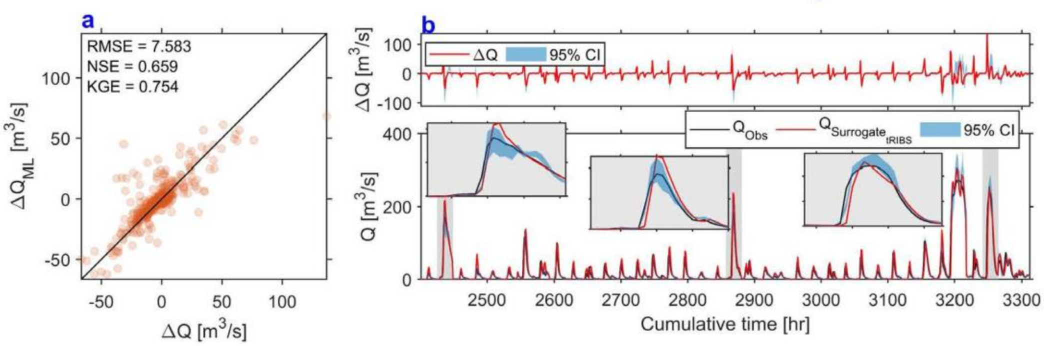

Hydrologic Ensemble Prediction Framework
a
Observation
Prediction Interval
Q [m^3/s]
Time
b
Observation
"Optimal" prediction
Error
Q [m^3/s]
Time
$Q^{obs} = Q^{sim} + error$
$Q^{sim} = tRIBS(IC, BC, x, \theta)$
$error = ML(x)$
Boundary condition
tRIBS
Parameters
Simulated flow
Synthetic forcings
PCE
(c1)
Surrogate
Simulated flow
Model error
Observed flow
(c2)
Real forcings
Probabilistic error model
Real forcings
Ensemble errors
Simulated flow
Ensemble simulated flows
(c3)


Experimental Design (Houston)
Area: 46.9 km²
Mesh nodes: 136,423
Triangle cells: 271,215
Buildings: 20,000
Grid cell: 3 m
dt: 0.1 sec
a
New Mexico
Oklahoma
Texas
08074540
Houston
35° N
30° N
25° N
105° W 100° W 95° W
b
500 m
30.4 m
5 m
c
d
1100×18h-synthetic rainfall events
Rainfall [mm/hr]
tRIBS results for 1100 events
Discharge [m^3/s]
Time [hr]
e
138 × 24h-real rainfall events
138 × 24h-real hydrographs
Time [hr]
f
Synthetic events
Real events
PDF [-]

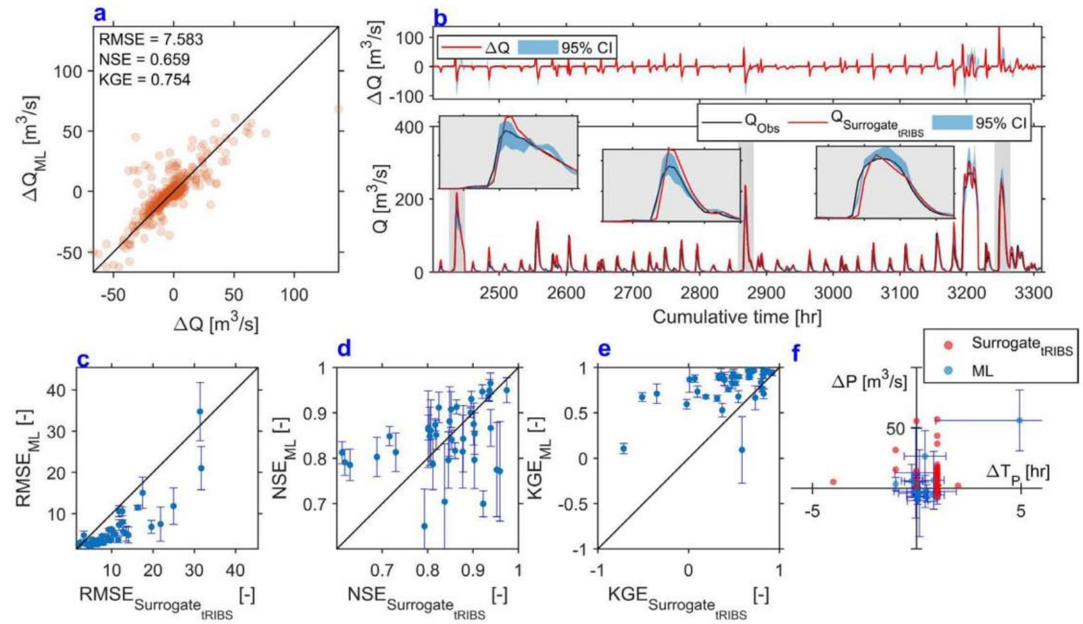
Surrogate Construction and Error Estimation



