RIL2022-02

PROCEEDINGS OF THE SIXTH ANNUAL PROBABILISTIC FLOOD HAZARD ASSESSMENT RESEARCH WORKSHOP

February 22-25, 2021

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Research Information Letter
Office of Nuclear Regulatory Research

Disclaimer

ABSTRACT

The U.S. Nuclear Regulatory Commission (NRC) Office of Nuclear Regulatory Research (RES) is conducting the multiyear, multi-project Probabilistic Flood Hazard Assessment (PFHA) Research Program to enhance the NRC's risk-informed and performance-based regulatory approach with regard to external flood hazard assessment and safety consequences of external flooding events at nuclear power plants. RES 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. Risk assessment of flooding hazards and consequences of flooding events is a recognized gap in the NRC's risk-informed, performance-based regulatory framework. The RES Probabilistic Flood Hazard Assessment Research Plan describes the objective, research themes, and specific research topics for the program. While the technical basis research, pilot studies, and guidance development are ongoing, 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.

These conference proceedings transmit the agenda, abstracts, presentation slides, and panel discussions for the Sixth Annual NRC Probabilistic Flood Hazard Assessment Research Workshop held virtually in February 2021 via web conference software. The workshop took place February 22–25, 2021 and was attended by members of the public; nuclear industry personnel, NRC technical staff, management, and contractors; and staff from other Federal agencies and academia. The workshop began with an introductory session that included perspectives and research program highlights from RES, the U.S. Geological Survey, and international working groups. NRC contractors and staff, as well as invited Federal, industry, academic, and public speakers, gave technical presentations (including virtual poster sessions) and participated in various styles of panel discussion. The workshop included eight focus areas:

(1) overview of flooding research programs of the NRC, other Federal agencies, and selected international organizations

(2) climate influences on flooding hazards

(3) precipitation processes and modeling

(4) riverine flooding processes and modeling

(5) coastal flooding processes and modeling

(6) PFHA modeling frameworks

(7) flood protection and flooding operating experience

(8) external flooding probabilistic risk assessment

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1 INTRODUCTION

This research information letter (RIL) details the Sixth Annual U.S. Nuclear Regulatory Commission (NRC) Probabilistic Flood Hazard Assessment (PFHA) Research Workshop held virtually from February 22–25, 2021. These proceedings include presentation abstracts and slides. The workshop was attended by members of the public; NRC technical staff, management, and contractors; and staff from other Federal agencies and academia.

The workshop began with an introduction from Ray Furstenau, Director, NRC Office of Nuclear Regulatory Research (RES). Following the introduction, staff members from RES and the U.S. Geological Survey (USGS) described their flooding research programs. Additionally, John Nakoski, RES, 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).

Technical sessions followed the introduction session. Most sessions began with an invited keynote speaker, followed by several technical presentations, and concluded with a panel of all speakers, who discussed the session topic in general. At the end of each day, participants provided feedback and asked generic questions about research related to PFHA for nuclear facilities. At the end of the third day, a virtual poster session was held with each poster presenter being assigned a unique web conferencing room where attendees were free to attend and leave at will.

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 and ML14296A442). 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 (ADAMS Accession No. ML15124A707). 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:

- current and future climate influences on flooding processes
- significant precipitation and flooding events
- statistical and mechanistic modeling approaches for precipitation, riverine flooding, and coastal flooding processes
- PFHA frameworks
- reliability of flood protection and mitigation features and procedures
- external flood protection and operating experience
- external flooding probabilistic risk assessment

1.4 Organization of Conference Proceedings

Section 2 provides the agenda for this workshop. The agenda is also available at ADAMS Accession No. ML21064A456.

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. ML21064A455. The complete workshop presentation package is available at ADAMS Accession No. ML21064A395.

Section 4 lists the workshop attendees, including remote participants, and Section 5 summarizes the workshop.

1.5 Related Workshops

The NRC's Annual PFHA Research Workshops take place approximately annually at NRC Headquarters in Rockville, MD. The proceedings from the Fifth Annual PFHA Research Workshop (held February 19–21, 2020) have been published as RIL-2021-01. NRC has published the collected proceedings from the first four workshops, listed below, as RIL-2020-01, available on the agency's public Web site:

- First Annual NRC PFHA Research Workshop, October 14–15, 2015
- Second Annual NRC PFHA Research Workshop, January 23–25, 2017
- Third Annual NRC PFHA Research Workshop, December 4–5, 2017
- Fourth Annual NRC PFHA Research Workshop, April 30–May 2, 2019

In addition, an international workshop on PFHA 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 2×10^{-3} per year) from the Federal community. The NRC issued the proceedings as NUREG/CP-302, "Proceedings of the Workshop on Probabilistic Flood Hazard Assessment (PFHA)," in October 2013 (ADAMS Accession No. ML13277A074).

2 WORKSHOP AGENDA

U.S.NRC
United States Nuclear Regulatory Commission
Protecting People and the Environment

6th Annual Probabilistic Flood Hazard Assessment Research Workshop

Via MS Teams, February 22-25, 2021 (Start Time: 10:00AM EST)

DAY 1 AGENDA: MONDAY, FEBRUARY 22, 2021

Session 1A: Introduction
Session Chair: *Tom Aird, NRC/RES*

10:00 - 10:10	Welcome, Webinar Logistics ***Kenneth Hamburger****, *NRC/RES*	1A-0
10:10 - 10:25	Opening Remarks ***Ray Furstenau****, *Director, NRC Office of Nuclear Regulatory Research (NRC/RES)*	1A-1
10:25 - 10:45	NRC PFHA Research Program Overview ***Joseph Kanney****, *NRC/RES*	1A-2
10:45 - 11:05	U.S. Geological Survey Flooding-Related Programs and Recent Activities ***Julie Kiang****, *Robert Mason, U.S. Geological Survey*	1A-3
11:05 - 11:25	Committee on the Safety of Nuclear Installations (CSNI) Working Group on External Events (WGEV) ***John Nakoski****, *NRC/RES (WGEV Chair)*	1A-4
11:25 - 11:40	**Break**	

Session 1B: Climate
Session Chair: *Joseph Kanney, NRC/RES*

11:40 - 12:10	KEYNOTE - Seasonally Dependent Changes in Multimodel and Large Ensemble Simulations ***Lai-Yung (Ruby) Leung****, *Pacific Northwest National Laboratory (PNNL)*	1B-1
12:10 - 12:40	Challenges Associated with Multi-Hazard Characterization of Landfalling Hurricanes ***Scott Weaver****, *National Institute of Standards and Technology (NIST); Dereka-Caroll Smith, Joint NIST-UMD-NCAR Research Associate*	1B-2
12:40 - 13:10	Quantifying Shifts in Joint Rainfall-Surge Hazard due to Future Climate Warming ***Avantika Gori****, *Ning Lin, Princeton University*	1B-3
13:10 - 13:30	Climate Panel Discussion *All Speakers*	1B-4
13:30 - 14:30	**Lunch**	

**** denotes speaker***

Session 1C: Precipitation
Session Chair: *Elena Yegorova, NRC/RES*

14:30 - 15:00	KEYNOTE- On the Applicability of Kilometer-Scale Heavy Precipitation in Flood Risk Assessments ***Andreas Prein****, *Jordan Powers, Erin Towler, David Ahijevych, National Center for Atmospheric Research (NCAR)*	1C-1
15:00 - 15:25	Tropical Cyclone Rainfall-driven Flood Risk Assessment ***Ali Sarhadi****, *Kerry Emanuel, Massachusetts Institute of Technology (MIT)*	1C-2
15:25 - 15:55	Does PMP have an AEP? CO-NM REPS findings bridge deterministic and probabilistic approaches ***Bill McCormick****, *Mark Perry, Colorado Division of Water Resources; Kelly Mahoney Rob Cifelli, National Oceanic and Atmospheric Administration (NOAA)*	1C-3
15:55 - 16:20	Local Intense Precipitation (LIP) Flooding PFHA Pilot Study ***Rajiv Prasad****, *Yong Yuan, Pacific Northwest National Laboratory (PNNL)*	1C-4
16:20 - 16:30	**Break**	
16:30 - 16:50	Precipitation Panel Discussion *All Speakers*	1C-5
16:50 - 17:00	**Session 1D: Day 1 Wrap-up Discussion**	

DAY 2 AGENDA: TUESDAY, FEBRUARY 23, 2021

10:00 - 10:05 Day 2 Welcome

Session 2A: Riverine Flooding
Session Chair: *Mark Fuhrmann, NRC/RES*

10:05 - 10:35	KEYNOTE - Estimating Flood Frequency using Stochastic Storm Transposition, Gridded Precipitation Data, and Physics-based Modeling ***Daniel Wright****, *Guo Yu, University of Wisconsin-Madison; Kathleen Holman, U.S. Bureau of Reclamation (USBR)*	2A-1
10:35 - 11:05	Probabilistic Flood Hazard Assessment for a Small Watershed in Eastern Tennessee: Methodology and Lessons Learned ***Periandros Samothrakis****, *Craig Talbot, Kit Ng, and Stewart Taylor, Bechtel Corporation*	2A-2
11:05 - 11:30	Probabilistic Assessment of Multi-mechanism Floods in Inland Watersheds Due to Snowmelt-Driven Extreme Streamflow Events	2A-3

* denotes speaker

Shih-Chieh Kao*, Scott T. DeNeale, Oak Ridge National Laboratory (ORNL); Michelle Bensi, Somayeh Mohammadi, University of Maryland (UMD); Elena Yegorova, Joseph Kanney, U.S. Nuclear Regulatory Commission(NRC); Meredith Carr, U.S. Army Corps of Engineers,* Engineer Research and Development Center, Coastal and Hydraulics Laboratory *(USACE/ERDC/CHL)*

11:30 - 11:45	**Break**	
11:45 - 12:15	Updating design flood estimates at sites with changing variability ***Jory S Hecht****, Nancy A. Barth, Karen R Ryberg and Angela E Gregory, U.S. Geological Survey (USGS)*	2A-4
12:15 - 12:45	Historical and Paleoflood Analyses for Probabilistic Flood Hazard Assessments—Approaches and Review Guidelines ***Karen Ryberg****, Tessa Harden, Jonathan Friedman and Jim O'Connor, U.S. Geological Survey (USGS)*	2A-5
12:45 - 13:05	Riverine Flooding Panel Discussion *All Speakers*	2A-6
13:05 - 14:05	**Lunch**	

Session 2B: Coastal Flooding

Session Chair: *Meredith Carr, USACE/ERDC/CHL*

14:05 - 14:35	KEYNOTE - A Risk Analysis Framework for Tropical Cyclones (RAFT) ***Karthik Balaguru****, Wenwie Xu, David Judi, Lai-Yung (Ruby) Leung, Pacific Northwest National Laboratory (PNNL)*	2B-1
14:35 - 15:05	Storm Surge Modeling Uncertainty ***Victor M. Gonzalez****, Norberto C. Nadal Caraballo, U.S. Army Corps of Engineers, Engineer Research and Development Center, Coastal and Hydraulics Laboratory (USACE/ERDC/CHL)*	2B-2
15:05 - 15:35	Coastal Flooding PFHA Pilot Study ***Karlie Wells****, Victor M. Gonzalez, Norberto C. Nadal Caraballo, U.S. Army Corps of Engineers, Engineer Research and Development Center, Coastal and Hydraulics Laboratory (USACE/ERDC/CHL)*	2B-3
15:35 - 16:05	Probabilistic assessment of multi-mechanism floods in coastal areas due to hurricane-induced storm surge and river flow ***Somayeh Mohammadi****, Michelle Bensi, University of Maryland (UMD); Shih-Chieh Kao, Scott T. DeNeale, Oak Ridge National Laboratory (ORNL); Elena Yegorova, Joseph Kanney, U.S. Nuclear Regulatory Commission (NRC)*	2B-4
16:05 - 16:25	Coastal Flooding Panel Discussion *All Speakers*	2B-5
16:25 - 16:40	**Session 2C: Day 2 Wrap-up Discussion**	

* denotes speaker

Day 3 Agenda: Wednesday, February 24, 2021

10:00 - 10:05	**Day 3 Welcome**	
	Session 3A: Modeling Frameworks **Session Chair: *Tom Nicholson, NRC/RES***	
10:05 - 10:35	KEYNOTE - Stochastic Hydrology in the Tennessee Valley ***Miles Yaw****, *Tennessee Valley Authority (TVA)*	3A-1
10:35 - 11:05	Riverine PFHA Pilot (WAT) ***William Lehman****, *Sara O'Connell, Brennan Beam and David Ho, Leila Ostadrahimi, U.S. Army Corps of Engineers Hydrologic Engineering Center (USACE/HEC)*	3A-2
11:05 - 11:35	Structured Hazard Assessment Committee Process for Flooding (SHAC-F) for Probabilistic Flood Hazard Assessment (PFHA) ***Rajiv Prasad****, *Philip Meyer, Pacific Northwest National Laboratory (PNNL); Kevin Coppersmith, Coppersmith Consulting; Norberto C. Nadal-Caraballo, Victor M. Gonzalez, U.S. Army Corps of Engineers, Engineer Research and Development Center, Coastal and Hydraulics Laboratory (USACE/ERDC/CHL)*	3A-3
11:35 - 11:55	Modeling Frameworks Panel Discussion *All Speakers*	3A-4
11:55 - 12:10	**Break**	
	Session 3B: Flood Protection and Flooding Operating Experience **Session Chair: Tom Aird, NRC/RES**	
12:10 - 12:40	KEYNOTE - Modeling of the May 2020 Michigan Dam Breaches ***Edward Stowasser****, *Wesley Crosby and Christopher Warren, U.S. Army Corps of Engineers (USACE)*	3B-1
12:40 - 13:10	Developing a Framework for Flood Barrier Testing Strategies ***Zhegang Ma****, *Sai Zhang and Curtis L. Smith, Idaho National Laboratory (INL); Chad L. Pope, Idaho State University (ISU)*	3B-2
13:10 - 13:40	Qualitative Risk Ranking Process of External Flood Penetration Seals ***Marko Randelovic****, *Electric Power Research Institute (EPRI)*	3B-3
13:40 - 14:00	Flood Protection and Flood Operating Experience Panel Discussion *All Speakers*	3B-4
14:00 - 14:10	**Session 3C: Day 3 Wrap-up Discussion**	
14:10 - 15:10	**Lunch**	

* denotes speaker

Session 3D: Posters

15:10 - 16:30 Investigating Current and Future Precipitation Frequency Estimates for the State of Maryland: Challenges of Applying Machine Learning for Temporal Downscaling of Climate Model Projections 3D-1

Azin Al Kajbaf*, *Michelle T. Bensi, Kaye L. Brubaker, University of Maryland (UMD)*

15:10 - 16:30 Riverine Flooding HEC-WAT Pilot Project Dam Break Modeling 3D-2

Brennan Beam*, *William Lehman, Sara O'Connell, David Ho, U.S. Army Corps of Engineers Hydrologic Engineering Center (USACE/HEC)*

15:10 - 16:30 Nationwide (USA) Pluvial Flood Modeling via Telemac2D 3D-3

Max Kipp*, *Leo Kreymborg, Mike DePue, Atkins North America*

15:10 - 16:30 Combining the best of both worlds, using detailed flood analyses to inform rainfall accumulation characteristics for the World-Record July 1942 "Smethport" Storm – Supporting PMP and flood frequency analyses 3D-4

Bill Kappel*, *Applied Weather Associates (AWA); Joe Bellini, Aterra Solutions, LLC*

15:10 - 16:30 A Tale of Two Cores: harmonized paleoflood hydrologic data works best for estimating flood frequency and magnitude 3D-5

Ray Lombardi*, *Lisa Davis, University of Alabama (UA)*

Day 4 Agenda: Thursday, February 25, 2021

10:00 - 10:05 **Day 4 Welcome**

Session 4A: External Flooding PRA

Session Chair: *Joseph Kanney, NRC/RES*

10:05 - 10:35 Insights, limits and projections for EDF's external flooding PRAs 4A-1

Jeremy Gaudron*, *Cecile Luzoir, Electricité de France (EDF)*

10:35 - 11:05 Methodology developed for the Belgian External Flooding PSA 4A-2

Bogdan Golovchuk*, *Filip Van Opstal, Tractebel ENGIE*

11:05 - 11:35 External Flooding PRA Guidance 4A-3

Marko Randelovic*, *Electric Power Research Institute (EPRI); Raymond E. Schneider, Westinghouse Electric Company*

11:35 - 11:50 **Break**

* denotes speaker

11:50 - 13:20 **Session 4B: Special Panel Discussion - Drivers of Uncertainty in External Flood Probabilistic Risk Assessment**

Session Chair: *Michelle (Shelby) Bensi, University of Maryland*

Panelists:

***Fernando Ferrante**, Electric Power Research Institute (EPRI)*
***Norberto Nadal-Carraballo**, U.S. Army Corps of Engineers (USACE)*
***Kit Ng**, Bechtel Corporation*
***Jeremy Gaudron**, Électricité de France (EDF)*
***Bogdan Golovchuk**, Tractebel ENGIE*
***Ray Schneider**, Westinghouse Electric Company;*
***Curtis Smith**, Idaho National Laboratory (INL)*
***Jeff Mitman**, U.S. Nuclear Regulatory Commission (NRC)*

13:20 - 13:30 **Break**

13:30 - 13:50 **Session 4C: Workshop Wrap-up Discussion**

* denotes speaker

3 PROCEEDINGS

3.1 Day 1: Session 1A – Introduction

Session Chair: Thomas Aird, NRC/RES/DRA

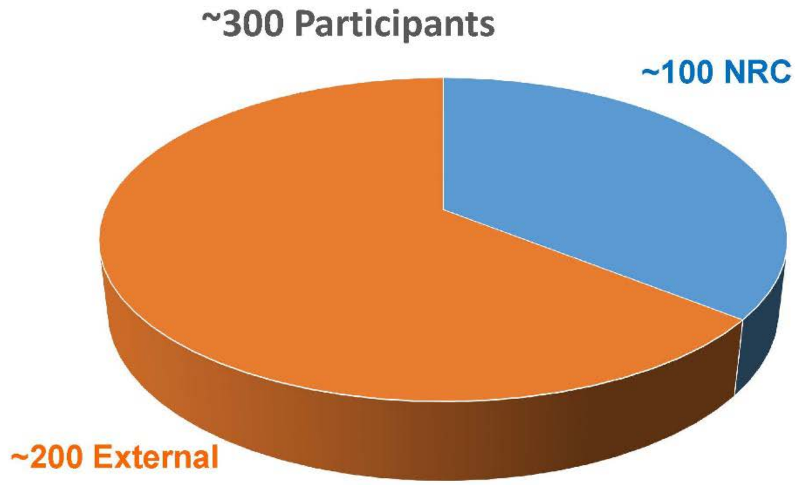
There are no abstracts for this introductory session.

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. ML21064A417)

Workshop Participation Snapshot



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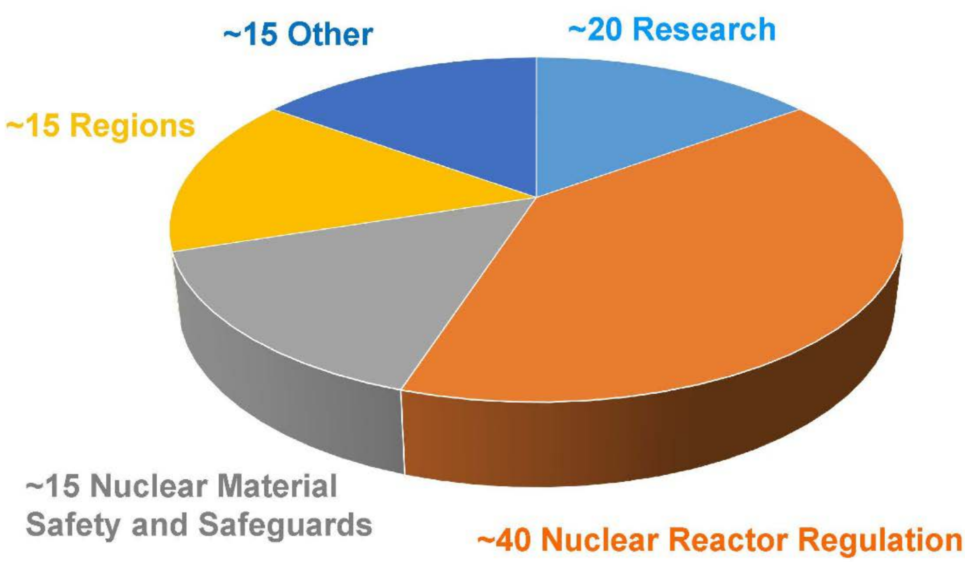
NRC Participation Drill Down



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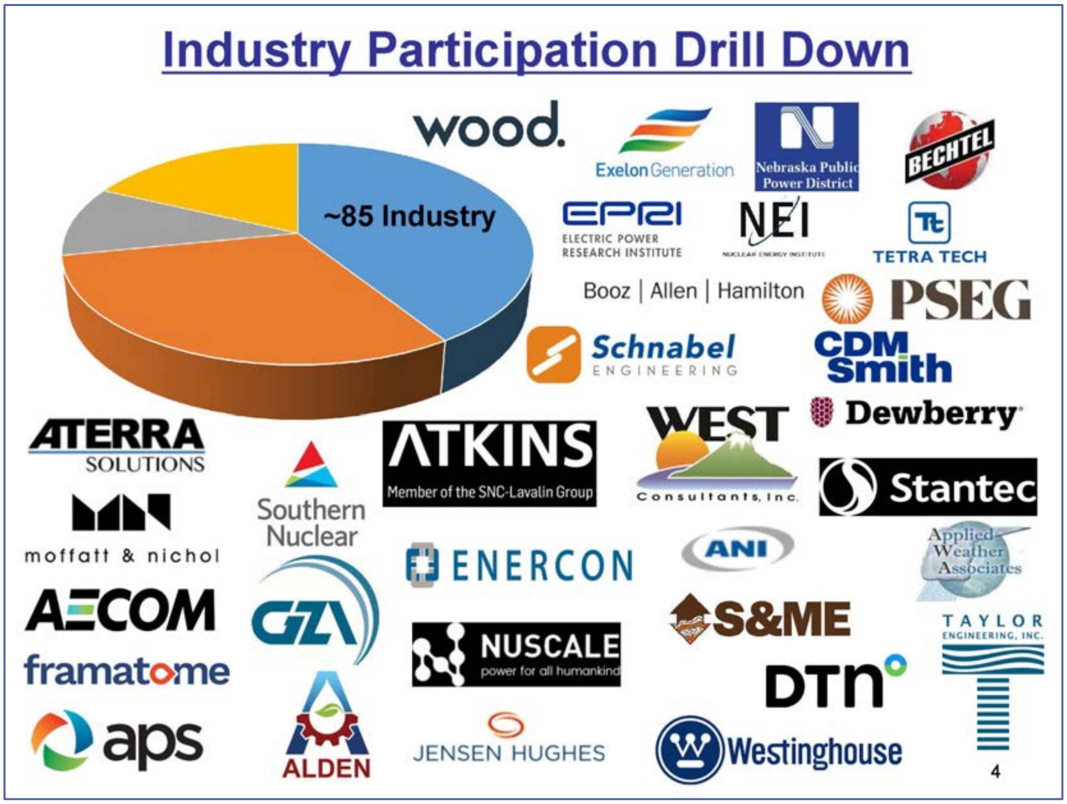
Industry Participation Drill Down
~85 Industry
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Exelon Generation
Nebraska Public Power District
BECHTEL
EPRI
ELECTRIC POWER RESEARCH INSTITUTE
NEI
TETRA TECH
Booz | Allen | Hamilton
PSEG
Schnabel ENGINEERING
CDM Smith
Dewberry
ATERRA SOLUTIONS
Southern Nuclear
ATKINS
Member of the SNC-Lavalin Group
WEST Consultants, Inc.
Stantec
moffatt & nichol
ENERCON
ANI
Applied Weather Associates
AECOM
GZA
S&ME
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Westinghouse
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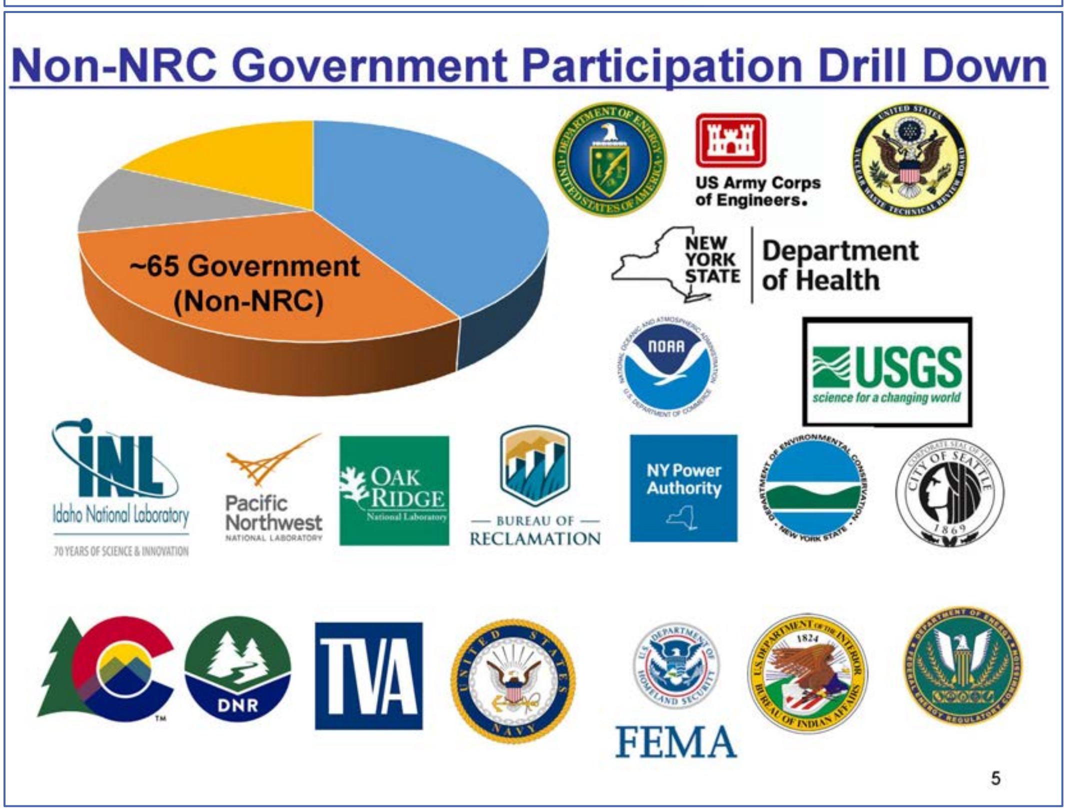
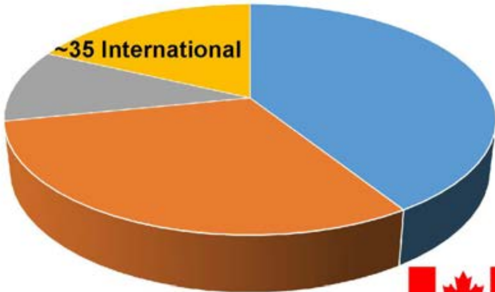

Non-NRC Government Participation Drill Down
~65 Government (Non-NRC)
US Army Corps of Engineers.
NEW YORK STATE Department of Health
NOAA
USGS
science for a changing world
INL
Idaho National Laboratory
70 YEARS OF SCIENCE & INNOVATION
Pacific Northwest
NATIONAL LABORATORY
OAK RIDGE
National Laboratory
BUREAU OF RECLAMATION
NY Power Authority
TVA
DNR
FEMA
5

International Participation Drill Down



Environment Canada

Government of India AERB Atomic Energy Regulatory Board

GRS

CNSC CCSN

EDF

TEPCO

IRSN INSTITUT DE RADIOPROTECTION ET DE SÛRETÉ NUCLÉAIRE

JAEA

Finolex Cables Limited

CRIEPI Central Research Institute of Electric Power Industry

KINS 한국원자력안전기술원 KOREA INSTITUTE OF NUCLEAR SAFETY

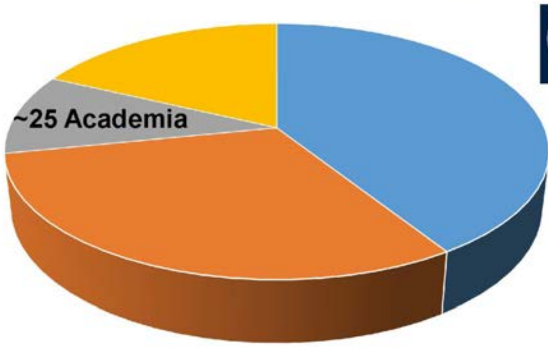
Authority for Nuclear Safety and Radiation Protection

KAERI Korea Atomic Energy Research Institute

TRACTEBEL ENGIE

6

Academic Participation Drill Down



UNIVERSITY OF OXFORD

WISCONSIN UNIVERSITY OF WISCONSIN-MADISON

LAMAR UNIVERSITY

GEORGE MASON UNIVERSITY

MURRAY STATE UNIVERSITY

UNIVERSITY OF MARYLAND 1856

NC STATE UNIVERSITY

UNIVERSITY OF WATERLOO

VIRGINIA COMMONWEALTH UNIVERSITY MCV RPI 1838

UK Kentucky Geological Survey

MIT Massachusetts Institute of Technology

THE UNIVERSITY OF ALABAMA

7

PFHA Research Objective

- NRC's Risk-Informed Regulatory Policy has been translated into practice in some external hazard areas (e.g., seismic, high winds)
- Flood hazard assessment is a significant gap
  - Deterministic approaches do not quantify uncertainties
- PFHA research is aimed at filling this gap
  - Quantify uncertainties
  - Support risk-informed decisionmaking

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Addressing Current and Future Needs

- Recent experience has highlighted importance of risk-informing flood hazard assessments
  - Flooding events at or near NPPs in U.S. and abroad
  - Post-Fukushima flood hazard reevaluations and integrated assessments
- Ongoing and new risk-informed initiatives
  - FLEX, Risk-informed categorization and treatment of SSCs, Risk-informing inspections and other licensing and oversight activities
- Recent and upcoming revisions to industry consensus standards point to increased role for probabilistic hazard assessment
- Readiness for licensing new and advanced reactor designs

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NRC Phased Approach

- Phase 1: Technical basis
  - Technical basis research essentially complete
    - Climate
    - Precipitation
    - Riverine flooding
    - Storm surge
    - Reliability of flood protection and mitigation
    - Compound flooding
    - Modeling frameworks
- Phase 2: Pilot Studies
    - 3 Pilot studies initiated in FY20
- Regulatory Guidance

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Current PFHA Research Focus

- In FY21 NRC/RES continues to focus on PFHA Pilot Studies to:
  - Fine-tune scenario-specific issues
  - Demonstrate development of hazard curves for multiple flooding mechanism and spectrum of impacts
  - Inform development of guidance
- 3 PFHA Pilots
  - Site-scale Flooding (Local Intense Precipitation)
  - Riverine Flooding
  - Coastal Flooding
- Discussion with User Offices on scope and format of guidance
  - PFHA workshops provide valued input from a broad cross-section of partners and stakeholders

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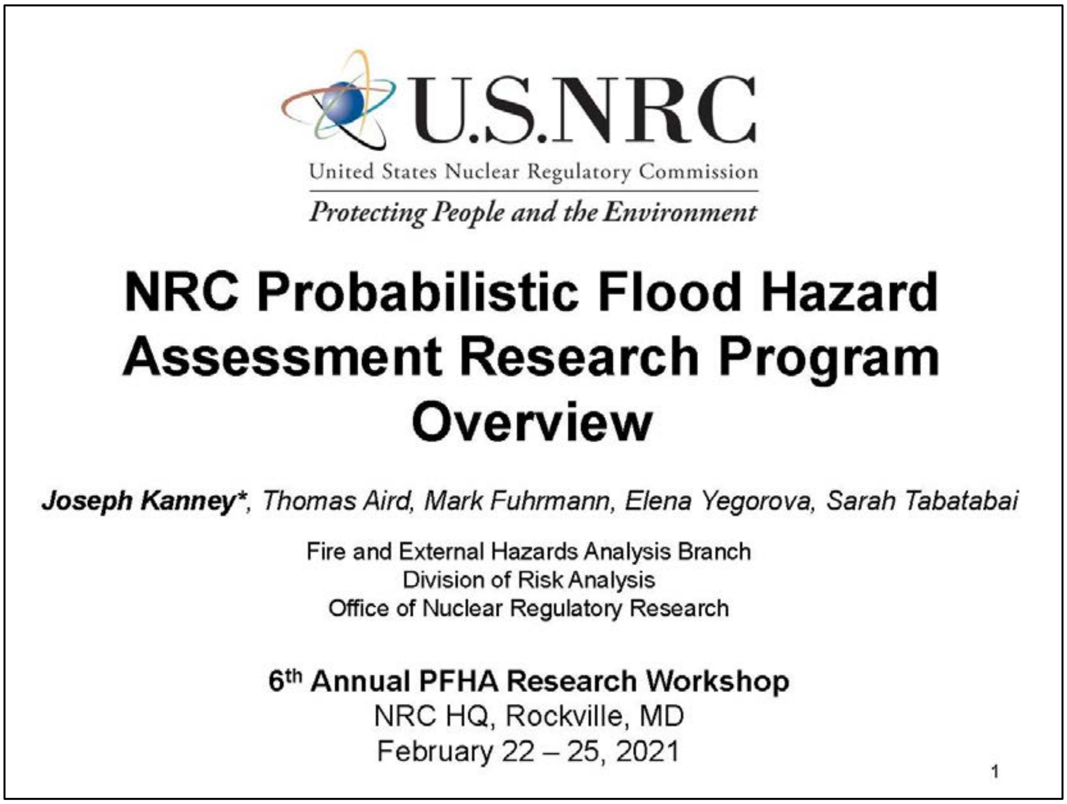
3.1.2 Presentation 1A-2: NRC Probabilistic Flood Hazard Assessment Research Program Overview

Authors: Joseph Kanney, Thomas Aird, Mark Fuhrmann, Elena Yegorova, and Sarah Tabatabai, NRC Office of Nuclear Regulatory Research

Speaker: Joseph Kanney

3.1.2.1 Presentation (ADAMS Accession No. ML21064A418)



Outline

- Objectives
- Key Challenges
- Research Approach
- Progess
- Next Steps

2

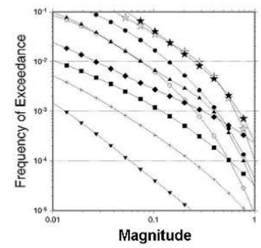
PFHA Research Objectives

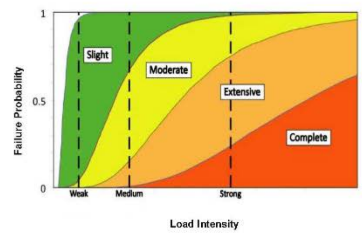
- Develop resources, tools and selected guidance to:
  - Address significant gap in the technical basis for guidance for probabilistic assessment of external hazards
    - Probabilistic: seismic, high winds
    - Deterministic: flooding
  - Support risk-informed licensing and oversight activities involving 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

Key Challenges

- Hazard Curve Development
  - 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 Curve Development
  - Information on reliability of flood protection features and procedures is sparse
  - Cliff-edge effects





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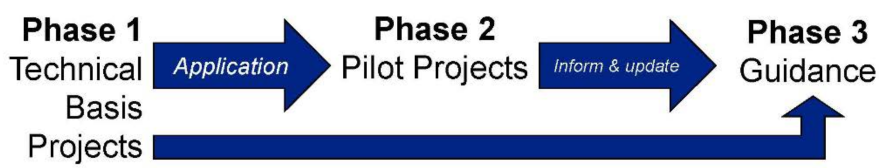
Phased Research Approach



- Phase 1 – Technical Basis Research: ***~Complete!***
  - Climate and precipitation
  - Mechanistic, statistical and probabilistic modeling of riverine and coastal 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
  - Riverine Flooding
  - Coastal Flooding
- Phase 3 – Develop Guidance: ***In Progress***

5

Climate and Precipitation

- **Potential Climate Change Impacts to NPPs (PNNL)**
  - ***CONUS: PNNL-24868*** *available at https://www.osti.gov/biblio/1259942*
  - ***Southeast US: PNNL-26226 Rev 1*** *available at https://www.osti.gov/biblio/1593340*
  - ***Midwest US: PNNL-27452 Rev1*** *available at https://www.osti.gov/biblio/1524249*
  - ***Northeast US: PNNL-29079*** *available at https://www.osti.gov/biblio/1605280*
- **Warm Season Precipitation Analysis (USACE/ERDC)**
  - ***Report ERDC/CHL TR-19-14*** *available at https://erdc-library.erdc.dren.mil/jspui/handle/11681/33883*
- **Cool Season Precipitation Analysis (USACE/ERDC)**
  - ***Report ERDC/CHL TR-20-7*** *available at http://dx.doi.org/10.21079/11681/36415*
- **Precipitation Frequency Estimates in Orographic Regions (USBR)**
  - ***NUREG-CR report in publication***
- **Application of Point Precipitation Frequency Estimates to Watersheds (ORNL)**
  - ***NUREG/CR-7271*** *available at https://www.nrc.gov/reading-rm/doc-collections/nuregs/contract/cr7171/index.html*
- **Numerical Modeling of Intense Precipitation Processes (UC Davis/USGS)**
  - ***Peer-reviewed publications: Mure-Ravaud, et al. (2019a,b)*** *https://www.sciencedirect.com/science/article/pii/S0048969719306734*
  - *https://www.sciencedirect.com/science/article/pii/S0048969719306291*
  - ***NUREG-CR report in publication***
- **Convection-Permitting Modeling for Intense Precipitation Processes (NCAR)**
  - *In Progress (completion expected in FY21)*

6

Riverine and Coastal Flooding

- **Application of State-of-Practice Flood Frequency Analysis Methods and Tools (USGS)**
  - ***USGS Scientific Investigation Report (SIR) 2017-5038*** *available at https://pubs.er.usgs.gov/publication/sir20175038*
  - ***USGS SIR 2020-5065 available at*** *https://pubs.er.usgs.gov/publication/sir20205065*
- **Technical Basis for Extending Frequency Analysis Beyond Current Consensus Limits (USBR)**
  - ***NUREG/CR in review***
- **Eastern US Riverine Flood Geomorphology Feasibility Study (USGS)**
  - ***USGS SIR 2017-5052*** *available at https://pubs.er.usgs.gov/publication/sir20175052*
- **Eastern US Riverine Flood Geomorphology Comprehensive Study (USGS)**
  - ***USGS SIR in publication***
- **Framework for Technical Review of Paleoflood Information (USGS)**
  - ***USGS Techniques and Methods Report in publication***
- **Quantifying Uncertainties in Probabilistic Storm Surge Models (USACE)**
  - ***Report ERDC/CHL SR-19-1*** *available at https://erdc-library.erdc.dren.mil/xmlui/handle/11681/32293*
  - ***Report ERDC/CHL TR-19-4*** *available at https://apps.dtic.mil/docs/citations/AD1073835*
  - ***ERDC/CHL report in review***
  - ***NUEG/CR report in preparation***

7

Reliability of Flood Protection

- Effects of Environmental Factors on Manual Actions for Flood Protection and Mitigation at Nuclear Power Plants (PNNL)
  - ***NUREG/CR-7256*** *available at https://www.nrc.gov/reading-rm/doc-collections/nuregs/contract/cr7256/*
- Critical Review of the State of Practice in Probabilistic Risk Assessment for Dams (ORNL, UMD)
  - ***Report ORNL/TM-2019/1069*** *available at https://www.osti.gov/biblio/1592163/*
- Performance of Flood Penetration Seals at NPPs (Fire Risk Management, Inc.)
  - ***NUREG report in review***
- Erosion Processes in Embankment Dams (USBR)
  - ***NRC Research Information Letter (RIL) in publication***
- Flood Barrier Testing Strategies (INL/ISU)
  - *In progress, completion in March, 2021*

8

Modeling Frameworks & NHID

- Modeling Plant Response to Flooding Events (INL)
  - ***NUREG/CR report in publishing***
- Probabilistic Flood Hazard Assessment Framework Development (USACE)
  - ***RIL in preparation***
- Structured Hazard Assessment Committee Process for Flooding (SHAC-F) (PNNL & USACE)
  - ***NUREG/CR in review***
- Methods for Estimating Joint Probabilities of Coincident and Correlated Flooding Mechanisms for Nuclear Power Plant Flood Hazard Assessments (ORNL & UMD)
  - *In progress (completion expected FY21)*
  - ***Task 1 &2 ORNL Report TM-2020/1447*** *available at https://www.osti.gov/biblio/1637939/*
- Development of Natural Hazard Information Digests for Operating NPP Sites (INL)
  - ***Completed*** *(continue with updates/maintenance)*

9

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)**
  - *In Progress; completion expected in FY21*
- **Riverine Flooding PFHA Pilot (USACE/HEC)**
  - *In Progress; completion expected in FY22*
- **Coastal Flooding Pilot PFHA Pilot (USACE/ERDC)**
  - *In Progress; completion expected in FY22*

10

Phase 3: PFHA Guidance

- **FY 21-22: Develop draft guidance documents based on:**
  - Technical basis research
  - Pilot projects
  - User office needs
  - Stakeholder & public Interactions

- **FY22: Publish draft guidance for public comment**
- **FY23: Finalize guidance**

11

Past Workshops

- **Proceedings of 1st-4th Annual NRC PFHA Research Workshops**
  - ***NRC RIL 2020-01 available at*** *https://www.nrc.gov/reading-rm/doc-collections/research-info-letters/2020/index.html*
- **Proceedings of 5th Annual NRC PFHA Research Workshop**
  - ***RIL 2021-01 available at*** *https://www.nrc.gov/reading-rm/doc-collections/research-info-letters/2021/index.html*

12

Questions?

Contact: joseph.kanney@nrc.gov

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3.1.2.2 Questions and Answers

Question:
Are Intensity Duration Frequencies a valid probabilistic way to try to estimate future hazard assessment on the precipitation aspect of the flooding calculations?

Joe Kanney:
Yes. We have looked at that in several pieces of the research that I mentioned. Specifically, the work we did with the Army Corps on the warm season and cool season precipitation. That was essentially looking at developing intensity, duration, frequency curves. But that is not the only way to do it. There is the mechanistic modeling approach and we have also investigated that.

Question:
Are the reports mentioned available for the public?

Elena Yegorova:
Yes, these are public reports

Question:
Do the flood evaluation methods for riverine flooding cover the phenomena causing the flooding at the site of The Fort Calhoun Nuclear Generating Station?

Joe Kanney:
Yes, it is part of the work that we're doing with Oak Ridge and University of Maryland on joint probability. One of the cases that were looking at there is an inland flooding situation where snowmelt is a contributing mechanism. And that was sort of the distinguishing feature of the Fort Calhoun flooding back in 2011.

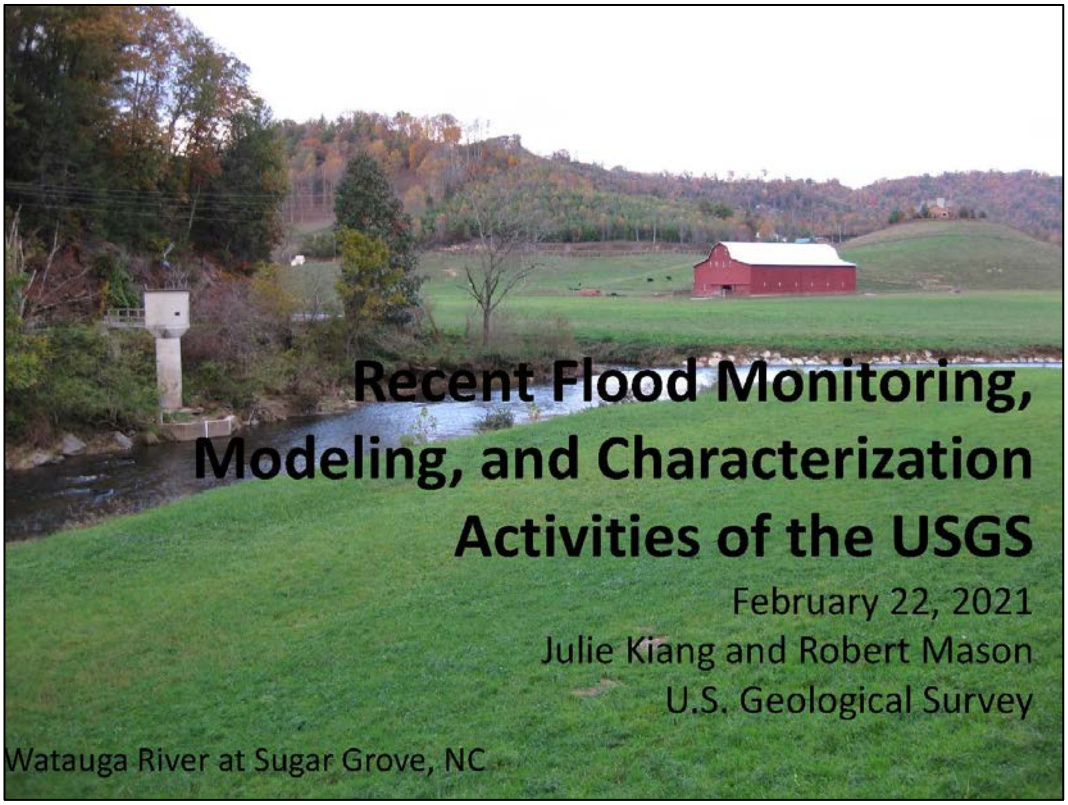
Question:
Can we know where these pilot studies are?

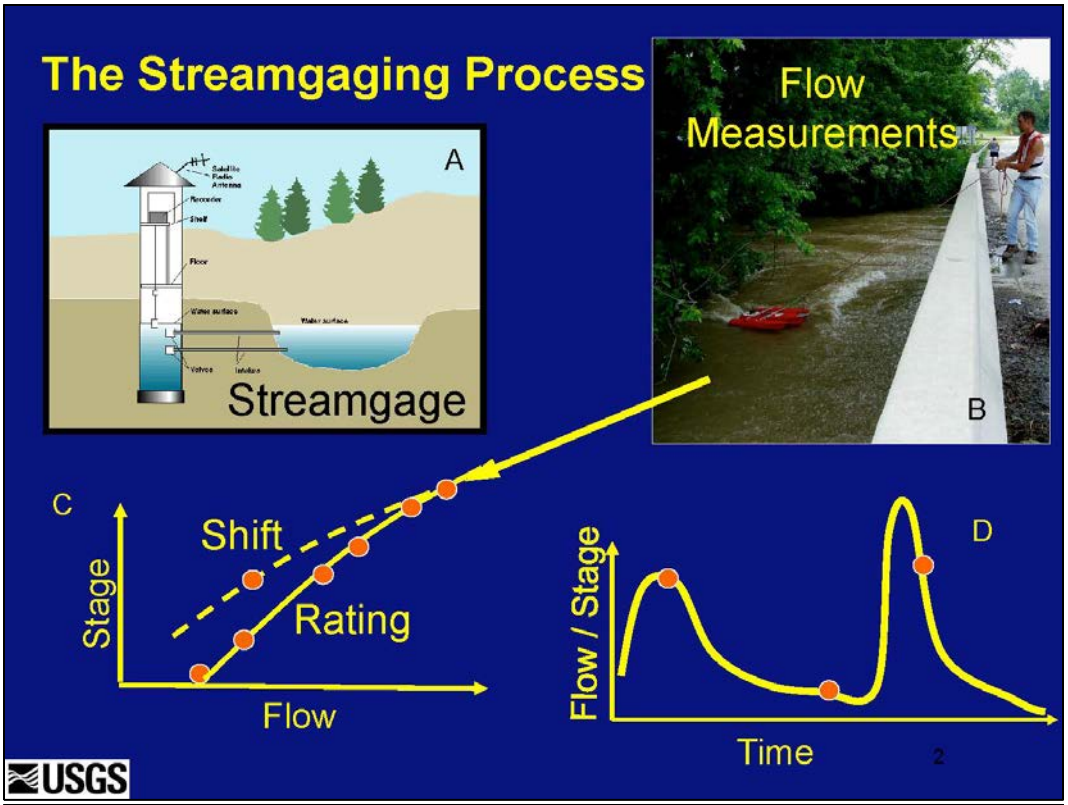
Joe Kanney:
Yes. The local intense precipitation pilot study is based on a on a real plant, but we are making some modifications to add interesting features. So that one is not specific for a particular location. For the riverine flooding pilot, we have selected the Trinity River basin in Texas. That was based upon the availability of information. Some work that was done in previous Army Corps studies provides useful background info to leverage. We wanted to leverage as much existing information data and previous studies as we could. We are also looking at an area along the coast in in Texas, sort of near the Beaumont area.

3.1.3 Presentation 1A-3: U.S. Geological Survey Flooding-Related Programs and Recent Activities

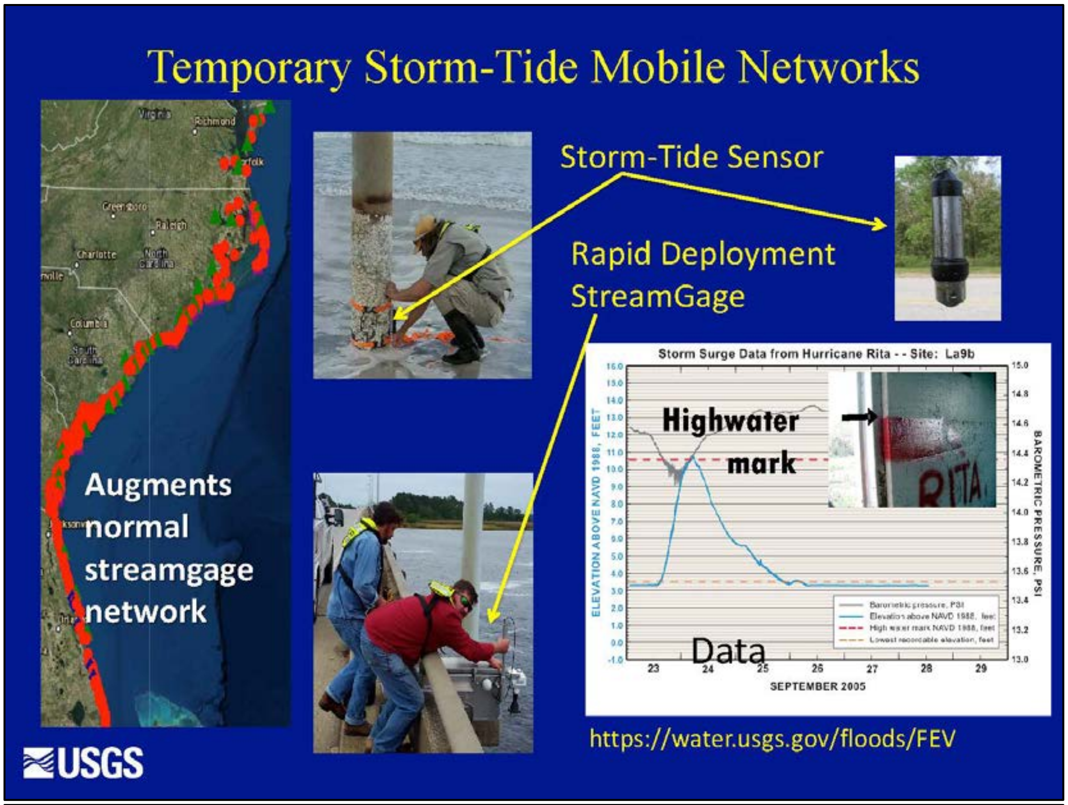
Speakers: Julie Kiang and Robert Mason, U.S. Geological Survey

3.1.3.1 Presentation (ADAMS Accession No. ML21064A419)

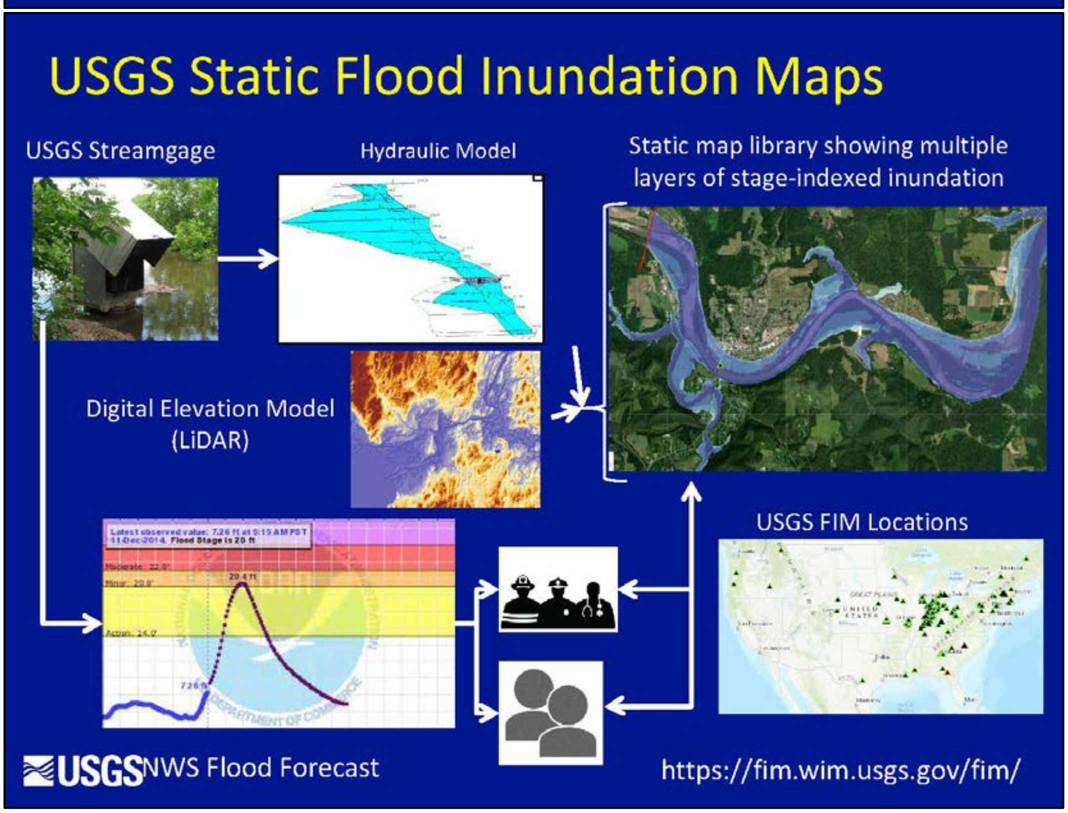



The Streamgaging Process
A
Streamgage
Flow
Measurements
B
C
Shift
Rating
Stage
Flow
D
Flow / Stage
Time
USGS


New Technologies for Flood Measurements
USGS



Temporary Storm-Tide Mobile Networks
Storm-Tide Sensor
Rapid Deployment StreamGage
Augments normal streamgage network
Storm Surge Data from Hurricane Rita - - Site: La9b
Highwater mark
Data
ELEVATION ABOVE NAVD 1988, FEET
BAROMETRIC PRESSURE, PSI
SEPTEMBER 2005
https://water.usgs.gov/floods/FEV
USGS



USGS Static Flood Inundation Maps
USGS Streamgage
Hydraulic Model
Static map library showing multiple layers of stage-indexed inundation
Digital Elevation Model (LiDAR)
USGS FIM Locations
USGS
NWS Flood Forecast
https://fim.wim.usgs.gov/fim/

IWRSS iFIM Development

- Quilting of NWS NWM, USACE dynamic HecRas Maps, and USGS static FIMs
- Coordinated development based on storm forecasts
- Currently FUO to FEMA with aspirations for public dissemination through NWS NWC
- Plan envisions post-event documentation and evaluation (remotely sensed images, HWMs, etc.

USGS

Quick Response Flood Inundation Mapping
Multiple Remote Sensing Data Sources + Automated Processing

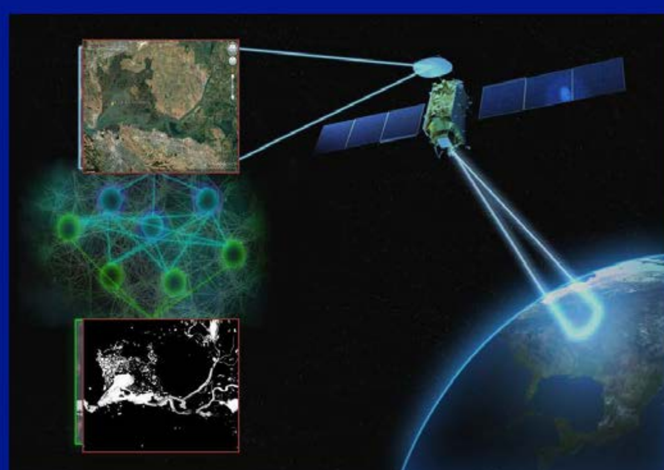
Satellite Images + Ground Observations

↓

AI/ML Processing
Hydraulic Analysis

↓

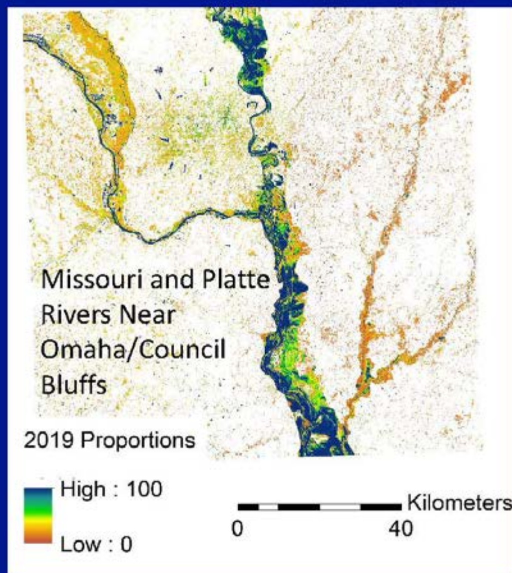
Detailed Flood Inundation Maps

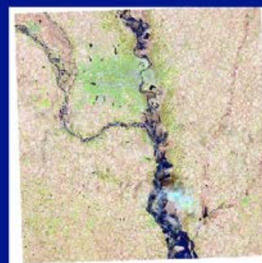


USGS

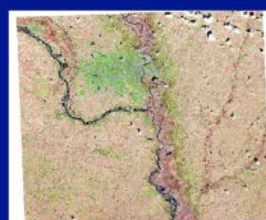
Jack Eggleston
jegglest@usgs.gov

Remotely Sensed Dynamic Surface Water Extent





2019-04-15



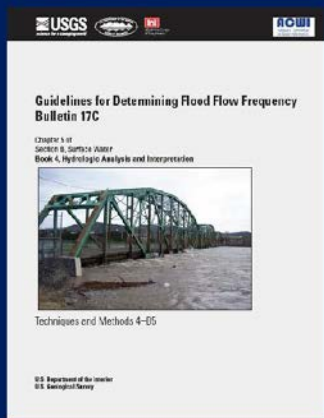
2020-04-09

USGS

FLOOD FREQUENCY

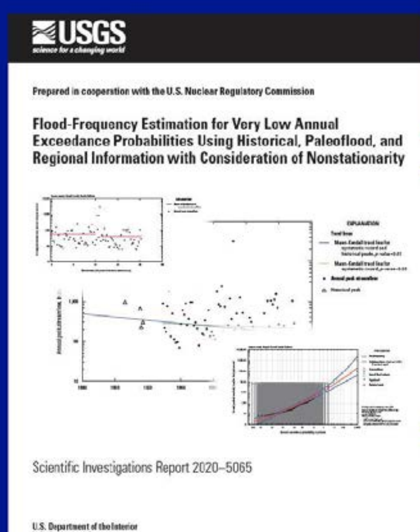
USGS

Bulletin 17C – Progress on regional skew

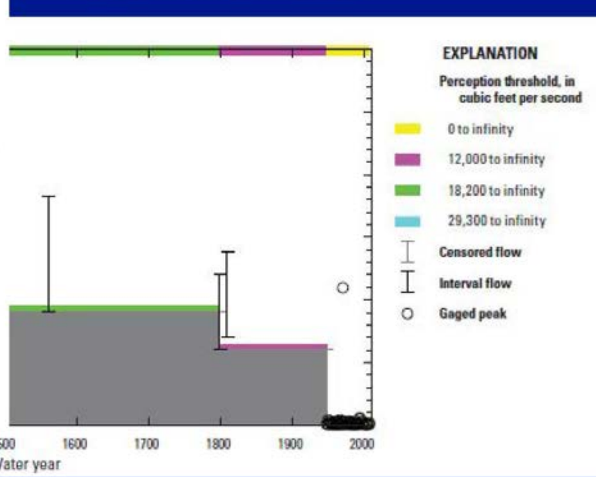


≈USGS

Paleoflood and historical data



- Bulletin 17C can make better use of paleoflood and historical data because we can describe it more fully now.



≈USGS

HISTORICAL AND PALEOFLOOD ANALYSES FOR PROBABILISTIC FLOOD HAZARD ASSESSMENTS – APPROACHES AND REVIEW GUIDELINES

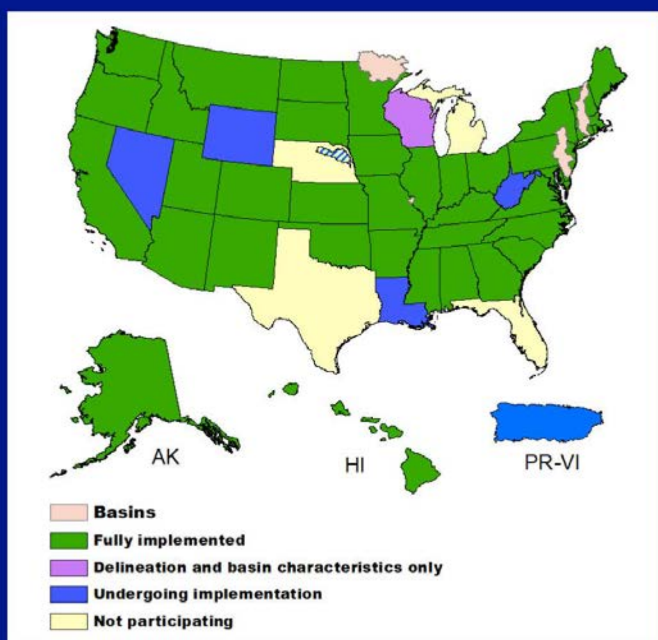
Ryberg, Harden, Friedman, O'Connor

Tuesday, 12:15 Eastern

≋USGS

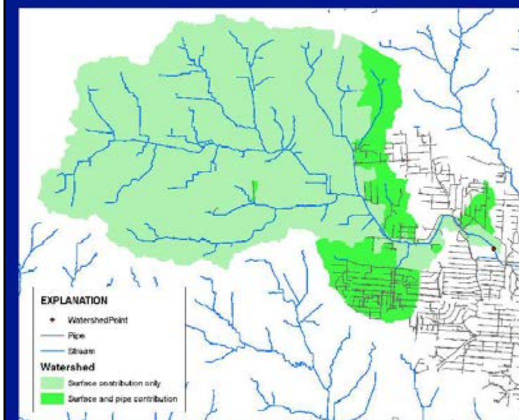
StreamStats

- Most of the nation has been implemented with regional equations
- Evaluating machine learning alternatives
- New custom functions



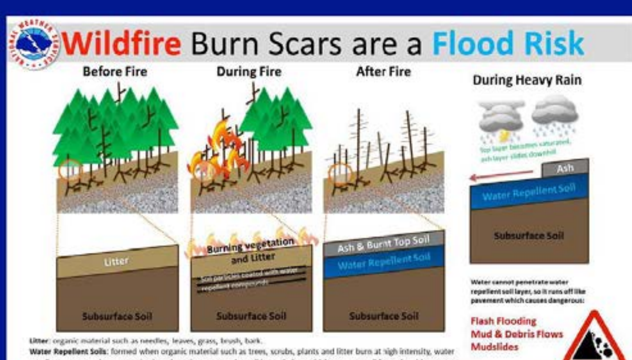
≋USGS

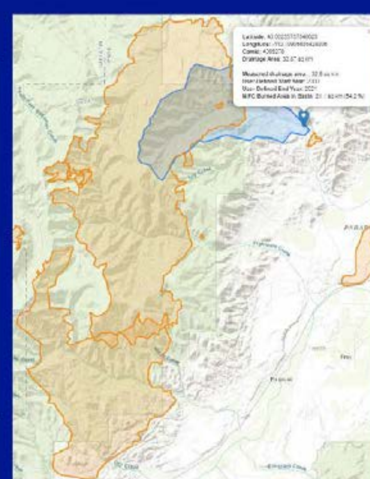
Urban hydrology: Mapping storm drains for accurate basin delineation



USGS

Fire-Hydrology (proof of concept)



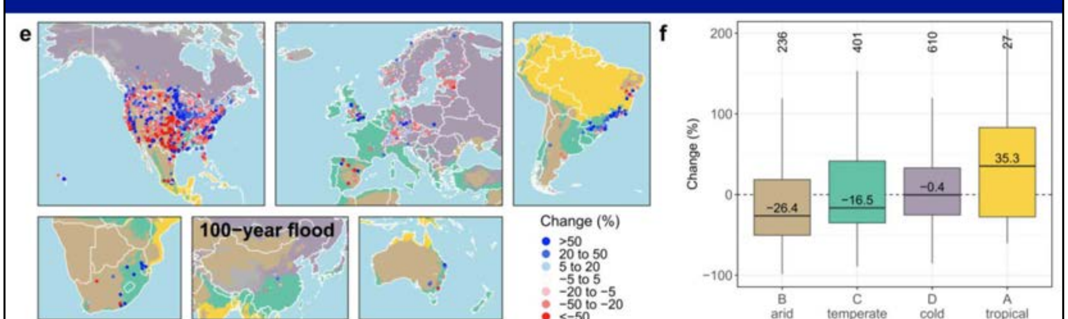


USGS

FLOOD TRENDS

≋USGS

What is the change in the magnitude of the 100-year floodssince the 1970s?



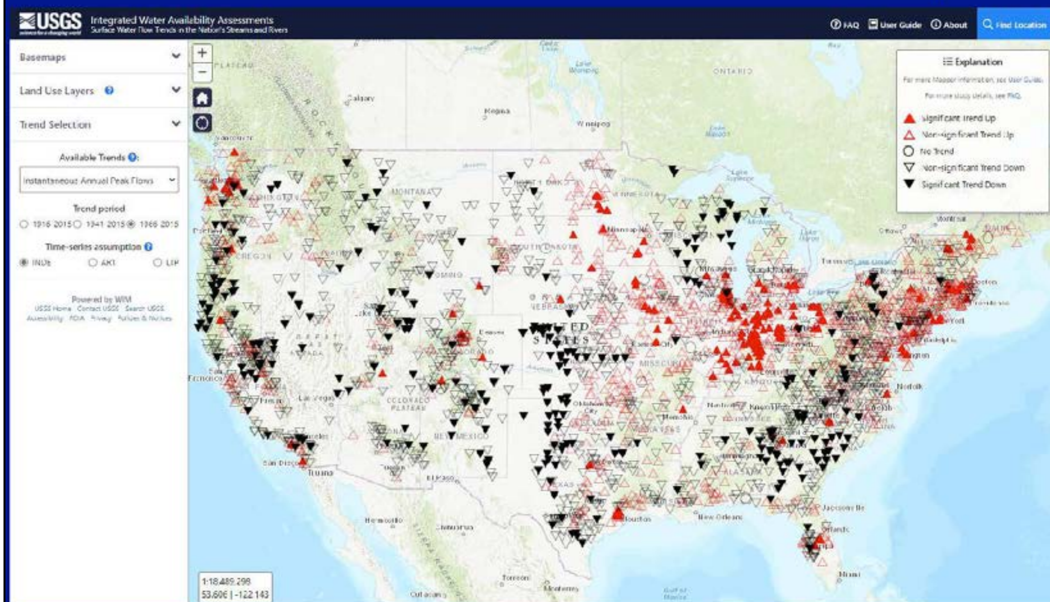
The magnitude and frequency of floods are changing substantially in different climates of the globe.

Monitoring our rivers are critical because long-term records are necessary to understand and communicate how major floods are changing relative to the past.

≋USGS

L. Slater, G. Villarini, S.A. Archfield, D. Faulkner, R. Lamb, A. Khouakhi, Jiabo Yin, 2021, Global Changes in 20-year, 50-year and 100-year River Floods, Geophysical Research Letters, in press.

Peak flow trends: interactive map



http://iwaas.wim.usgs.gov/sw-flow-trends

UPDATING DESIGN FLOOD ESTIMATES AT SITES WITH CHANGING VARIABILITY

Hecht, Barth, Ryberg, and Gregory

Tuesday, 11:45 Eastern

3.1.3.2 Questions and Answers

Question:
Where can we access new generalized skew estimates for the states? Is it available now? Ex: Virginia?

Julie Kiang:
We unfortunately haven't been able to update our list at the old ACWI website, but it's available here: Regional Skew and Flood Frequency Reports from the USGS (acwi.gov)

Question:
Is USGS also measuring and analyzing snowpack or snow water equivalent?

Robert Mason:
We have a project that is looking at monitoring snow and snowpack in some of our specialty basins. We have a program that is identifying some 10 river basins. Those river basins are going to be monitored in detail for precipitation, runoff, snow, and the like. And in some of those basins, there will be instrumentation to monitor snowpack.

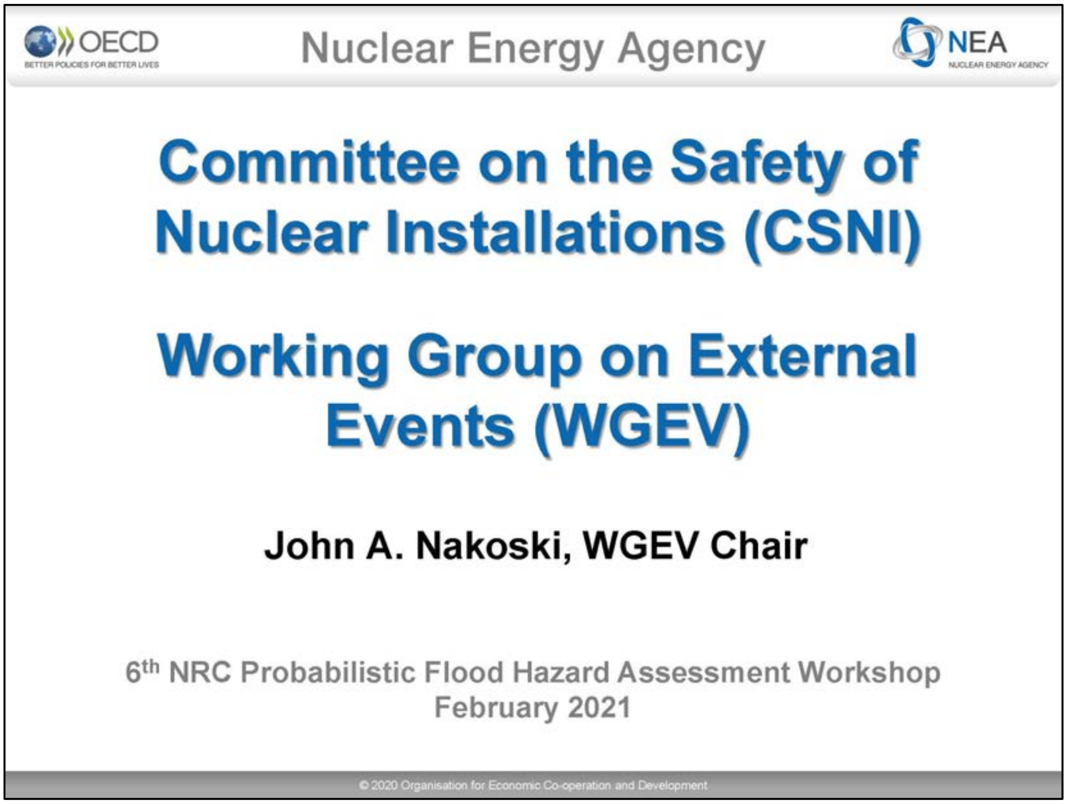
Question:
Studies are focusing on discharge frequencies as in Bulletin 17 C. However, NRC's flood frequency analysis for reactor safety analysis is focusing on flood stage and inundation. Noticing that frequency patterns of discharge and stage are somewhat different, please discuss how USGS flood frequency studies fit into the safety analysis for nuclear power plants.

Julie Kiang:
There's definitely differences in the data and in the information that we're putting out there. To make that translation from the discharge, which is what we have the best data on and that can translate up and down the stream more easily, there needs to be a site-specific analysis to do that. This is to understand what a particular discharge might translate to in terms of stage.

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

Speaker: John Nakoski, NRC/RES/DRA (WGEV Chair)

3.1.4.1 Presentation (ADAMS Accession No. ML21064A420)



WGEV Administration

- **WGEV Chair:** John A. Nakoski (NRC, USA)
- **WGEV Bureau:** Vincent Rebour (IRSN, France), Gernot Thuma (GRS, Germany), ShiZhong Lei (CNSC, Canada), Min Kyu Kim (KAERI, South Korea)
- **WGEV Participants from:**
  - Belgium (BelV), Canada (CNSC), Czech Republic (SUJB), Finland (STUK), France (IRSN, EdF), Germany (GRS), Japan (NRA), Netherlands (ANVS), Poland (PPA), Romania (CNE), South Korea (KAERI), Sweden (SSM), Switzerland (ENSI), United States (NRC, DOE, EPRI)
  - European Commission, International Atomic Energy Agency, and World Metrological Organization
- **NEA Technical Secretariat:** Marina Demeshko
- **Established in 2014**
- **Meets twice a year**

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

Completed Activities

- NEA/SEN/SIN/WGEV(2015)1 – Technical Note on Severe Weather with Concurrent Flooding and High Winds
- NEA/CSNI/R(2017)13 – Proceedings for the Workshop on Severe Weather and Storm Surge
- NEA/CSNI/R(2018)7 – Examination of Approaches for Screening External Hazards
- NEA/SEN/SIN/WGEV(2018)1 – Topical Report on Riverine Flooding
- NEA/SEN/SIN/WGEV(2018)13 – Proceedings for the Workshop on Riverine Flooding
- NEA/CSNI/R(2020)9 – Concepts and Definitions for Protective Measures in Response to External Flooding Hazards

Ongoing Activities (1 of 3)

- **Benchmark on Hazard Frequency and Magnitude Model Validation for External Events**
  - Finalization of the benchmark specification – November 2018
  - Gather input from benchmark participants – July 2019
  - Final Report – March/April 2021
  - For more information contact Curtis Smith (Curtis.Smith@inl.gov) or Vincent Rebour (Vincent.Rebour@irsn.fr)
- **High winds and tornadoes**
  - Survey responses – February 2020
  - Preparation of initial draft report – June 2020
  - Final report – March 2021
  - Workshop – October 2021

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

Ongoing Activities (2 of 3)

- **Combinations of External Hazards**
  - Hazards and Impact Assessment and Probabilistic Safety Analysis for Nuclear Installations (joint project of WGEV and WGRISK)
  - Kick-off meeting – February 2020
  - Survey responses – September 2020
  - Preparation of initial draft report – July 2021
  - Final survey response report – May 2022
  - Joint WGEV/WGRISK workshop – Fall of 2022

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Ongoing Activities (3 of 3)

- **Uncertainties in the Assessment of Natural Hazards**
  - **Phase 1 - Sources of Uncertainty**
  - **Phase 2 - Methods to Deal with Uncertainties**
  - **Phase 1 Decision on Spectrum of natural hazards to consider – March 2021**
  - **Phase 1 Workshop on Sources of Uncertainty – March 2022**
  - **Phase 2 Report Structure and Content decided – September 2022**
  - **Phase 1 Technical Report and Workshop Proceedings – December 2023**
  - **Phase 2 Workshop on Methods to Deal with Uncertainties – March 2024**
  - **Phase 2 Technical Report and Workshop Proceedings – December 2024**

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

Potential Future Activities

- **Local Intense Precipitation –** under development
- **Topical discussions – next WGEV meeting topics**
  - Space weather
  - Improving data sources for hazards assessment

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3.2 Day 1: Session 1B – Climate

Session Chair: Joseph Kanney, NRC/RES/DRA

3.2.1 Presentation 1B-1 (KEYNOTE): Seasonally Dependent Changes in Multi-model and Large-Ensemble Simulations

Author: L. Ruby Leung, Pacific Northwest National Laboratory (PNNL)

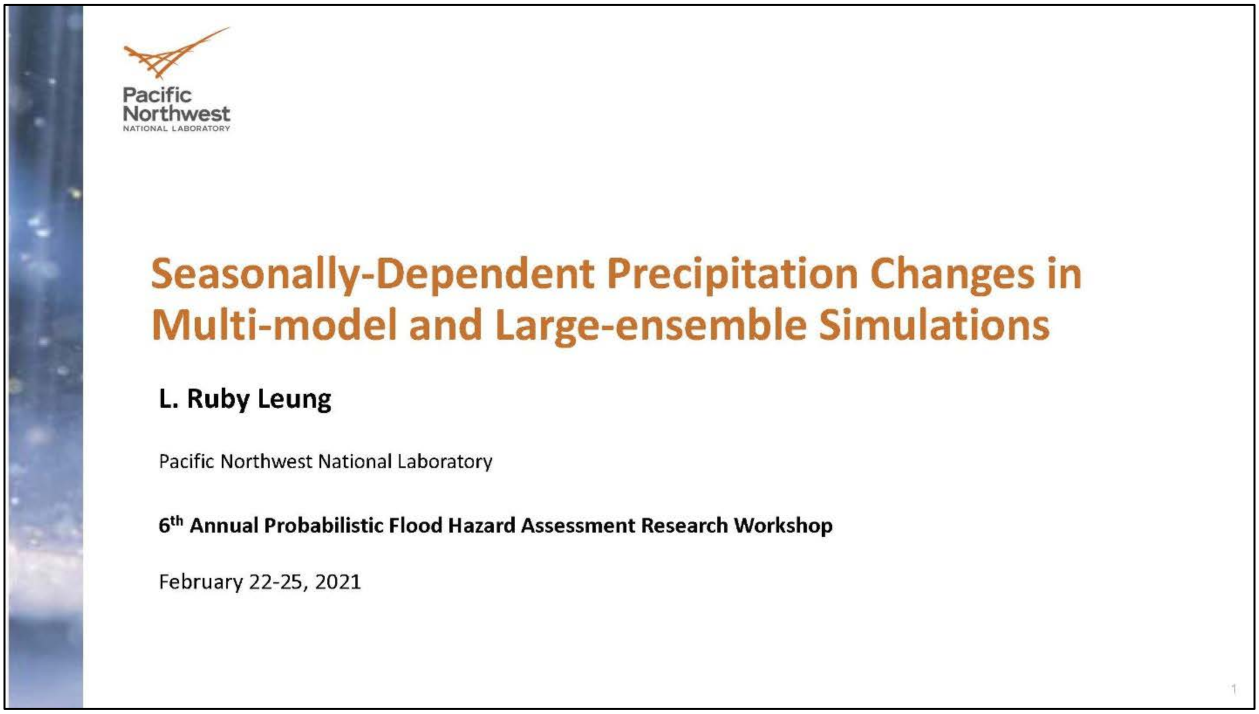
Speaker: L. Ruby Leung

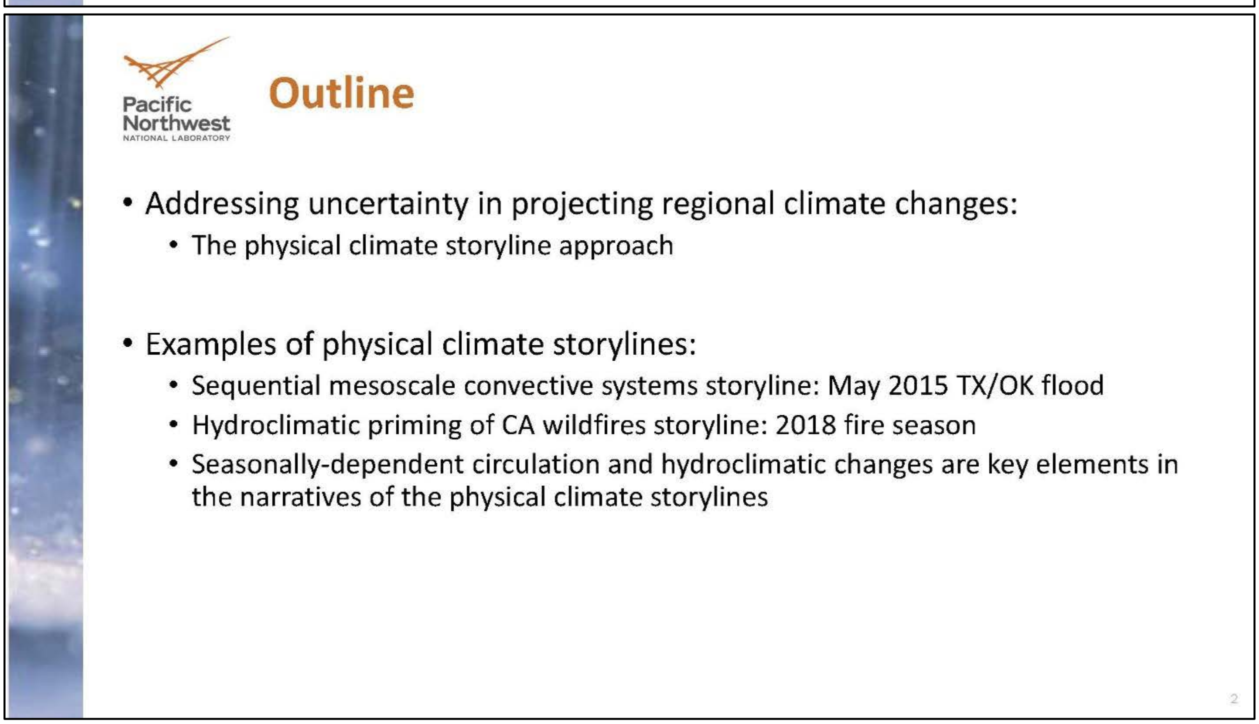
3.2.1.1 Abstract

Warming induced by anthropogenic emissions of greenhouse gases can induce changes in precipitation and other components of the water cycle. The seasonal cycle of precipitation is dominantly influenced by the annual cycle of solar insolation and land-sea contrast, but even precipitation seasonality can be altered by global warming in many ways, with implications for floods, droughts, wildfires, and food production. Climate models projected a sharpening of the wet season in the US Southwest under warming, with mean and extreme precipitation increasing in winter but decreasing in spring and fall. Warming will also induce seasonally dependent changes in the US Midwest. In a high-emission scenario, the likelihood of an extremely wet late spring is projected to increase by 15 times over this century while the likelihood of an extremely dry late summer will increase by 10 times. Understanding the mechanisms behind these changes is important, particularly in support of the physical climate

storyline approach in which climate risk is communicated not by probabilities but using narratives of physically self-consistent unfoldings of past events or plausible future events.

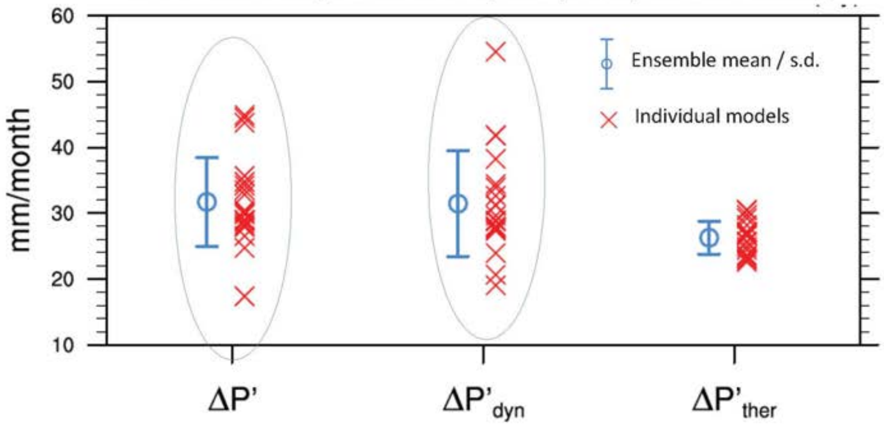
3.2.1.2 Presentation (ADAMS Accession No. ML21064A421)





Uncertainty in large-scale circulation changes dominates uncertainty in regional precipitation changes

Inter-model spread of tropical precipitation change

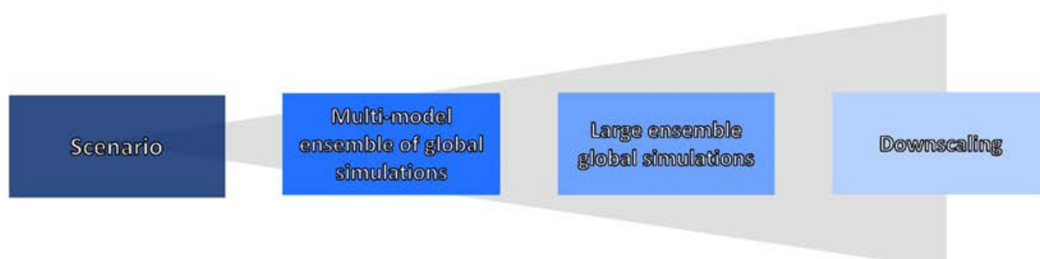


(Xie et al. 2015 NCC)

3

Modeling in the context of deep uncertainties

How to make pragmatic choices given limitations to fully explore the uncertainty space?



Forcing uncertainty | Model uncertainty | Internal variability | Model complexity

4

Storyline approach

- Storylines are "**qualitative description of plausible future evolutions**, describing the characteristics, general logic and developments underlying a particular quantitative set of scenarios" (IPCC)
- **Scenario storylines:**
  - A narrative description of a scenario, highlighting the main characteristics, relationships between key driving forces and the dynamics of their evolution.
  - By definition, **no probabilities** need to be attached to scenarios, and they are not predictions
- **Physical climate storylines:**
  - **Physically self-consistent** unfolding of past events, or of plausible future events or pathways (Shepherd et al. 2018)
  - **Conditioned on a set of assumptions** and built from causal arguments
  - A common question: **if** this event were to happen in the future, how would it **look like**?
  - But it's also important to ask: how **likely** will the event happen in the future?

5

Physical climate storylines

Selection of an event with high societal impacts

How may the event look like in the future?

- **Fine-resolution** modeling of the event
- **Add perturbations**: counter-factual or future
- Short duration and fine-resolution allow the event to be **more realistically simulated**
- Can afford to run a **large ensemble** of the event to characterize uncertainty
- **Mechanistic understanding**: thermodynamic effect, local feedback (e.g., land-atmosphere interactions, snow-albedo feedback)

Metrics of extreme events and fine-scale processes

How likely will the event happen in the future?

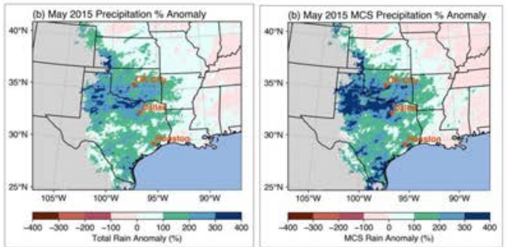
- **Large-scale circulation** context
- Well suited for **global models at relatively coarse resolution** (CMIP/LEN)
- Provide **boundary conditions** for fine-scale modeling of the event
- **Develop narratives** of large-scale circulation changes
- **Mechanistic understanding**: dynamical effect, teleconnections

Metrics of large-scale circulation in the context of extreme events

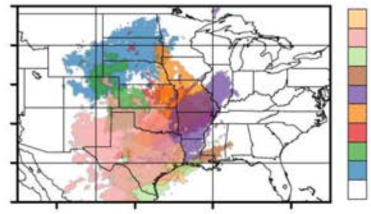
6

A sequential MCS storyline: May 2015 TX/OK flood

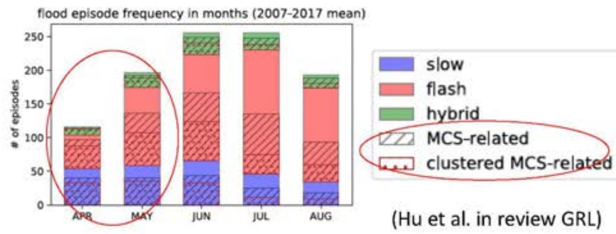
TX//OK total and MCS precipitation in May 2015 is 200-400% above normal



A cluster of 9 MCSs within 4 days



Combining an MCS database and NOAA flood event database: MCSs account for the majority of floods in spring



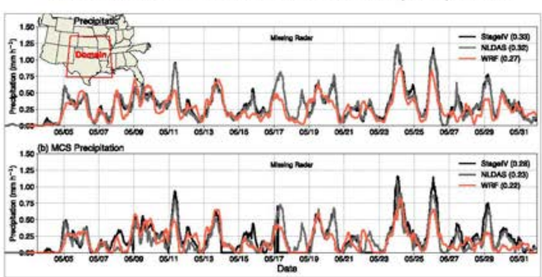
(Hu et al. in review GRL)

7

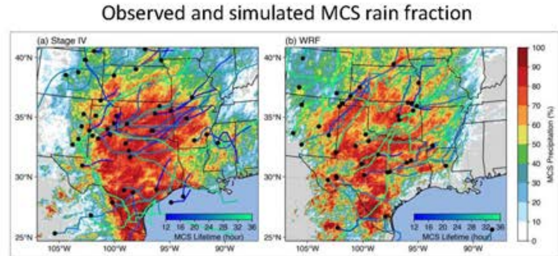
A sequential MCS storyline: modeling the flood event

- A WRF simulation at 3 km grid spacing well reproduces the total and MCS rainfall
- Perturbation experiments will be performed using a pseudo-global warming approach, emphasizing the thermodynamic effect

Observed and simulated total and MCS precipitation



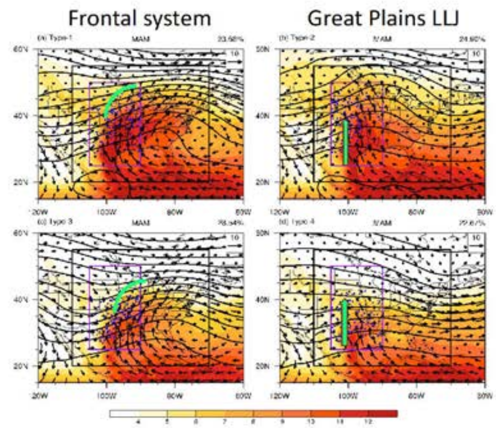
Observed and simulated MCS rain fraction



8

A sequential MCS storyline: environment favorable for MCSs in spring

MCS large-scale environments favorable for MCSs in spring

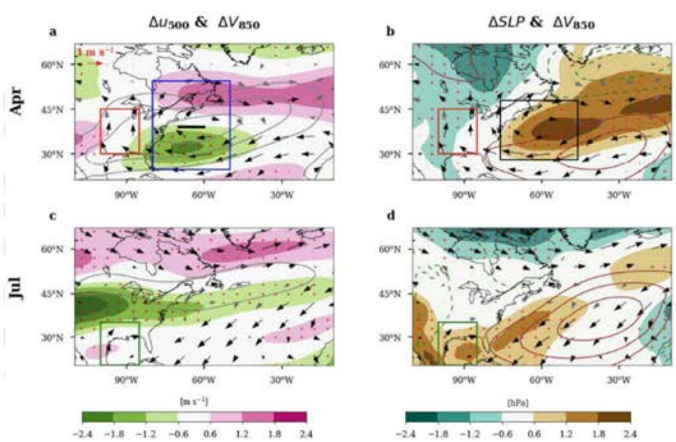


(Song et al. 2019 JCLIM)

- Self-organizing map analysis identifies four types of large-scale environments favorable for MCS initiation in spring
- They feature frontal system and the Great Plains low-level jet (GPLLJ)

A sequential MCS storyline: seasonally-dependent future changes in circulation

Different changes in spring vs. summer

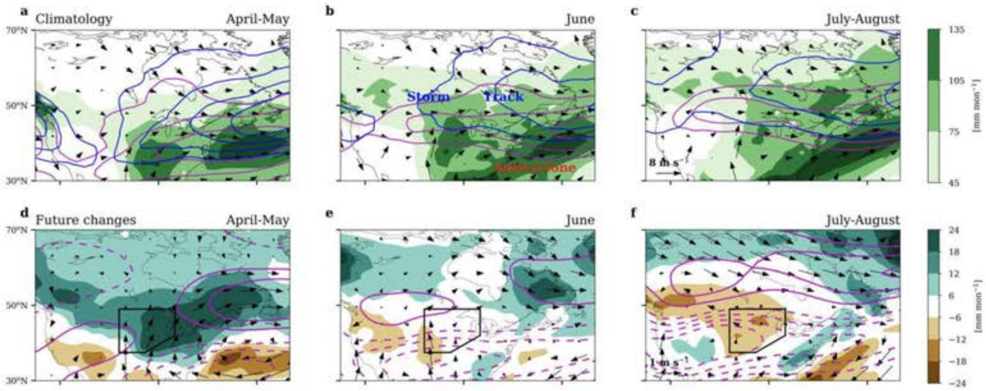


(Zhou et al. 2021 GRL)

- Competing effects of the **poleward shift of the westerly jet** and **enhanced land-sea temperature contrast** under warming drive seasonally-dependent changes in the GPLLJ
- **GPLLJ enhancement in spring and fall but little change in summer**

Seasonally-dependent future changes analogous to climatological seasonal evolution

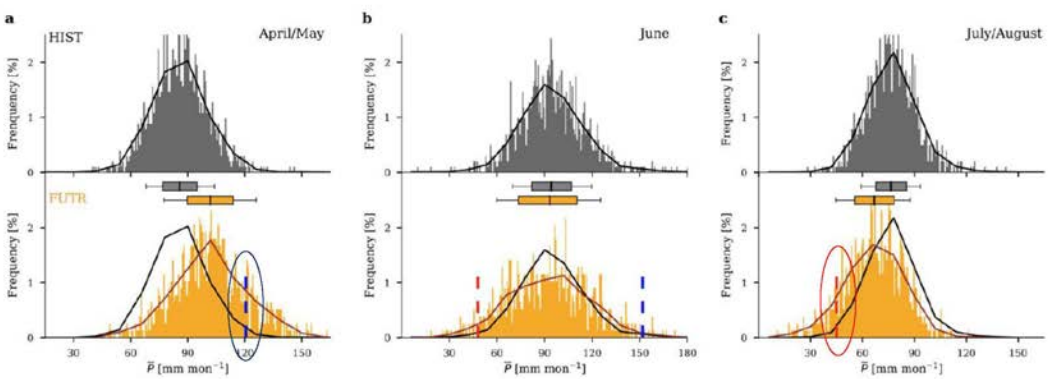
Climatological poleward migration of jet + future poleward jet shift
= late spring wetting and late summer drying



(Zhou et al. in review JCLIM)

Seasonally-dependent future changes in wet and dry extremes in the U.S. Midwest

- The likelihood of an extreme wet late spring increases by 15 (8) times under high (intermediate) scenario over this century
- The likelihood of an extreme dry late summer increases by 10 (5) times



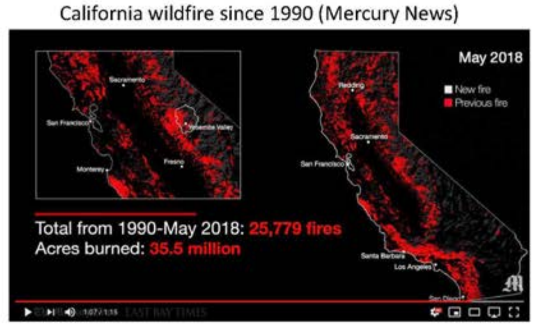
(Zhou et al. in review JCLIM)

CA Wildfires storyline: 2018 fire season

- The Mendocino Complex Fire in 2018 is the second largest recorded fire in California's history
- A total of 459,123 acres burned between July 27 and Sep 18, causing at least $267 million (2018 USD) in damages (property lost and fire suppression cost)
- California has a long history of wildfires, with burned area increasing by 3.6% per year between 1984 and 2017

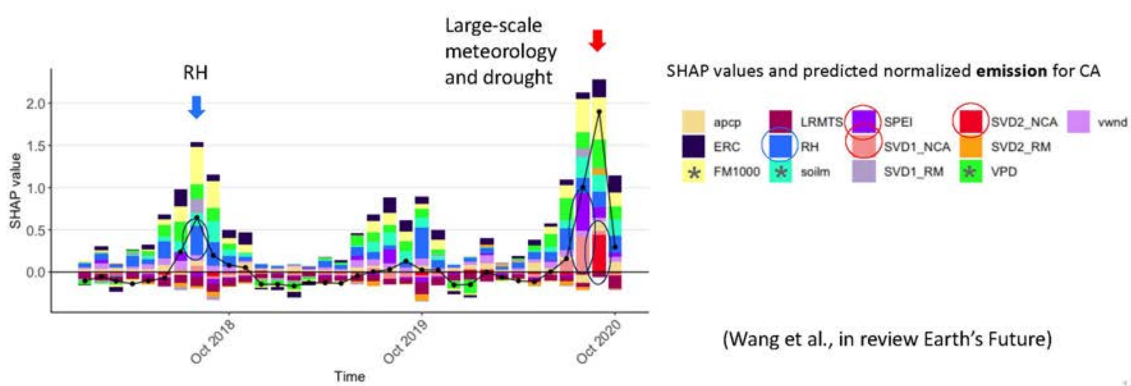
Image of the Mendocino Complex Fire and smoke captured by NASA's Aqua satellite on August 06, 2018 with the MODIS instrument

California wildfire since 1990 (Mercury News)



CA Wildfires storyline: a machine learning model

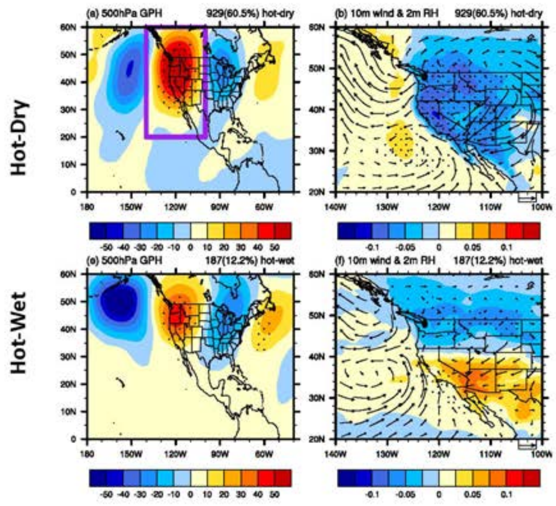
- Develop an ML model (XGBoost) to **predict monthly burned area** at 0.25° x 0.25° over the US including **local meteorology**, **large-scale meteorological pattern**, **land-surface properties**, and **socioeconomic** and other static variables as predictors
- Identify the **relative importance of the predictor variables** using Shapley additive explanations (SHAP)



(Wang et al., in review Earth's Future)

Pacific Northwest NATIONAL LABORATORY

CA Wildfires storyline: circulation favoring wildfires



- About **60%** of wildfires in 1984-2017 occur under **hot-dry conditions** with higher pressure, NE wind, lower relative humidity, higher temperature, and downward motion
- **Hot-wet** conditions account for **12%** of wildfires when anomalous convection and lightning trigger wildfires

(Dong et al. 2021 JGR-A)

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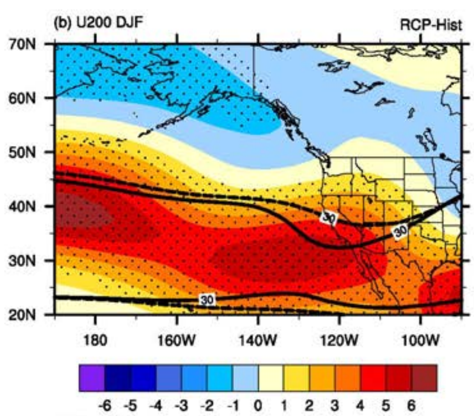
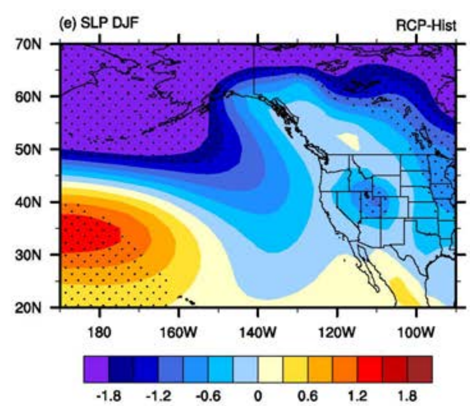
Pacific Northwest NATIONAL LABORATORY

CA Wildfires storyline: changes in winter circulation increasing winter precipitation

Eastward extension of westerly jet: steer storm tracks toward CA



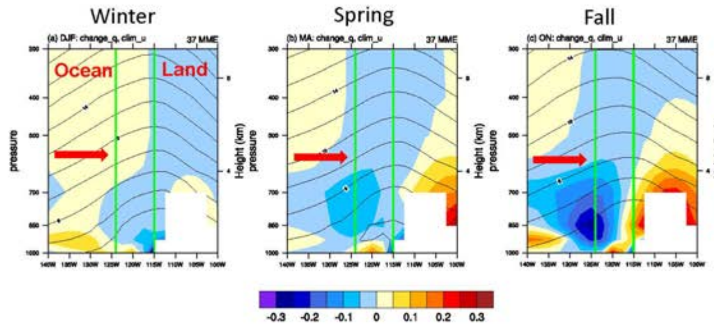
Deepening of Aleutian Low: moisture advection towards CA



(Dong et al. 2019 JCLIM)

16

CA Wildfires storyline: changes in mean moisture advection induce seasonality changes



Contour: climatological zonal wind (m/s)

Shaded: changes in zonally asymmetric specific humidity (g/kg)

✓Winter:

$\Delta q_{land} < \Delta q_{ocean}$

- Wet advection by westerly wind

✓Spring & Fall:

$\Delta q_{land} > \Delta q_{ocean}$

- Dry advection by westerly wind

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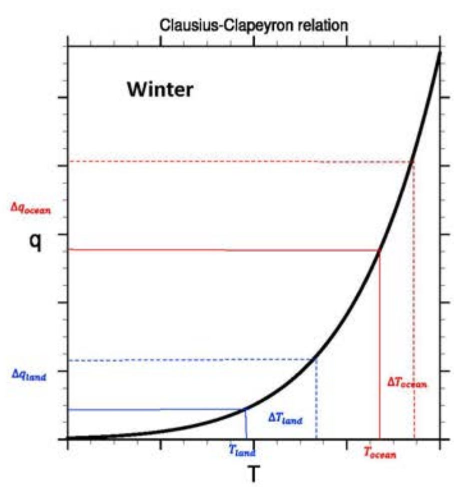
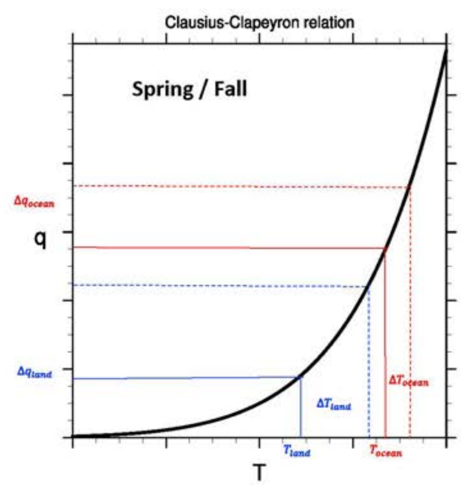
CA Wildfires storyline: nonlinear Clausius-Clapeyron relation induces drying in spring and fall

$T_{land} < T_{ocean}$, $\Delta T_{land} > \Delta T_{ocean}$ → Δq_{land} vs Δq_{ocean}?