ML-enabled Ensemble Error for Accurate Q Prediction



ML-enabled Ensemble Error for Accurate Q Prediction

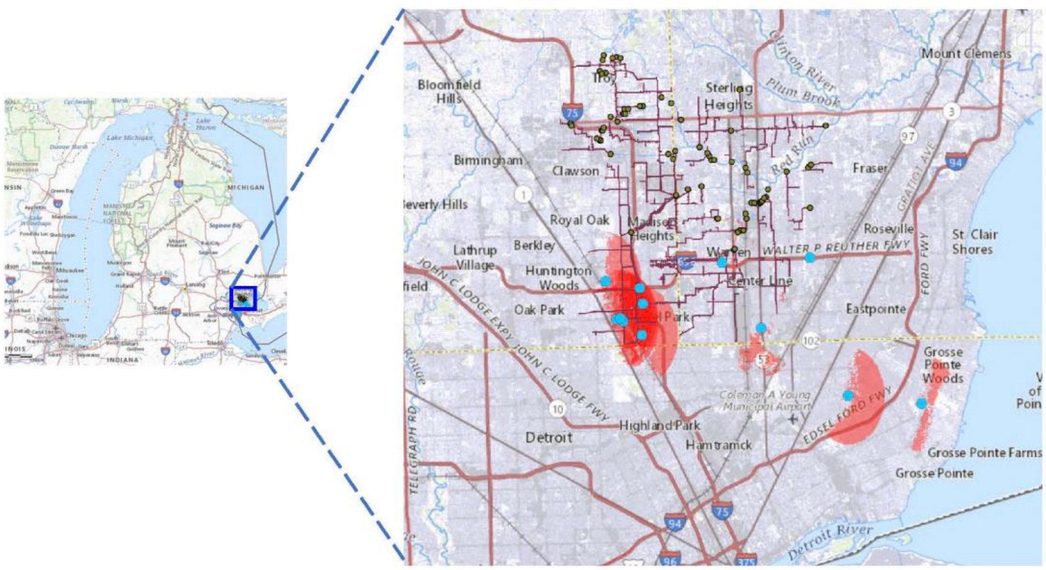


Urban Flooding: A Novel Framework

1. Resolving flooding dynamics at "human" scales (10^0~10^2 m)
   - ✓ **High- fidelity hydrodynamic model**
2. Uncertainty quantification for high-resolution flooding simulation
   - ✓ **Uncertainty quantification framework with surrogates based on Polynomial Chaos Expansions**
3. Probabilistic error estimation to address accuracy of streamflow prediction
   - ✓ **Predict flooding information with surrogate models <u>and</u> ML-enabled prediction of errors**

Challenges: Scarcity of Flooding Spatial Data

Challenges: Scarcity of Flooding Spatial Data



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- NSF EAR grant 1151443 CAREER Award, 2011
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- Blue Waters Computational Fellowship (E. Agee)
- Streeter Fellowship at the UofM (J. Kim, M. C. Dwelle)
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Collaborators:

N. Katopodes (U of Michigan, CEE)
C. Dwelle (U of Michigan, CEE) – *former Ph.D. student*
F. Sedlar (U of Michigan, CEE) – *former M.S.E. student*
Tao Tao (U of Michigan, CEE) – *former B.S.E. student*
… and many more