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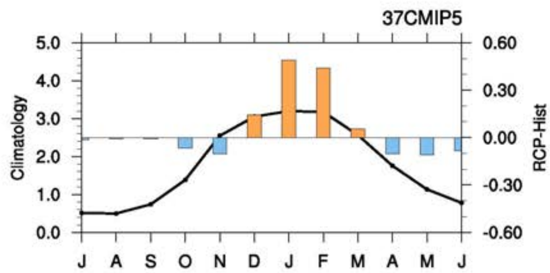
CA Wildfires storyline: sharpening of seasonal precipitation

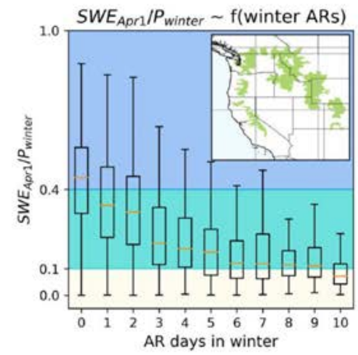
- **Changing seasonality** of mean and extreme precipitation, AR frequency, snowpack and runoff towards sharpening has implications for wildfires (e.g., longer fire season)

A **sharpening of precipitation seasonal cycle** in California projected by CMIP5 models



(Dong et al. 2019 JCLIM)

More AR days in winter →
Less April 1st SWE and **reduced summer runoff**



(Chen et al. 2019 JGR-A)

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Summary

- Physical climate storylines can take advantage of fine-scale and coarser-scale models to address different questions at relevant scales
  - Fine-scale models can realistically simulate extreme events (e.g., MCS floods)
  - PGW experiments using fine-scale models can inform how the historical events may look like in the future with warming (and increased moisture)
  - Global simulations in CMIP and LEN simulations can inform how likely the historical events may happen in the future
  - Seasonally-dependent circulation and hydroclimate changes are ubiquitous with implications for extreme events (e.g., monsoon, Mediterranean climate, U.S. Great Plains)
- Mechanistic understanding of the future changes is key in providing multiple lines of evidence, which requires deep analysis
- Selection of storylines, modeling approaches, metrics, and analyses would benefit from dialogues between climate scientists and stakeholders

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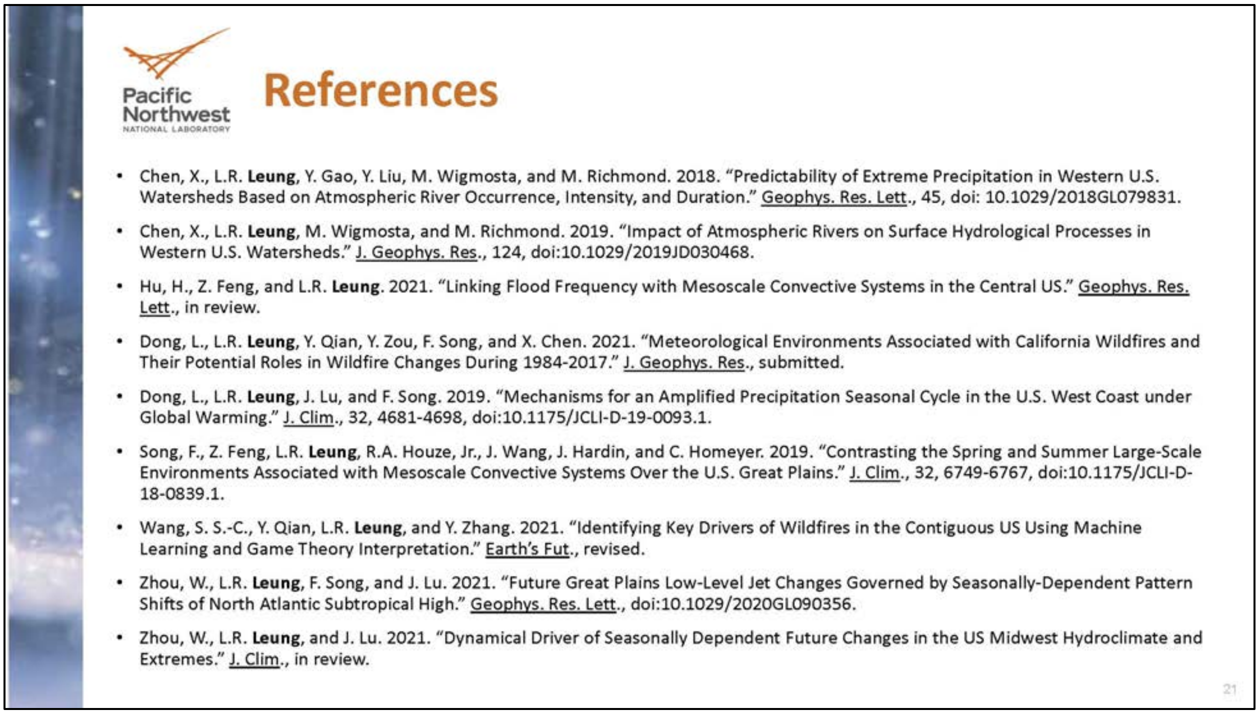


3.2.1.3 Questions and Answers

Question:
How does the issue of probabilities inform or are informed by the storyline models?

Ruby Leung:
What we're trying to do in the storyline approach is to breakdown the problem into two separate questions because, if we ask a single question, then we really need to explore the full uncertainty space. For example, if you want to know what's the probability of extreme precipitation, like the 99th percentile precipitation, in the future, then you need a model that is able to simulate extreme precipitation and you also need a model that runs large ensemble simulations to account for uncertainty and things like that. So, the unique thing about the storyline approach is really trying to break down this question into two sub questions related to the uncertainty, like what might be the likelihood of a particular historical event happening again in the future. The way we look at this is by using CMIP models and large ensemble simulations. There are already many such simulations available based on multiple models and based on several global models running large ensemble simulations. First, for a particular historical event that we're interested in, we need to understand the large-scale circulation context. What supported that particular event? Is it because of some blocking circulation, or is it because of teleconnections or things like that? Once we understand the meteorological context of that particular event, then we look into these CMIP and large ensemble simulations and try to understand if these types of conditions going to happen more in the future, and why. So, asking why or the mechanistic understanding is really what we're trying to emphasize in the storyline approach.

Question:
Please briefly discuss what are the key factors and processes to transform from physical climate storylines to short term, extreme rainfall events needed for extreme flooding analysis used for reactor safety analysis.

Ruby Leung:
When you mean short term, do you mean short term as in a weather forecasting time scale or are you referring to the future? I'm assuming that it is the second kind that you are referring to rather than weather forecasting. So, in the context of understanding how flooding events might change in the future, in the storyline approach, first you must select a particular historic event. That might be something that you really worry about in the context of nuclear power plants. One example is this May 2015 case that I discussed. Once you select this example then you can simulate it using a fine scale model which should be quite skillful in simulating that type of event. And then you perturb the boundary conditions of your model by changing, for example, the temperature and moisture. Then you can see how, because of the warming and the moisture, such a flood event might become more intense in the future. But in terms of the probability, then we must look at the global simulations to understand the meteorological context of that event and look at how the circulation might change.

3.2.2 Presentation 1B-2: Challenges Associated with Multi-Hazard Characterization of Landfalling Hurricanes

Authors: Scott Weaver[1], Dereka-Carroll Smith[2], [1]National Institute of Standards and Technology; [2]Joint NIST-UMD-NCAR Research Associate

Speaker: Scott Weaver

3.2.2.1 Abstract

As hurricane characteristics evolve due to climate-related factors, it is of paramount importance to accurately measure event-based hurricane-related hazards, and their interaction with the antecedent and subsequent geophysical environment, to inform climate attribution and adaptation strategies. Unfortunately, post windstorm analysis of hurricane disasters in 2017 and 2018 have reaffirmed the existence of significant gaps in our ability to adequately measure surface level wind speeds and extreme rainfall in landfalling hurricanes – two physical parameters that cause significant loss of life and property in these events. Underpinning these measurement science deficiencies are low spatial and temporal resolution of ground-based environmental observations, and frequent issues with the instrumentation needed to collect hurricane hazard data. While these challenges have been noted in the wind community for some time, in some instances (e.g., Hurricane Maria) they also extend to water-related hazards. Accordingly, there is a critical need to improve current measurement practices in landfalling hurricanes, given that their temporal evolution, variation in intensity, and historical context are important for objectively quantifying both the primary hazards and their secondary perils in efforts to refine understanding of their societal impacts. The discussion will outline the wind and rainfall measurement science issues in Hurricanes Michael and Maria and the implications for exploring flood characterization research questions in the context of climate variability and change as part of the NIST-led interagency National Windstorm Impact Reduction Program.

3.2.2.2 Presentation (ADAMS Accession No. ML21064A422)

Challenges Associated With Multi-hazard Characterization of Landfalling Hurricanes

Scott Weaver, Director, National Windstorm Impact Reduction Program (NWIRP)

Dereka Carroll-Smith, Research Associate

Engineering Laboratory
National Institute of Standards and Technology

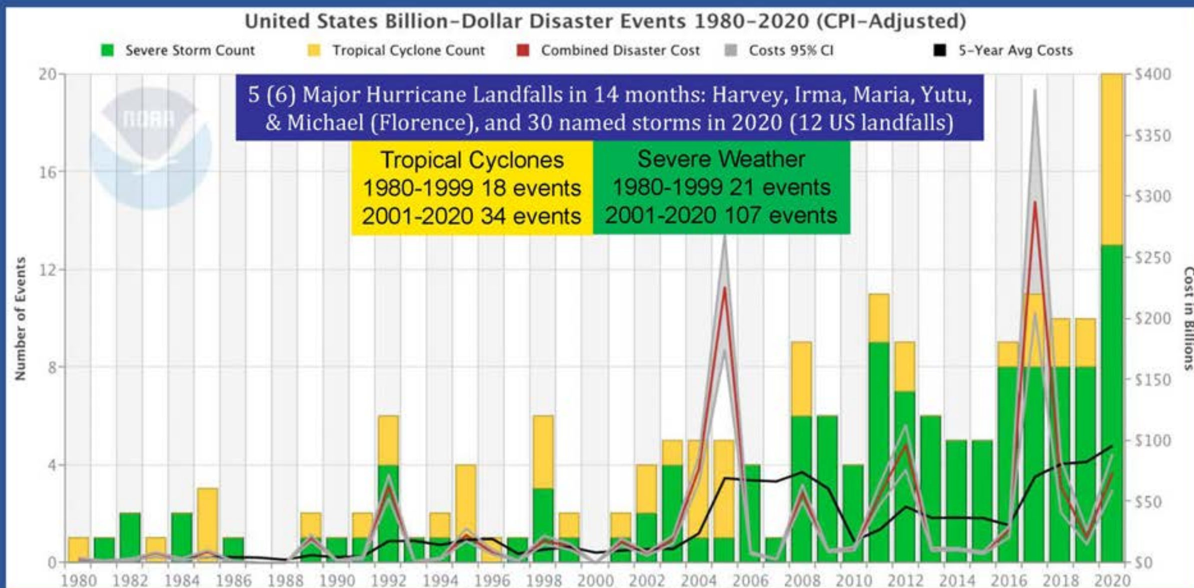
NRC Workshop
February 22, 2021

The Theme of This Talk

Connectivity between the fields of Climate Science, Meteorology, and Engineering through the lens of multi-hazard measurement science challenges in hurricane disasters

2

Windstorm Disasters –Wind and Water

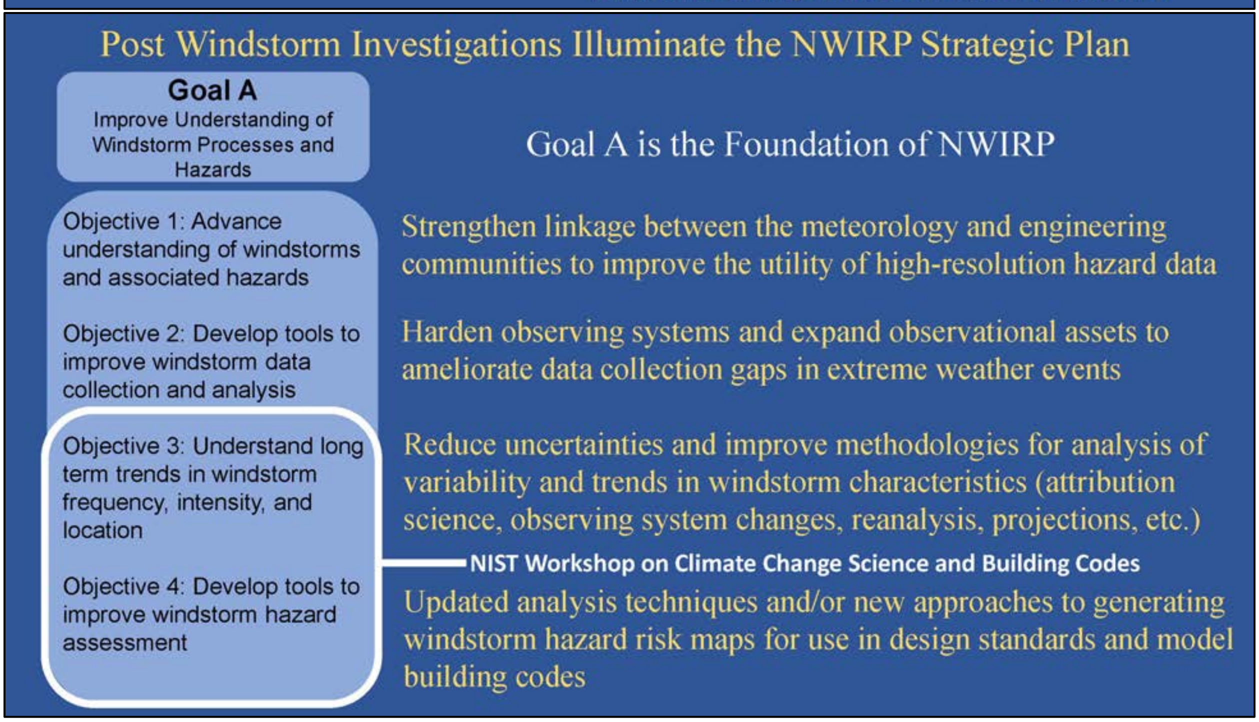


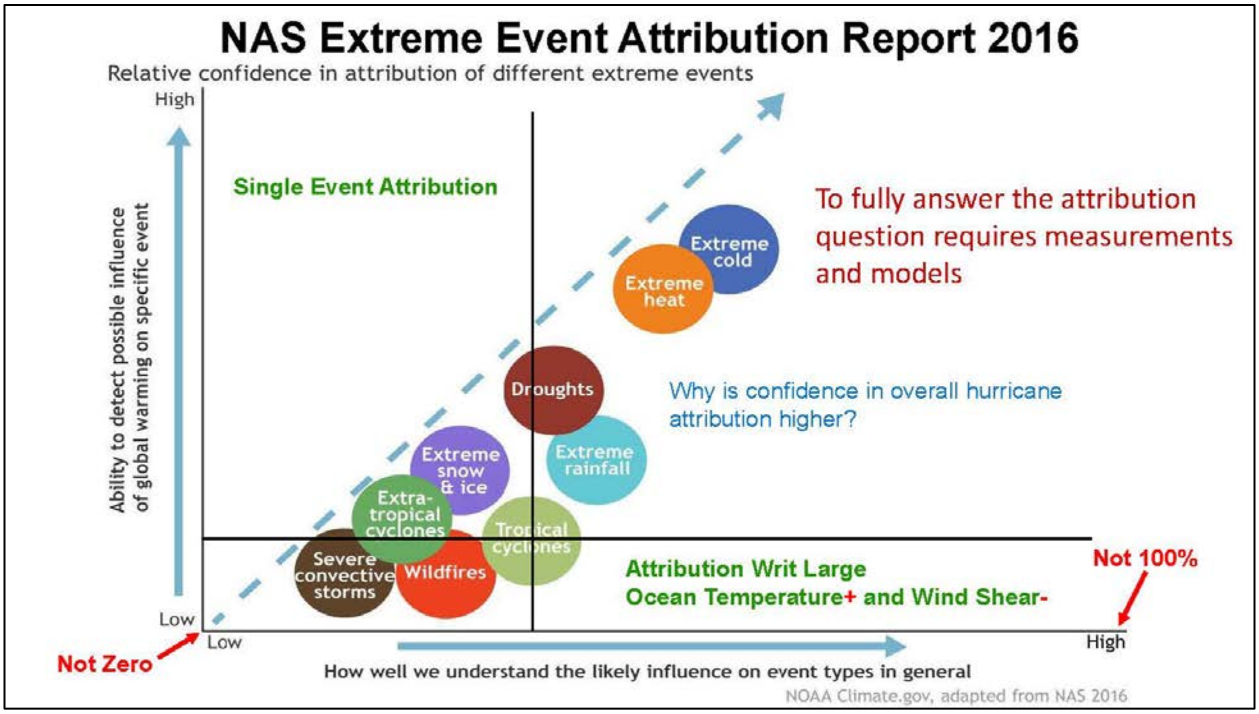
Courtesy of Adam Smith, NOAA/NCEI

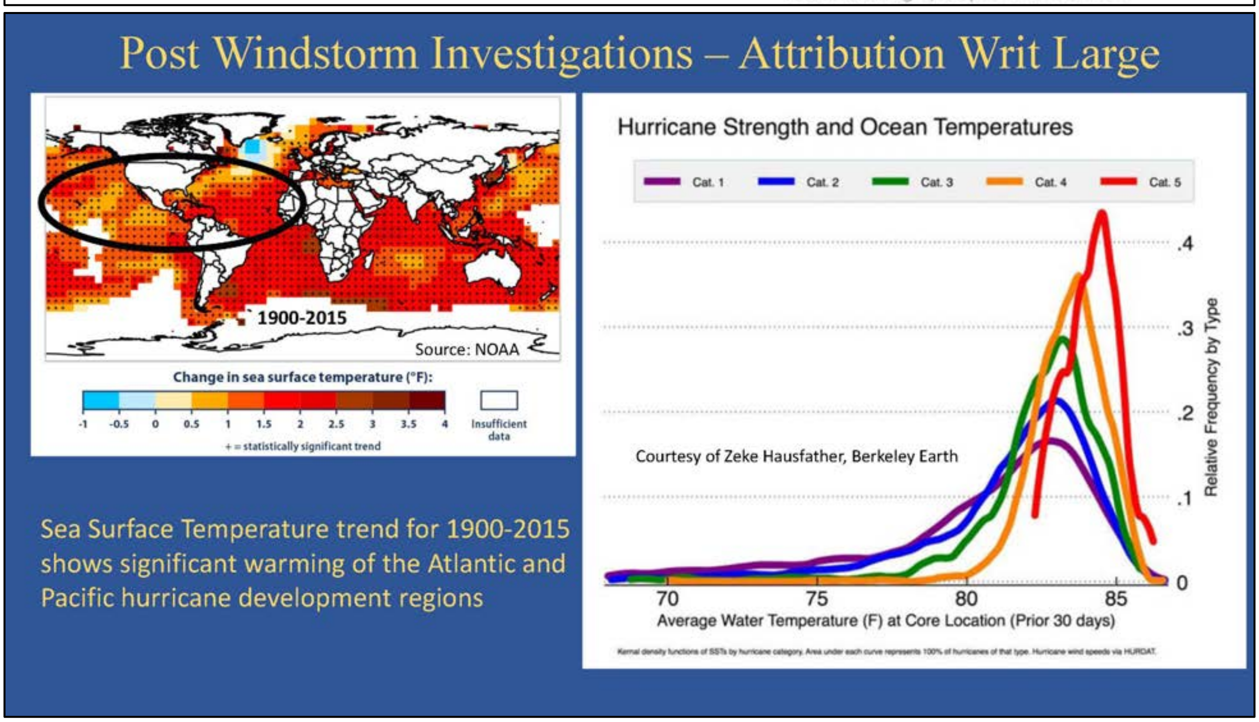
Why is NIST interested in climate and weather disasters?

NIST
National Institute of Standards and Technology
U.S. Department of Commerce

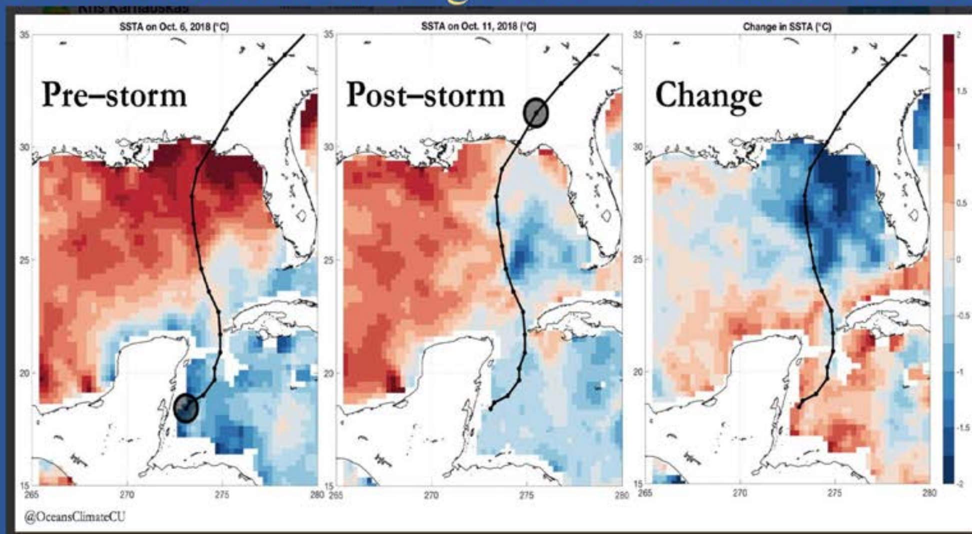

NWIRP
Strategic Plan
for the
National Windstorm Impact Reduction Program
FEMA
NIST
The NWIRP Strategy: Spanning the Spectrum of Research to Applications (R2A2R)
Goal A
Improve Understanding of Windstorm Processes and Hazards
Goal B
Improve Understanding of Windstorm Impacts on Communities
Goal C
Improve Windstorm Resilience of Communities Nationwide
R
2
A
Congress directs NWIRP "to coordinate all federal post windstorm investigations to the extent practicable."


Post Windstorm Investigations Illuminate the NWIRP Strategic Plan
Goal A
Improve Understanding of Windstorm Processes and Hazards
Objective 1: Advance understanding of windstorms and associated hazards
Objective 2: Develop tools to improve windstorm data collection and analysis
Objective 3: Understand long term trends in windstorm frequency, intensity, and location
Objective 4: Develop tools to improve windstorm hazard assessment
Goal A is the Foundation of NWIRP
Strengthen linkage between the meteorology and engineering communities to improve the utility of high-resolution hazard data
Harden observing systems and expand observational assets to ameliorate data collection gaps in extreme weather events
Reduce uncertainties and improve methodologies for analysis of variability and trends in windstorm characteristics (attribution science, observing system changes, reanalysis, projections, etc.)
NIST Workshop on Climate Change Science and Building Codes
Updated analysis techniques and/or new approaches to generating windstorm hazard risk maps for use in design standards and model building codes


NAS Extreme Event Attribution Report 2016
Relative confidence in attribution of different extreme events
High
Low
Ability to detect possible influence of global warming on specific event
Single Event Attribution
To fully answer the attribution question requires measurements and models
Extreme cold
Extreme heat
Droughts
Why is confidence in overall hurricane attribution higher?
Extreme snow & ice
Extreme rainfall
Extra-tropical cyclones
Tropical cyclones
Severe convective storms
Wildfires
Attribution Writ Large
Ocean Temperature+ and Wind Shear-
Not 100%
Not Zero
Low
High
How well we understand the likely influence on event types in general
NOAA Climate.gov, adapted from NAS 2016


Post Windstorm Investigations – Attribution Writ Large
1900-2015
Source: NOAA
Change in sea surface temperature (°F):
-1 -0.5 0 0.5 1 1.5 2 2.5 3 3.5 4
Insufficient data
+ = statistically significant trend
Sea Surface Temperature trend for 1900-2015 shows significant warming of the Atlantic and Pacific hurricane development regions
Hurricane Strength and Ocean Temperatures
Cat. 1
Cat. 2
Cat. 3
Cat. 4
Cat. 5
Courtesy of Zeke Hausfather, Berkeley Earth
Relative Frequency by Type
.4
.3
.2
.1
0
70
75
80
85
Average Water Temperature (F) at Core Location (Prior 30 days)

Post Windstorm Investigations – Hurricane Michael

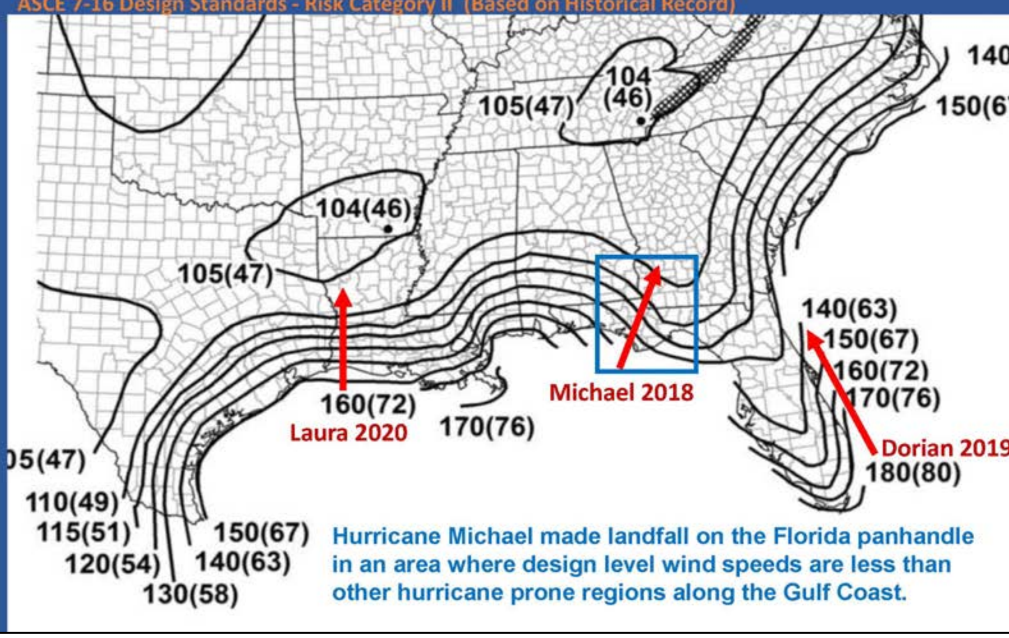


Up to 2C SST anomaly in northern Gulf of Mexico. Hurricane Michael underwent rapid intensification in the midst of moderate vertical wind shear. Analogous to expected increases in both SST and wind shear associated with climate change.

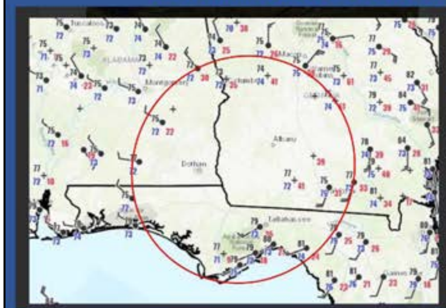
Figure Courtesy of Professor Kris Karnauskas, University of Colorado

Post Windstorm Investigations – Hurricane Michael

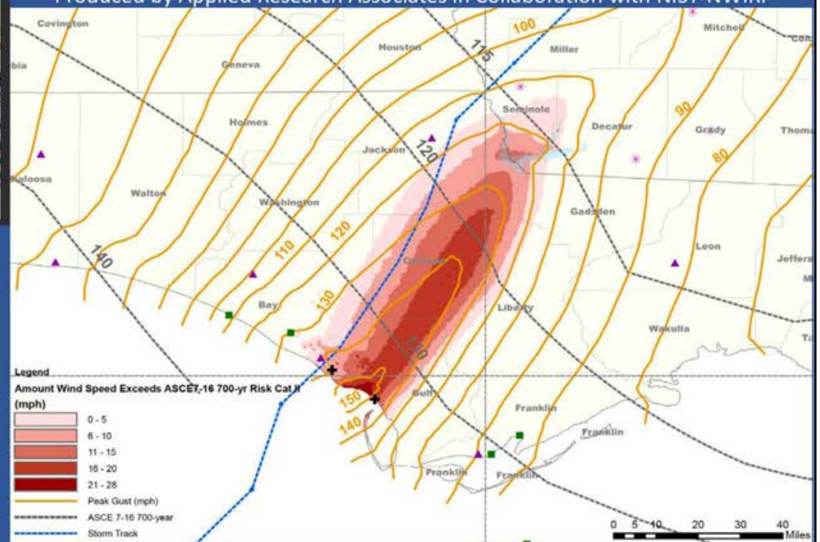
ASCE 7-16 Design Standards - Risk Category II (Based on Historical Record)



Hurricane Michael – An Above Design Level Event



Produced by Applied Research Associates in Collaboration with NIST-NWIRP



FEMA-NIST Mission Assignment

Wind maps are developed by applying a model fit to available surface wind observations from ASOS/AWOS and other in situ data sources, if available (ongoing research to incorporate radar obs)

NIST Hurricane Maria Program

NWIRP Strategic Objectives	Project	Legislative Authorities
1-4	**Multi-Hazard Characterization** Wind, Rainfall, Flooding, Storm Surge, Landslides	NCSTA
7-9	**Deaths and Injuries** Associated Technical Conditions	NCSTA
5-6,10-12	**Critical Building Performance** Structural Elements/Lifeline Dependence	NCSTA
13-14	**Emergency Communications** Public Reception and Response	NCSTA
5, 9-12	**Infrastructure Support** Power/Water etc. & Linkage to Critical Facilities	NWIRA
7-8	**Critical Social Functions/Recovery** School Function and Impact on Education	NWIRA
7-8	**Business Interruption/Recovery** Midsize Manufacturing and Supply Chain	NWIRA

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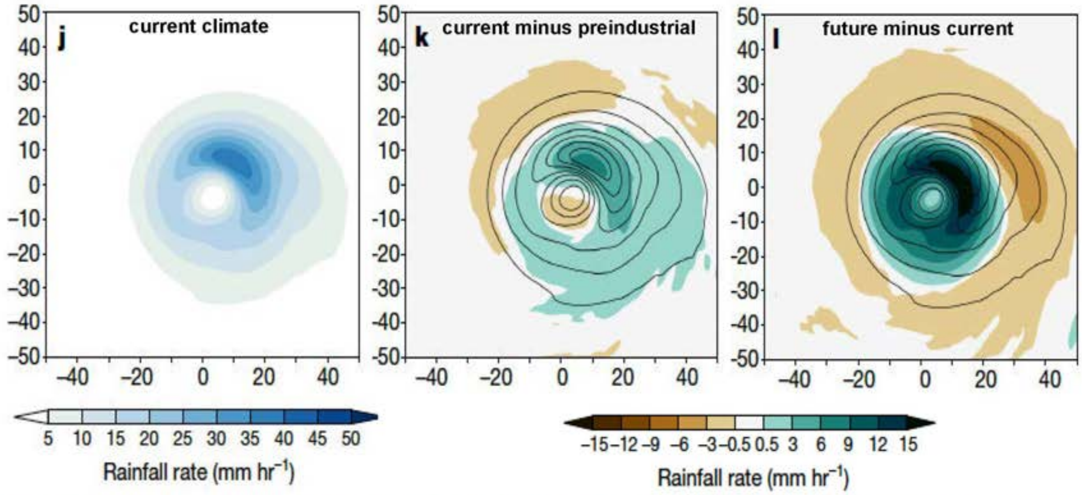
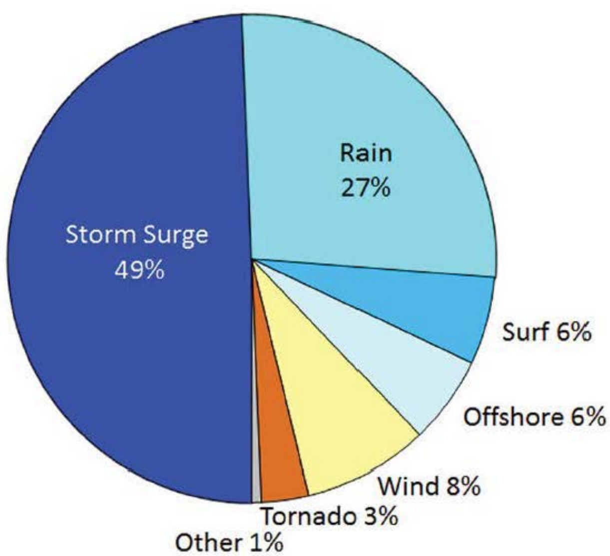
Single Event Attribution of Hurricane Maria



The simulated intensity of hurricane Maria's rainfall, increases from the preindustrial to the current climate, intensifying further as warming continues.

Patricola and Wehner, Nature, 2018 – With Permission

Hurricane Fatalities as Function of Hazard 1963-2012



Rainfall fatalities ~2.5 times that of wind + tornado

Statistics are sensitive to outliers

1970-99 period had 6 storm surge related deaths

When analysis period is expanded to 1963-2012:
1139 Storm Surge Fatalities
627 rainfall fatalities
186 wind fatalities

Data Source: NOAA/National Hurricane Center, Rappaport 2014

Rainfall Analysis of Hurricanes Irma and Maria

Data

- Rain Gauge Network obtained from NOAA/National Weather Service.
- NOAA/NCEP Stage IV Data. Combines radar and gauges. 4km.
- UCSB Climate Hazards Infrared Precipitation with Stations (CHIRPS). Combines infrared satellite measurements with rain gauge data. 5km/daily/1981-present.
- NASA GPM/IMERG. Combines data from all GPM passive microwave instruments and merges with rain gauge estimates. 10km/30-minute/2014-present.

Points to Consider

- Topography enhances rainfall production.
- Rainfall measurement systems may show significant variability.
- Rainfall can be used as a flood proxy in addition to or in the absence of large area-wide inundation estimates.
- Rainfall is the primary input to hydrologic models which are used to produce estimates of flood inundation and landslide density.

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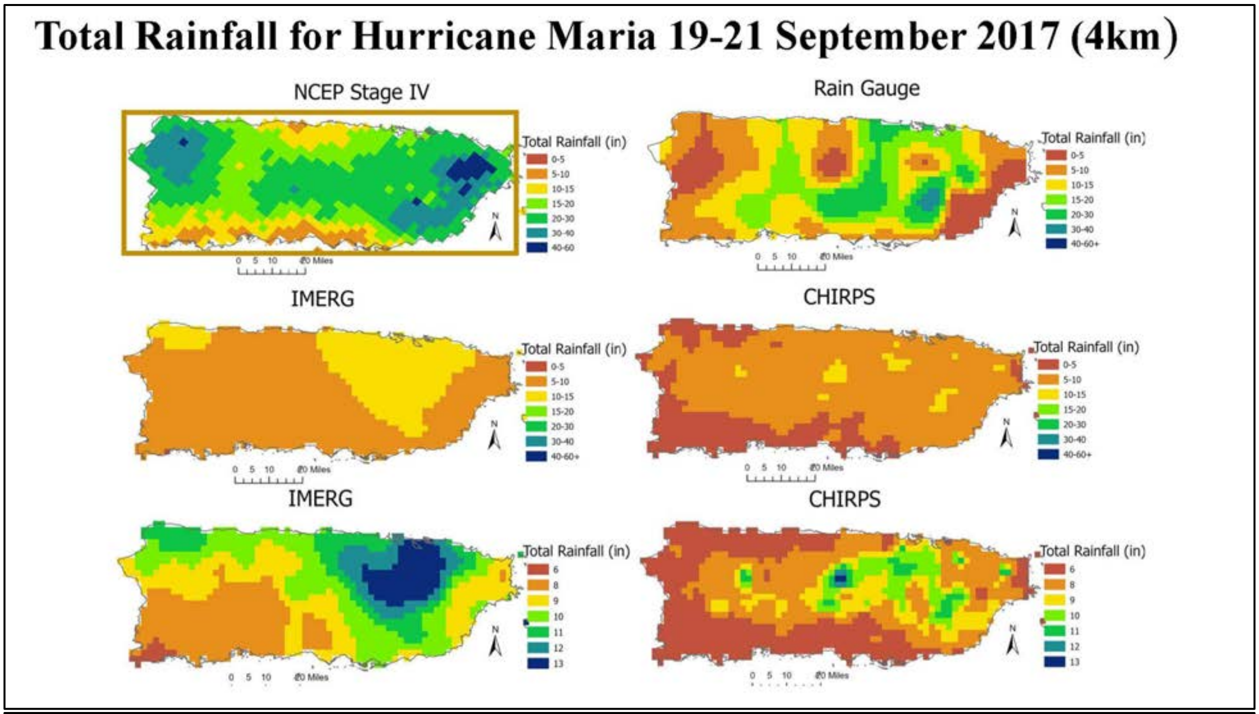
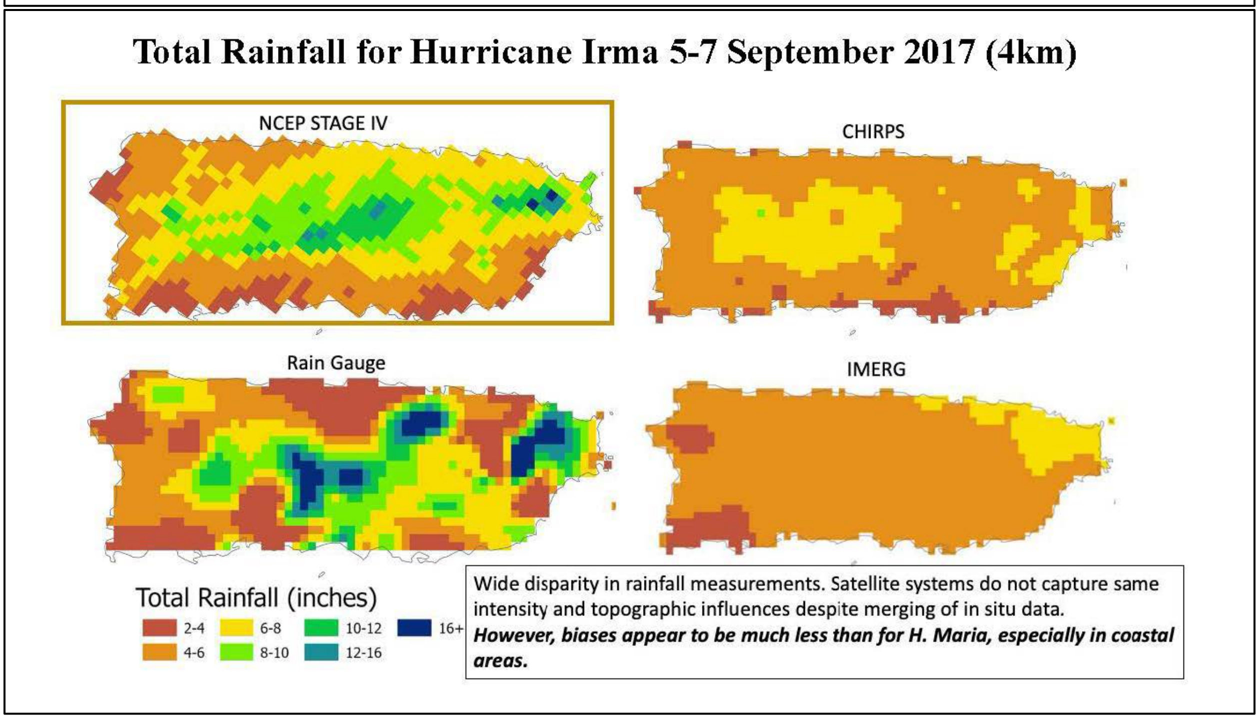
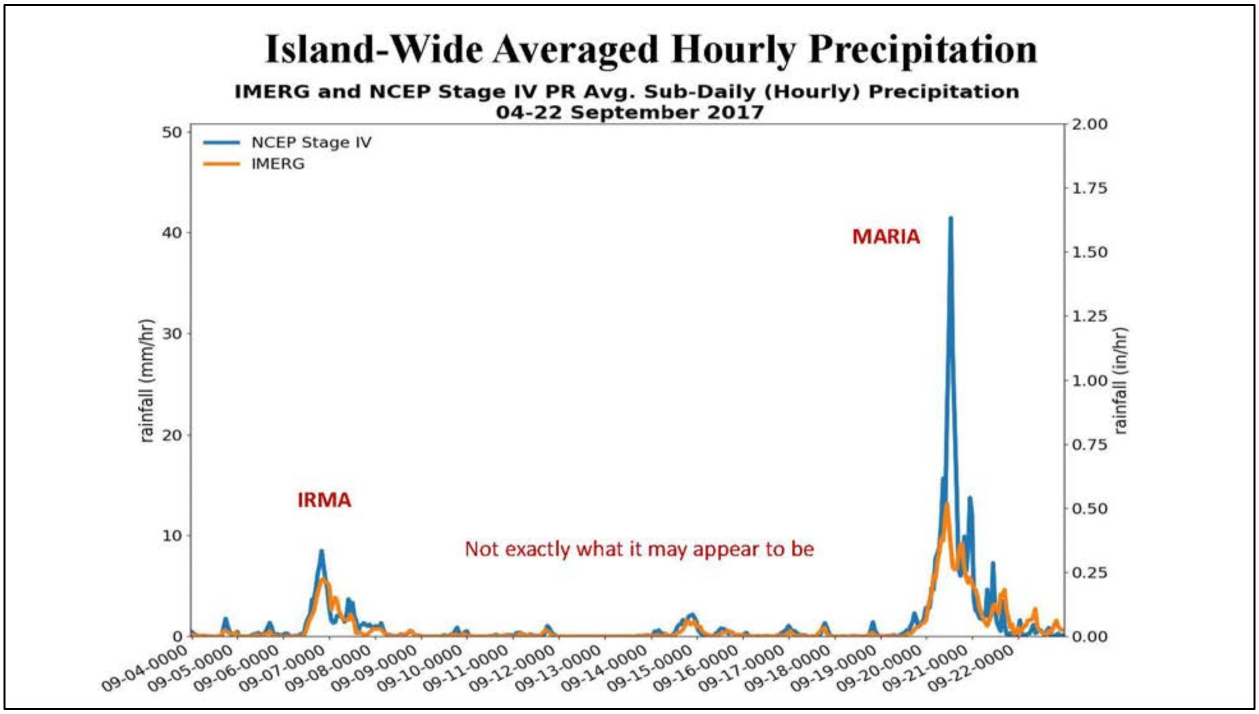
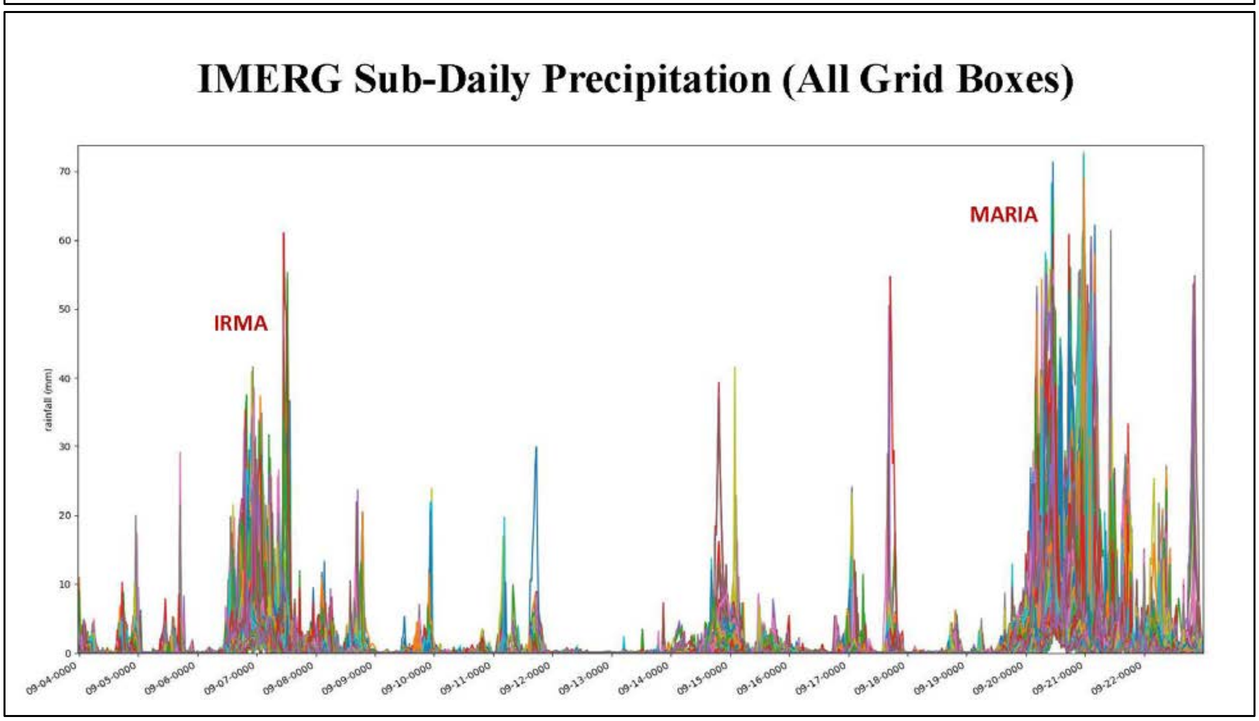
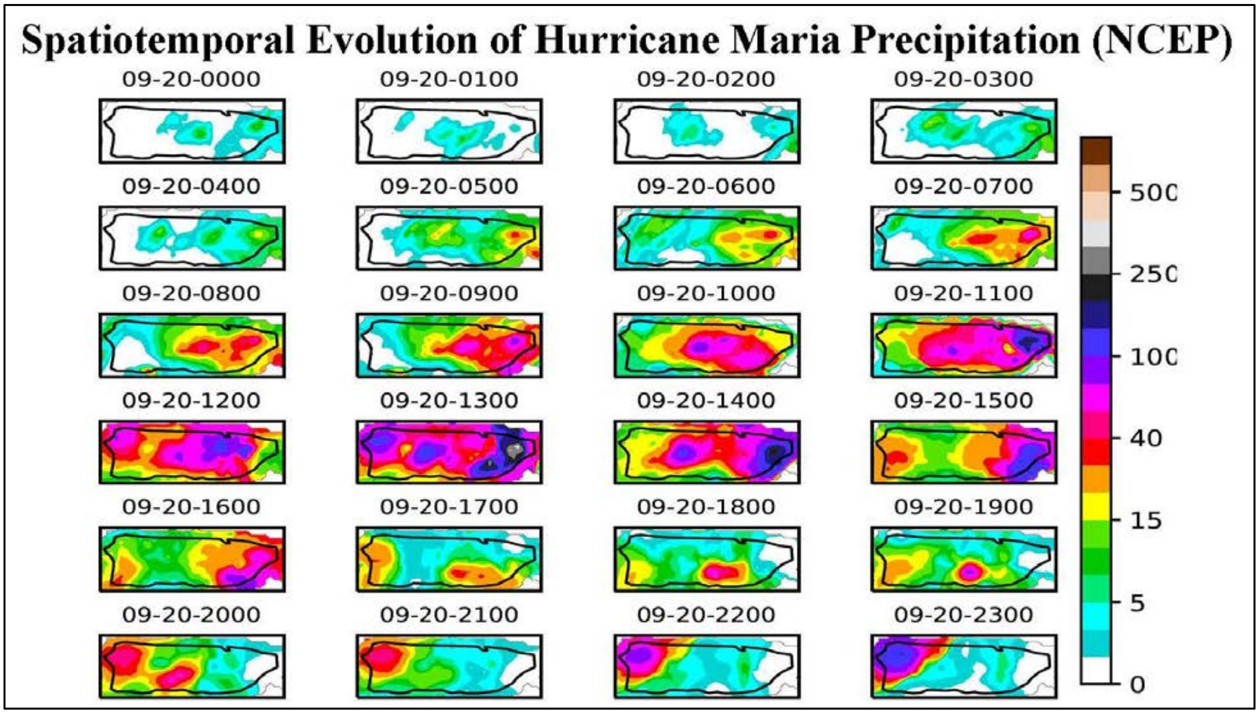
Topography is the Connective Tissue for Inland Hazards


Total Rainfall for Hurricane Maria 19-21 September 2017 (4km)
NCEP Stage IV
Rain Gauge
IMERG
CHIRPS
IMERG
CHIRPS
Total Rainfall (in)
0-5
5-10
10-15
15-20
20-30
30-40
40-60
40-60+
6
8
9
10
11
12
13
0 5 10 20 Miles
N


Total Rainfall for Hurricane Irma 5-7 September 2017 (4km)
NCEP STAGE IV
CHIRPS
Rain Gauge
IMERG
Total Rainfall (inches)
2-4
4-6
6-8
8-10
10-12
12-16
16+
Wide disparity in rainfall measurements. Satellite systems do not capture same intensity and topographic influences despite merging of in situ data.
However, biases appear to be much less than for H. Maria, especially in coastal areas.