Additional Slides

Geophysical Research Letters

RESEARCH LETTER
10.1029/2021GL093585

Breaking Down the Computational Barriers to Real-Time Urban Flood Forecasting

Valeriy Y. Ivanov[1], Donghui Xu[1], M. Chase Dwelle[1], Khachik Sargsyan[2], Daniel B. Wright[3], Nikolaos Katopodes[1], Jongho Kim[4], Vinh Ngoc Tran[4], April Warnock[5], Simone Fatichi[6], Paolo Burlando[7], Enrica Caporali[8], Pedro Restrepo[9], Brett F. Sanders[10], Molly M. Chaney[11], Ana M. B. Nunes[12], Fernando Nardi[13], Enrique R. Vivoni[14], Erkan Istanbulluoglu[15], Gautam Bisht[16], and Rafael L. Bras[17]

[1]Department of Civil and Environmental Engineering, University of Michigan, Ann Arbor, MI, USA, [2]Sandia National Laboratories, Livermore, CA, USA, [3]Department of Civil and Environmental Engineering, University of Wisconsin-Madison, Madison, WI, USA, [4]School of Civil and Environmental Engineering, University of Ulsan, Ulsan, South Korea, [5]SRI International, Ann Arbor, MI, USA, [6]Department of Civil and Environmental Engineering, National University of Singapore, Singapore, [7]Institute of Environmental Engineering, ETH Zürich, Zürich, Switzerland, [8]Department of Civil and Environmental Engineering, University of Florence, Firenze, Italy, [9]Consulting Engineer, Minneapolis, MN, USA, [10]Department of Civil and Environmental Engineering and Department of Urban Planning and Public Policy, University of California, Irvine, CA, USA, [11]Department of Civil and Environmental Engineering, Princeton University, Princeton, NJ, USA, [12]Department of Meteorology, Federal University of Rio de Janeiro, Rio de Janeiro, Brazil, [13]Water Resources Research and Documentation Centre, University for Foreigners of Perugia, Perugia, Italy, [14]School of Earth and Space Exploration & School of Sustainable Engineering and the Built Environment, Arizona State University, Tempe, AZ, USA, [15]Department of Civil and Environmental Engineering, University of Washington, Seattle, WA, USA, [16]Atmospheric Sciences and Global Change Division, Pacific Northwest National Laboratory, Richland, WA, USA, [17]School of Civil and Environmental engineering and School of Earth and Atmospheric Sciences, Georgia Institute of Technology, Atlanta, GA, USA

Key Points:

- There is presently no means to forecast urban flooding at high resolution due to prohibitive computational demands and data uncertainties
- Proposed framework combines high-fidelity modeling and probabilistic learning to forecast flood attributes with uncertainty in real-time
- The framework can be extended to other real-time hazard forecasting, requiring high-fidelity simulations of extreme computational demand

Supporting Information:

Supporting Information may be found in the online version of this article.

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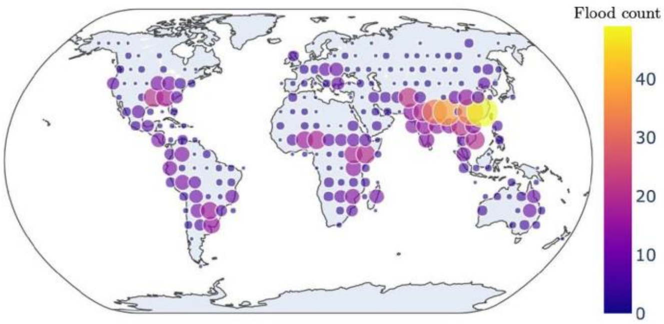
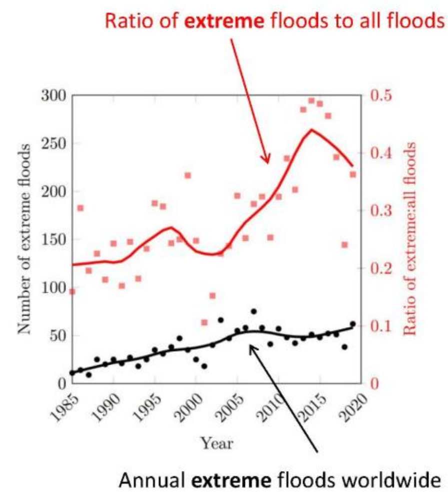
ivanov@umich.edu;
donghui.xu@pnnl.gov