Island-Wide Averaged Hourly Precipitation
IMERG and NCEP Stage IV PR Avg. Sub-Daily (Hourly) Precipitation
04-22 September 2017
NCEP Stage IV
IMERG
rainfall (mm/hr)
rainfall (in/hr)
MARIA
IRMA
Not exactly what it may appear to be
09-04-0000
09-05-0000
09-06-0000
09-07-0000
09-08-0000
09-09-0000
09-10-0000
09-11-0000
09-12-0000
09-13-0000
09-14-0000
09-15-0000
09-16-0000
09-17-0000
09-18-0000
09-19-0000
09-20-0000
09-21-0000
09-22-0000


IMERG Sub-Daily Precipitation (All Grid Boxes)
MARIA
IRMA


Spatiotemporal Evolution of Hurricane Maria Precipitation (NCEP)
09-20-0000
09-20-0100
09-20-0200
09-20-0300
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100
40
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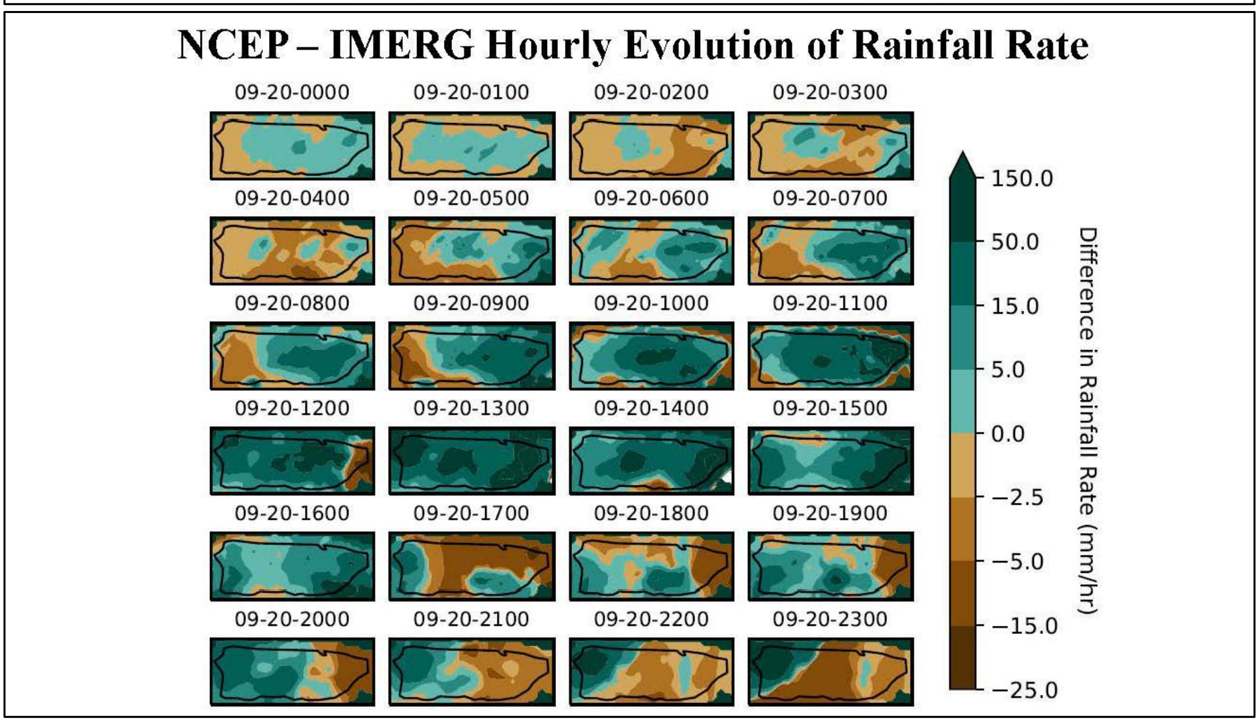
NCEP – IMERG Hourly Evolution of Rainfall Rate
09-20-0000
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09-20-0700
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09-20-1600
09-20-1700
09-20-1800
09-20-1900
09-20-2000
09-20-2100
09-20-2200
09-20-2300
150.0
50.0
15.0
5.0
0.0
−2.5
−5.0
−15.0
−25.0
Difference in Rainfall Rate (mm/hr)

Potential Future Work

- Analyze additional datasets (e.g., CMORPH).
- Assess Hurricane Maria rainfall as a function of relevant focus regions and/or watersheds.
- Conduct climatological analysis of Puerto Rico rainfall to contextualize recent extreme hurricane rainfall.
- Conduct additional case studies of CONUS landfalling hurricanes with exceptional rainfall amounts over flat terrain.
- Leverage results to make recommendations relevant to the National Windstorm Impact Reduction Program Strategic Objectives.

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3.2.2.3 Questions and Answers

Question:
When you showed the maps from ASCE 7, one thing that immediately came to mind was: what about making maps showing potential changes in different climate scenarios? Is there enough information or confidence in the climate simulations to produce practical maps like that?

Scott Weaver:
Thanks for the question. You are speaking my language when you talk about generating these maps for future scenarios. Obviously, the maps in ASCE-7 part of a voted-on standard. The scientific information in the historical record is used to generate the map, and then there are various ASCE committees who vote on them. They ask questions such as: (1) whether these are going to be the master; (2) do we need to tweak them in anyway; and (3) are there more uncertainties here or there? So, there's that element to eventually getting adopted into the official standard. To the question that you're asking about confidence, one of the hurdles would be whether the stakeholders involved in developing those official standards feel comfortable with that. That’s one issue. But the way I look at it, from the climate science perspective, is just like you mentioned. I've brought this question up exactly as you phrased it: can't we develop some scenario maps? What would this this map would look like if we're on this trajectory, or another trajectory. Maybe it would change significantly, maybe change only slightly, or maybe stay the same. But I think that it can be done.

From what I understand, you could even use synthetic hurricane models. These maps are anchored in observations, but there just aren't enough landfalls. So, they use Monte Carlo simulation techniques, or they develop synthetic probabilities based on the historical record to generate thousands of landfalling storms. That's how they come up with the mean recurrence interval for the map. The question is: what does that anchor to? I’ve had preliminary discussions with the folks who generate those hazard maps. If they had confidence in the SST projections in the Atlantic and in the Gulf of Mexico, they would be able to generate scenario maps. So that could be done. I think it's just a matter of how and if it would be adopted by the standards committees. But my point of view on it is, you know, get the information out there. Maybe it's not officially adopted right away, but for communities or states or regions that are interested in knowing that information, I think it would be highly relevant to their decision-making processes.

3.2.3 Presentation 1B-3: Quantifying Shifts in Joint Rainfall-Surge Hazard due to Future Climate Warming

Authors: Avantika Gori, Ning Lin, Princeton University

Speaker: Avantika Gori

3.2.3.1 Abstract

Compound flooding, characterized by the co-occurrence in space and/or time of multiple flood mechanisms, is a major threat to coastlines across the globe. Tropical cyclone (TC) events are responsible for many compound floods due to their wind-driven storm surge and extreme rainfall. However, the dynamics between rainfall and storm surges, as well as possible shifts in their statistical dependence under future climate change, is still not well understood. We investigate the relationship between TC storm surges and rainfall under current and future conditions for the US East and Gulf coasts by utilizing large sets of synthetic tropical cyclones derived from eight GCMs. We model each synthetic TC within a basin-scale hydrodynamic model to estimate storm tides at the coast and estimate TC rainfall using a simplified physics-based model. We then quantify the joint distributions of rainfall and storm surge across the US coastline and evaluate how their joint hazard could increase by the end of the 21st century due to climate warming. We also investigate which TC characteristics are likely to produce both extreme rainfall and extreme storm tides, and quantify which regions of the coastline are most vulnerable to joint rainfall-surge hazard. Our study provides a step forward in understanding how TCs contribute to coastal compound flood hazard and how climate change could exacerbate joint flood hazard in the future.

3.2.3.2 Presentation (ADAMS Accession No. ML21064A423)

QUANTIFYING SHIFTS IN JOINT RAINFALL-SURGE HAZARD UNDER FUTURE CLIMATE WARMING

Avantika Gori, Ning Lin, Dazhi Xi

Princeton University, Department of Civil and Environmental Engineering

PRINCETON UNIVERSITY

Ning Lin
Hurricane Hazards and Risk Analysis
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NDSEG

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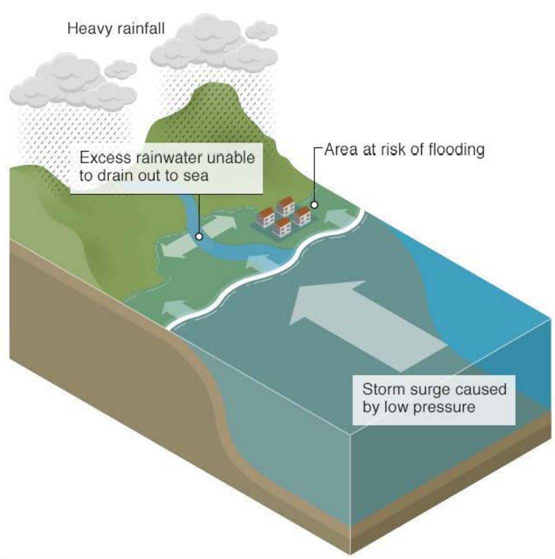
What is Compound Flooding?

- Compound flooding results from the the occurrence of multiple types of flooding (rainfall, riverine, storm surge) simultaneously or sequentially such that overall hazard is increased.

(Zscheischler et al., 2018, Nature)



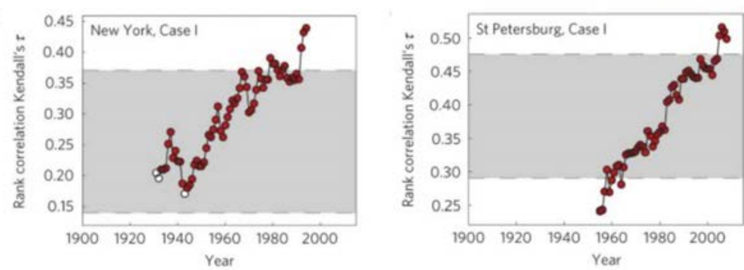
Source: Douglas Maraun/Science Advances BBC

Coastlines across the world are vulnerable to compound flooding

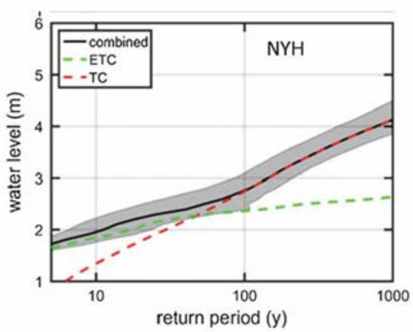
Couasnon et al. (2019), NHESS

Dependence between storm surge and precipitation may have been rising

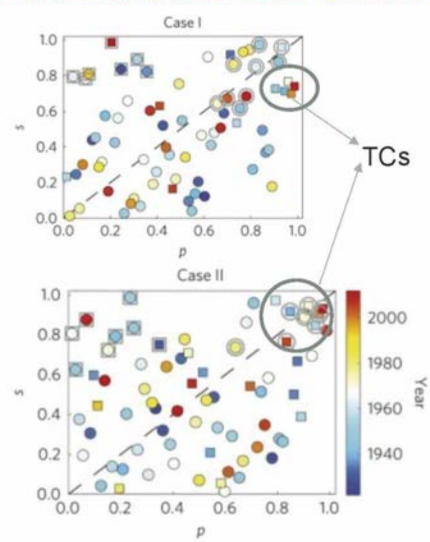
Wahl et al. (2015) *Nature*



Tropical cyclones (TCs) are one of the main causes of compound flooding along the US East and Gulf Coast



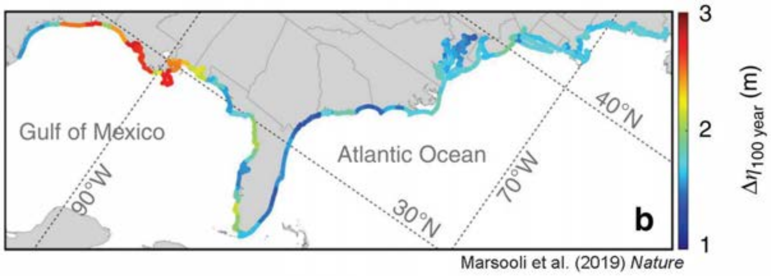
Orton et al. (2018) *Nat Hazards*



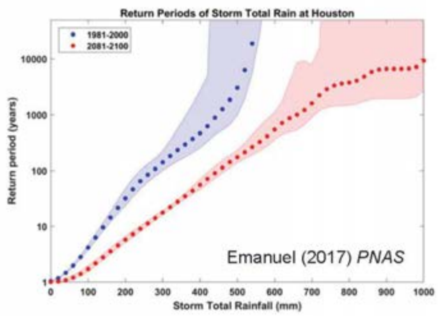
Rescaled pairs of ranks of storm surge (*s*) and precipitation (*p*) for NYC; Wahl et al. (2015) *Nature*

The threat of TC compound flooding may be rising…

Projections of future storm surge and rainfall hazard due to climate change



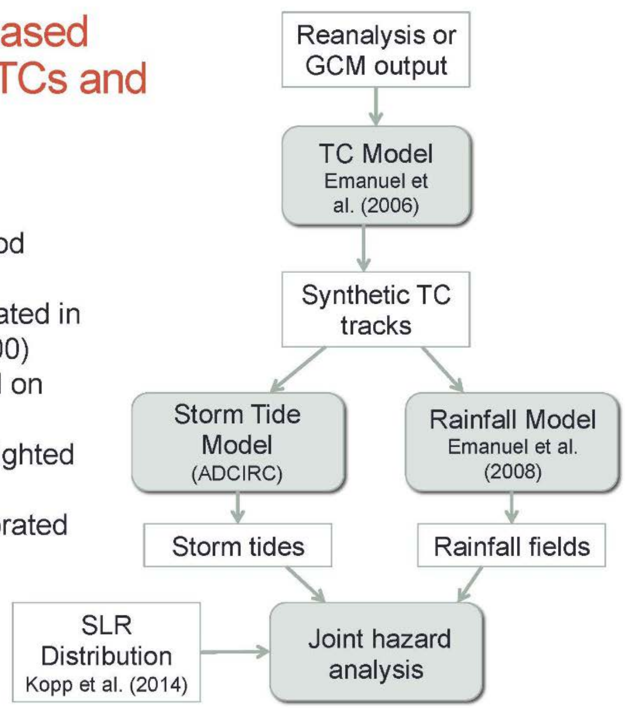
Marsooli et al. (2019) *Nature*



Will the interaction of these hazards also increase due to climate change?

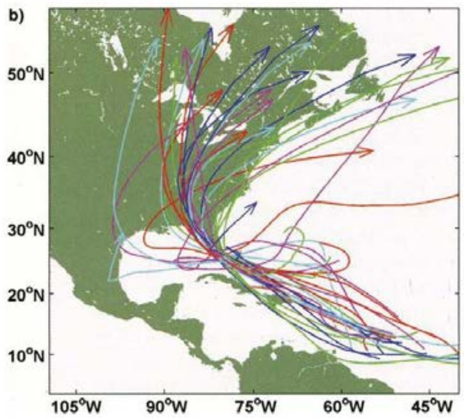
We utilize physics-based models to simulate TCs and their hazards

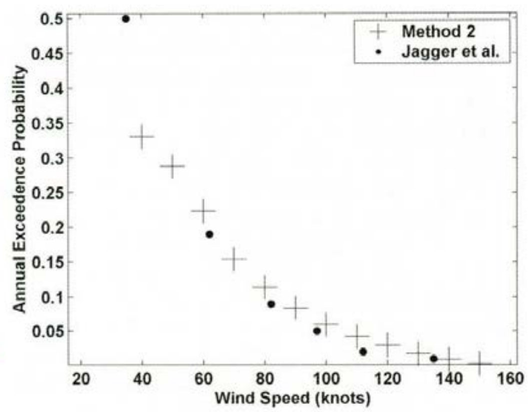
- NCEP reanalysis data represents historical period (1980-2005)
- 8 CMIP6 GCMs incorporated in future analysis (2070-2100) and bias corrected based on historical period
- Composite projection weighted average of 8 models
- Probabilistic SLR incorporated in hazard analysis



Synthetic TC Tracks

- Obtained 6200 synthetic TCs (track, intensity, size) generated from the statistical-deterministic TC model for each GCM in each period





Emanuel et al. (2006), *Bull. of the AMS*

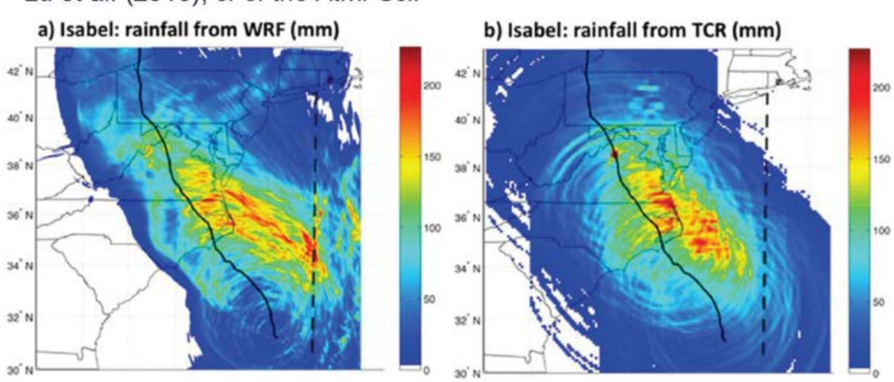
TC rainfall (TCR) model

$$P_{\text{rate}} = \epsilon_p \frac{\rho_{\text{air}}}{\rho_{\text{liquid}}} q_s (w_f + w_h + w_t + w_s + w_r)$$

Frictional, Topographic, Stretching, Shear, Cooling

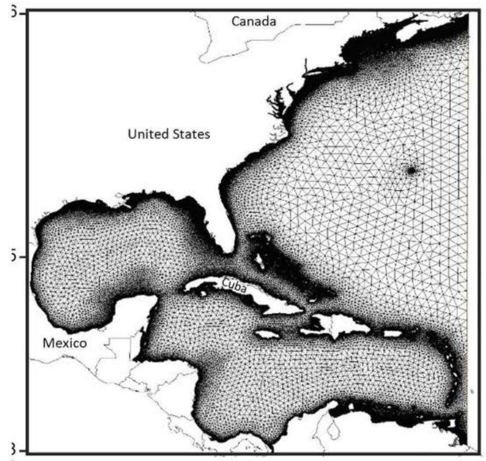
More recently, Xi et al. (2020) compared TCR against historical TC rainfall for entire US

Lu et al. (2018), *J. of the Atm. Sci.*



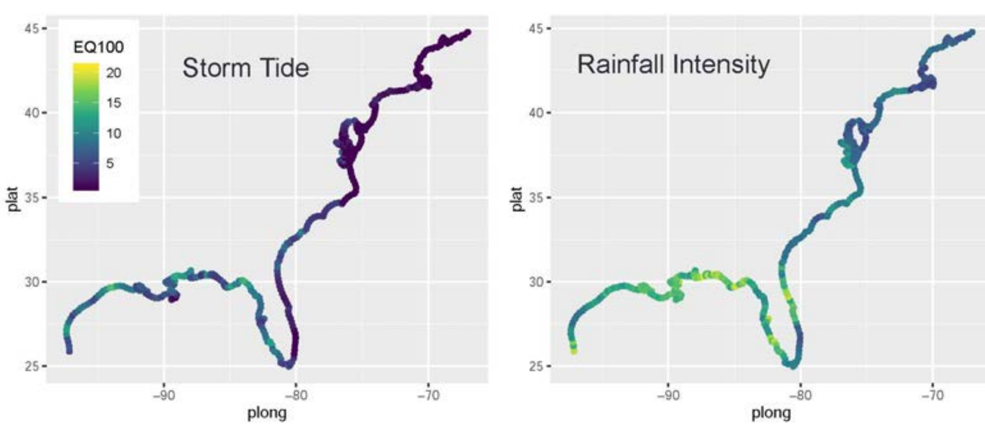
Hydrodynamic storm tide model (ADCIRC)

- 2D depth integrated shallow water model developed by Luettich and Westerink
- North Atlantic basin scale mesh developed in Marsooli & Lin (2018)
- 8 tidal constituents
- Pressure: Holland (1983)
- Wind: Emanuel & Rotunno (2011)



Marsooli & Lin (2018), *JGR Oceans*

Future storm climatology and SLR cause the 100yr storm tide to become ~1yr event and 100yr rainfall to become <5yr event in some locations



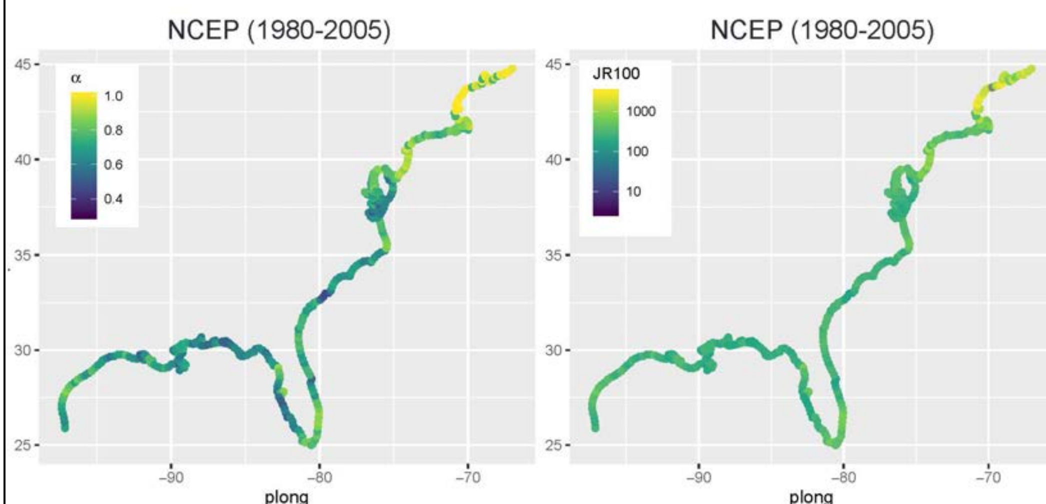
Quantifying statistical dependence between storm tide and rainfall

Bivariate Threshold Excess Model (Coles, 2000)

- Joint exceedances are modeled with bivariate logistic model
  - $G(x,y) = \exp(-(x^{-1/a} + y^{-1/a})^{a})$
  - a → 1 : Complete Independence
  - a → 0 : Complete Dependence

- We define critical thresholds of storm tide (x) and rainfall intensity (y) as their 100-year levels during the historical period
  - What is the return period of joint exceedance in the historical period?
  - Considering future sea level rise, future storm climatology, and their combination

High rainfall-surge dependence along GoM and low dependence along NE coastline in historical period



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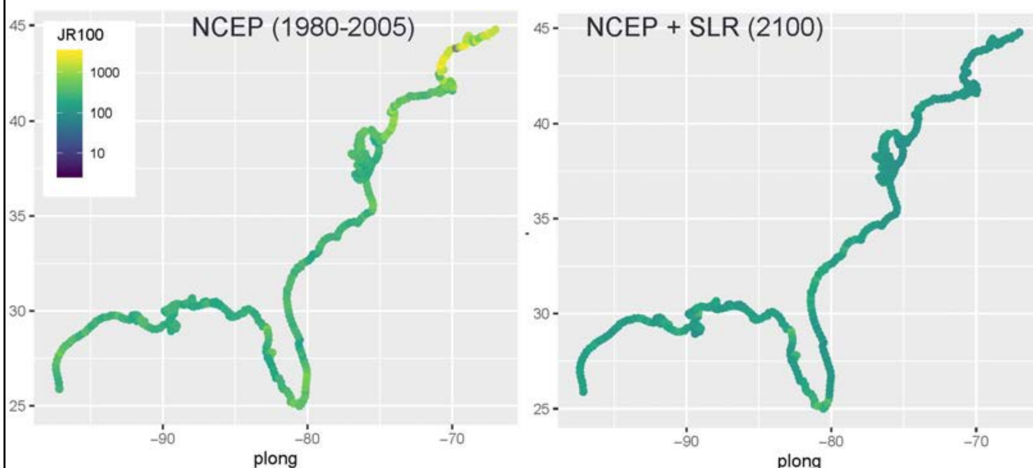
Impact of SLR alone increases frequency of joint exceedance events

- We use a standard Monte Carlo approach to randomly perturb each storm tide – rainfall pair according to the SLR distribution (as in Mofthakhari et al. 2017)



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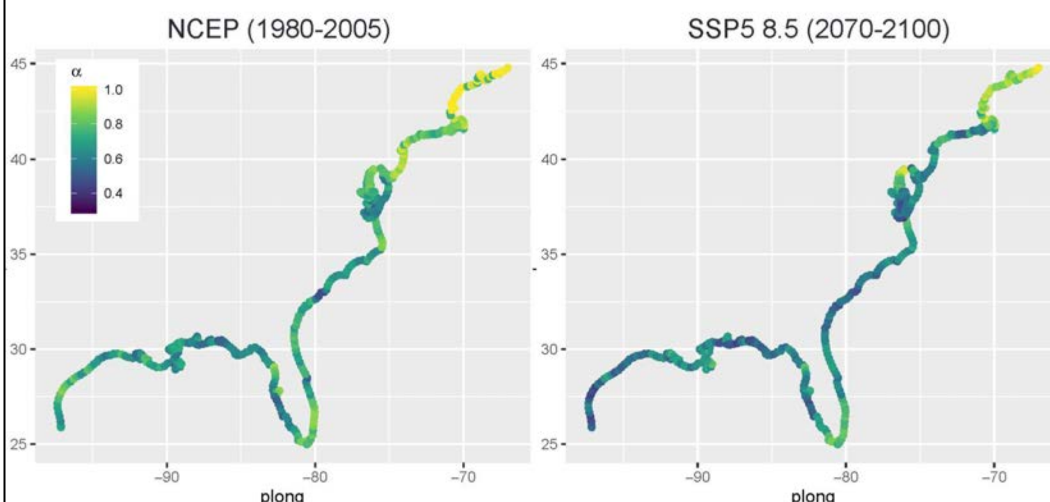
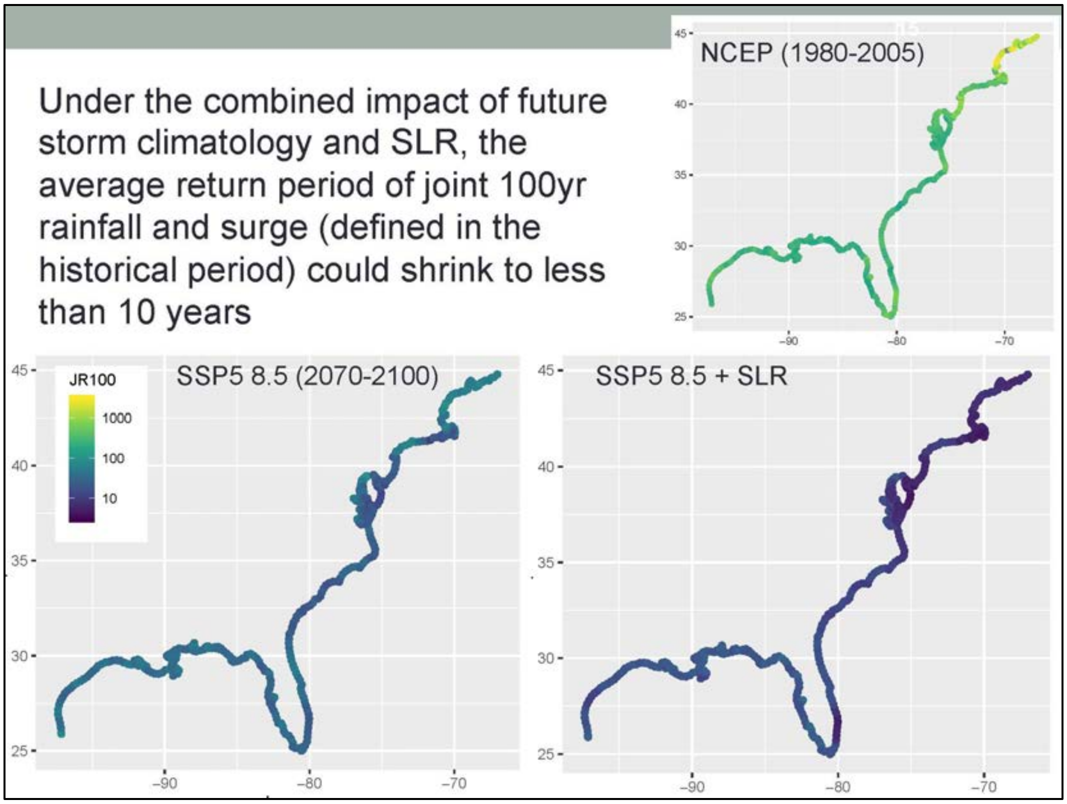
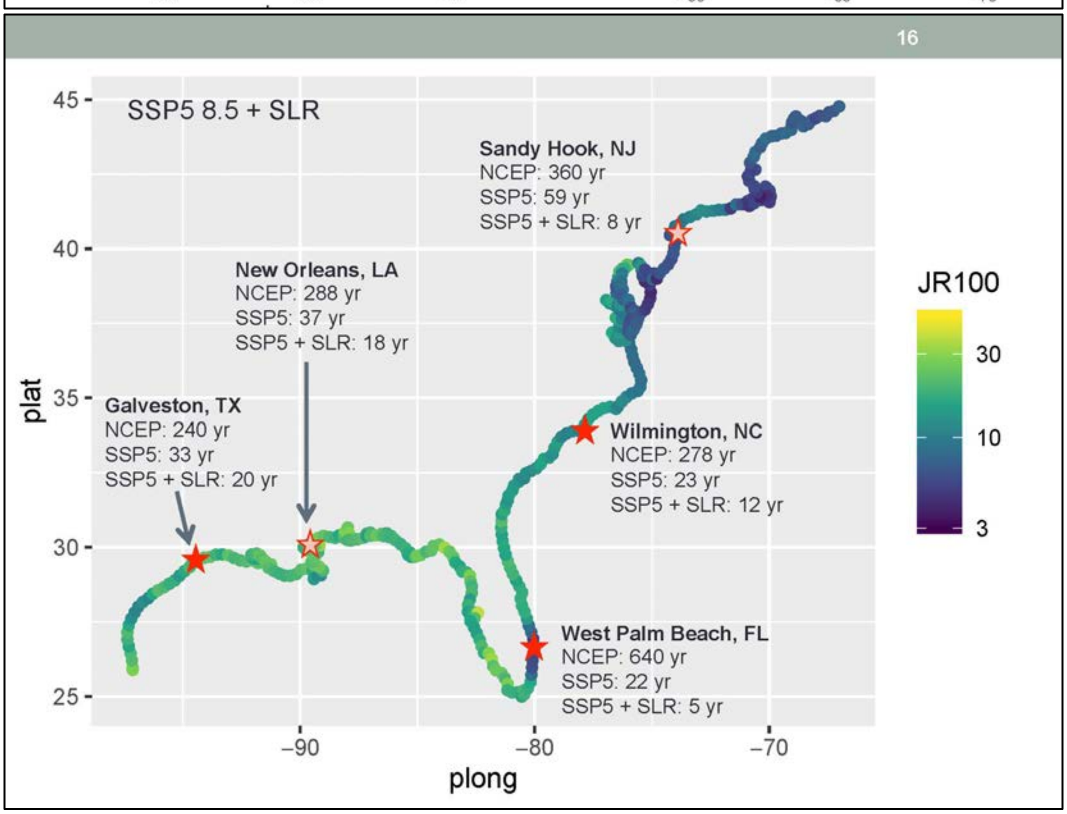
How do changes in storm climatology exacerbate joint hazard?

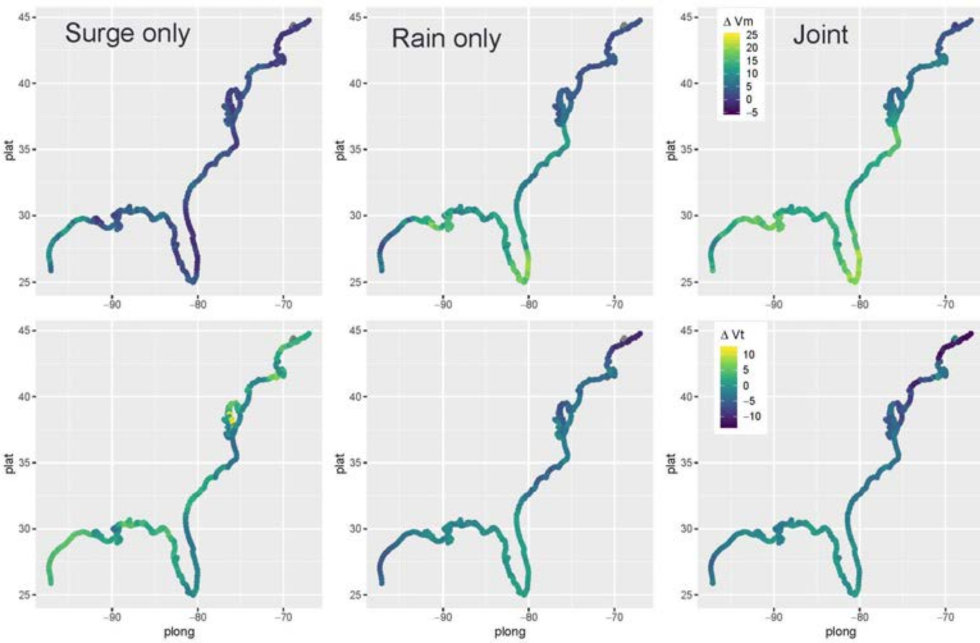
- Increase in either (or both) hazards (similar to impact of SLR)
- Increase in statistical dependence between hazards




Under the combined impact of future storm climatology and SLR, the average return period of joint 100yr rainfall and surge (defined in the historical period) could shrink to less than 10 years
NCEP (1980-2005)
SSP5 8.5 (2070-2100)
SSP5 8.5 + SLR
JR100
1000
100
10
45
40
35
30
25
−90
−80
−70


16
SSP5 8.5 + SLR
Sandy Hook, NJ
NCEP: 360 yr
SSP5: 59 yr
SSP5 + SLR: 8 yr
New Orleans, LA
NCEP: 288 yr
SSP5: 37 yr
SSP5 + SLR: 18 yr
Galveston, TX
NCEP: 240 yr
SSP5: 33 yr
SSP5 + SLR: 20 yr
Wilmington, NC
NCEP: 278 yr
SSP5: 23 yr
SSP5 + SLR: 12 yr
West Palm Beach, FL
NCEP: 640 yr
SSP5: 22 yr
SSP5 + SLR: 5 yr
JR100
30
10
3
plat
plong
45
40
35
30
25
−90
−80
−70

What storm characteristics are associated with rain and/or surge hazard?



Limitations and Future Work

- How can we account for antecedent rainfall and/or interaction with other weather systems?
- Does non-linear interaction of SLR and storm tides significantly impact total water levels?
- How does increase in joint hazard severity translate to coastal flood impacts?
    - Our work can be used to develop boundary conditions for local-scale flood models

3.2.3.3 Questions and Answers

Question:
Did you consider nonstationarity in your modeling?

Avantika Gori:
In this case, no. We assume that the NCEP storms are all derived from one stationary climate and then all the future storms from 2017 to 2100 are generated under a future stationary climate. So, we're mostly looking at just the change between two different climate states.

Question:
Do you have plans to include the riverine watershed contribution to the flooding?

Avantika Gori:
Yes, ideally. However, I think adding in the riverine contributions is difficult because you can have independently high river flows that are not necessarily related to the tropical cyclone, and you can also have inland rainfall from the TC that runs off as river discharge. I think simulating the inland rainfall component is very difficult for these TC systems and the relatively simple TCR model isn't complex enough to account for rainfall that happens significantly inland from the coast.

Question:
Are changes in the tidal conditions due to climate included in the simulations that you've done?

Avantika Gori:
It's mostly a linear treatment of the sea level rise impacts. We model the storm surges within the hydrodynamic model and then we just increase linearly the total water level based on the probabilistic rates of sea level rise.

3.2.4 1B-4: Climate Panel Discussion

Moderator: Joseph Kanney, NRC/RES/DRA

Panelists:
Lai-Yung (Ruby) Leung, Pacific Northwest National Laboratory (PNNL)
Scott Weaver, National Institute of Standards and Technology (NIST)
Avantika Gori, Princeton University

Question (to panel):
With respect to application of climate models to flood hazard assessment for critical infrastructure such as nuclear power plants, high hazard dam, etc., what do you consider to be the grand challenge in getting us there. And conversely, are there any pieces that you consider be low hanging fruit for which we could make significant progress with a limited or modest effort?

Ruby Leung:
I think part of the grand challenge in flood hazard assessment for critical infrastructure, is that the interest is in very low probability events, which often are not easy to simulate. Therefore, when combining the uncertainty in projecting how that might change in the future, I think that is really a big challenge. We don't have a very good approach that can allow us to both look at this type of extreme event as well as capturing the uncertainty.

Scott Weaver:
First of all, I definitely agree with Ruby's point. Then, thinking about this question, I don't know if they are grand challenges, but several things come to mind. One of the things is that we often talk a lot about precipitation, but we know that flooding is more than just how much rain can fall. If you have a tropical cyclone make landfall during a drought, you're going to very different response than if a pluvial episode preceded the event. Our last speaker talked a little bit about that in their last slide. They hinted at that.

One of the things in the other panelist talks I was really interested in is the low-level jet. I conducted research on the low-level jet many years ago. That was that was my primary research topic for quite a while. That's a driver of precipitation, but what we found is that in reanalysis and in many of the CMIP models, especially in the warm season over the central US. there's a lot of uncertainty based on how the models partition the precipitation mechanisms. There are two mechanisms. One is land-atmosphere interactions (precipitation recycling that's driven by radiation interacting with the land surface and evaporation and those kinds of quantities). And then you have the transported moisture from the Gulf of Mexico, typically through mechanisms like the low-level jet. What a lot of groups were seeing is that the CMIP models do not partition that appropriately, when you compare it to observations. So, that could give you a wildly different answer even if you're projecting the proper scenario. The response is very sensitive, especially in the summertime. So, the mechanisms that underpin that, I think are really important. Not just focusing on what generates precipitation, but how the models respond in the coupling to the land.

Moderator (to Scott Weaver):
Would you consider that a low hanging fruit item?

Scott Weaver:
To be honest, I'm not very active in this line of research now. But I don't think it's really improved. I'm not sure it's been analyzed as vigorously as it was in CMIP-3. Taking a look at CMIP-5 and now CMIP-6, I don't think it's low hanging fruit because you would need a significant amount of research into understanding the processes in the models and relating that to the observations. So, it's not low hanging fruit, but I personally think it's doable. It would depend on what the more recent model iterations are showing

Moderator (to Ruby Leung):
Could you speak about the capability of the more recent models?

Ruby Leung:
I think simulating the Great Plains low-level jet is still quite challenging, especially for global models. But, as I advocated, I think the storyline approach can help a bit. I do think that regional models can capture this type of process much better in terms of both the larger scale impact on the Great Plains low-level jet as well as the local processes like soil moisture and land-atmosphere interaction. So, by isolating that type of problem using regional models, relative to only using global models to give us the large-scale circulation context, I think we can make some headway there in better understanding the Great Plains low-level jet, and in simulating them.

Avantika Gori:
The question is a little bit outside of my area of research. But from the research I do on coastal multi-mechanism flooding, I think another big issue is rainfall duration. We've seen a lot of empirical evidence of hurricanes stalling along the coastline, which increases the duration of flood impacts and increases the duration of extreme rainfall. I think it's quite difficult to simulate

that in a probabilistic way, so one of the big challenges I see ahead is being able to account for those sort of worst case scenarios that actually may become more frequent in the future.

Question (to panel):
I'd just like to take advantage of your collective expertise to address a question that I've heard in the media and just anecdotally. When you are talking about forecasting, the uncertainty grows as we forecast further into the future. The one-day look ahead has more skill than the three-day and the three day has more skill than looking out over seven days in advance. However, for climate modeling, this situation seems to be reversed. The confidence in the projection that we have for the next decade is lower than that which we have for projections that are or 50 or 100 years out in the future. Can you explain why this is the case?

Ruby Leung:
I can take a crack at that first. When we talk about forecasting in the context of weather, we're really talking about what we call an initial value problem. So essentially you tell the model (doesn't matter whether it's a statistical model or dynamical model) what we have now at this time, and then you try to forecast out a day or two days. The errors in the initial condition grow rapidly because we're dealing with a very nonlinear system. Weather itself is a very nonlinear system, and therefore the longer you go into the future, the errors become larger, and you lose predictability. But when you are talking about climate change, this is what we call a boundary value problem. We're really looking for the response to some forcing. The forcing might be coming from greenhouse gases. Some of it might be coming from land use or land cover change. So, the father out you go, the signals usually become stronger. For example, if we continue to emit greenhouse gases the signals related to that forcing will grow in the future. So, at some point you are really trying to look for the signals larger than the noise. The noise is the internal variability in the climate system model. So, when you look out into the future you have more confidence because the signals become larger than the noise.

Scott Weaver:
When we look at the climate scenarios and the emission scenarios, they don't diverge in the near term. They really begin to separate, climate forcing begins to diverge from different scenarios, as you go out in time. But there's also an analogy to this (idea that the weather forecast goes awry much quicker) even in the shorter time frame. I would advise not using a weather forecast beyond, say, seven or eight days. Then you get into this kind of dark period in the two-week to four-week range and then you start recovering skill after that. It's the same principle. So, if you're trying to predict what is this summer going to be like from a hydrological standpoint in the U.S, it's going to be regionally dependent, but the boundary conditions that Ruby mentioned (e.g., the status of soil moisture, the status of longer-term forcing mechanisms like El Nino in La Nina events) give us added confidence in longer term predictability. But there is this handoff between the weather time scale and when you start being able to see those slower evolving components of the climate system take shape and be able to give you some indication of what might happen. That's also another active area of research, maybe not in the climate change space per say, but in trying to understand, what's going to happen in that two-week to six-week timeframe. That's a rough, difficult period to deal with because of these issues.

Question (to panel):
What is the single largest contribution to the uncertainty in climate projections for rainfall and flooding (taking out the emission scenarios obviously)?

Avantika Gori:
I'm not sure about the single largest contribution, but I believe that there is a lot of uncertainty in directly utilizing rainfall estimates from GCMs. I think you run into a resolution problem, where the very extreme short duration rain events tend to be under-estimated. But it's not clear how to provide a better estimate of them, especially for cases like Hurricane Harvey where you have the intense TC rainfall. You also have interaction with fronts and the stalling that produces very significant rainfall. I think that's a very large contribution to the uncertainty in the sense that I don't think it's well captured among the global models. But I think it's hard to incorporate in a risk sense.

Scott Weaver:
I agree with Avantika. I don't claim to know what the single largest uncertainty is. But, thinking of Ruby's talk earlier, I'll again focus on the low-level jet and the finding that the jet is not really sensitive to the climate change signal in the summer. That may be true, and that's obviously an interesting finding. But look at internal variability or these natural climate variability modes like the Atlantic Multidecadal Oscillation (AMO) or the Pacific Decadal Oscillation (PDO) (there are arguments about whether some of these exist, but I'm not going to go into that). When we look at the footprints that have been gleaned from observations, we actually see that in summertime, the low-level jet can be strengthened by a cool phase of the AMO, for instance. And so, I think that how these multidecadal, or even interannual natural variability modes interact with the climate change signal (whether in phase or out of phase) is an additional level of uncertainty that's important. And, depending on which model characterizes those connections better than others, I think increases uncertainties. Not necessarily that they need to get the timing correct all the time. We're not going to predict them 100 years in the future, but the sensitivity to those kinds of modes, I think is important.

Ruby Leung:
I also think that the probably the single largest uncertainty in projecting rainfall and flooding changes is related to circulation. The circulation phenomenon could be the Great Plains low-level jet. It could be the upper-level jet and similar things. And if we further decompose this uncertainty in the circulation (like the Great Plains low-level jet), we can see that some of this uncertainty is related to uncertainty of how the models respond to certain forcing like greenhouse gases. But a major part of that uncertainty is just internal variability itself, and this uncertainty is almost irreducible because there's no way one can predict 50 years from now whether the AMO will be in a positive or negative phase or things like that. Unfortunately, that is a large part of the uncertainty, whereas uncertainty related to how a model responds to external forcing could potentially be reduced by improving the models, by improving the understanding of how the climate system responds to external forcing. But internal variability is essentially, I think, irreducible uncertainty.

Question (to panel):
Considering the recent extreme weather events that we've seen in the Midwest, can you briefly explain what are the major factors that control the polar vortex dynamics and what conditions lead to cold weather outbreaks such as what we've seen in the Midwest recently. What do current climate projections tell us, if anything, about polar vortex dynamics in the future?

Ruby Leung:
I have only a superficial understanding, but I can take a crack at it. When we talk about the polar vortex, there is the tropospheric polar vortex, and then there is the stratospheric polar vortex. In

the context of the recent extreme cold weather event, it is definitely related to the stratospheric polar vortex. To begin with, you need to have planetary waves in the troposphere with very long wavelengths (wave number one and two). When you have this kind of planetary wave, it can propagate up to the stratosphere and, because in the stratosphere the wind is of opposite direction, the wave cannot be sustained in the stratosphere and therefore the wave breaks. When the wave breaks it weakens the stratospheric polar vortex and then the cold air descends and rapidly warms because of adiabatic warming. This causes what we call sudden stratospheric warming. This sudden stratospheric warming perturbs the jet stream in the troposphere, and the movement of the jet stream creates blocking and things like that. I think this is what happened in the recent cold air outbreak events. But what causes the planetary wave to begin with? There is a lot of uncertainty and many different factors. Some people say that reduced sea ice in the Berants Sea and the Kara Sea might create this kind of planetary wave. There are also other factors, like colder temperatures in Siberia and Eurasia, that could also create this kind of planetary wave. Overall, I think there's quite a bit of uncertainty in terms of projecting into the future. Whether this kind of planetary wave would be excited more and how that may affect the stratospheric polar vortex is highly uncertain. What is actually more certain, from most of the models that we have seen, is simply that by getting a warmer temperature in the future you would reduce the temperature variance because there would be less action of cold air from the North and advection of warm air from the South. And this reduced temperature variance would significantly cut down the probability of cold air outbreaks in the future. I think this is the most certain part that we know. Other parts related to these kinds of mechanisms affecting the polar vortex and things like that is still very much in a research phase.

Scott Weaver:
I'll add one small comment. In the spring, in some of the 1.5-degree simulations versus the 2-degree simulations, we see increased temperature variability over the Midwest. So, you could also be getting more cold air outbreaks in the spring despite the mean temperature increasing because the variability is increasing. We didn't talk much about that variability increase here; we talked mostly about mean changes. But changes in variability have been observed, and it would be great to have more research on understanding if there's a greenhouse gas forcing component for that, just in general, whether it's precipitation or temperature.

3.3 Day 1: Session 1C – Precipitation

Session Chair: Elena Yegorova, NRC/RES/DRA

3.3.1 Presentation 1C-1 (KEYNOTE): On the Applicability of Kilometer-Scale Heavy Precipitation in Flood Risk Assessments

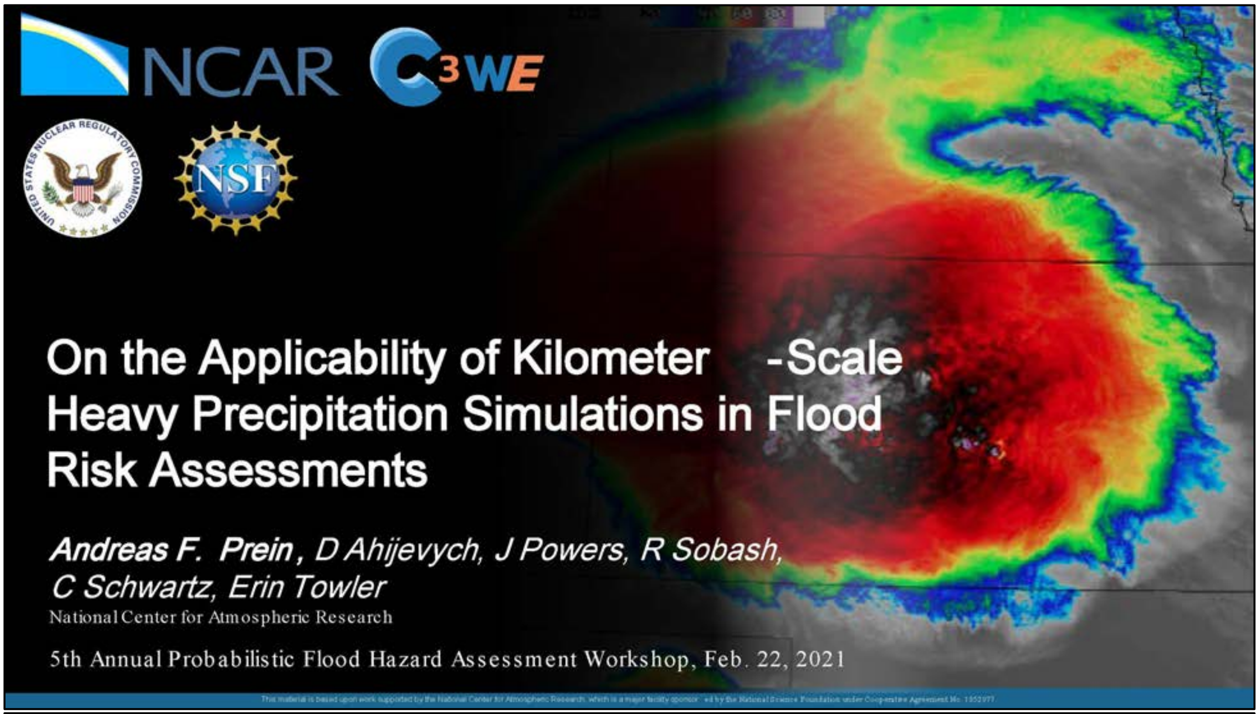
Authors: Andreas Prein, Jordan Powers, Erin Towler, David Ahijevych, National Center for Atmospheric Research

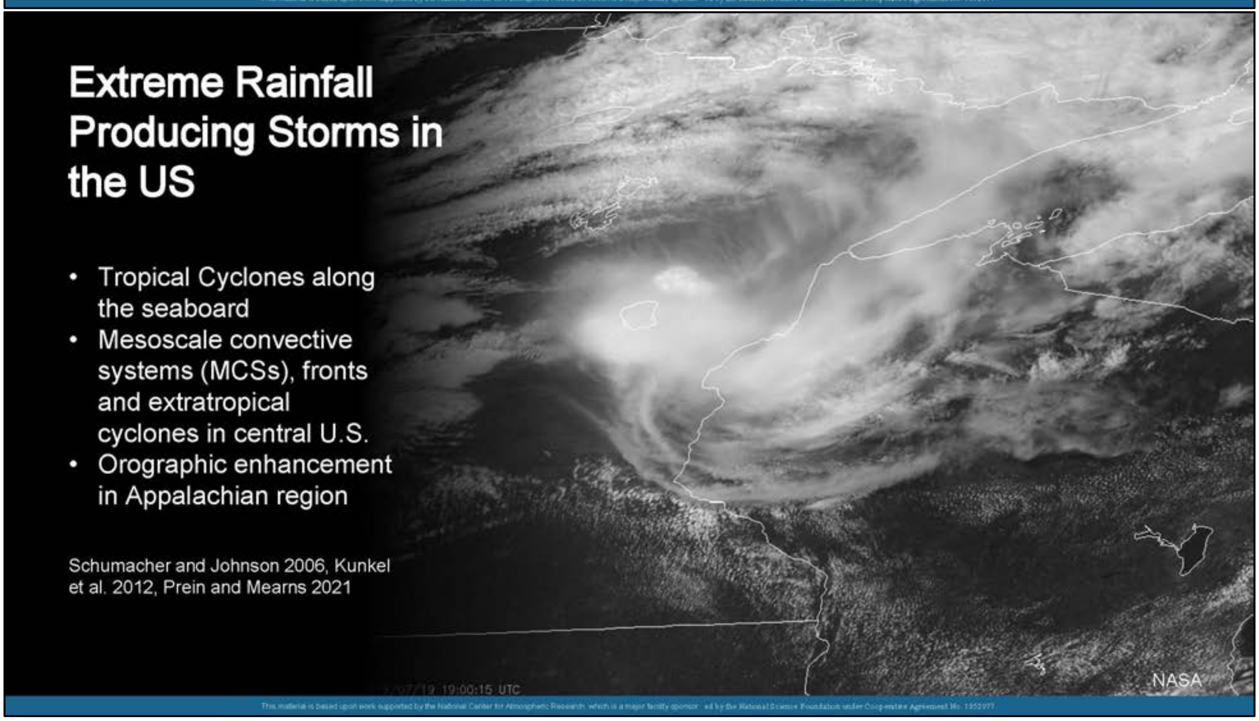
Speaker: Andreas Prein

3.3.1.1 Abstract

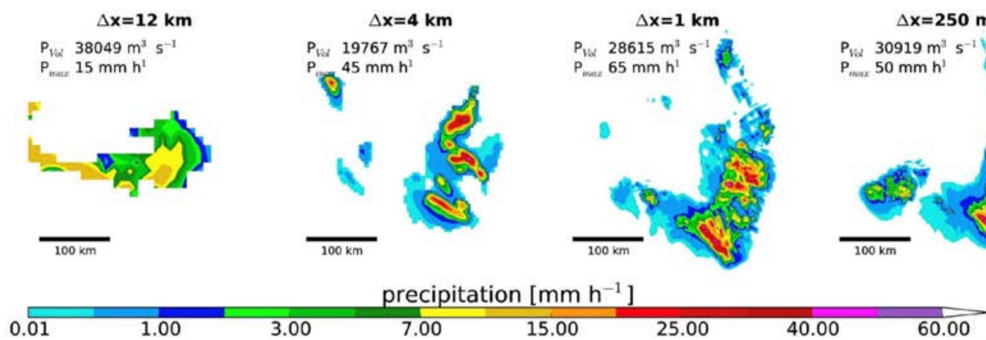
The resilient design of critical infrastructure such as roads, dams, and power plants is essential for human safety. Designed standards are traditionally based on observational records, which can be problematic since structures, such as nuclear power plants, should withstand very rare extreme events such as flood return periods of up to one million years. Comparatively short observational records, sampling, and measurement biases create substantial uncertainties in return period estimates of rare flood events. Here we assess if simulated precipitation from kilometer-scale atmospheric models can be used to improve flood risk estimates of critical infrastructure. Therefore, we use three kilometer-scale 36-hour weather forecast datasets that cover the central and eastern U.S. and compare simulated extreme events to high-resolution multi-sensor and station-based precipitation observations. We show that kilometer-scale models can accurately simulate extreme storm characteristics such as movement speed, orographic precipitation gradients, mean and extreme precipitation intensities, and the location of peak precipitation accumulations. The simulations can outperform gridded precipitation observations that solely rely on gauges in capturing extreme accumulations. Decreasing the model grid spacing from 3 km to 1 km results in minor improvements, and computational resources should rather be invested in simulating additional extreme precipitation events at 3 km grid spacing than decreasing the grid spacing to 1 km. We conclude that kilometer-scale simulations have the potential to reduce uncertainties in flood risk estimates for critical infrastructure.

3.3.1.2 Presentation (ADAMS Accession No. ML21064A424





Model Resolution Dependence of Simulating Heavy Rainfall



Prein et al. 2021

Kilometer-sale (convection-permitting) models feature step improvement in simulating heavy rainfall.

This material is based upon work supported by the National Center for Atmospheric Research, which is a major facility sponsored by the National Science Foundation under Cooperative Agreement No. 1852977.

NRC project NR. 31310019S0015

”Convection-Permitting Modeling for Intense Precipitation Processes”

Probable Maximum Precipitation (PMP)

Does not allow quantification of uncertainties in hazard estimates in either a physical or a risk sense.

Convection-Permitting Models

Can they facilitate a more physically-based probabilistic flood risk assessments?

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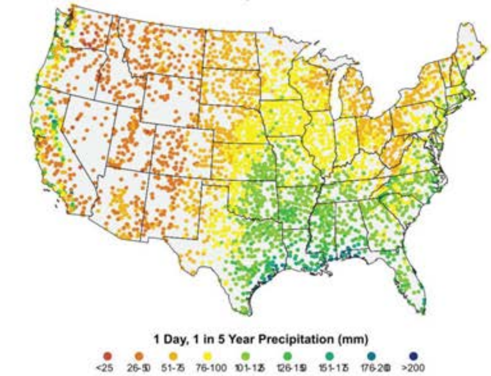
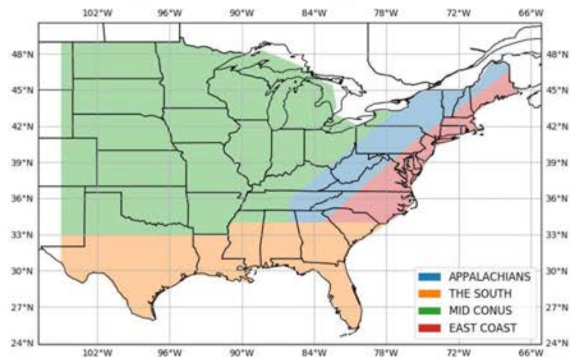
Intense Precipitation Events in Eastern CONUS

Daily, 1-in-5-yr precipitation amount for 3646 stations for the period of 1950–2010



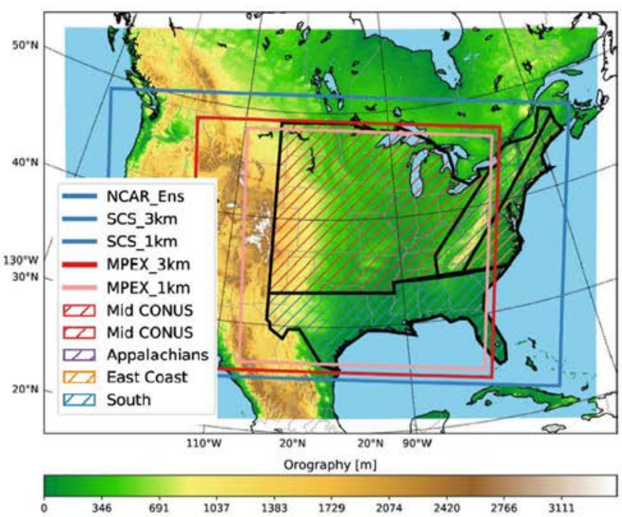
Kunkel et al. 2012

Evaluation in Four Regions



This material is based upon work supported by the National Center for Atmospheric Research, which is a major facility sponsored by the National Science Foundation under Cooperative Agreement No. 1852977.

Analysis Region and Datasets



Dataset	Δx	Elements	Period	References
NCAR Real-time Ensemble	3 km	10-member ensemble forecasts	5/1/2015-12/31/2017	Schwartz et al. (2014, 2015a, 2015b), Romine et al. (2014)
NCAR MPEX Ensemble	3 km & 1 km	10-member ensemble forecasts	5/15/2013-6/15/2013	Schwartz et al. (2017)
NCAR Severe Weather Study	3 km & 1 km	Deterministic forecasts; 500 cases	2010-2017	Sobash et al. (2019), Schwartz et al. (2019)

- 10,570 36-hour WRF simulations/forecasts at 3-km horizontal grid spacing (1.8 mi)
- 810 36-hour simulations at Δx=1 km (0.6 mi)

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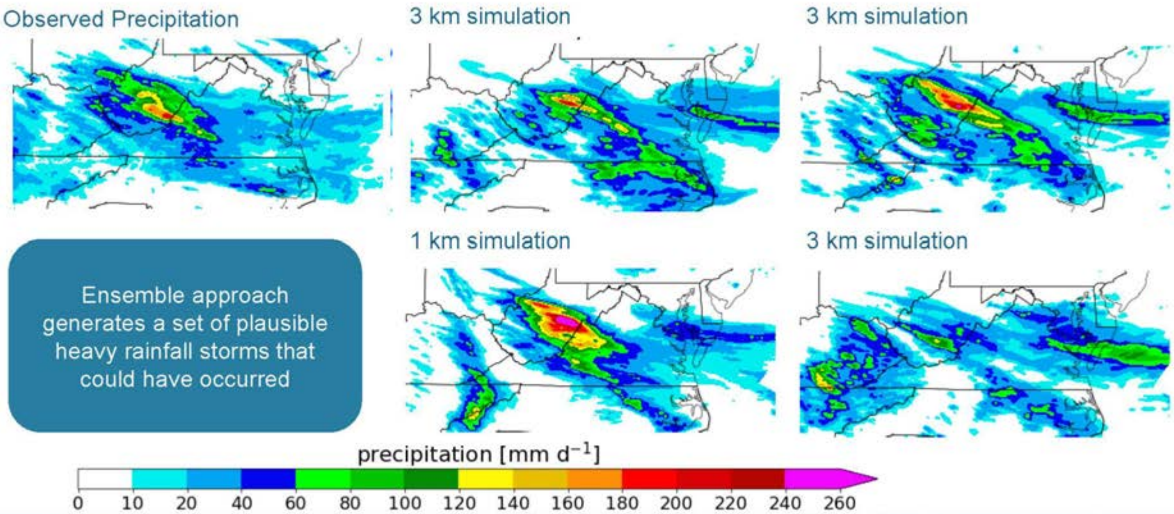
West Virginia Flooding of 2016



Ensemble approach generates a set of plausible heavy rainfall storms that could have occurred

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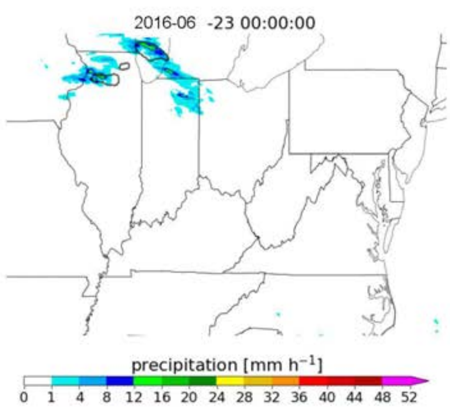
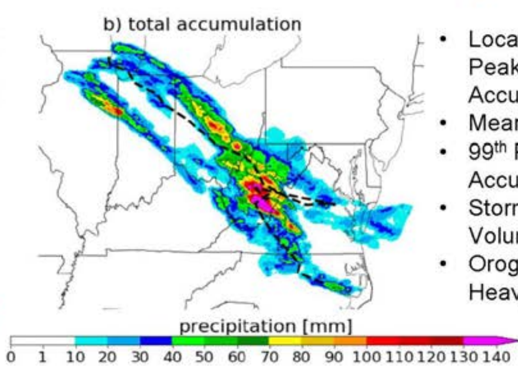
Lagrangian Evaluation Framework

West Virginia Flooding of 2016





Key Evaluation Metrics:

- Location of Peak Rainfall Accumulation
- Mean Hourly P99 Rainfall
- 99th Percentile Event Accumulation
- Storm Total Rainfall Volume
- Orographic Gradients of Heavy Rainfall

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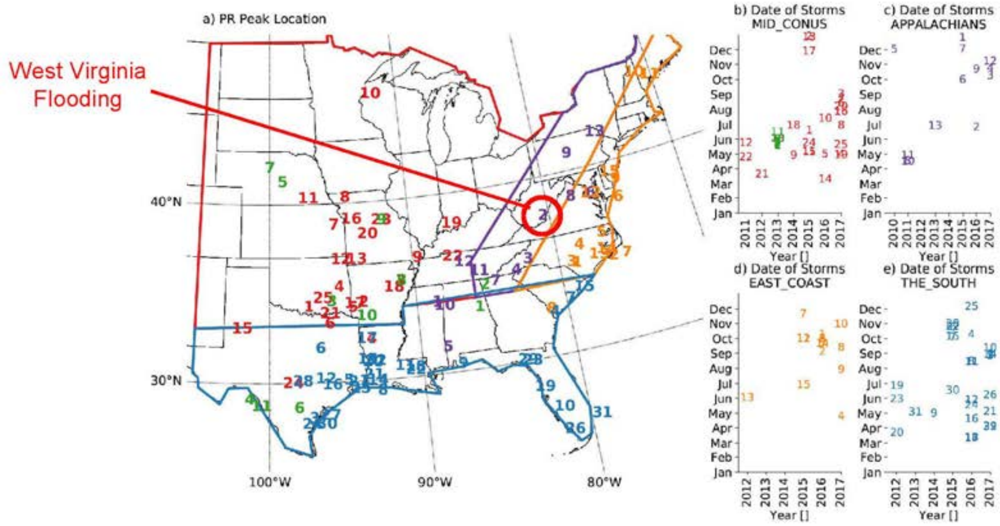
Selected Heavy Precipitation Events



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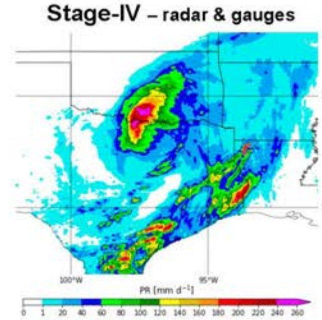
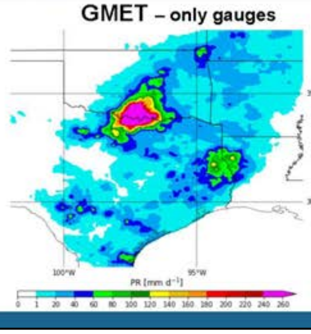
Observational Uncertainties

Data Name	Period	Δx/Δt	Ensemble size	Source
Stage IV	2001–present	4 km/hourly	deterministic	159 radar stations, ~3,000 gauges
MRMS	2014–present	1 km/2.5 min.	deterministic	180 radar stations, gauges, NWP, lightning, satellite
PRISM	1982–present	4 km/daily	deterministic	13,000 gauges and radar after 2002
GMET	1980–2016	12 km/daily	100 members	12,000 gauges

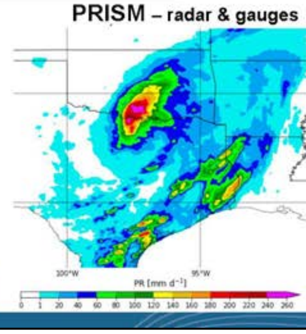
Stage-IV – radar & gauges



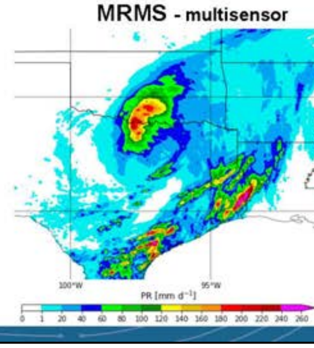
GMET – only gauges



PRISM – radar & gauges



MRMS - multisensor



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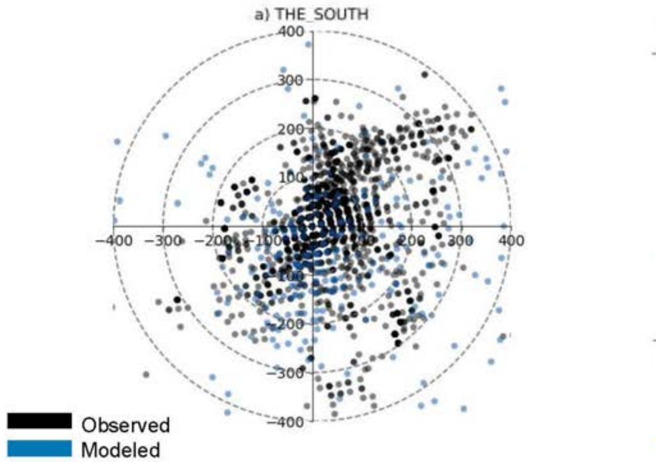
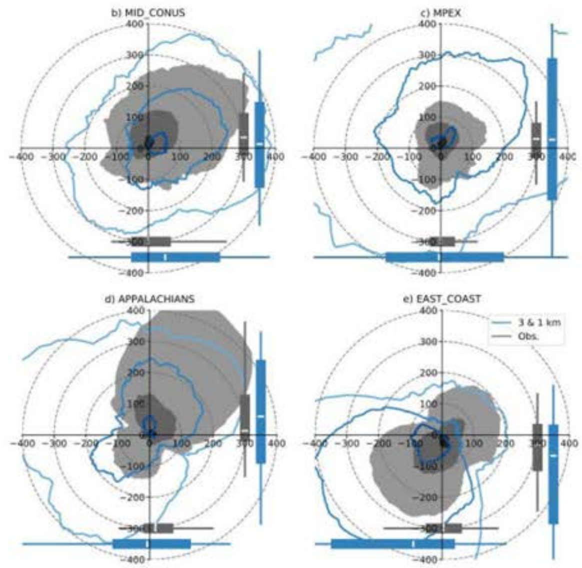
Simulating the Location of Peak Rainfall Accumulation





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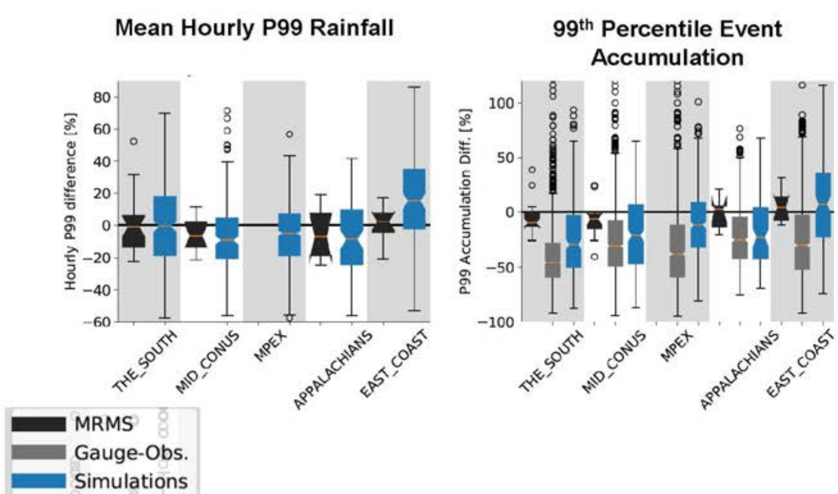
Biases in Simulated Heavy Rainfall Storms Compared to Stage -IV Observations



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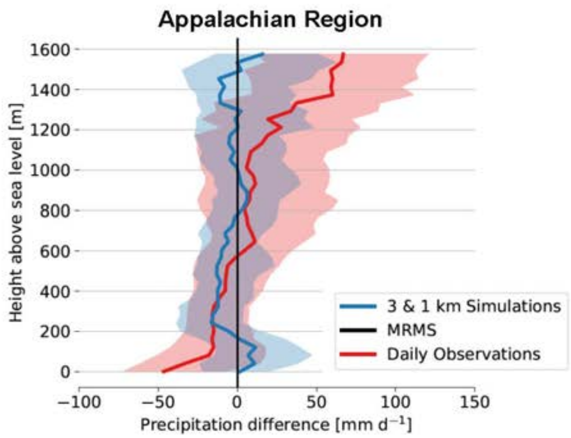
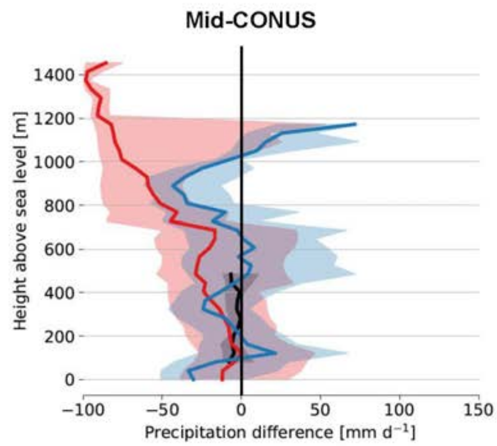
Kilometer Scale Simulations can Capture the Orographic Gradients of Heavy Rainfall Events





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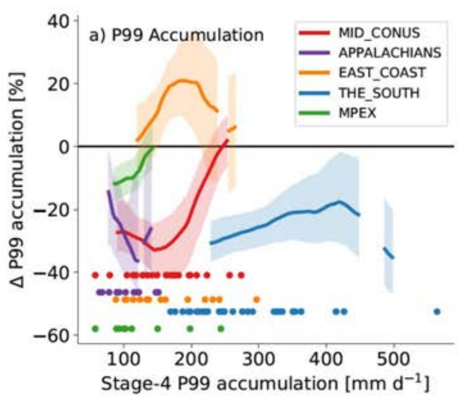
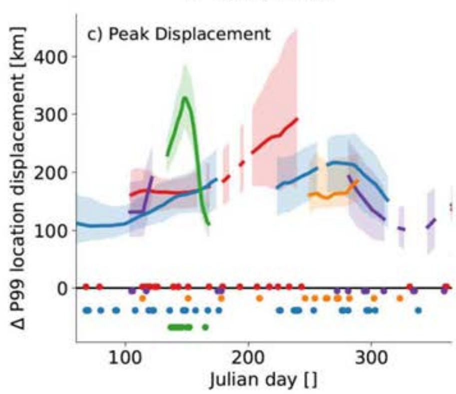
Biases Dependent on Storm Intensity and Season

Biases in simulated peak precipitation decrease with storm intensity



Biases in the simulated location of the peak accumulation location are larges in late summer



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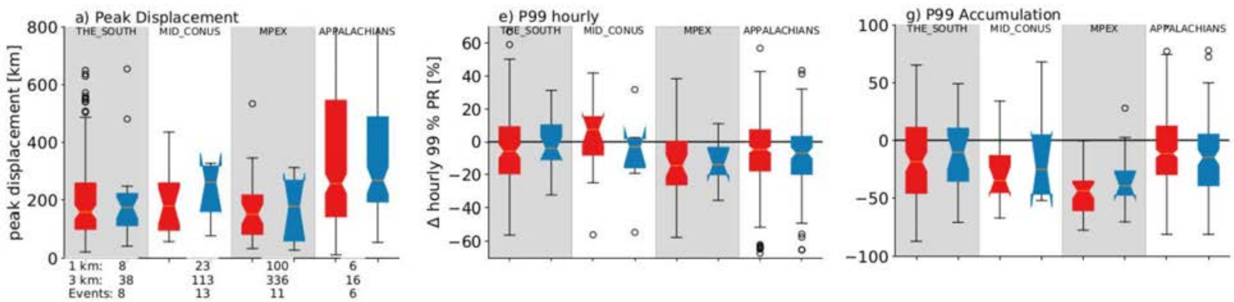
The Benefit of Using 1 km Instead of 3 km Model Resolution



3 km simulations
1 km simulations

Increasing the model resolution form 3 km to 1 km results in minor improvements that might not justify the ~30-fold increase in computational costs.

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Summary

- Convection-permitting models (CPMs) can capture recently observed intense rainfall events east of the Continental Divide
- CPMs can outperform purely station based datasets in capturing peak accumulations, orographic gradients, and storm total precipitation volumes
- Systematic biases exist (e.g., underestimation of peak accumulations) that need bias correction for usage in flood risk modeling

This work is sponsored by NRC under the Interagency Agreement Number 31310019S0015

NCAR UCAR | prein@ucar.edu

CPM rainfall simulation ratings for the criteria of realism, variability, and computational cost

	CPM Rainfall Simulations		
Source	Realism	Variability	Cost
Operational Forecasts			
Downscale Reanalysis			
Downscale GCMs			

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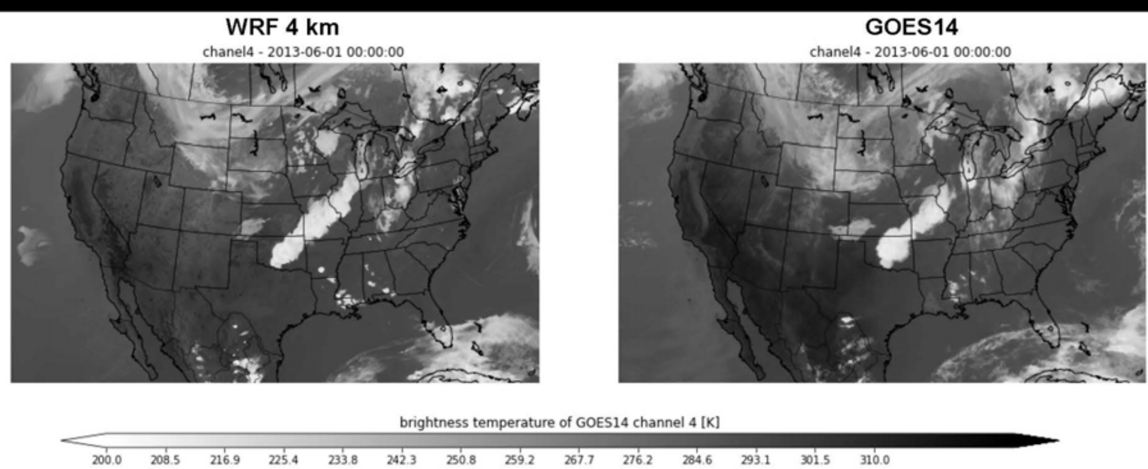
40-Year 4-km WRF CONUS Simulation

Comparison of Simulated and Observed Cloud Brightness Temperature

USGS sponsored HyTEST project
1979 to present
Finished by Sept. 2021



CPM rainfall simulation ratings for the criteria of realism, variability, and computational cost

	CPM Rainfall Simulations					
Source	Realism	Variability		Cost		
Operational Forecasts	High	Lower	Higher (if ensembles)	Lesser (if existing)	Greater (continuous)	Lesser (event-based)
Downscale Reanalysis	High	Lower		Greater (if new)		
Downscale GCMs	Med/High	Higher		Greater (if new)		

4 km 20-year current and future climate for CONUS

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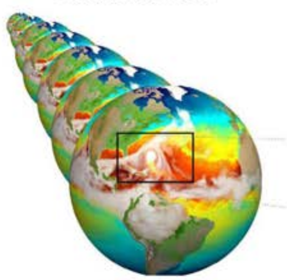
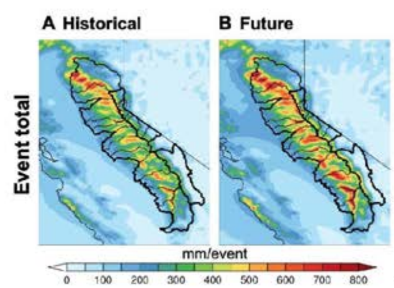
Framework for using CPM output in flood risk assessments

Search for Extreme Weather Conditions in Global Climate Models



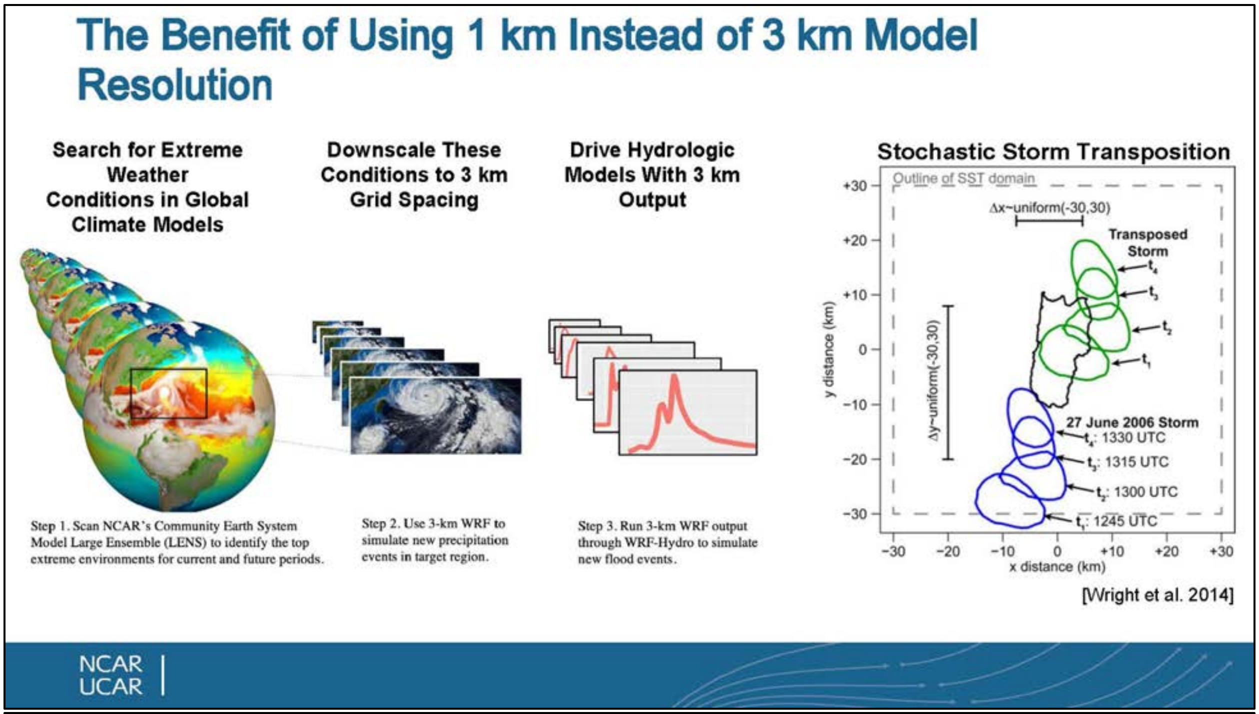
- E.g., NCAR's Large Ensemble Simulations
- 40 runs covering 1920 – 2100
- Total of 7,200 modeling years

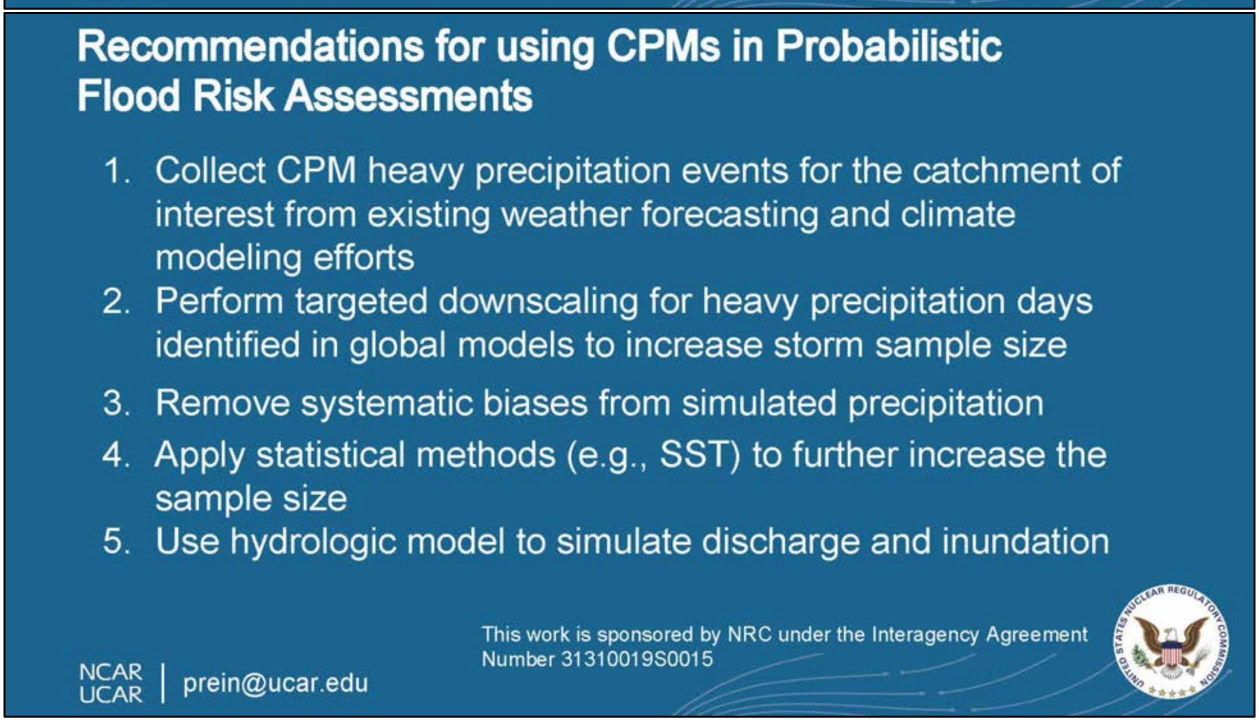
- Use NCARs Large-Ensemble Simulations
- Allows to simulate the ~400 year event explicitly
- Computational costs are ~0.1 % of continuously running simulations



Huang et al. 2020

NCAR | UCAR





3.3.1.3 Questions and Answers

Question:
Can you speak to the computational costs of running 1-km simulation versus 3-km simulation? And where do you see that in five or ten years, progressing to being more efficient.

Andreas Prein:
The costs are increasing by a factor of 10 if you increase the grid spacing. If we go from 3-km spacing to 1-km, you have a factor of 30 computational cost increase. What this means is basically you could run 30 3-km simulations for the cost of a single 1-km simulation. Of course, as time goes on, higher resolution runs will become more affordable. But, at least at the moment, I think it would be better to invest the resources with the current models to have a larger sample of 3-km simulations, then a smaller sample of 1-km simulations.

3.3.2 Presentation 1C-2: Tropical Cyclone Rainfall-driven Flood Risk Assessment

Authors: Ali Sarhadi, Kerry Emanuel, Massachusetts Institute of Technology (MIT)

Speaker: Ali Sarhadi

3.3.2.1 Abstract

Tropical cyclones (TCs) bring heavy and prolonged rainfall to coastal cities and generate devastating inland flooding in the US. Despite substantial progress on understanding the risk of extreme rainfall from TCs in recent years, less has been learned on translating these extreme rainfall events into extreme flooding on the ground. In the present study, we develop a pluvial hydrodynamic model to translate rainfall intensity from TCs into inland flood inundation risk in coastal areas on the west side of Buzzard Bay —an urbanized back-barrier bay— in Massachusetts. The model implements a 2D hydraulic modelling, rainfall intensity, and land surface characteristics (geometry, land use, roughness, antecedent moisture, and soil infiltration). Using the continuity of mass and momentum equations, the model simulates dynamic flood depth in response to high resolution spatio-temporal variations of rainfall intensity during TC events across the area. The 1-hr rainfall intensity data used in this study are derived from a large number of synthetic TCs (generated from historical climate through 1979-2019) and TCs observed by NEXRAD during the year 1995-2019 in the study area. The developed model is evaluated by comparing flood inundation areas during observed TC events (extracted from the Synthetic-Aperture Radar (SAR) image processing) with those simulated by the model for the same events. After simulating maximum level of flood from each synthetic TC, a probabilistic risk framework is applied to quantify the flood levels for different return periods in each grid cell in the area. The results reveal the depth and inundated extent of the high consequence floods from TCs (with return period of up to 100 year), especially in vulnerable populated areas. Our methodology can be applied for other susceptible coastal regions, providing critical insight for developing proactive strategies to enhance the resiliency of infrastructure and populated centers against the damaging floods.