FLOODS

Count of **extreme** floods for 1985-2019 on a 7.5°×7.5° grid

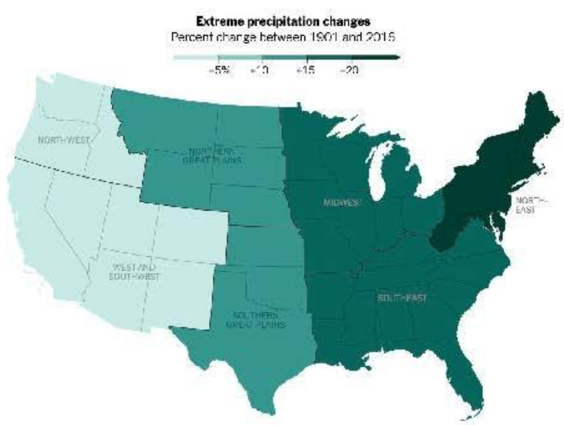




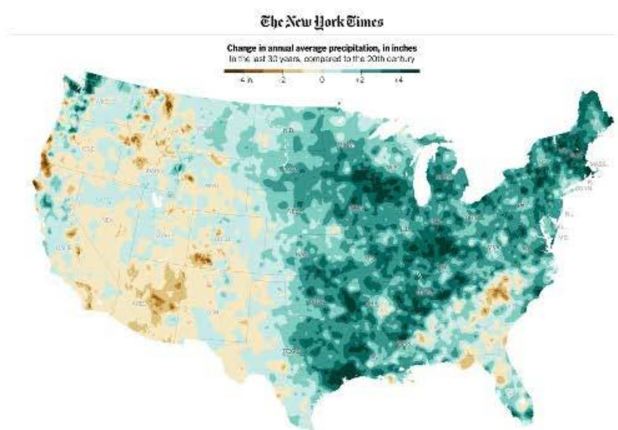
Extreme floods: events exceeding Flood Magnitude (FM) of 6 (FM = log_{10}(*flood duration* × *severity* × *affected area*)[1])

Brakenridge, 2016. "Global active archive of large flood events," Dartmouth Flood Observatory.

Changing Precipitation Patterns



Source: Climate Science Special Report: Fourth National Climate Assessment · Map shows changes in 5-year maximum daily precipitation between 1901 and 2016.



Source: NOAA's National Centers for Environmental Information

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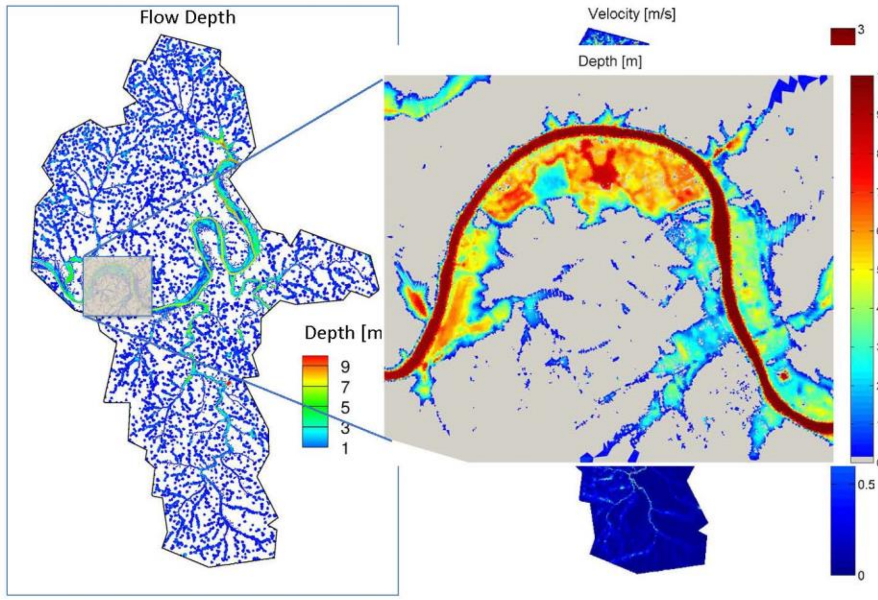
Nashville 2010 Flood Reconstruction