3.3.2.2 Presentation (ADAMS Accession No. ML21064A425)

Tropical Cyclone Rainfall-driven Flood Risk Assessment

ALI SARHADI
KERRY EMANUEL

Seminar at the 6th Annual NRC PFHA Research Workshop

LORENZ CENTER
MIT | DEPARTMENT OF EARTH, ATMOSPHERIC AND PLANETARY SCIENCES

Jan. 22nd, 2021

Massachusetts Institute of Technology

HURRICANE FLOOD RISK

- Risk of extreme rainfall from TCs is increasing under a warming climate (Emanuel 2005, 2017), Examples: Hurricanes *Katrina*, *Harvey*, *Galveston*


//svs.gsfc.nasa.gov/4186

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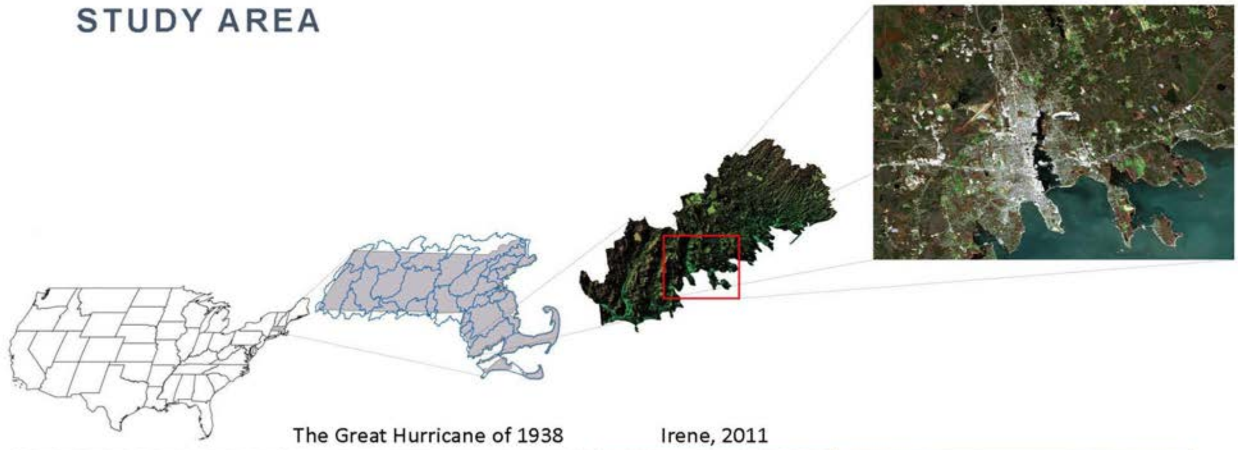
STUDY AREA



The Great Hurricane of 1938 Irene, 2011

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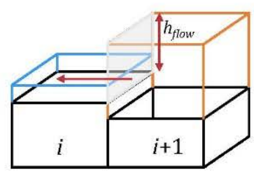
SUB-GRID DYNAMIC HYDRAULIC MODEL

- **Continuity Equation**

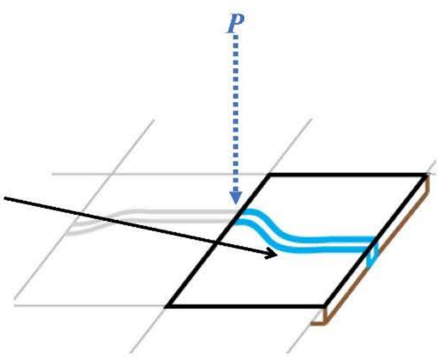


$$V_{i,j}^{t+\Delta t} = V_{i,j}^{t} + \Delta t(Q_{i-\frac{1}{2},j}^{t+\Delta t} - Q_{i-\frac{1}{2},j}^{t+\Delta t} + Q_{i-\frac{1}{2},j}^{t+\Delta t} - Q_{i-\frac{1}{2},j}^{t+\Delta t} + dx \times dy\,(P_{i,j}^{t+\Delta t} - I_{i,j}^{t+\Delta t}))$$

$$dx \times dy = Cell\ surface\ area$$

- **Momentum equation**

$$Q_{f,i+1/2}^{t+\Delta t} = \frac{q_{f,i+1/2}^{t} - g h_{f,flow}^{t}\,\Delta t S_{i+1/2}^{t}}{1 + g\Delta t n^2 \left|q_{f,flow}^{t}\right| \left[\left(h_{f,flow}^{t}\right)^{7/3}\right]} (\Delta x - w_{c,flow})$$



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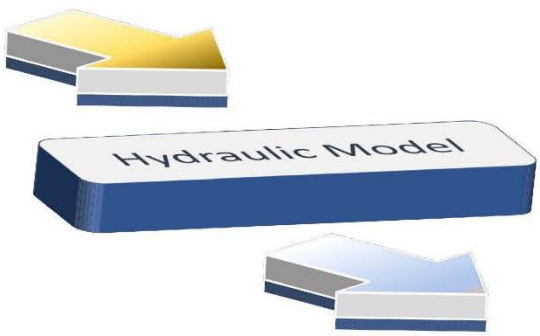
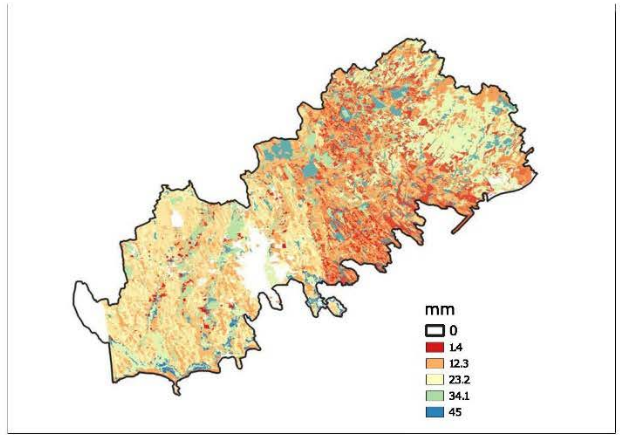
DATASET

Model





Flood Inundation Mapping

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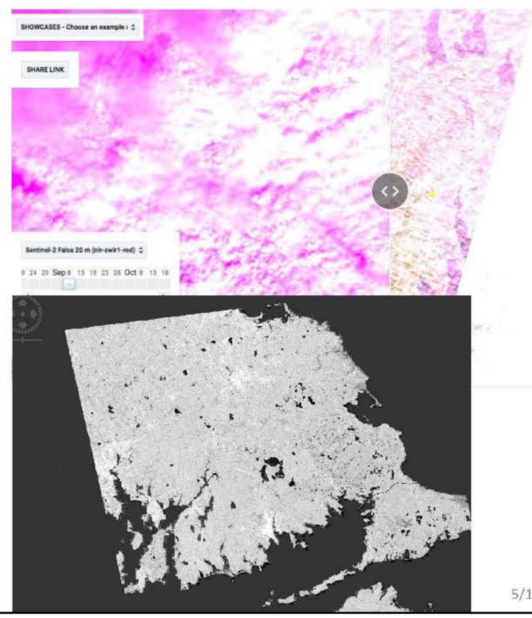
MODEL VALIDATION

Pluvial Flood Validation

1- Multispectral Remote Sensing

2- Radar Image Processing



Sentinel-1 SAR (Synthetic Aperture Radar)

- Resolution (down to 5 m) and coverage (up to 400 km)
- Not impeded by cloud cover or a lack of illumination
- With a 12-day repeat cycle

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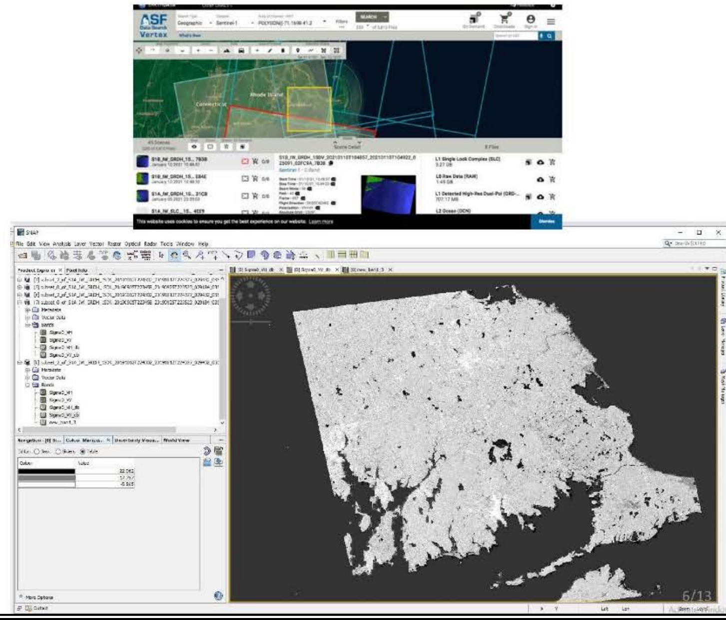
SENTINEL-1 SAR (SYNTHETIC APERTURE RADAR)

Hurricane Michael

2018-10-12
https://search.asf.alaska.edu/

- SAR image – Sentinel-1
- Orbital file correction
- Radiometric Calibration
- Geometric Calibration
- Back Scatter image generation
- Threshold detection
- Flood inundation Map



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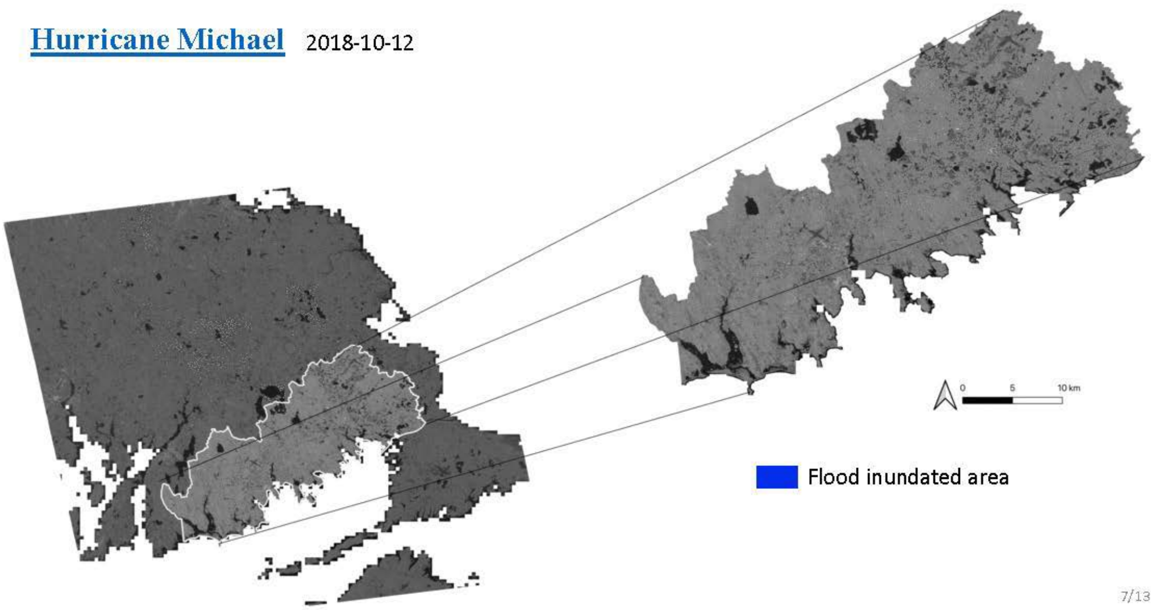
MODEL VALIDATION: S.A.R. RADAR IMAGE PROCESSING

Hurricane Michael 2018-10-12



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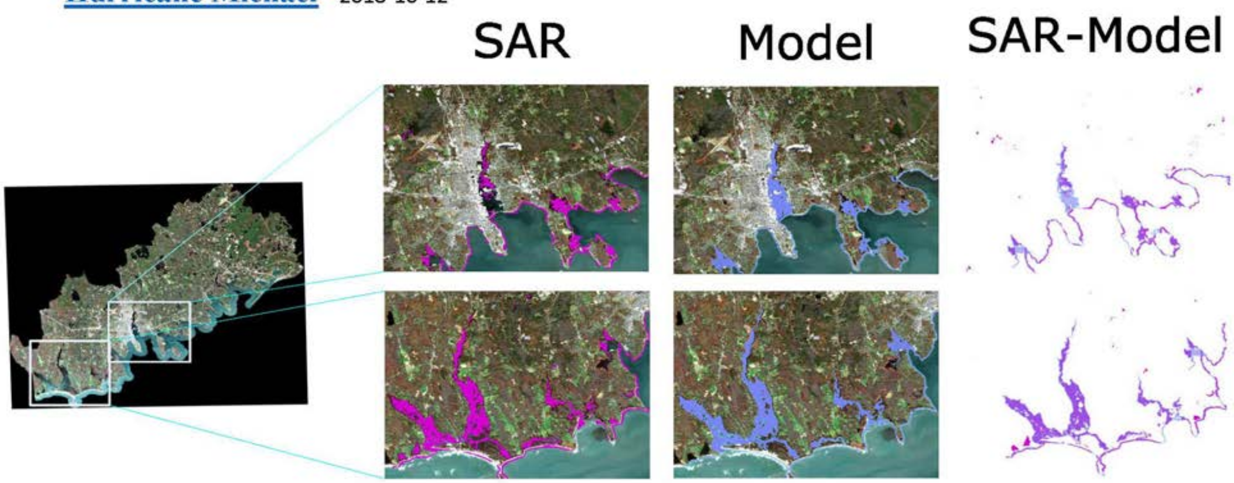
MODEL VALIDATION

Hurricane Michael 2018-10-12



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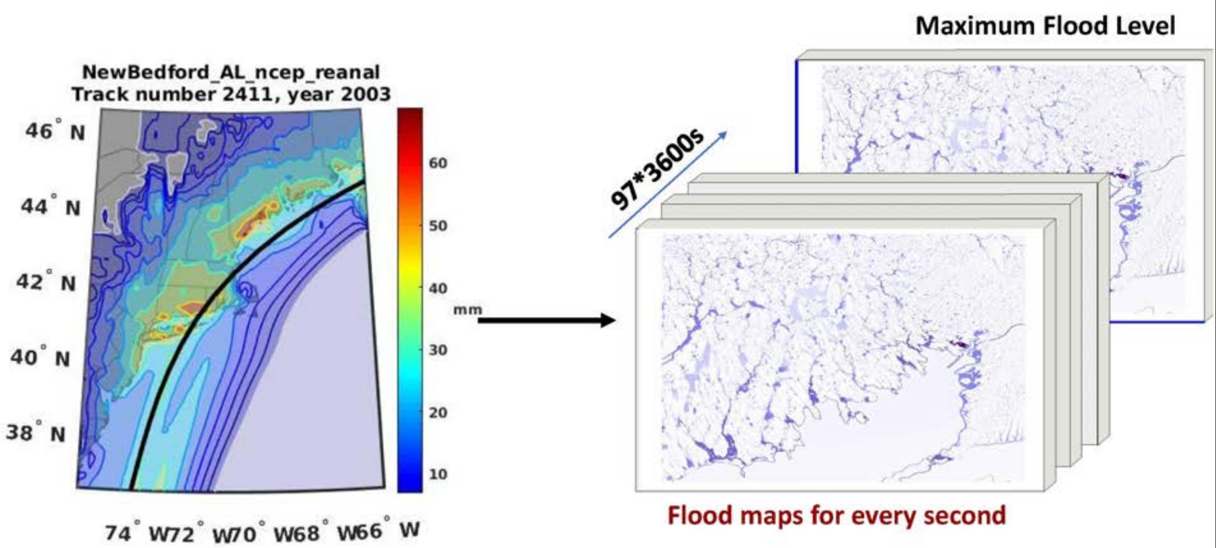
RAINFALL-DRIVEN FLOODING FROM SYNTHETIC TRACKS



Resolution: 0.03 degree

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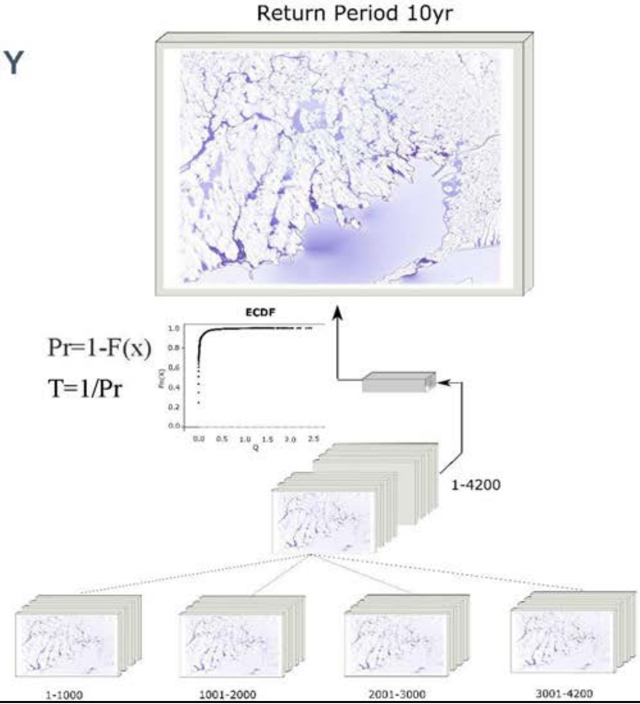
FLOOD FREQUENCY ANALYSIS



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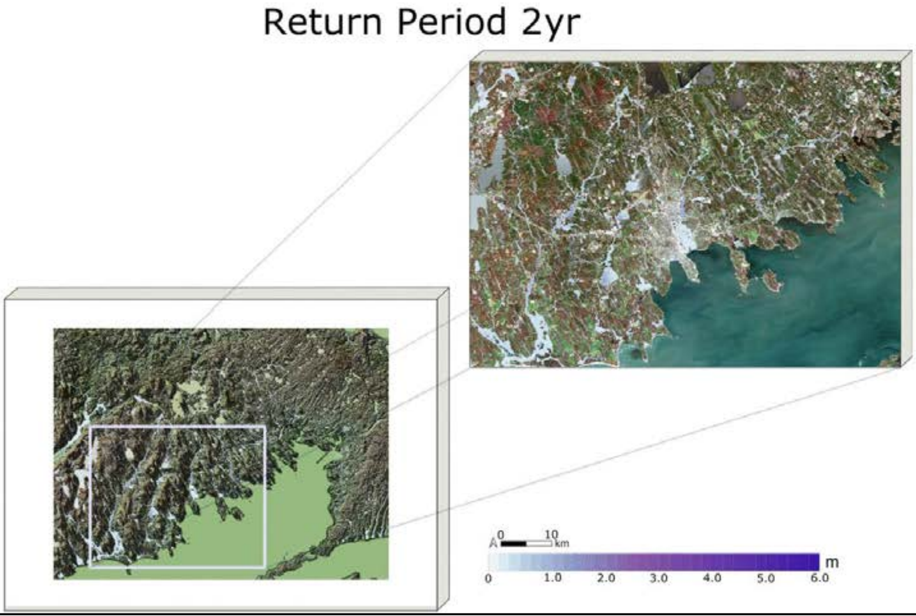
RISK OF RAINFALL-DRIVEN FLOODING



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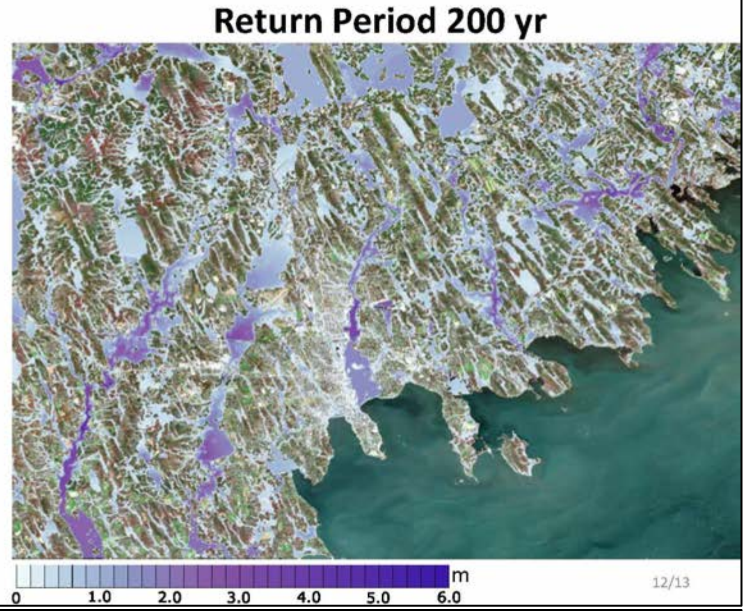
RISK OF RAINFALL-DRIVEN FLOODING

- Resilient infrastructure designs
- Update building codes
- Reform zoning codes
- Fortify critical infrastructure and hazardous facilities



12/13

Next Steps

- Flood risk from hurricanes under a warming climate in the future decades
- Coupled rainfall driven and storm surge hydrodynamic modelling

13/13

3.3.2.3 Questions and Answers

Question:
What was the source of the synthetic hurricanes in the presentation?

Ali Sarhadi:
These are synthetic models which are produced at MIT, generated based on historical climate. The way that we generate them is that we embed the computational detailed hurricane models within global climate models. In this way, we can generate thousands of these synthetic hurricanes. Here we use them to cover spatial variability of rainfall intensity from hurricanes to come up with that flood risk map.

Question:
Are these based on NCEP reanalysis?

Ali Sarhadi:
Yeah, these are baseline NCEP.

Question:
You use satellite data for model validation. What are the limitations of doing that?

Ali Sarhadi:
This is pluvial flood modeling and the limitation with that is the frequency of satellite images. You know these are very short time-scale hazards. They happen within days, and we may not have any satellite to provide high resolution images to cover those flooded areas. So, this is one of the big problems that we have with these satellite radar images.

Question:
How did you handle the boundary conditions such as the blockage with surge and tide for the discharge point of the river?

Ali Sarhadi:
That's a good question. Up till now we have modeled inland flooding from tropical cyclones and the next step is going to be adding storm surge driven floods from hurricanes. For that, as I mentioned, we're going to design a multi-dimensional dynamic risk model to quantify that concurrent risk of inland flooding and storm surge driven flooding. So, it's still going on.

Question:
How do you assign frequency to flood elevations for each grid? By counting how many times the grid was inundated?

Ali Sarhadi:
For that, the fairly straightforward way is forming a cumulative distribution function and then, by sorting those flood events, we are able to estimate flood level for different return periods. That's based on the magnitude of different events.

Question:
You modeled an urban area. Did include urban features such as roads, berms, and buildings?

Ali Sarhadi:
We did. I showed that map for roughness coefficient. To calculate that we used land use maps. We implemented roads and infrastructure, using Manning coefficients. For roads and buildings, the infiltration is kind of zero, and we added that in our model.

Question:
You mentioned those land use maps. Do those capture non-stationarity? Or are those maps just one snapshot of the urban use?

Ali Sarhadi:
We used a stationary-based methodology to quantify flood level. We didn't implement any nonstationary-based model. But in in the discussion panel, I will discuss different nonstationary models that we can implement for inland flooding and for compound extremes. We already developed some nonstationary-based copulas. We address that in compound extremes, but not yet for this case.

3.3.3 Presentation 1C-3: Does PMP have an AEP? CO-NM REPS Findings Bridge Deterministic and Probabilistic Approaches

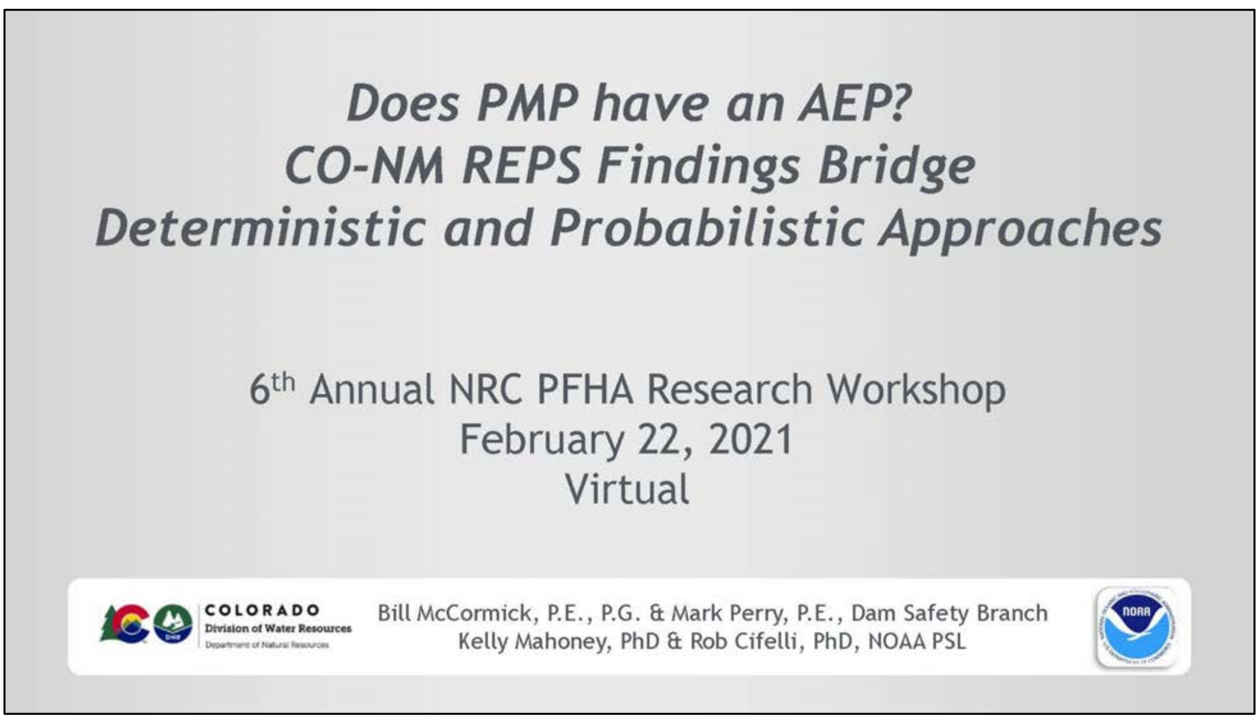
Authors: Bill McCormick[1], Mark Perry[1], Kelly Mahoney[2], Rob Cifelli[2], [1]Colorado Division of Water Resources, [2]National Oceanic and Atmospheric Administration, Physical Sciences Laboratory

Speaker: Bill McCormick

3.3.3.1 Abstract

Conventional wisdom has been that rainfall estimates derived from Probable Maximum Precipitation (PMP) methodologies are not associated with any Annual Exceedance Probability (AEP). The CO-NM Regional Extreme Precipitation Study analyzed both deterministic PMP and probabilistic precipitation frequency methods for deriving extreme precipitation estimates. PMP and precipitation frequency tools were co-developed, and this approach allowed, for the first time, PMP rainfall estimates to be directly compared to precipitation frequency estimates in an AEP framework. Within this intercomparison framework, we evaluate the relevance and assess the feasibility of defining PMP estimates in the context of AEP and compare the differences in PMP vs precipitation frequency-derived rainfall estimates at two locations in Colorado. Dynamical weather model output from NOAA's operational High Resolution Rapid Refresh (HRRR) model is used to illuminate potentially interrelated factors and provide insight into potential differences between the two methodologies. Our presentation highlights the strengths and weaknesses of the currently available extreme precipitation estimating methods and postulates possible paths forward.

3.3.3.2 Presentation (ADAMS Accession No. ML21064A426)



Discussion Outline

- REPS Project Background
- PMP and Precipitation Frequency terminology
- Comparing PMP and PF estimates at sites around Colorado
- Why might we expect variation?
- How does Colorado Dam Safety handle variation
- Ideas for the future

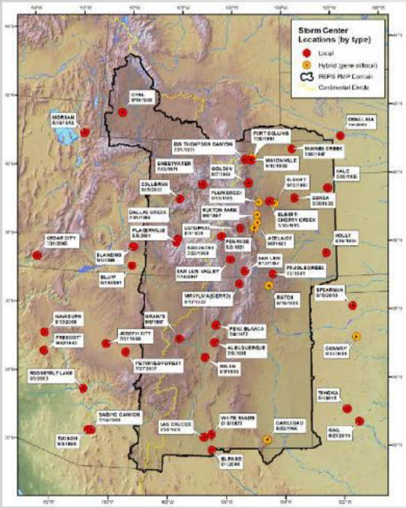
Background and Context

3-Task study to answer the following questions:

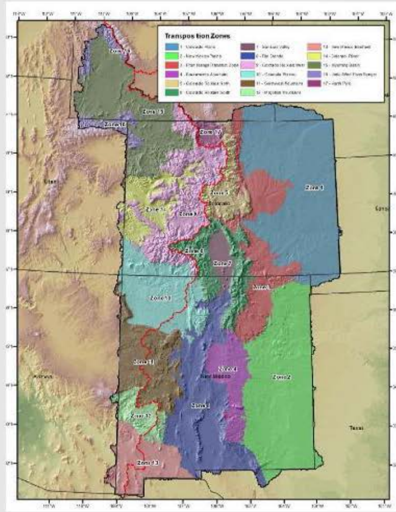
- How much and how hard can it rain?
- What are the probabilities of it raining very much and very hard?
- What is the AEP of PMP?
- How can we use these independently derived estimates of extreme rainfall in a state dam safety regulatory environment? i.e. standards based and/or risk based
- Are Dynamical Weather Models and techniques a viable methodology for the future of extreme rainfall estimating?

REPS Project documentation:
https://dwr.colorado.gov/services/dam-safety

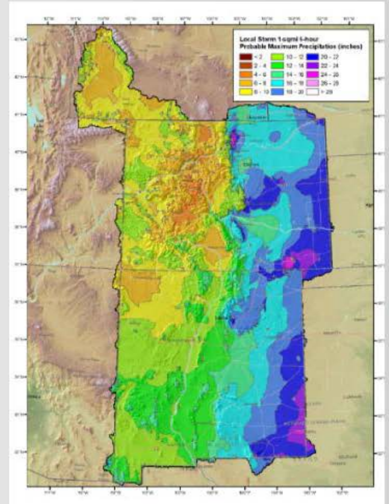
REPS Task 1 - Deterministic PMP



REPS PMP Local Storm coverage

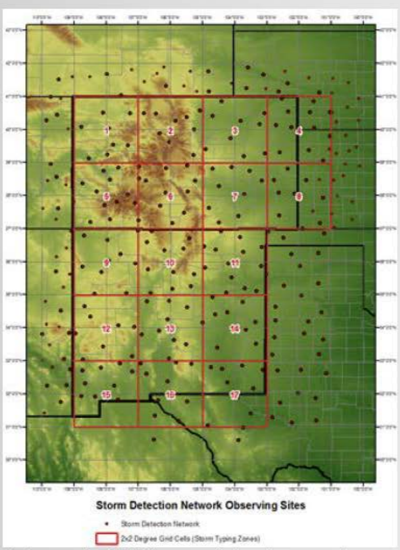


REPS PMP Transposition Zones

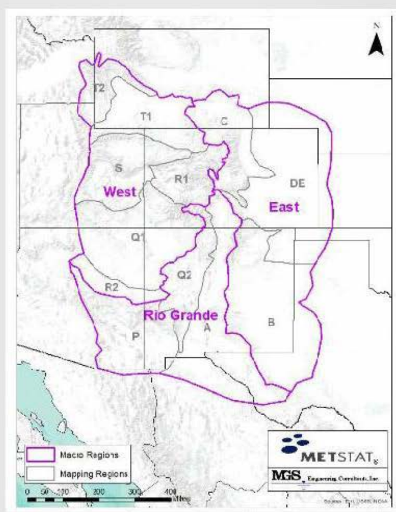


REPS Local Storm PMP 1 sq mi 6-hr duration.

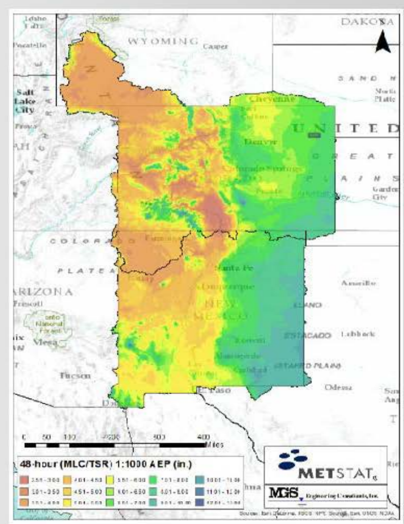
REPS TASK 2 - Probabilistic Regional PF



Network of daily precipitation stations (black dots) and 17 Storm Typing Zones (red boxes)



Macro Regions (purple) and homogeneous mapping regions (grey)

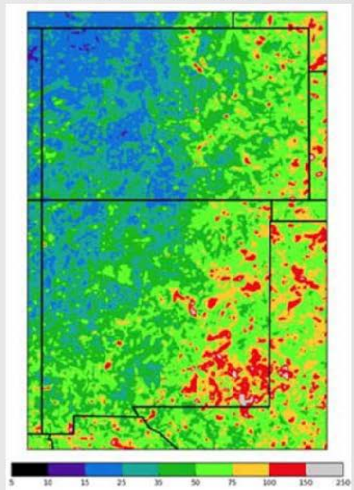


Isopluvial map of 48-hour precipitation maxima for an AEP of 1:1,000 for MLCs

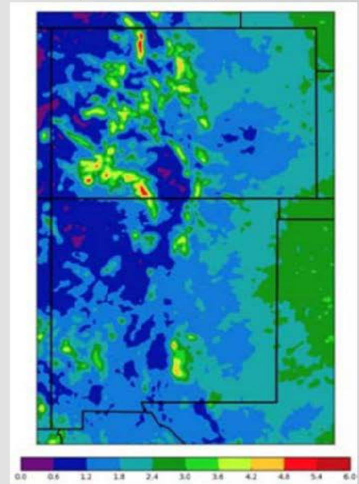
REPS Task 3 - Dynamical Weather Modeling

- Model data: continuous in space and time, can be analyzed for maximum values, frequency statistics using the same dataset, absent additional, inconsistent assumptions
- Allow comparisons between PMP, PF using same data
- (Prototype examples from REPS limited by short period of record)

Max 6h precip (~PMP)
2012-01-24 to 2017-01-24



Probability of 10mm precip
/12 hours (~PF)



*over 5 year prototype period

REPS PMP vs. Probabilistic Precipitation Frequency

REPS PMP

- Cataloging and reconstruction of historical storms and storm transposition within homogeneous climate regions
- Applies in-place maximization factor, moisture-supply factor, and orographic factor
- Warm season, Liquid precip only

REPS Precipitation Frequency

- Storm typing, macro regions, hetero. super regions, homo. mapping regions
- Regional L-moment statistical analysis of annual maximum precipitation series
- Areal reduction factors developed by stochastic storm transposition
- All-phase precip

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REPS Storm Typing

REPS PMP and PF use Storm Typing to separate datasets into homogeneous populations of independent weather events.

- Makes REPS dataset ideal for analyzing notional AEP of PMP (Nathan et al, 2016)

REPS PMP Storm Types: 2-hr Local Storm, 6-hr Local Storm, 24-hr Local Storm/Hybrid, 72-hr General Storm, 72-hr Tropical Storm

REPS PF Storm Types: 2-hr Local Storm, 6-hr Meso-scale with Embedded Convection (MEC), 48-hr Mid-latitude Cyclone/Tropical Storm Remnant (MLC/TSR)

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PMP Terminology

Theoretical PMP: Greatest depth of precipitation for a given duration physically possible over a given area size at a geographic location and time of year. Exceedance probability is zero and theoretical PMP is unknown.

Operational PMP: Estimate of PMP determined by standard procedure by hydrometeologists by storm transposition and adjustment factors. Has some likelihood of exceedance.

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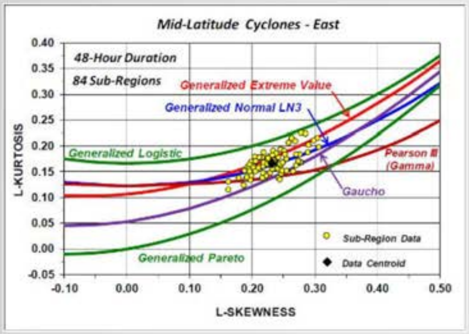
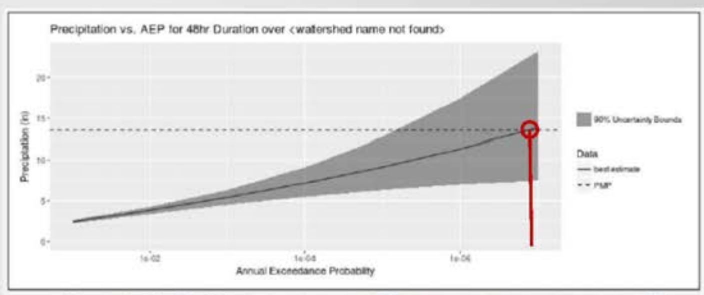
In Practice - PMP, as calculated, has an AEP

Notional Annual Exceedance Probability (AEP): Intersection of extreme precipitation frequency curve and an operational PMP estimate.



L-Moment ratio diagram depicting regional L-Skewness and L-Kurtosis values for homogeneous sub-regions in the Eastern region of the project area for 48-Hour precipitation maxima for MLCs



48-hr (MLC/TSR) Precipitation vs AEP best estimate plot with 90% confidence bounds (grey) and PMP value plotted.
Notional AEP of PMP shown in red (~9x10e-6)

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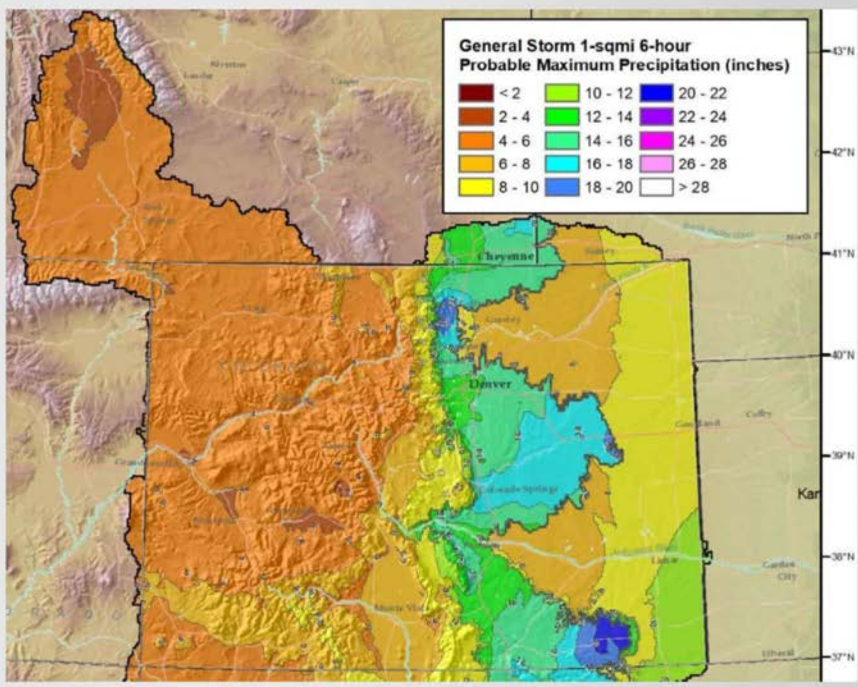
REPS 6-hr LS PMP



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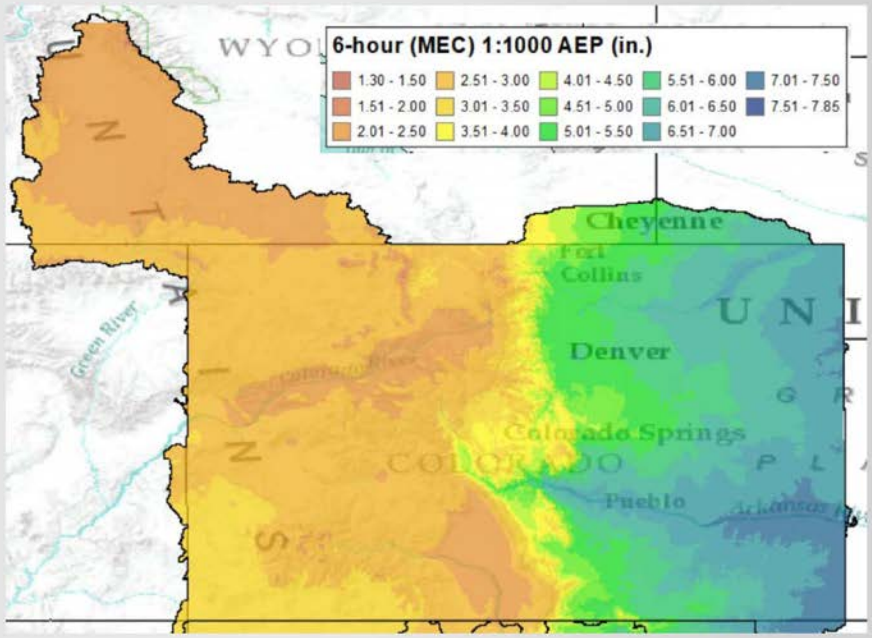
REPS 6-hr MEC
10e-3 Precipitation
Frequency



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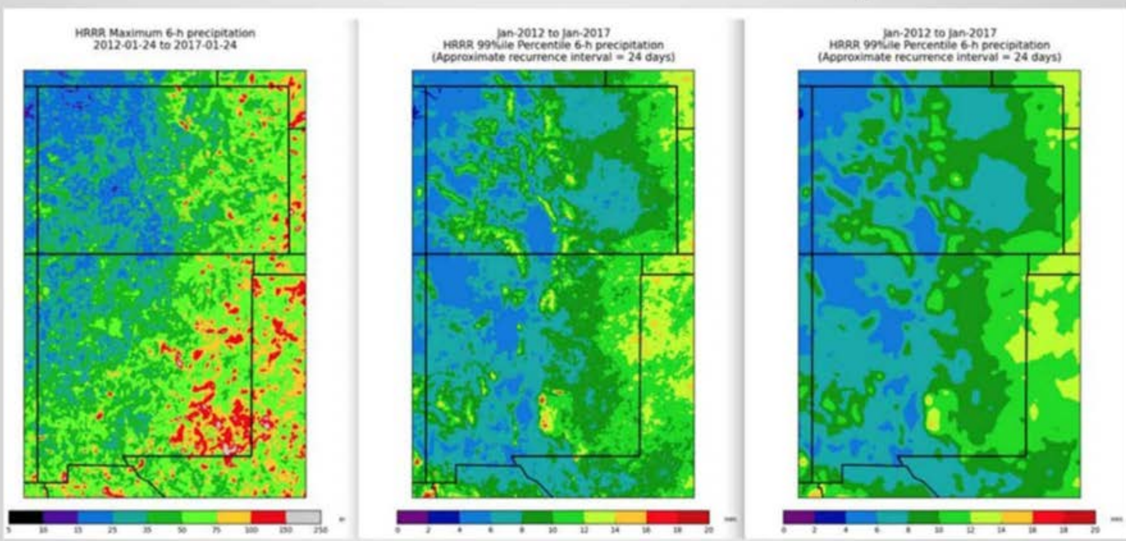
HRRR Model 6-hr Data Analysis



HRRR 6-hr (a) Maxima, (b) 99th percentile and (c) 99th percentile smoothed with Gaussian filter. Jan 2012-Jan 2017 data

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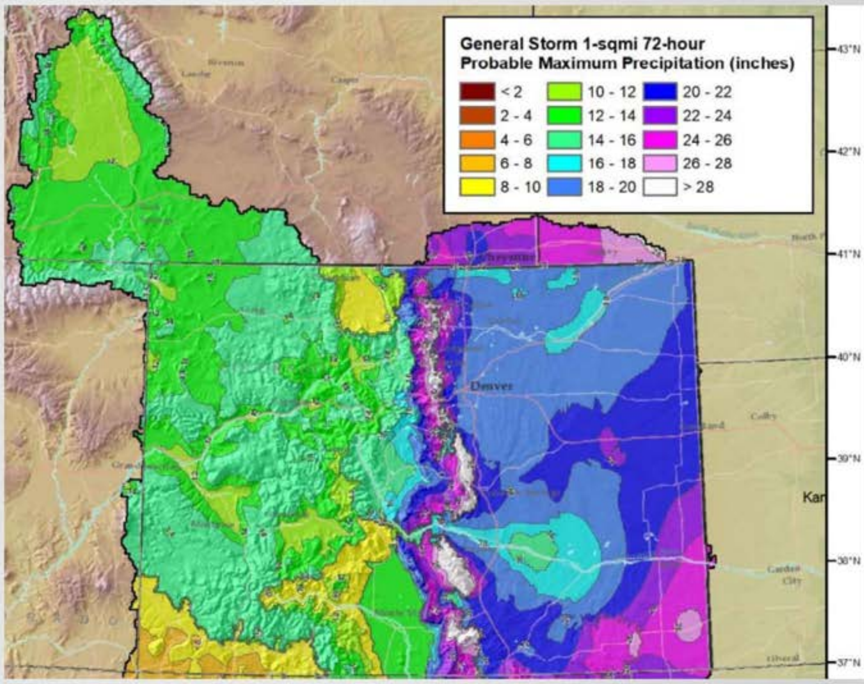
REPS 72-hr GS PMP



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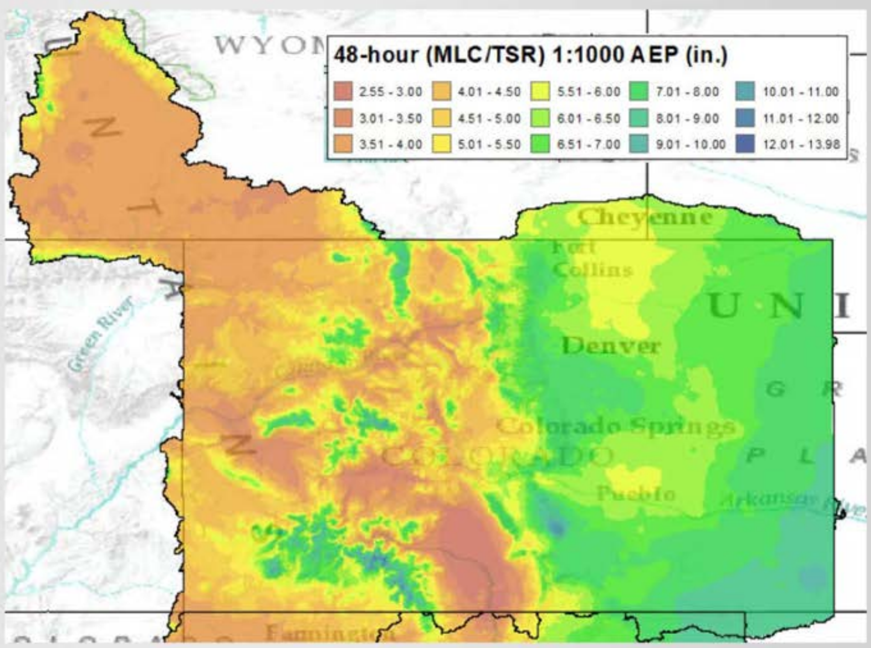
REPS 48-hr MLC/TSR 10e-3 Precipitation Frequency



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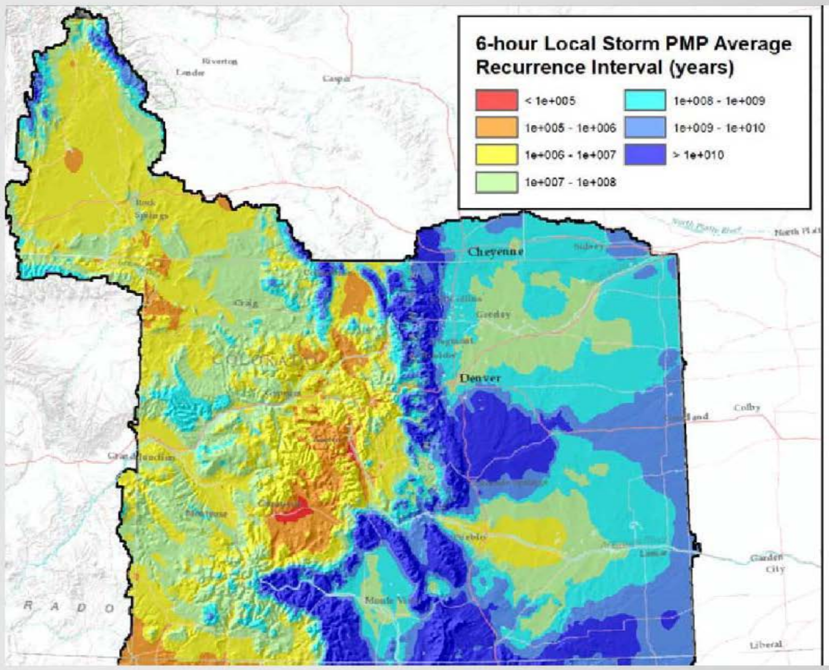
Notional ARI of REPS 6-hr LS PMP (from REPS 6-hr MEC PF), 1sqmi

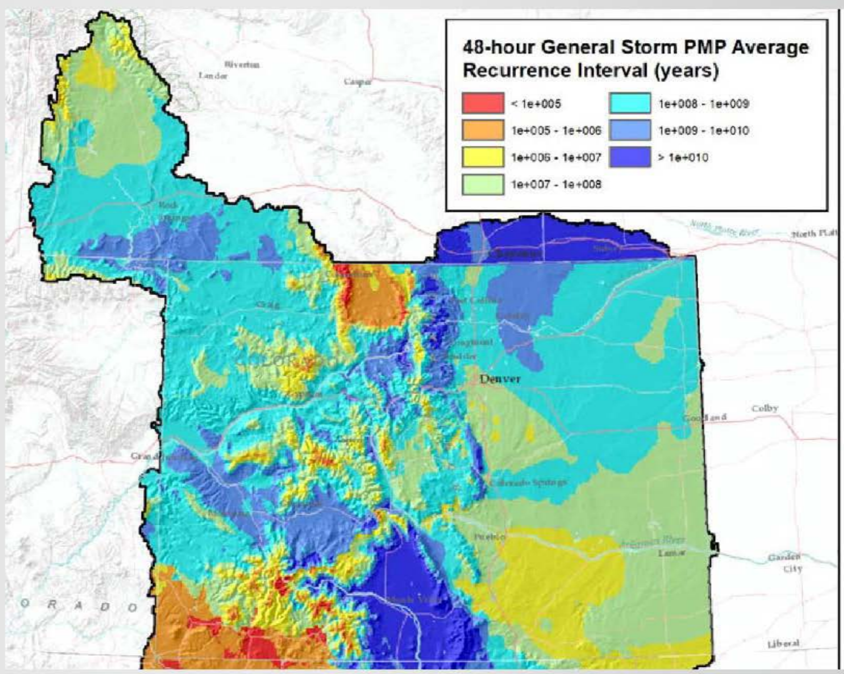
- >1x10e10 along Front Range
- <1x10e5 in central mountains

Higher ARI east of Rockies & closer to Gulf moisture sources is contrary to results from Schaefer (1999) along Gulf coast [Implications for operational PMP estimates (historical

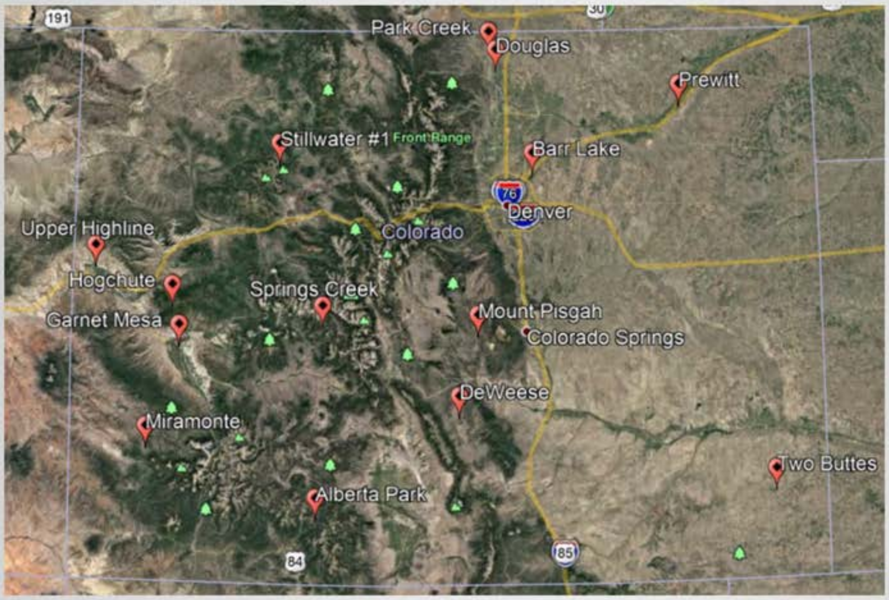


Notional ARI of REPS 48-hr GS PMP (from REPS 48-hr MLC/TSR PF)

- Lower notional ARIs of GS PMP (vs LS PMP), consistent trend as 100-YR ratios
- Again, hot spot at Northern Front Range (active weather region) but also SLV (inactive)



Summary of Results at Selected Sites in Colorado



- Comparison of:
  - 2-hr Local
  - 6-hr MEC
  - 48-hr MLC/TSC
- With PMP at these key durations
- All 3 Macro Regions
- 6 of 10 TZ's

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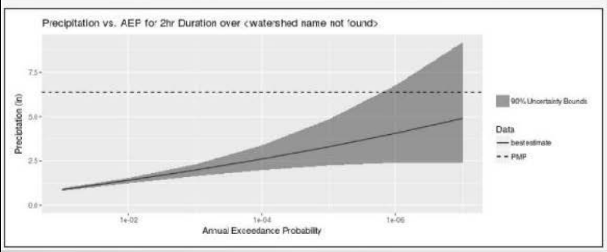
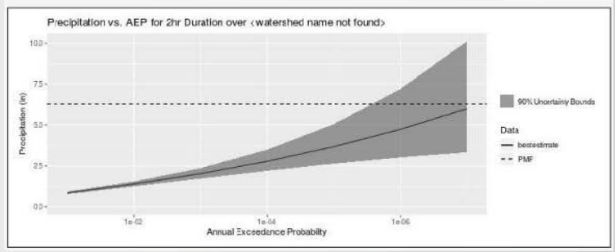
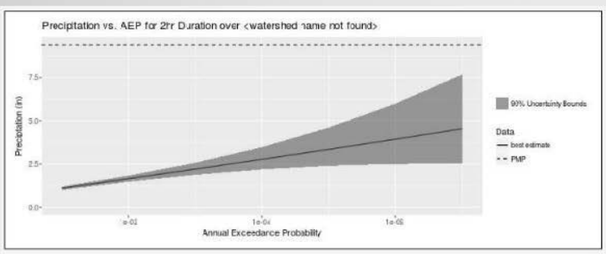
Representative AEP of PMP Plots, 2-hr Local



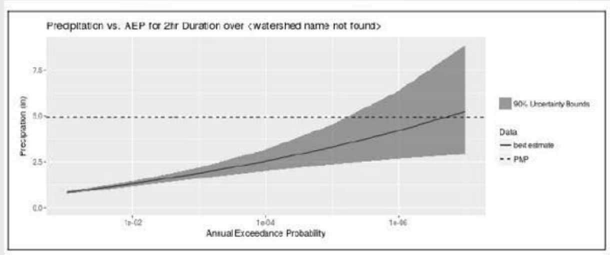
Mount Pisgah (E), PMP/AEP ratio = 1.30



Miramonte (W), PMP/AEP ratio = 1.05



Alberta Park (RG), PMP/EAP ratio = 2.07



Spring Creek (W), PMP/AEP ratio = 0.94

Summary of Results in Colorado

Summary of AEP of PMP Analyses Across Colorado

Dam Name	DAMID	Basin Size (sq mi)	Tranposition Zone	Macro Region	Ratio 2-hr PMP/AEP (10e-7)	Ratio 6-hr PMP/AEP (10e-7)	Ratio 48-hr PMP/AEP (10e-7)
Park Creek	030308	3	3	E	1.47	1.76	1.29
Barr Lake	020101	15	1	E	1.03	1.04	1.17
Douglas	030126	44	3	E	1.51	1.52	1.25
Mount Pisgah	120129	73	5	E	1.30	0.95	0.98
Prewitt	640108	105	1	E	1.24	1.20	1.21
DeWeese	130103	371	6	E	1.44	1.21	1.12
Two Buttes	670236	470	1	E	1.48	1.32	1.21
Alberta Park	200101	2	6	RG	2.07	1.98	0.79
Garnet Mesa	410107	8	14	W	1.02	0.88	1.41
Stillwater #1	580135	9	9	W	1.20	1.16	
Hogchute	420127	11	9	W	1.39	1.33	0.89
Upper Highline	720234	13	14	W	1.16	0.97	1.34
Spring Creek	590108	20	9	W	0.94	0.90	1.05
Miramonte	600113	36	14	W	1.05	1.02	1.19
Averages		84	6 out of 10	rg-1, e-7, w-6	1.31	1.23	1.15

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Why Might There Be Differences?

- **Conceptual Difference**: Operational PMP is an attempt to calculate an upper limit, regardless of likelihood. PF tells us how likely extreme precip may be.
- **Correlations**:
  - Skewness - Nathan et al (2016) calculated lower notional AEP for shorter duration PMP (by SST) due to low skewness in arrival distribution
  - Storm Typing - also reported that separating annual maxima by storm type resolved inconsistencies in the upper tails of arrival distributions for SST
  - Area size - Laurenson and Kuczera (1999) estimate notional AEP of PMP is more remote for smaller area sizes
  - Access to moisture supply: Schaefer found more likely PMP closer to moisture supply
- **Errors & uncertainty**:
  - PMP: Availability of historical storms for PMP, transposition limits, adjustment factors, REPS PMP is liquid-phase precipitation only
  - PF: Epistemic & Aleatory uncertainty (look at confidence bounds), spatial interpolation, REPS PF is all-phase precipitation

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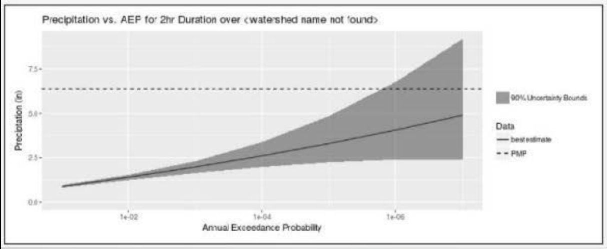
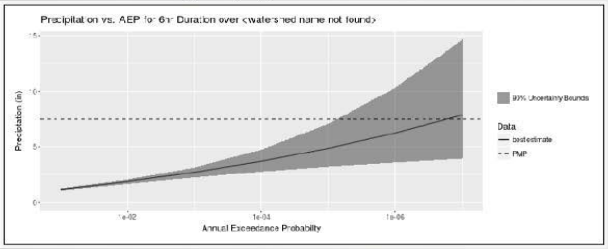
State Regulation in the Absence of Certainty



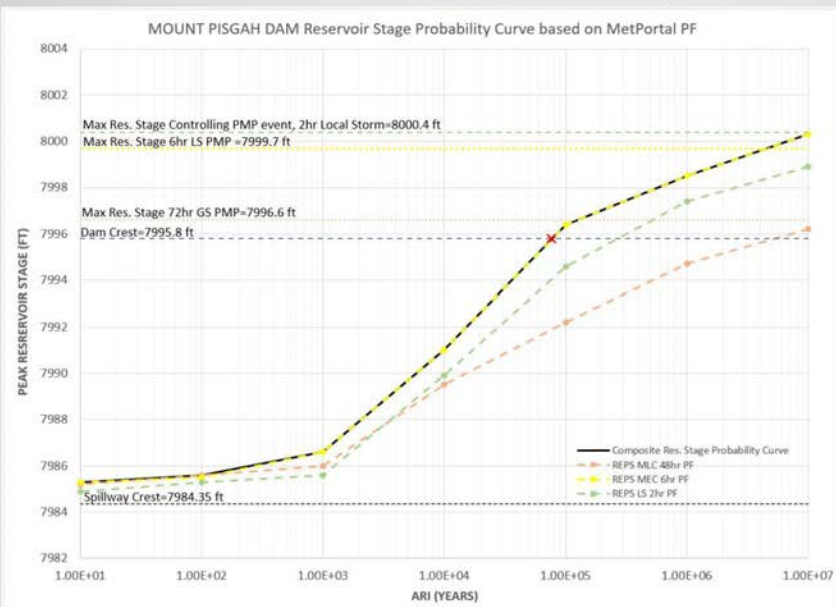
Mount Pisgah (E), PMP/AEP ratio = 1.30



Mount Pisgah (E), PMP/AEP ratio = 0.95

- Risk-Based Approach
  - REPS Rainfall
  - Mountain Hydrology Runoff
  - Hydrologic Hazard Analysis (LL)
  - Peak Flow Verification
    - Res. Stage Hydrologic Loading Curves
    - Bulletin 17C analyses
    - Historic Flood Research
    - Peak flow envelope curves
  - Risk Assessment
    - Residual (non-breach) risk
    - ALARP principles
  - Consequence reduction Recommendations

Existing Spillway Evaluation



- Res. Stage Hydrologic Loading Curves
- 6-hr MEC rainfall controls
- Critical Loading ARI = 76,500 yrs.

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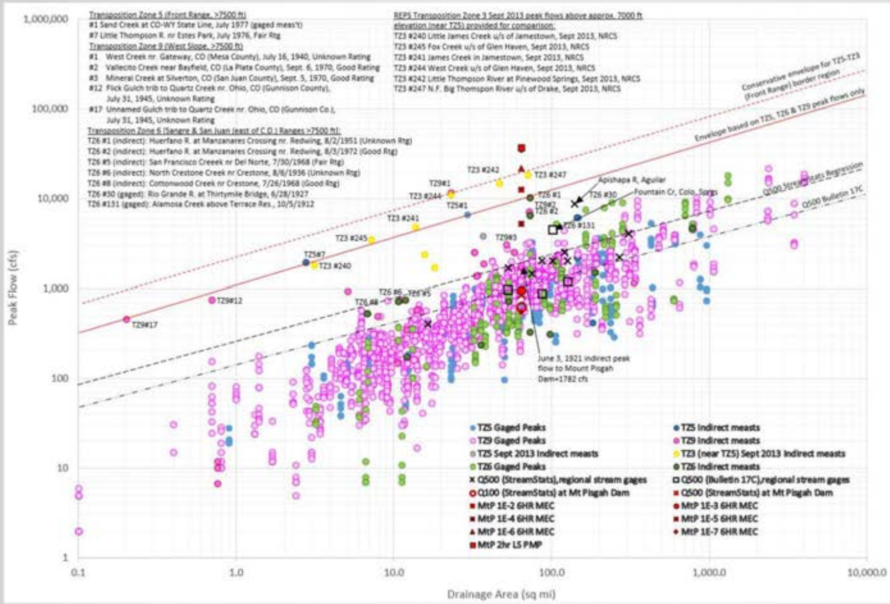
Verification - Regional Envelope Plots



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Existing Dam - Risk Assessment

PFM Failure Likelihood Rating	PFM Failure Likelihood Description
VERY HIGH	The annual failure likelihood is more frequent (greater) than 1/1,000 (10^{-3}). There is direct evidence or substantial indirect evidence to suggest it has initiated or is likely to occur in the near future.
HIGH	The annual failure likelihood is between 1/10,000 (10^{-4}) and 1/1,000 (10^{-3}). The fundamental condition or defect is known to exist; indirect evidence suggests it is plausible; and key evidence is weighted more heavily toward "more likely" than "less likely".
MODERATE	The annual failure likelihood is between 1/100,000 (10^{-5}) and 1/10,000 (10^{-4}). The fundamental condition or defect is known to exist; indirect evidence suggests it is plausible; and key evidence is weighted more heavily toward "less likely" than "more likely".
LOW	The annual failure likelihood is between 1/1,000,000 (10^{-6}) and 1/100,000 (10^{-5}). The possibility cannot be ruled out, but there is no compelling evidence to suggest it has occurred or that a condition or flaw exists that could lead to initiation.
REMOTE	The annual failure likelihood is more remote than 1/1,000,000 (10^{-6}). Several events must occur concurrently or in series to cause failure, and most, if not all, have negligible likelihood.

Confidence Level	Description
STRONG	The team *is confident* in the risk characterization, and it is *unlikely that additional information would change the order of magnitude* of the assigned category to the point where the decision to take (or not take) action to reduce risk or reduce uncertainty would change.
MEDIUM	The team *is relatively confident* in the risk characterization, *but key additional information might possibly change the order of magnitude* of the assigned category to the point where the decision to take (or not take) action to reduce risk or reduce uncertainty may change.
POOR	The team *is not confident* in the risk characterization, and it is *entirely possible that additional information would change the order of magnitude* of the assigned category to the point where the decision to take (or not take) action to reduce risk or reduce uncertainty could change.

Consequence Categories	
LEVEL 1	Downstream discharge results in limited property and/or environmental damage. Average life loss is less than 1. Although life-threatening releases occur, direct loss of life is unlikely due to severity of location of the flooding, effective detection and evacuation.
LEVEL 2	Downstream discharge results in moderate property and/or environmental damage. Average life loss is in the range of 1 to 10. Some direct loss of life is likely, related primarily to difficulties in warning and evacuating recreationists/travelers and small population centers.
LEVEL 3	Downstream discharge results in significant property and/or environmental damage. Average life loss is in the range of 10 to 100. Large direct loss of life is likely, related primarily to difficulties in warning and evacuating recreationists/travelers and small population centers, or difficulties evacuating large population centers with significant warning time.
LEVEL 4	Downstream discharge results in extensive property and/or environmental damage. Average life loss is in the range of 100 to 1,000. Extensive direct loss of life can be expected due to limited warning for large population centers and/or limited evacuation routes.
LEVEL 5	Downstream discharge results in extremely high property and/or environmental damage. Average life loss is greater than 1,000. Extremely high direct loss of life can be expected due to limited warning for very large population centers and/or limited evacuation routes.

- Likelihood
- Consequences
- Confidence

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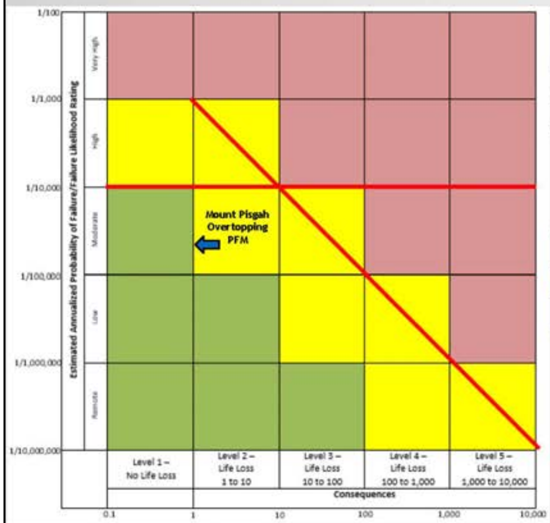
Risk Based Conclusions and Recommendations



Spillway Capacity Q (cfs)	Loss of life estimate by RCEM method			Hydrologic Hazard Category
	Overtopping dam breach + spillway base flood	Spillway base flood	Incremental life loss	
7000	1.7	~0	1.7	Extreme
15,000	2.2	~0	2.2	Extreme
25,000	2.7	0.1	2.6	Extreme
50,000	3.0	0.8	2.2	Extreme

Shows additional expense to enlarge spillway not justified due to limited risk reduction and increased residual risk.

Red	Unacceptable level of risk. Actions required to reduce risk.
Yellow	Increased justification to reduce or better understand risks. ENSURE ALARP principles are addressed.
Green	Risk monitoring zone, decreased justification to reduce or better understand risks. REVIEW ALARP.

Recommendations to reduce consequences

- Early Warning System (blue arrow shows reduced consequence level)

Recommendation to reduce failure likelihood:

- Reinforce existing spillway and embankment against spillway flow erosion

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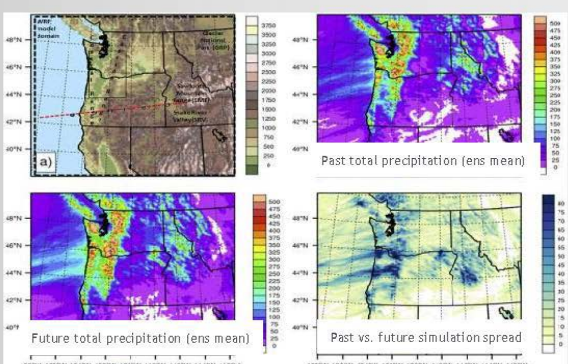
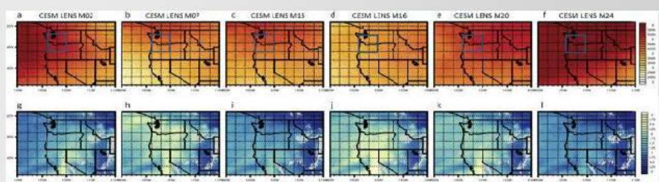
Next Steps to Improve Extreme Rainfall Estimates

Dynamical weather models can help shift from historical-looking approaches:

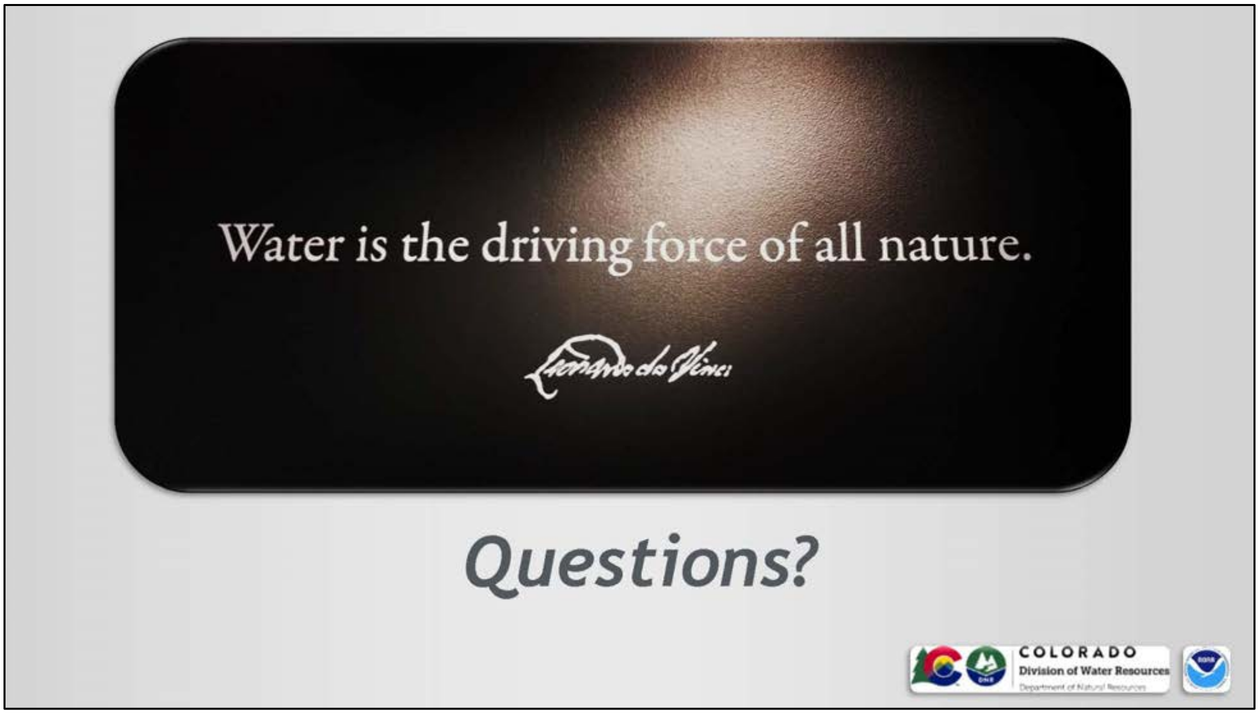
- Existing methods are backward-looking, only incorporating events ***after*** they happen.
- For both PF and PMP, model data bolsters coverage in space and time for both past *and* future extreme precipitation estimation
- Climate change projections suggest an increasing upper bound on extreme precipitation
- Dynamical weather models can be used to assess the impact of potential future climate scenarios on extreme rainfall





Various climate scenarios tested (change in temperature top, change in moisture bottom)

- Example of re-simulating extreme precipitation events in future climate scenarios
- Can also use future climate projections to adjust future probability frequencies, etc.



3.3.3.3 Questions and Answers

Question:
How does REPS precipitation frequency account for snow? How does including snow in the analysis affect the associated precipitation depths and frequencies?

Mark Perry:
The precipitation frequency is total precipitation. The assumption of MetStat and Mel Schaefer was that it was better to analyze the total precipitation because that's what they had from the gauge data. They didn't necessarily have phase information, so they analyzed total precipitation in their annual maximum series. If you look on our website tool for the REPS precipitation frequency, you'll see they provided freezing level data by percentile exceedance and then also 1000 millibar temperatures by month. There's also a seasonality analysis by storm type. So, we handle the phase of the precipitation on the hydrology modeling end. I can tell you that there's not much effect in the short storms. Kelly and Rob's group at NOAA looked at the HRRR data for phase differences, and there's not much difference in the annual maximum series between rain and total precipitation at the two-hour duration for thunderstorms and the six-hour duration for MECs. The main difference is in the long duration storms, as you probably expect, the mid-latitude cyclones mainly. So that's where we would mainly try to account for that difference.

Question:
Did you look at how close the 2013 Colorado flood precipitation came to your PMP estimates? And, in general, how did REPS PMPs differ from those in the HMRs?

Bill McCormick:
Given the geographic distribution and area size of the 2013 storm, we haven't looked at it specifically. We have done a couple basin analyses in the region of the 2013 storm. I think the highest measured total storm rainfall anywhere up and down the Front Range was in Boulder,

which had close to 20 inches of rain over seven days. Our studies with smaller-size basins are relatively comparable to that. They're not a lot more than 20 inches. I know the HDSC did a post-storm analysis of the 2013 storm and found that the precipitation frequency was less than one in a 1000. That's all they could say about it. So, our numbers were relatively comparable. With respect to comparison to the HMRs, on the front range the general storms are generally less than the HMRs and the local storms are generally higher than the HMRs. This may be due to the lack of local storms and how we separated some of those general storms from the original HMR storm catalogs that they used. So far, you know we're pretty happy with how things are turning out there. Things look reasonable and like I say, it is generally less for general storms, most times more for local storms.

Question:
In your opinion, could a bounded S-shaped distribution be considered in order to account both for a heavy tail distribution of high values and the physical limits of the precipitation (i.e. PMP)? This has been used by Swiss hydrologists for dam safety studies.

Mark Perry:
I have not seen that. I think it would be an interesting approach. I know traditionally the approach by Mel Schaefer and Metstat has been to use the GEV distribution. But I think it sounds like an interesting approach.

Question:
How reliable are the AEP estimates for frequencies smaller than 10^{-6}? What were the record lengths (years) of data used for the AEP?

Bill McCormick:
The tool does give us the 90% confidence interval, which gives us some idea of how reliable it is out past 10^{-6}. Our study was state of practice. Mel and METStat used their all their high-end tools that they have used for similar studies performed for the Bureau of Reclamation, U.S. Corps of Engineers, and Tennessee Valley Authority. So we have the same level of confidence in our tools as these other folks are expressing for their studies.

Mark Perry:
The record lengtsh varies by storm type. If you look in the REPS report for each storm type, MetStat provides the number of gauges used and the average station years. They also looked at correlation and then provided an equivalent independent record length. Just looking at the local thunderstorms, for the two-hour annual maximum series they used 341 stations with an average station record length of 41 years, and an equivalent independent record length of 15,000 years.

3.3.4 Presentation 1C-4: Local Intense Precipitation (LIP) Flooding PFHA Pilot Study

Authors: Rajiv Prasad, Yong Yuan, Pacific Northwest National Laboratory

Speaker: Rajiv Prasad

3.3.4.1 Abstract

As part of the U.S. Nuclear Regulatory Commission's (NRC's) Probabilistic Flood Hazard Assessment (PFHA) Research Program, the Pacific Northwest National Laboratory (PNNL) is currently performing a pilot study for probabilistic assessment of local intense precipitation (LIP) flood hazards at nuclear power plants (NPPs). The project includes (1) reviewing existing software packages used to perform LIP flood hazard assessments, (2) reviewing aleatory variability and epistemic uncertainty that influence LIP flood event modeling, (3) performing a LIP probabilistic flood hazard assessment (PFHA) for a hypothetical NPP site, and (4) transferring knowledge to the NRC.

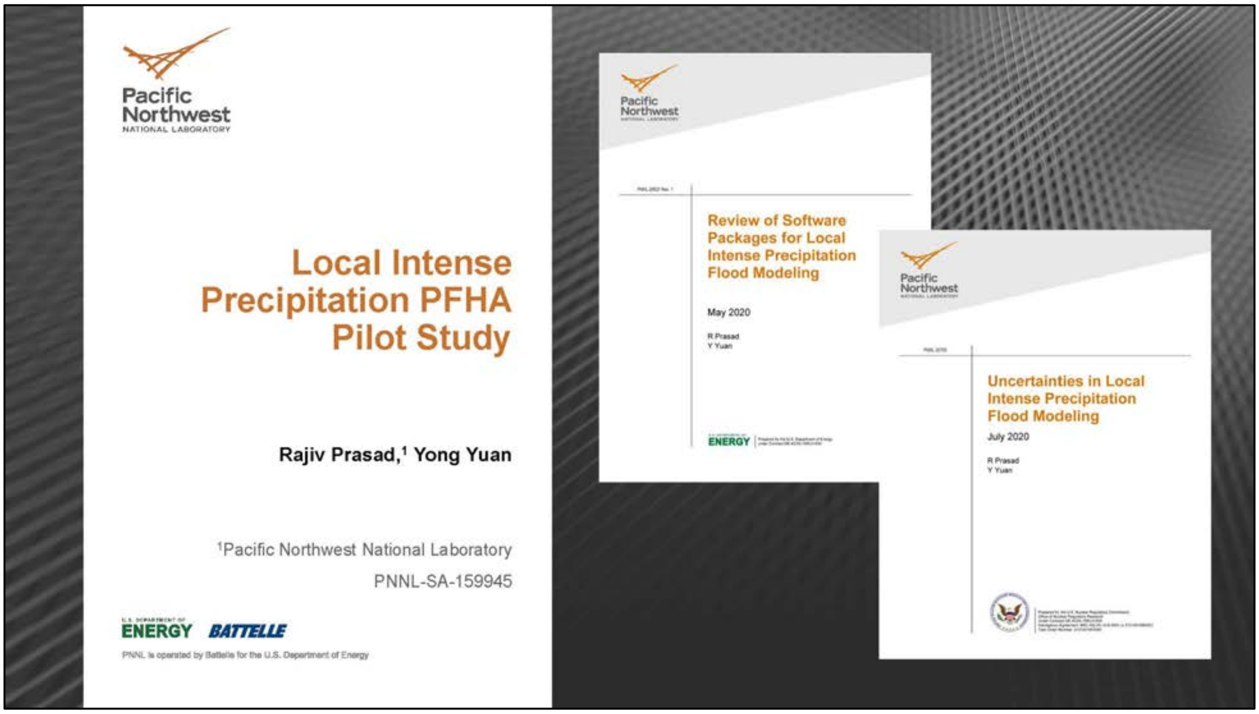
PNNL has completed Tasks 1 and 2 of this project. In Task 1, a review of available LIP flood modeling approaches and their implementation in readily available simulation software packages was conducted. The review focused on a few select, representative software packages to minimize effort spent on reviewing software with similar mathematical bases. The review included some unique issues and challenges that are relevant for simulating LIP floods on industrial sites with high building density like NPP sites. These issues included presence of obstacles to flood flow (e.g., buildings, vehicle barrier systems, temporary equipment), drainage characteristics (e.g., roof drainage, stormwater drainage system, infiltration, sheet flow), and temporal patterns of LIP events. Three general types of models were reviewed: (1) one-dimensional hydraulic models driven by estimated LIP runoff, (2) two-dimensional hydrology-hydraulics models, and (3) smooth-particle hydrodynamics models. The review findings were summarized in a table for easy reference.

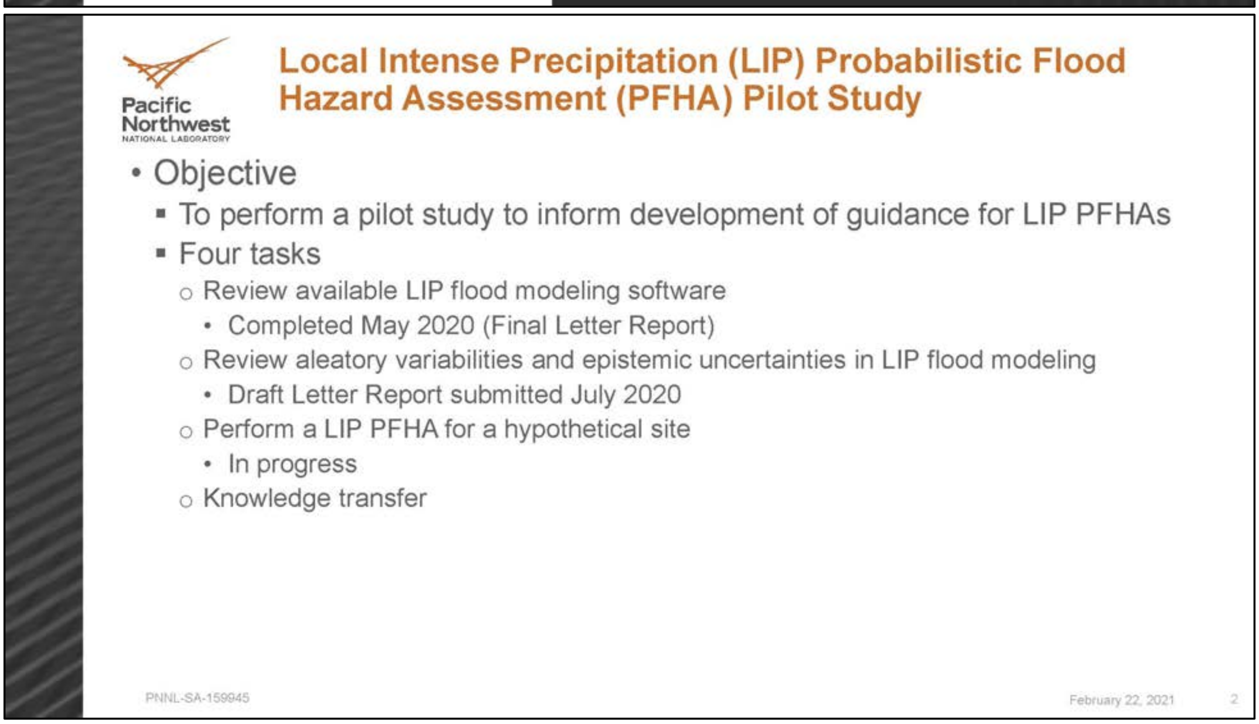
In Task 2, uncertainties associated with LIP flood modeling were reviewed including: (1) aleatory variabilities that arise from the inherent natural variability of the hydrometeorological system and (2) epistemic uncertainties that arise from the analysts' incomplete knowledge of the hydrometeorological processes and site configuration. Accounting for these sources of uncertainty in LIP PFHA modeling requires (1) probabilistic characterization of hydrometeorological inputs, initial conditions, and boundary conditions and (2) inclusion of alternative plausible hydrometeorological process combinations and site configurations. The variability in the hydrometeorological inputs, initial conditions, and boundary conditions is characterized using probability distributions. The choices of these probability distributions and estimation of the parameters of the chosen distributions introduce additional epistemic uncertainties into LIP PFHA. Approaches used to estimate probabilistic precipitation inputs, initial conditions, and boundary conditions were described. Approaches used to include the effects of climate change in hydrologic applications were also described.

Sources of epistemic uncertainty in LIP flood simulations at NPP sites include process representation (e.g., multiple approaches to represent runoff generation, stormwater drainage, and hydraulic routing), site configurations (e.g., site layout, flow features, status of temporary flood protection, blockage of drains), model resolution, and site alterations and regional changes (e.g., known/planned site alterations, land-use changes at and in the vicinity of the site). Epistemic uncertainties can be represented using alternative process representations (i.e., resulting in alternative conceptual models of the site), alternative model parameter sets, and alternative site configurations. These uncertainties can be included into a logic tree as individual

branches weighted appropriately based on their likelihood.

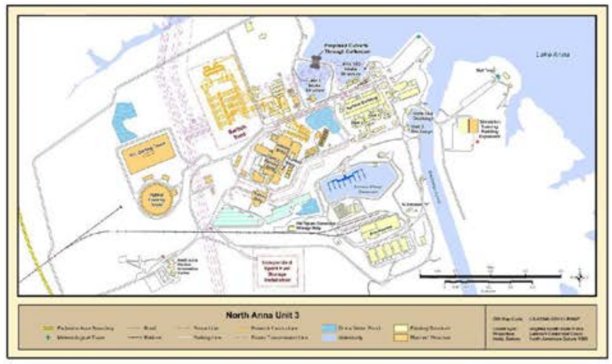
3.3.4.2 Presentation (ADAMS Accession No. ML21064A427)





LIP PFHA Pilot Study: Task 1

- Review available LIP flood modeling software
  - Focus on a few select, representative simulation software packages
    - Mathematical bases: 1-D, 2-D, and 3-D models
    - Readily available
  - Relatively unique characteristics of industrial sites
    - High density of built-up areas
    - Complex flowpaths
    - Variable surface characteristics
    - Roof drains and stormwater conveyance
- Challenges
  - Verification and validation
    - Benchmarking
    - Data limitations



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LIP PFHA Pilot Study: Task 1
LIP Flood Characteristics

- Characteristics of LIP floods on industrial sites
  - **Buildings and other obstacles**
  - **Vehicle Barrier Systems (VBS)**
  - Roof drainage
  - Stormwater drainage
  - Infiltration
  - Sheet flow
  - Hydraulic configuration
  - LIP storm temporal pattern

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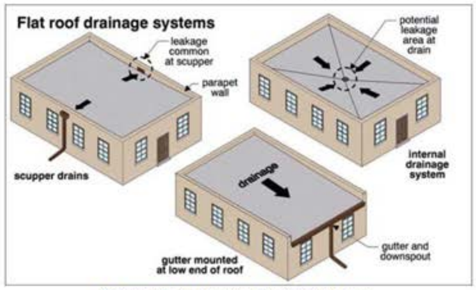
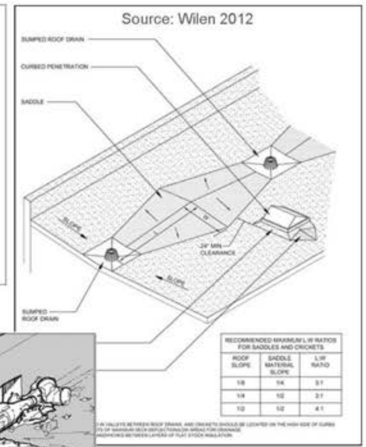
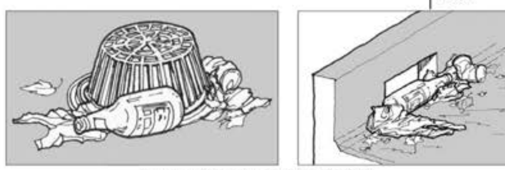
LIP PFHA Pilot Study: Task 1
LIP Flood Characteristics

- Characteristics of LIP floods on industrial sites
  - Buildings and other obstacles
  - Vehicle Barrier Systems (VBS)
  - **Roof drainage**
  - Stormwater drainage
  - Infiltration
  - Sheet flow
  - Hydraulic configuration
  - LIP storm temporal pattern



Source: Keith Messick Architecture blog

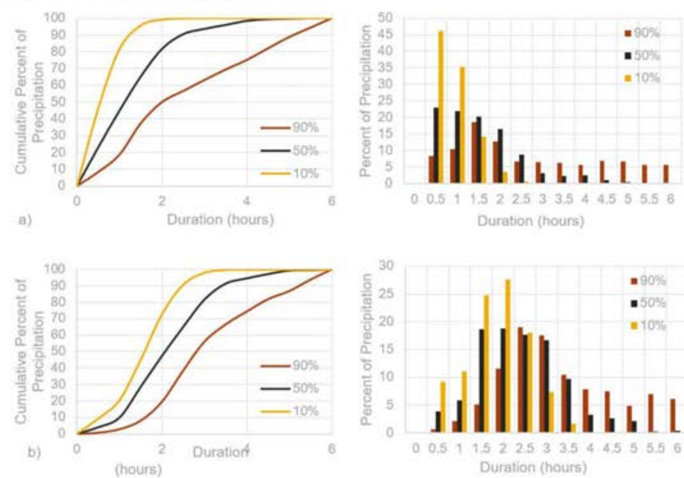




Source: Patterson and Mehta 2010

LIP PFHA Pilot Study: Task 1
LIP Flood Characteristics

- Characteristics of LIP floods on industrial sites
  - Buildings and other obstacles
  - Vehicle Barrier Systems (VBS)
  - Roof drainage
  - Stormwater drainage
  - Infiltration
  - Sheet flow
  - Hydraulic configuration
  - **LIP storm temporal pattern**



Six-hour temporal distribution curves for the Interior Highlands region a) first quartile, b) second quartile. Left: cumulative percent of total precipitation, right: incremental percent of total precipitation. Source: NOAA Atlas 14, Volume 11.

LIP PFHA Pilot Study: Task 1
Selected Flood Simulation Software Packages

- Reviewed flood simulation software packages
  - Description, capabilities, computational setup, and model limitations

Table 1. Selected LIP flood modeling software.

Class	Software Package Name	Model Type
1-D	HEC-HMS + HEC-RAS	Hydrologic Model (HEC-HMS), Hydraulic /Water Quality Model (HEC-RAS)
2-D	FLO-2D	Combined Hydrologic and Hydraulic Model
2-D	Delft3D-FLOW	Hydraulic Model
2-D	OpenFlows FLOOD	Combined Hydrologic and Hydraulic Model
2-D	EPA SWMM	Combined Hydrologic and Hydraulic Model
2-D	PCSWMM	Combined Hydrologic and Hydraulic Model
2-D	XPSWMM	Combined Hydrologic and Hydraulic Model
3-D	Neutrino	3-D hydrodynamic model based on Smoothed Particle Hydrodynamics

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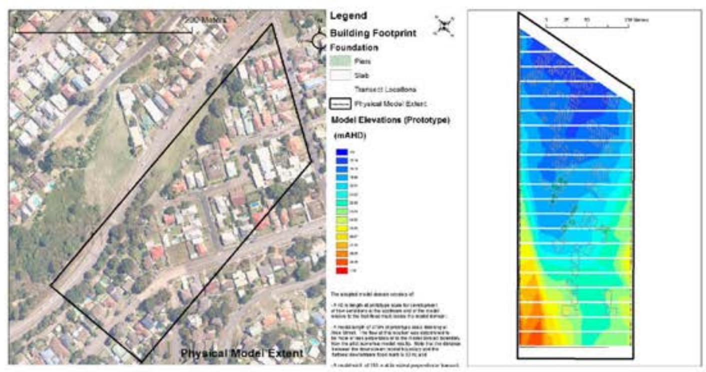
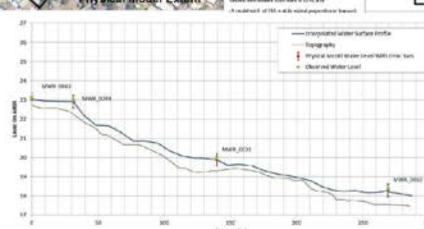
LIP PFHA Pilot Study: Task 1
Verification and Validation (V&V) aspects

- V&V of LIP flood models
  - Code verification
    - Checking code results against known analytical solutions
  - Benchmarking
    - Checking code results against known analytical solutions, laboratory experiments, and field studies
  - Model validation
    - Comparing code results against physical scale model experiments and real-world datasets





Source: Smith et al. 2016

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LIP PFHA Pilot Study: Task 2
Variabilities and Uncertainties in LIP Flood Simulations

- Aleatory variabilities arise from the inherent natural variability in a system
- Epistemic uncertainties arise from the incomplete knowledge of the hydrologic and hydraulic system
- Sources of aleatory variability
  - Precipitation: magnitude, duration, temporal distribution
  - Temperature: magnitude, seasonality
  - Initial conditions: soil moisture, stormwater drainage system state, surface storage and ponding
  - Boundary conditions: upstream discharge, downstream water levels
  - Effects of climate change
    - Can affect precipitation, temperature, initial conditions, and boundary conditions

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LIP PFHA Pilot Study: Task 2
Variabilities and Uncertainties in LIP Flood Simulations

- Sources of epistemic uncertainties
  - Process representation
    - Runoff generation mechanisms, stormwater interaction, hydraulic routing, flow transitions, surface roughness effects
  - Site configuration
    - Aboveground features (buildings, vehicle barrier systems, flood protection features)
    - Subsurface stormwater drains' conveyance capacity
  - Model resolution
    - Spatial and temporal
  - Long-term temporal trends
    - Known/planned site changes, land-use changes

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LIP PFHA Pilot Study: Task 2
Aleatory Variability in Precipitation

- Precipitation frequency analysis
  - NOAA Atlas 14
  - Colorado-New Mexico Regional Extreme Precipitation Study
- Numerical weather prediction models
  - Colorado-New Mexico Regional Extreme Precipitation Study
    - NOAA Earth System Research Laboratory's High-Resolution Rapid Refresh (HRRR) model
  - Kavvas et al. (2018)
- Stochastic weather generators
  - Create synthetic time series of weather variables
  - Peleg et al. (2017): AWE-GEN-2d

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LIP PFHA Pilot Study: Task 2
Probabilistic Precipitation Input for LIP Flood Simulations

- Epistemic uncertainty in characterizing aleatory variability in precipitation

Table 1. Uncertainties in Probabilistic Precipitation Inputs

Method for Characterizing Aleatory Variability in Precipitation	Epistemic Uncertainties
Precipitation Frequency Analysis	Choice of probability distribution, parameters of the probability distributions
Numerical Weather Prediction Modeling	Rainfall processes included in the model, parameters of the process models, model spatial resolution, numerical solution method
Synthetic Weather Generation	Choice of probability distributions, parameters of the probability distributions, spatial correlation coefficients, dependence parameters

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LIP PFHA Pilot Study: Task 2
Aleatory Variability in Initial and Boundary Conditions

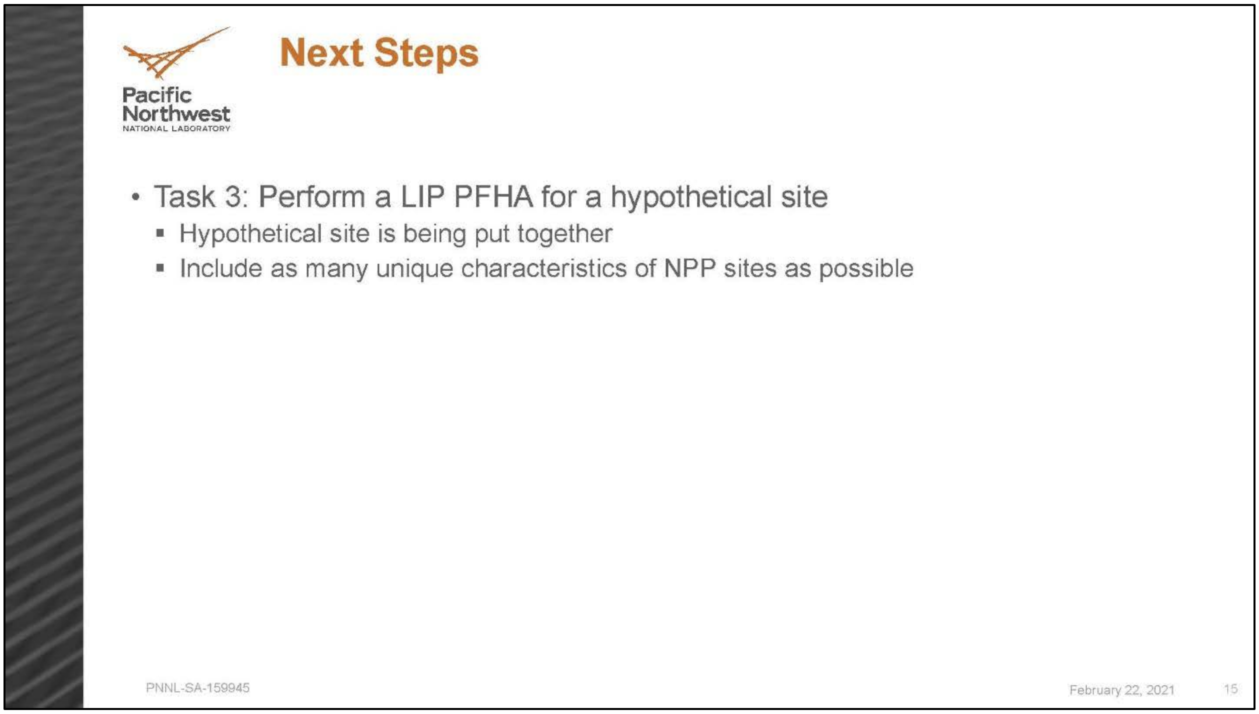
- Initial conditions
  - Soil moisture
    - USDA National Drought Mitigation Center, NWS Climate Prediction Center, NRCS Soil Climate Analysis Network
  - Stormwater drainage discharge
  - Surface storage and ponding
- Boundary conditions
  - Run-on from upstream areas
  - Water surface elevations in downstream, adjacent waterbodies
- Long-term temporal trends
  - Climate change: USGCRP's National Climate Assessments
- Sensitivity analyses
  - To determine the extent of effects of initial and boundary conditions in PFHA

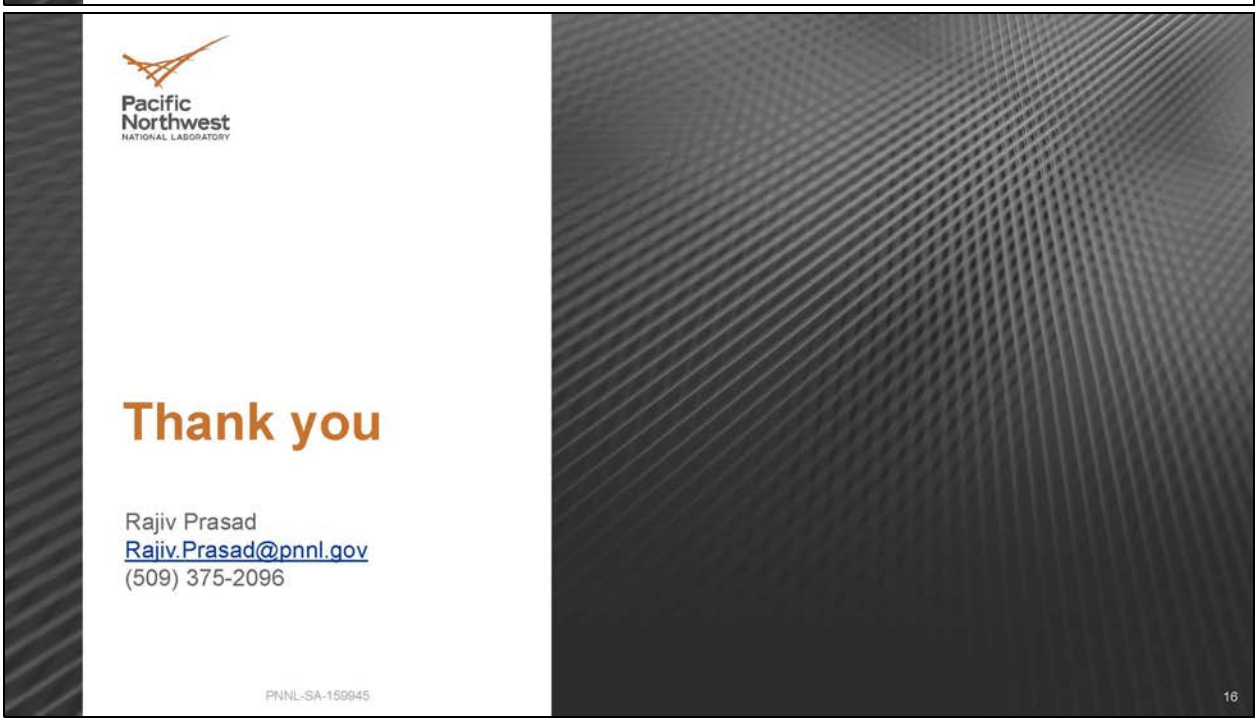
LIP PFHA Pilot Study: Task 2
Epistemic Uncertainties

- Epistemic uncertainties in representation of infiltration

Table 2. Commonly used infiltration methods or models and associated parameters.