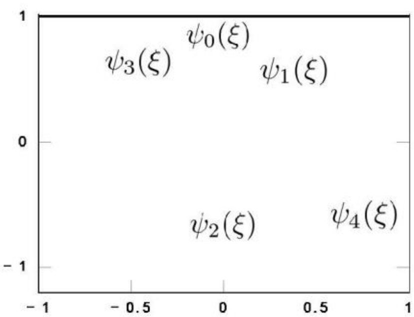


Computing with Surrogates

$$\mathcal{M}^{\mathrm{PC}}(\boldsymbol{\xi}) = \sum_{j=0}^{P} c_j \Psi_j(\boldsymbol{\xi})$$

Legendre polynomials
for *Uniformly* distributed r.v.'s
(up to third order)

$$\psi_0(\xi) = 1$$
$$\psi_1(\xi) = \xi$$
$$\psi_2(\xi) = \frac{1}{2}(3\xi^2 - 1)$$
$$\psi_3(\xi) = \frac{1}{2}(5\xi^3 - 3\xi)$$



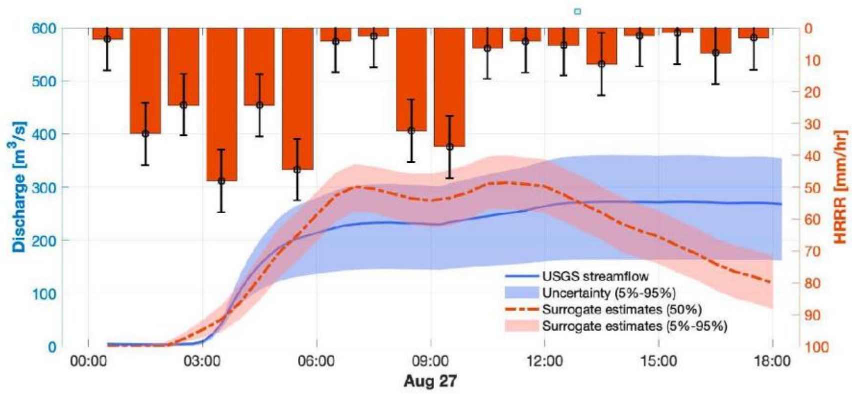
2nd-order PCE
(with three
uncertain variables ξ_1- ξ_3)

$$\mathcal{M}^{\mathrm{PC}}(\xi_1, \xi_2, \xi_3) = c_0 + c_1\psi_1(\xi_1) + c_2\psi_1(\xi_2) + c_3\psi_1(\xi_3) + c_4\psi_2(\xi_1) + c_5\psi_1(\xi_1)\psi_1(\xi_2) + c_6\psi_1(\xi_1)\psi_1(\xi_3) + c_7\psi_2(\xi_2) + c_8\psi_1(\xi_2)\psi_1(\xi_3) + c_9\psi_2(\xi_3)$$

Surrogate Model "Forecast": Outlet Discharge

Precipitation is treated as uncertain (fitted Gaussian process to the HRRR "forecast" rainfall): 10,000 realizations

Outlet discharge is "forecasted" at hour 0 using uncertain rainfall of the 18-h lead forecast



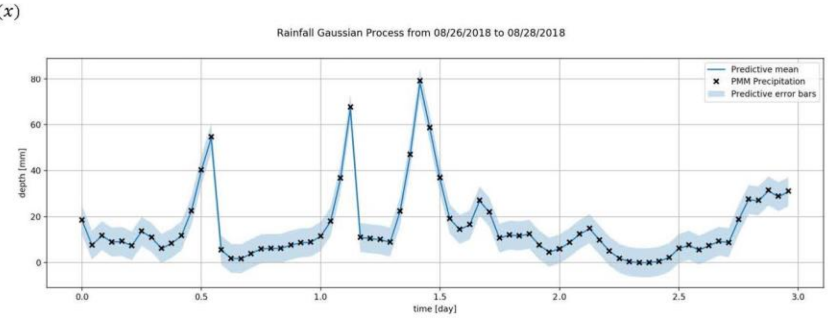
Reduction of Dimensionality of Input Field

Stochastic field inputs

- Gaussian process (GP) is used to make the stochastic field uncertainty
- Karhunen-Loève expansion (KLE)
  - $f(x;X) = m(x) + \sum_{i=1}^{d} X_i \sqrt{\lambda_i}\varphi_i(x)$

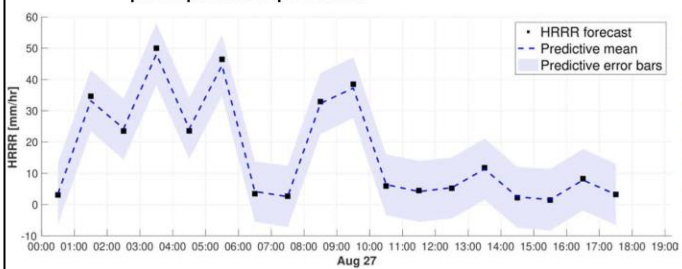
Rainfall time series example

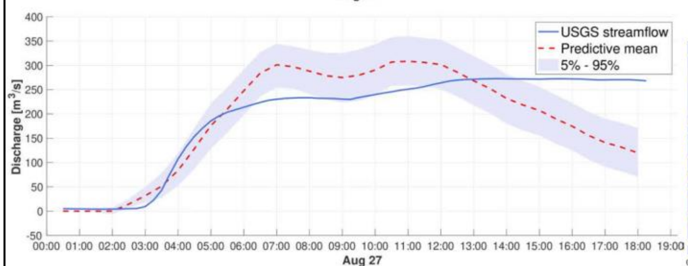
- 3-day hourly rainfall series
- Truncate at d = 25 with KLE
  - 90% variation



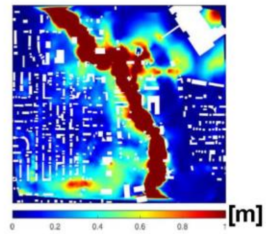
Mimicking Real-time Forecasting with Surrogate Models

- High-Resolution Rapid Refresh (HRRR) precipitation product

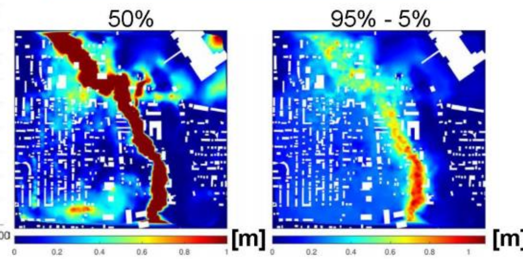




tRIBS-OFM with Radar Precipitation



Inundation with surrogate models



Computational Performance

Model	Simulation time for 24-hour event	Uncertainty Quantification with 10,000 simulations
tRIBS-OFM	52 [hours]	520,000 [hours] ≈ **60 [years]**
tRIBS-OFM parallel model	3 [hours] with 30 CPUs	30,000 [hours] ≈ **3.5 [years]**
PCE-based surrogate model	10^{-7} [hours]	10^{-3} [hours] ≈ **3.6 seconds**

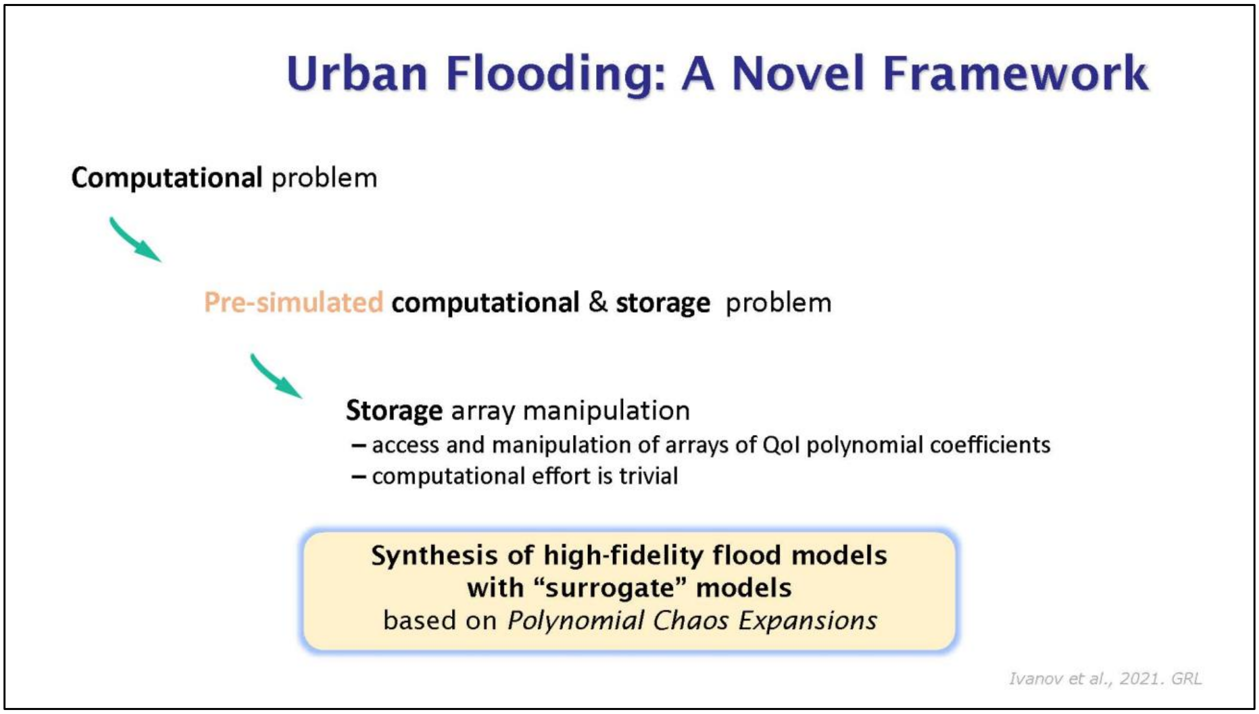
Computational burden in real-time

↓

Computational burden in pre-event period

↓

Data storage and manipulation in real-time



3.8.5.3 Questions and Answers

Question:

In some cases where we do have some observational data, it seems to me that you could apply that in the place that you applied it (in terms of improving the surrogate model), but you could also have applied that at the very beginning to do better calibration of the high-fidelity model. There's probably a balance to be struck between those two. Could you comment on that?

Answer:

Definitely. It's not something I really discussed, but the framework that we develop essentially, it's totally open to this. In other words, when we run high-fidelity simulations to train surrogate models, it's the type of information that we get for this inverse problem. In other words, we can extract effective parameter values and adjust aleatory uncertainty at the same time. Even though we train surrogate model representation, the same simulations can inform what's a more effective roughness coefficient or what is a more representative soil moisture field as an initial condition. So, it's all amenable for that type of assessment. We have not done it in that particular study. This parametric game was beyond the scope of our specificness, but it's definitely a part of the exercise.

By creating a more confident high-fidelity model simulation and still understanding that there is epistemic uncertainty, we may not even consider this if we have this additional machine learning exercise. That's the idea, that once we have the most effective response from the high-fidelity model, we have also the machine learning trained model that addresses the error. You may not really address the parametric uncertainty. We can capture this with the machine learning additional component.

Question:

How transportable is this function to other events at Houston or elsewhere. Or is every surrogate function going to need a large event and a detailed analysis?

Answer:

Essentially the machinery behind this methodology is not location specific. Just like in the case of the high-fidelity model, if you want to run it in a new location, you need to port the model. You need to provide new types of data, change boundary conditions and so on. The methodology presented here is identical in that sense. You would have to move the high-fidelity model to a new place, you would have to re-train surrogate models focusing on the variables of interest to you. But again, the method is not location specific. We have published a paper that addresses this issue.

Question:

Your final comment about the accessing the georeferenced footage reminds that many decades ago, after large flood events, the Army Corps, the USGS, and other agencies would perform what were called “bucket surveys”. They would go in after large flood events and to look at the effects, and the idea was to back-estimate what the possible precipitation was. For the last decade or so now, I’ve looked at events and thought to myself that it would be very useful to develop a high-tech version of the bucket surveys through the information that you referenced. We’ve got cameras everywhere: traffic cameras, security cameras, and then of course people taking videos posting them online. There are some citizen science websites like Watch Water and things like that where people are putting cameras or taking photos in the same location every time after a storm. If we could somehow collect and aggregate that information, I think it would be very useful. Could you comment on that.

Answer:

My former student actually a few years ago was working in Jakarta. Social media is used even more than what is used here, and you can access this data. So, my student, was looking at how you would use technology that is installed on roads, but also on social media posts to essentially derive information where the flood is happening like right now. If these kinds of data can be made publicly available, like the camera footage, I think universities will be very hungry to get these kinds of data. I don’t think they are, unfortunately. We have been looking, for example, at insurance claims, as one interesting and potential data stream. But again, it’s not something that’s easily available at the right level of spatial resolution. You can get it for a block but not necessarily at the level of the building. If these data can become publicly available, I think it will create an alternative and very useful data stream.

Question:

Can you maybe speculate a bit, what would it take to get there? Do you think this is something that university-based research groups could take the lead on? Does this need to be something that the federal or state agencies need to fund or organize? Where do you think is the best level, the best sector to lead this?

Answer:

Right now, the issue is the privacy. It’s both the footage from the streets and it’s also insurance claim’s locations. Right now, all these data, from my understanding, are not available for exactly these reasons. To make something like this publicly available, I don’t know what it has to go through. But I don’t think it’s that easy. Behind a lot of this is just the issue of privacy. If you can somehow de-humanize this information, like for example you have footage of traffic, and you can scrub license plate numbers, that could be one way to go, but who is going to do that?

Somebody from municipalities or maybe at the federal level should step in and make this technology available.

Comment:

Joseph Kanney: I think that's technically feasible. If you look at the Google Street Maps, all the faces are blurred, the license plates are blurred. So, I think there is a technical solution for that.

Shelby Bensi: I was just going to make a comment about the NHERI program. NHERI has these RAPID centers where they can go out and collect data. They use a street-view technology, which is I think the same that Google uses, but it's a different party. I think they can drive these cars around and it automatically scrambles that information. Just what you said, that's feasible. But I think that we have infrastructure in the U.S. set up to do these types of things. The question is, is just, is it rapid enough for the types of situations we're dealing with here, where things go away so fast. But we do have that whole system in place.

Valeriy Ivanov: I don't know about this system, but my comment, even if we start with a post-event analysis, just like what we were doing, it's already a big help. Literally, my graduate student had to scroll through a lot of Facebook posts and whatever they could find. It's extremely difficult to geolocate. But for us, as I said, if we'd run a high-fidelity model, we do need to say something about its performance and right now, it's sort of like stream flow or maybe like a few locations where we saw a car passing and it was half of the tire height, you know the flooding depth. So, I think even if it is possible in the model post-event analysis, I think it will create a path forward. The "real-timeness" of this may come in the next decade, but I think even right now they would be extremely useful if you could do it in post-event calibration or confirmation analysis.

Joseph Kanney: Shelby, I was just going to ask you if you could just give the full name of NHERI so folks online can look it up if they want to.

Shelby Bensi: Natural Hazards Engineering Research Infrastructure. These NFS funded centers, they have a SHAKE table and wind tunnels, but one of them is gaged specifically towards the rapid response and they have made all of these investments in infrastructure, whether that's the car top things, LiDAR systems, for this rapid response. I just don't know if they deploy fast enough to be rapid for some of the urban flooding things because those can go away within a day. I don't think they necessarily deploy that fast, but maybe it's something that NSF would be thinking about in the future.

Joseph Kanney: I think maybe you've identified the right program to take the lead on something like this.

4 SUMMARY AND CONCLUSIONS

4.1 Summary

This report includes the agenda and presentations for the Eighth Annual PFHA Research Workshop, including all presentation abstracts and slides and abstracts for submitted posters. The workshop was virtually attended by members of the public; NRC technical staff, management, and contractors; and staff from other Federal agencies and academia. Public attendees over the course of the workshop included industry groups, industry members, consultants, independent laboratories, and academic institutions.

4.2 Conclusions

As reflected in these proceedings, PFHA is a very active area of research for the NRC and its international counterparts, other Federal agencies, industry, and academia. Readers of this report will have been exposed to current technical issues, research efforts, and accomplishments in this area within the NRC and the wider research community.

The NRC projects discussed in these proceedings represent the main efforts in the first phase (technical basis phase) and second phase (pilot studies) of the NRC’s PFHA Research Program. This technical basis phase is complete, and the NRC has initiated the second phase (pilot project phase) that synthesizes various technical basis results and lessons learned to demonstrate development of realistic flood hazard curves for several key flooding phenomena scenarios (site-scale, riverine, and coastal flooding). The second phase is essentially two-thirds complete. The third phase (development of selected guidance documents) is also in progress. The NRC staff looks forward to further public engagement on the second and third phases of the PFHA research program in future PFHA research workshops.

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