Method or Model	Parameters
Green-Ampt model	hydraulic conductivity, soil suction, volumetric moisture deficiency, soil storage depth, percent impervious area
SCS Curve Number method	initial abstraction, curve number (based on land use, land cover, and hydrologic soil group), impervious percent
Horton model	initial infiltration rate, final infiltration rate, decay constant
Initial deficit and constant loss rate model	initial deficit, maximum deficit, constant loss rate, impervious percent
Initial and constant loss rate model	initial loss, constant loss rate, impervious percent
Exponential loss rate model	initial range, initial coefficient, coefficient ratio, precipitation exponent, impervious percent
Smith-Parlange loss model	initial water content, residual water content, saturated water content, bubbling pressure, pore size distribution, hydraulic conductivity, beta zero, impervious percent
Soil moisture accounting loss model	initial soil condition, maximum infiltration rate, impervious percentage, soil storage, tension storage, the soil percolation, upper and lower groundwater storage/percolation rate/coefficient





3.3.4.3 Questions and Answers

Question:
Are there any procedures already developed to collect the data for verification and validation of models which may be applied for evaluating the design basis flood at NPPs?

Rajiv Prasad:
There are some procedures that might be developed. One that I mentioned about in the talk was looking at trying to obtain data that informs some part of the LIP flood. For example, these could be something like high water marks or anecdotal information from events that are remembered by plant people or others. Those can give you spot data to check against if a particular event was associated with that data. That's one way. To my knowledge, there isn't a systematic flood data collection at NPP sites that relates to LIP events.

3.3.5 Precipitation Panel Discussion

Moderator: Elena Yegorova, NRC/RES/DRA
Panelists:
Andreas Prein, National Center for Atmospheric Research (NCAR)
Bill McCormick, State of Colorado, Water Resources Division
Kelly Mahoney, National Oceanic and Atmospheric Administration (NOAA)
Rajiv Prasad, Pacific Northwest National Laboratory (PNNL)

Question (to Panel):
Extreme flood events are typically caused by a combination of favorable conditions such as snowmelt, saturated soils, extreme rainfall, or high tides. How can we best account for the compounding effects of multiple processes on flooding?

Andreas Prein)
It's very good question. The models that we are using nowadays, for example the WRF simulations, are often already coupled with other components of the Earth system like surge models, or snow models. So, they really offer the opportunity to simulate all these effects in combination and their interactions, which is very attractive. The problem often is that this is fairly expensive. For example, if you think about rain on snow, you really must have realistic snow conditions first. This means you sometimes have to run for a very long time to build up the snowpack, if you don't have this information already. But I think a promising way forward is to use the capabilities of the models simulate all these combined impacts in combination.

Ali Sarhadi:
When you are talking about compound extremes, the most important thing is the damages arising from them. By definition, a compound extreme is when two or more hazards occur simultaneously, and their societal and environmental impact will be much greater than when they occur separately. So, it’s important to care about the damages arising from these compound extremes. The other important point is that we need to have a realistic perspective about hazards. When we're talking about tropical cyclones, it's not only about inland flooding because, at the same time, we're going to have hazards from storm surge and high winds. All of them occur at the same time. So, if we're going to have a realistic quantification of risk, we need to take into account all of these hazards at the same time. In this way we will be able to avoid any sort of underestimation in the risk. Another important thing that I was going to mention here is we are living under a nonstationary climate, and when we're talking about compound extremes, we need to implement that nonstationarity in our models. Currently used models, or most of them, are stationary based. We already know that the nature of risk in these compound extremes are changing under a changing climate arising from global warming, so we need to address that known nonstationarity in our risk models as well.

Rajiv Prasad:

I can just say that I agree that compounding hazards are a problem. NRC guidance usually asks for compounding hazards, sort of combinations that can happen. One thing to keep in mind is that sometimes these compounding situations arise sequentially, sometimes they can happen at the same time, and sometimes they can be lagged. So, the timing aspect of how they're combining is also quite necessary, particularly in case of LIP. For example, an LIP event could be caused by an embedded frontal system within a more synoptic event. If that happens, then you have to worry about not only the intense precipitation on the site, but what can happen in the adjoining water bodies. There could be effects from the larger storm on boundary conditions and things like that. So, I agree with the other commentors.

Question (to panel):
How can we optimally combine various sources of information to improve flood risk assessments?

Andreas Prein:
We should really do that. We should really try to leverage as much information as we have. So, I really like Bill’s talk for example. He looked at weather forecasting in addition to the observation and paleoclimate studies. I think this is a good example where they combined a lot of different information sources to get a better estimate of these very intense and rare events. This was a really good example of that.

Kelly Mahoney:
I would just add that, in Bill’s Colorado-New Mexico REP study, we started calling it an ensemble of ensembles because it wasn't just an ensemble of models and data sources. It was an ensemble of approaches and I think Bill and his team had the vision for that early on. I think that's really kind of a new idea in the field in terms of not looking for *the* best approach, but accepting that there are great benefits in layering them and using them as their own internal sets of checks and balances. In a way it sounds refreshingly basic, perhaps. But I think it's quite novel and kind of echoing Andreas’ point, championing that vision that Bill and his team had.

Question (to Rajiv Prasad):
You touched on discussing uncertainties in your analysis. What are the greatest uncertainties associated with local intense precipitation (LIP) flood modelling?

Rajiv Prasad:
Personally speaking, two sources come to mind straightaway. One is the natural variability associated with the LIP event itself, the interannual differences from year to year. How much rain did you get and how well we can predict it, particularly at AEP of 10^{-3} and lower? How to include that in the analysis is a challenge. That would usually control how much precipitation input you're getting on your site and then would control the uncertainty in the flood magnitude. Another one that comes to mind, particularly for LIP events, is the configuration of the site. How much do you know, and how accurately do you know what controls the flows on the site? For example, if the buildings are spaced such that you have these flow issues that I was talking about, such as contractions and expansions. If you do not know that with a great degree of confidence then there is a possibility that they can induce a lot of uncertainty in LIP flood hazards, particularly where some of the critical facilities might be located. So, to me, the greatest amount of uncertainty in terms of flood depends on which hazards you're talking about, and where on the site you are estimating those hazards.

Andreas Prein:
I can add a quick note. If you just think about the extreme rainfall part, it's often really the record length. For example, you look at precipitation frequency curves before and after Hurricane Harvey, the return values on these curves are very different if you include this event are not.

Our record lengths are often very short. Towards the end of my presentation, I talked about this. I think it's important to get a bigger sample size of realistic storms. Again, I think the high-resolution models can really help us there to build a bigger sample size to make better estimates.

Rajiv Prasad)
Yes, and also changes in frequency as we go along, with more data and particularly more data on extreme events. So nonstationarity, particularly in how they affect the main driver of these flooding events that you're trying to simulate, needs to be kept in mind. So, I completely agree, nonstationarity can be a big challenge.

Bill McCormick:
For our study, the researchers used some novel ways to trade space for time to increase their observations. Listening to Andreas' presentation, I am interested in just how we use those ensemble models. Accurate modeling going forward multiple times to get many thousands of years of records seemed really intriguing to me too, especially as you get more skill in your in your models and have confidence in the results that they're giving you. It seems like there's a lot of opportunity in that area.

Question (to Panel):
How can dynamical weather models be used to assess the impact of potential future climate scenarios on extreme rainfall?

Kelly Mahoney)
That's a big question and I really appreciated Ruby Leung's talk and breakdown of this earlier. Not to be repetitive, but you really need to layer approaches to get at this in a comprehensive way. Dynamical weather models offer so much. But when you are tackling the climate question that Ruby laid out so well, you're not just asking about a certain event or certain type of event, and so you need to have these approaches where you're taking advantage of the high-resolution aspects that Andreas highlighted so well. But with the whole climate category, when you started combining those, I think you absolutely should try the different approaches of applying the deltas for pseudo global warming and then applying the patterns for frequency changes and being able to map or kind of fill out the parameter space of that whole question.

Andreas Prein:
I fully agree that Ruby really laid out this topic really well in the morning. There are these large ensemble datasets that we have nowadays. These are just thousands of years of model data that you can look at. The premise there is really that these models are pretty good at simulating the large-scale patterns and then combining those simulations with very-high-resolution models. I think this is a promising way forward.

Ali Sarhadi:
I'd like to add something in the field of tropical cyclones. If we improve those dynamical weather models and enhance the resolution and the information that we get from them, it will help a lot in terms of preparedness for different disasters. When we're enhancing the forecasting of different extreme events like hurricanes you will have the chance to sort of translate those extremes and come up with the risk of flooding for each specific event. That way we can reduce the damages arising from these extremes.

Andreas Prein:
Maybe just one more note. I think this is what Kelly did in their study using existing data sets from the HRRR model and what we did with simulations we had at NCAR. We are doing a lot of climate modeling at very high resolution and these datasets are getting more and more. So just leveraging what's already there and collecting these kinds of datasets and heavy rainfall events

from these data sets, I think this low hanging fruit because it doesn't cost a lot and you get a lot of information out of them.

Kelly Mahoney:
Just building on that, I had no idea that Andreas' group was doing this whole project. To see we run parallel to each other is really great, because I completely agree it is low hanging fruit. It's just data mining. It's sitting there. It's not perfect, but connecting to the previous question about trading space for time and things that had to be done in the REPS project to tackle that short period of record for both observations and the modeling, I think a lot of times it's very easy to cite the shortcomings of the old PMP process in the different approximations that had to happen. But you know, a lot of that happens in the trading of space for time side too. You make a lot of statistical assumptions. I think that the dynamical weather model data that's just sitting out there offers at least a common point at which we can collectively step forward. Because you have these internally physically consistent data sets, you can trade space for time without taking on serious statistical or physical transposition-like approximations. It's not a silver bullet. It's not going to solve everything, but I think it tackles both of those like weaknesses and challenges in a "data exists" kind of way. I wanted to attempt to tie that into a bundle here.

Question (to Panel):
Could you further leverage these datasets by perturbing them? Something like Newman et al. (2015)?

Andreas:
Maybe. I think, that the stochastic storm transportation, for example, is a good method to use, and I guess this is what Kelly used or something similar.

Kelly Mahoney:
We've talked about doing this in a number of ways. For the REPS project we didn't actually perturb. Some of the other Tasks in the REPS project did things with transposing storms and we did do that a little bit with historical simulations. We wrote a section at the end of our report talking about this exactly. Working with the HERR, if you were to create a new data set and you wanted to sort of maximize it for precipitation, how you would do that in ways that sort of maximize the uncertainties in initial conditions. So, we kind of thought out loud on that, but didn't actually do it. The REPS project took historical events and then transposed them in the traditional PMP ways.

Question (to Bill McCormick)
What is the status of NOAA Atlas 14?

Bill McCormick)
As far as I know, there's a couple pieces of legislation that are intended to carry NOAA Atlas 14, to more of a national precipitation frequency atlas for the U.S. That's in two different Acts. The Floods Act and the Precip Act. They'll have to resolve the language of those two Acts to be consistent with each other. That legislation will, hopefully, be introduced in the near future, maybe as early as this week. Then it'll start going through the legislative process after that. So that's kind of exciting. There is language in both those acts with regards to NOAA Atlas 14 updates and consistent funding sources, and then also the PMP studies, updating all the HMRs. So I'm encouraging this community to stay tuned on some of those developments.

Question (to Panel):
The final question is about availability of data and modeling results. How do community researchers become aware of new available data (observational or synthetic), and have access to it understand its format, structure and assumptions?

Andreas Prein:
At the moment, at least on the modeling side, there's no really good overview of what's available. I think people who work in the field, like Kelly and I, probably know a lot of data sets that are out there. But I think it would be really worth thinking about maybe having a project where you collect all these datasets, make them available and, at least for heavy rainfall, offer some target events based in a specific data set or database.

Kelly Mahoney:
I think that that would be a logical next step to the “low hanging fruit” situation of having this pre-existing data. Like Andreas said, that's been a problem in the in the field for a long time. As soon as you could generate all this high-resolution information, the problem was storing it and then communicating it and getting it out there. So, it's probably a billion-dollar question, but definitely something not to overlook as we get further into the conversation of like to use it and how to generate new state of the art datasets. They don't serve anyone if people don't know about them. So not overlooking that very critical step is definitely a point for us as a community to keep in mind.

Bill McCormick:
From the operational standpoint, if anybody does a survey of datasets available, it might be interesting to query private sector consultants that are already using some of that data. I ran into some reports by a couple of consultants that do flood forecasting for the Denver area and they were both using HRRR data and WRF modeling. So, not only from the research side. It would be interesting to query the private sector side and see the interesting things that folks are doing with that data. The research to operations component is so useful.

3.4 Day 2: Session 2A – Riverine Flooding

Session Chair: Mark Fuhrmann, NRC/RES/DRA

3.4.1 Presentation 2A-1 (KEYNOTE): Estimating Flood Frequency using Stochastic Storm Transposition, Gridded Precipitation Data, and Physics-based Modeling

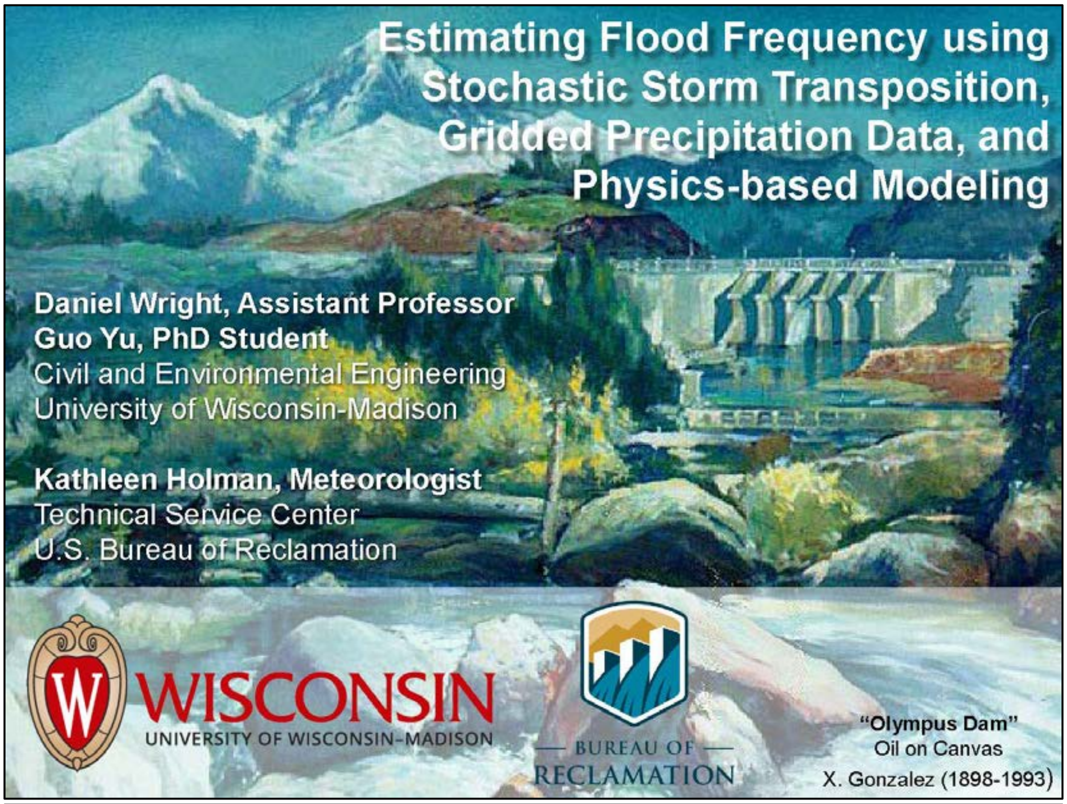
Authors: Daniel Wright[1], Guo Yu[1], Kathleen Holman[2], [1]University of Wisconsin-Madison, [2]U.S. Bureau of Reclamation

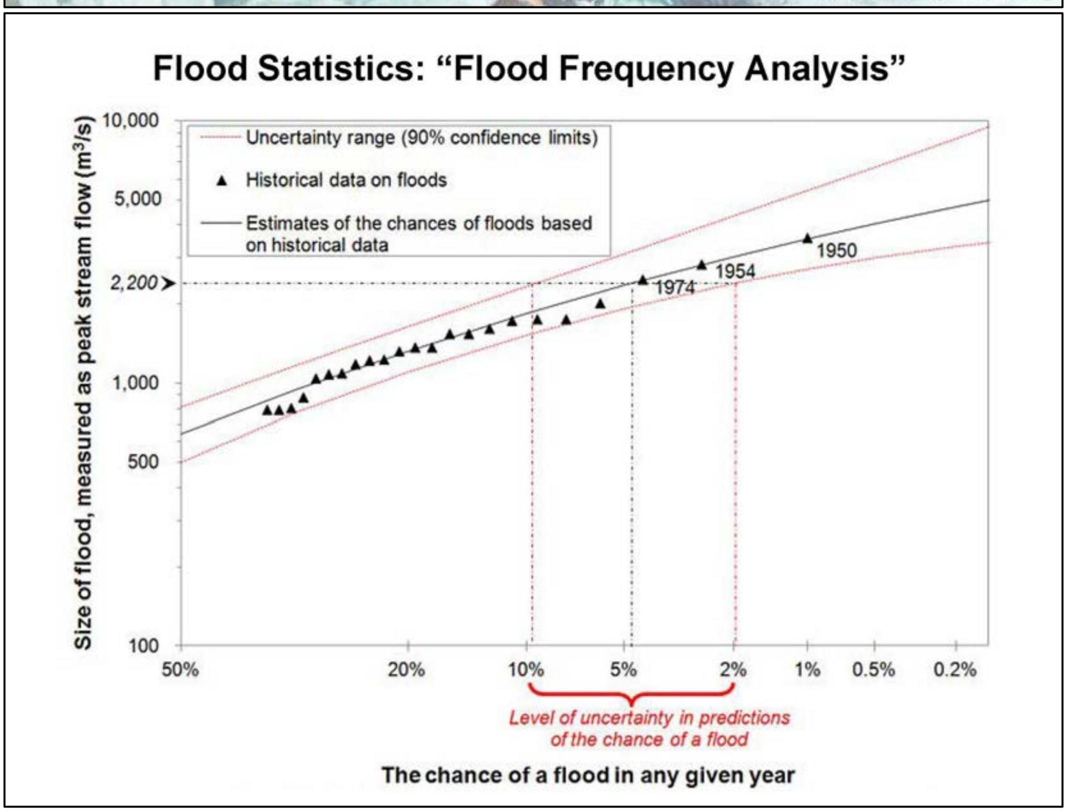
Speaker: Daniel Wright

3.4.1.1 Abstract

Predicting the frequency and severity of floods has been a longstanding topic of hydrologic research and practice. Despite the fact that every flood is a unique combination of multiple physical processes (rainfall, snow, and soil moisture, to name a few), the prediction of key metrics such as the 100-year flood has often been treated primarily as a statistical problem rather than a physics problem. In this presentation, we argue that flood frequency analysis can benefit from deeper consideration of the physical processes that cause floods, as well as from decades of progress in high-resolution precipitation gridded measurements and hydrologic simulations. We present a three-step “process-based” flood frequency analysis framework: 1. generating large numbers of realistic rainfall scenarios by coupling stochastic storm transposition gridded precipitation data; 2. using a physics-based hydrologic model to create a database of state variables including soil moisture and snowpack; 3. resolving large numbers of combined rainfall scenarios and watershed states using Monte Carlo numerical simulation. This framework allows us to reconstruct rainfall and flood frequencies that are comparable in accuracy to more conventional statistical approaches, and that can provide deeper insights into how physical drivers lead to flood frequency. We show results for two watersheds, both of which pose specific challenges to more conventional methods: 1.) an agricultural watershed in Iowa that is undergoing rapid hydrologic change; and 2.) a mountainous watershed in the Colorado front range that exhibits a complex seasonally-varying flood regime.

3.4.1.2 Presentation (ADAMS Accession No. ML21064A428)

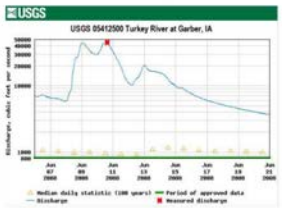




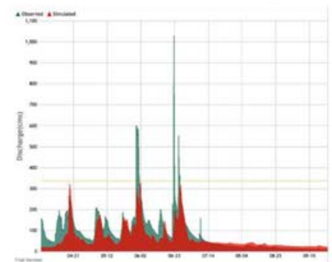
How can we use conceptual, observational, and modeling advances (i.e. physics) to improve flood frequency analysis?

Design storms? Covariates? Something else?

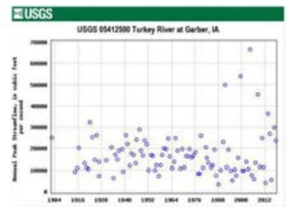
Flood Physics



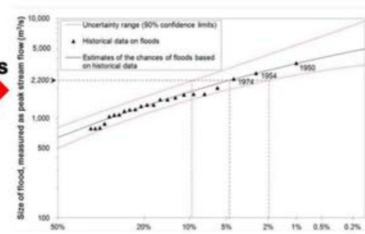
$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + g\frac{\partial \zeta}{\partial x} = -\frac{P\,\tau}{A\,\rho}$$



Flood Statistics



$$f(x|\mu, \sigma^2) = \frac{1}{\sqrt{2\sigma^2\pi}} e^{-\frac{(x-\mu)^2}{2\sigma^2}}$$



Observations

Models

Predictions

Conceptual Advances

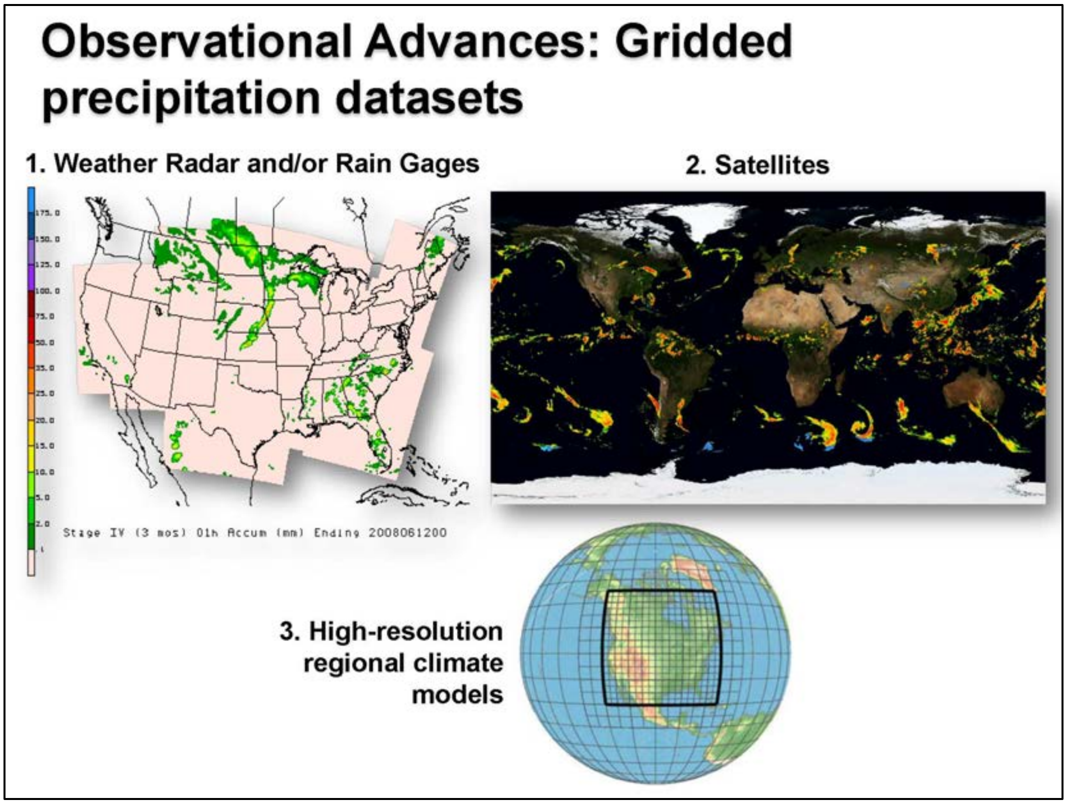
Then: "The belief was not uncommon as late as the 18th century that rivers derived their waters, even in times of floods, from the interior of the Earth and not from rain and snow." Robert E. Horton, 1931

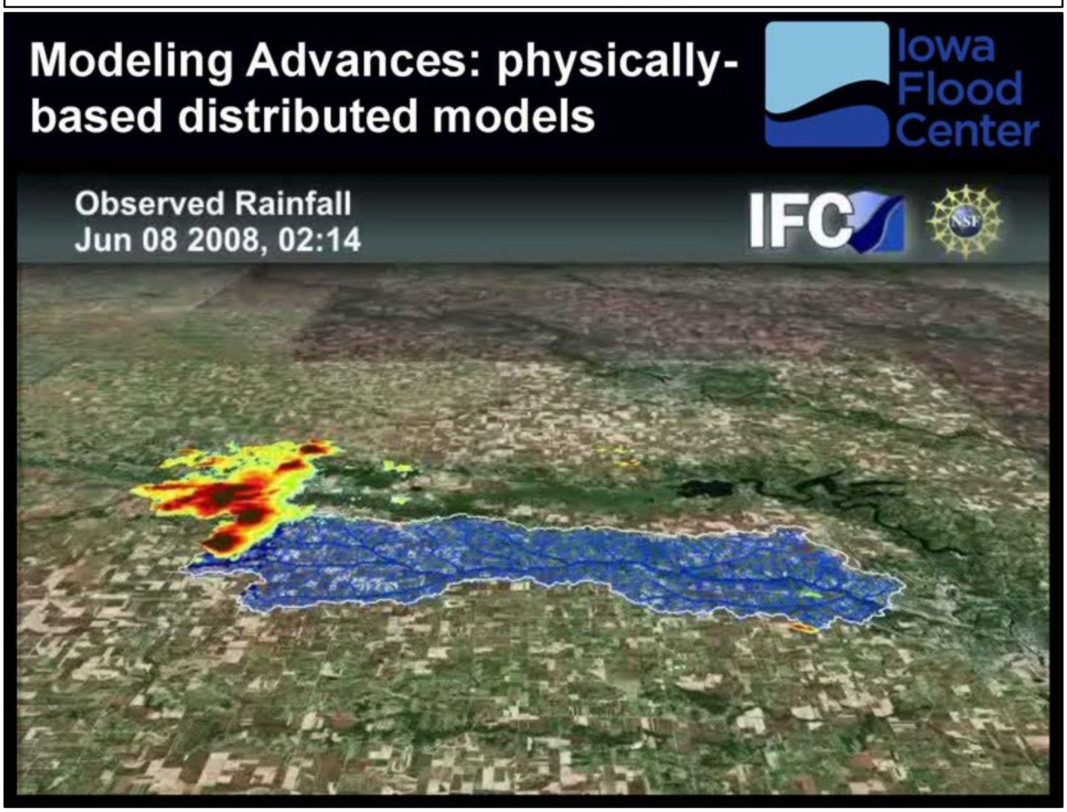
Now: Floods are "recipes"

Ingredients/spices:

- Rainfall
- Land properties
- Soil moisture
- Snowpack/snowmelt/frozen soils
- Agricultural practices
- Dams, reservoirs, lakes
- Flood control infrastructure

Image: http://www.berries.com


Observational Advances: Gridded precipitation datasets
1. Weather Radar and/or Rain Gages
Stage IV (3 mos) 01h Accum (mm) Ending 2008061200
2. Satellites
3. High-resolution regional climate models


Modeling Advances: physically-based distributed models
Iowa Flood Center
Observed Rainfall
Jun 08 2008, 02:14
IFC

One solution: Process-Based Flood Frequency Analysis

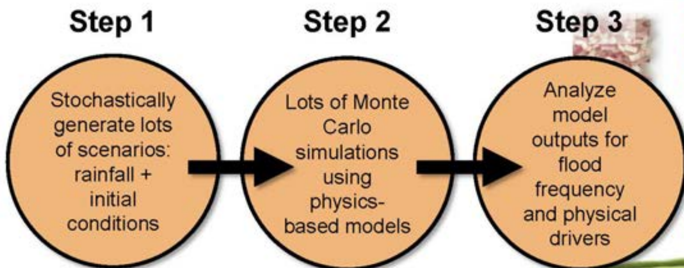
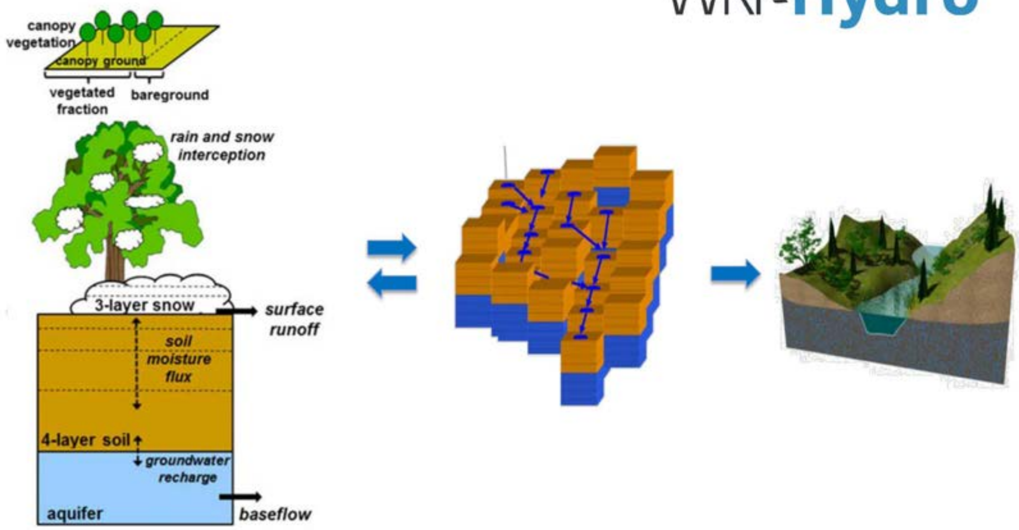


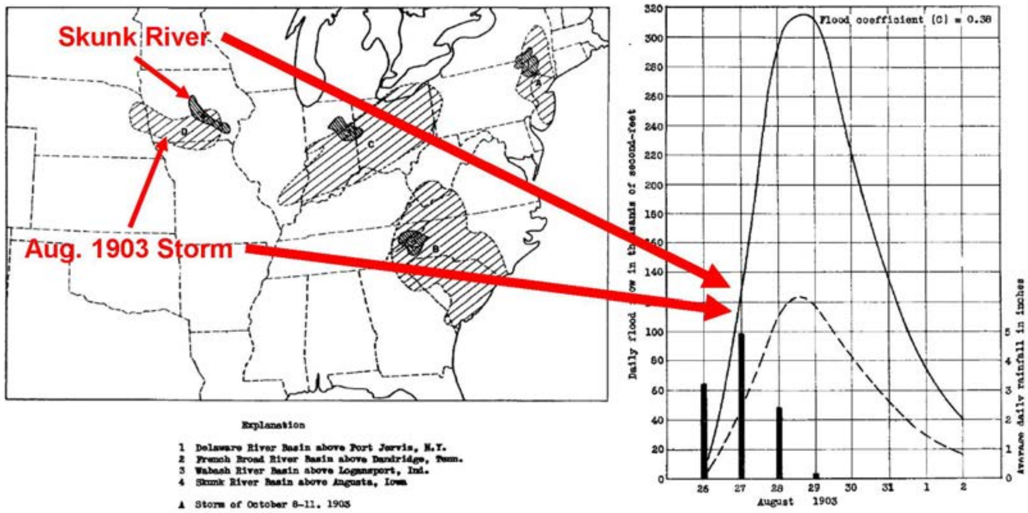
Image: http://www.berries.com

Captures variability and joint behavior of rainfall and other processes

WRF-Hydro®



Storm Transposition: Floods need rain!



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

Storm Transposition: 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

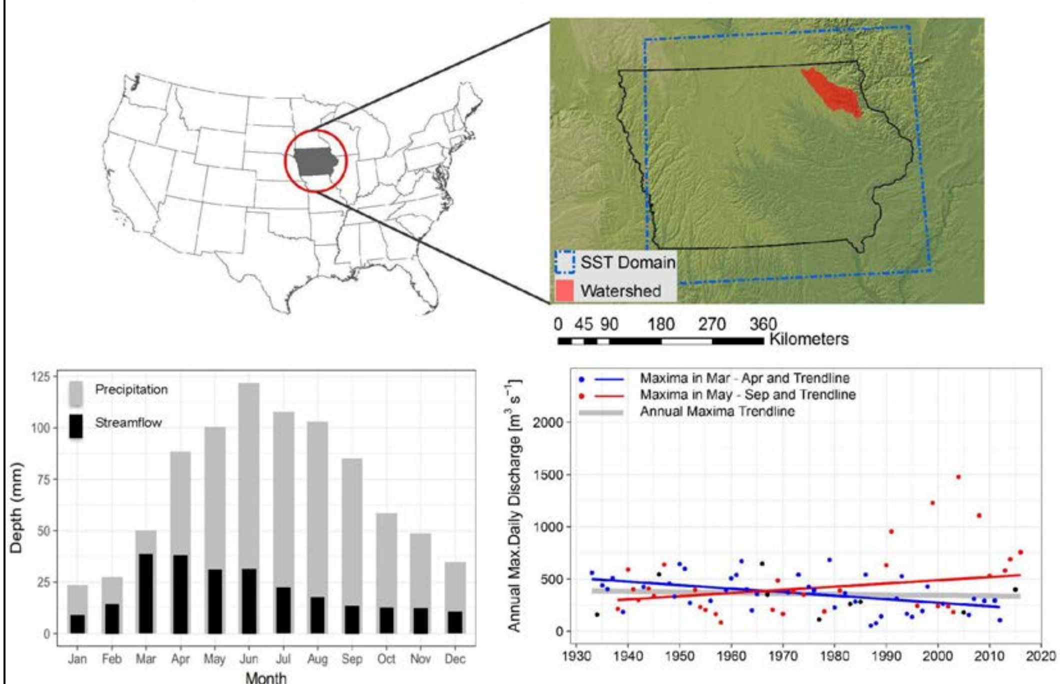
When estimating the frequency of rare floods from a given catchment using storm rainfall data, the pertinent question is: "What is the probability of a rainfall averaging more than d inches (in a specified duration) occurring *over the catchment in question* within a long period such as the life of the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

RainyDay Software

Open-Source, Python-based

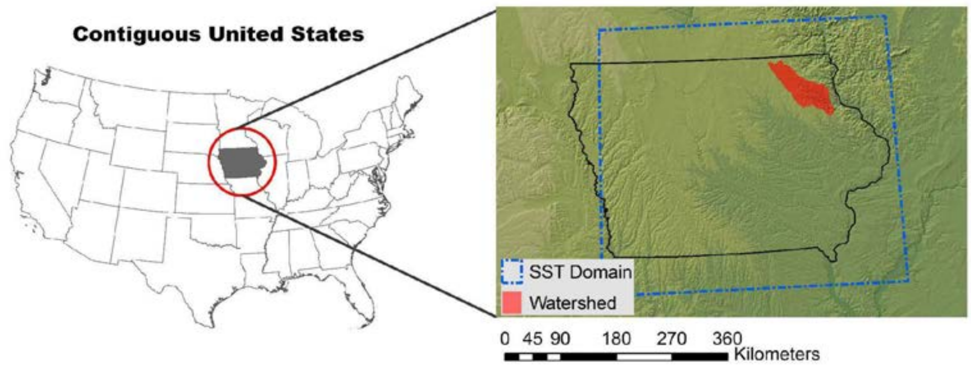
- Uses archives of <u>gridded rainfall observations:</u> radar, satellites, interp. rain gages, regional climate projections
- Uses Stochastic Storm Transposition to generate large numbers (10k+) of rainfall scenarios
- Can provides reasonable estimates to 1,000+ year recurrence intervals for rainfall and floods with a few decades of data

Example 1: Turkey River, Iowa



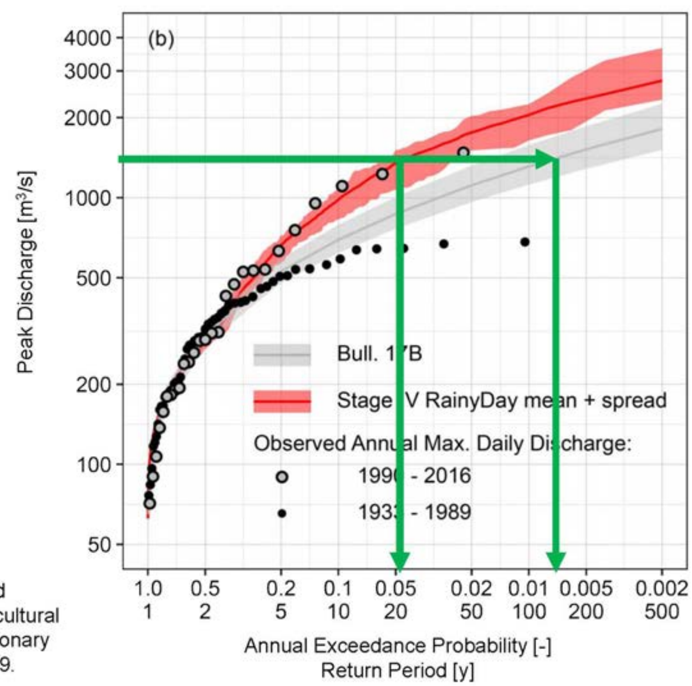
Storm "Transposition Domain"

NCEP Stage IV: weather radar + rain gages
2002-2016 (15 years)

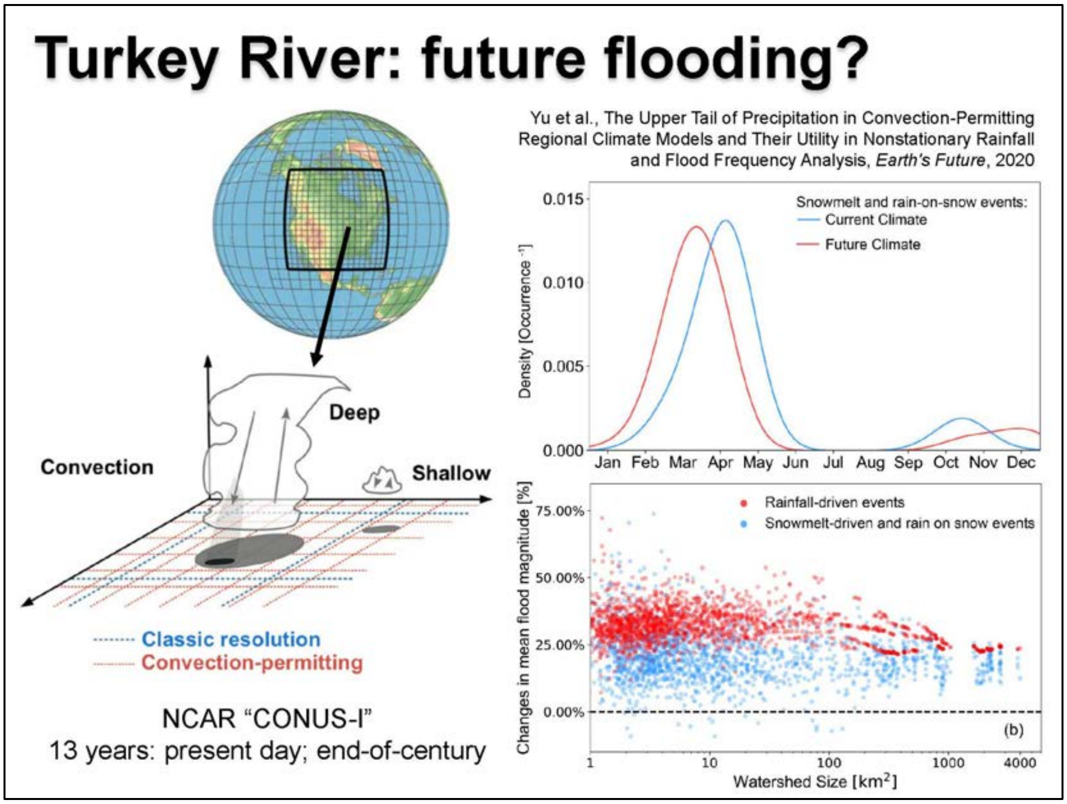


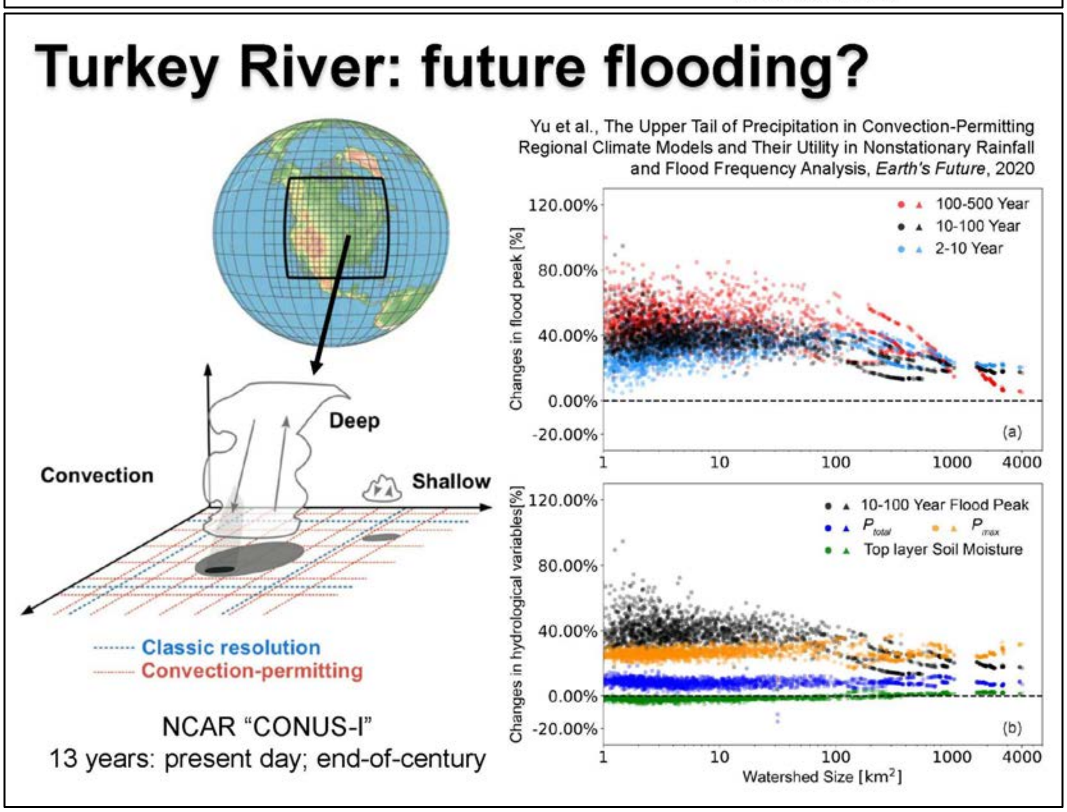
Yu et al., Process-Based Flood Frequency Analysis in an Agricultural Watershed Exhibiting Nonstationary Flood Seasonality, *HESS*, 2019.

Flood Frequency Estimates



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

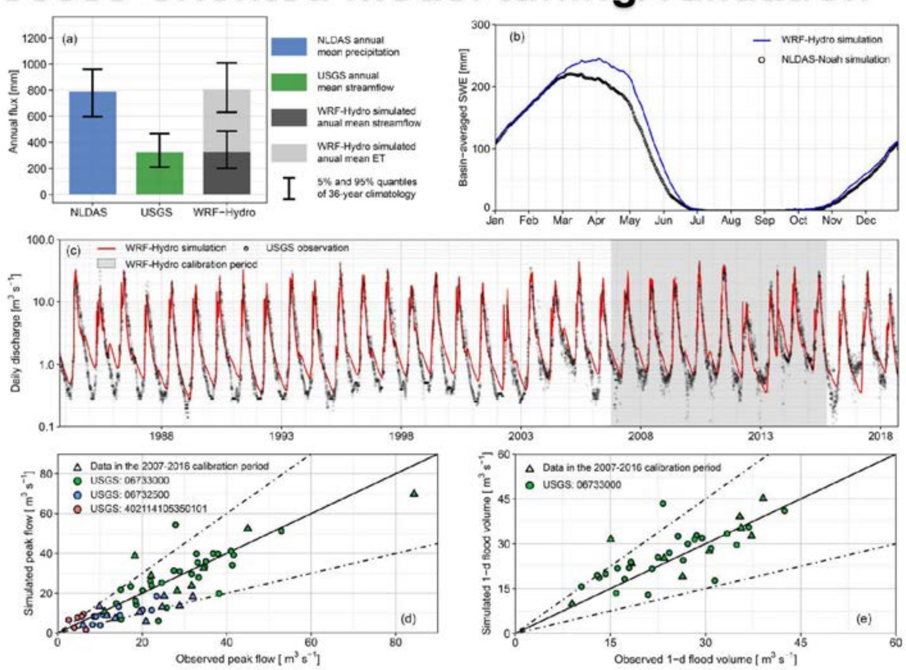

Turkey River: future flooding?
Yu et al., The Upper Tail of Precipitation in Convection-Permitting Regional Climate Models and Their Utility in Nonstationary Rainfall and Flood Frequency Analysis, Earth's Future, 2020
Convection
Deep
Shallow
Classic resolution
Convection-permitting
NCAR "CONUS-I"
13 years: present day; end-of-century
Snowmelt and rain-on-snow events:
Current Climate
Future Climate
Density [Occurrence⁻¹]
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec
Rainfall-driven events
Snowmelt-driven and rain on snow events
Changes in mean flood magnitude [%]
(b)
Watershed Size [km²]


Turkey River: future flooding?
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
Convection
Deep
Shallow
Classic resolution
Convection-permitting
NCAR "CONUS-I"
13 years: present day; end-of-century
100-500 Year
10-100 Year
2-10 Year
Changes in flood peak [%]
(a)
10-100 Year Flood Peak
P total
P max
Top layer Soil Moisture
Changes in hydrological variables[%]
(b)
Watershed Size [km²]

Example 2: Big Thompson River, CO

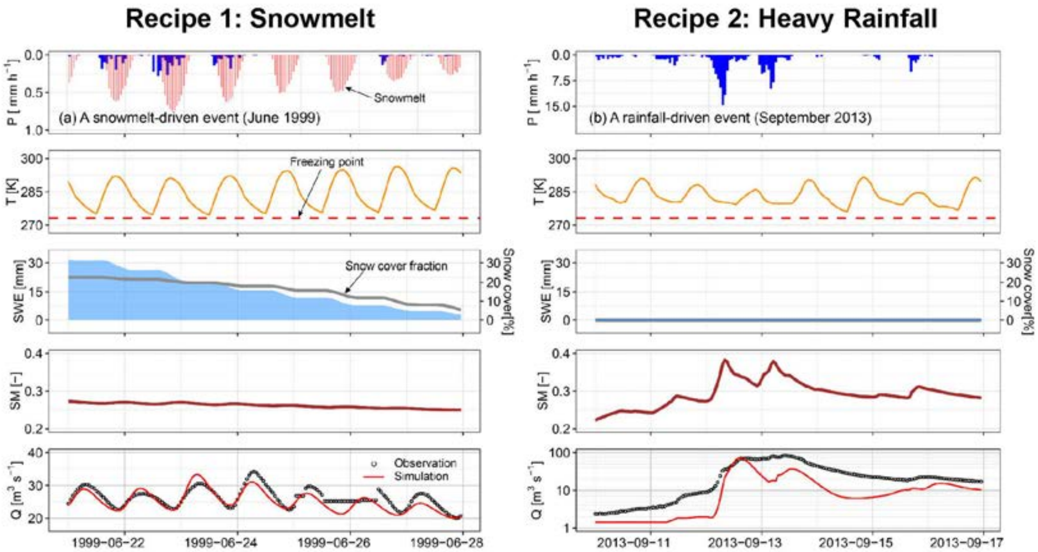
Yu et al., Connecting Hydrometeorological Processes to Low-Probability Floods in the Mountainous Colorado Front Range, in review, *WRR*

Process-oriented model tuning/validation



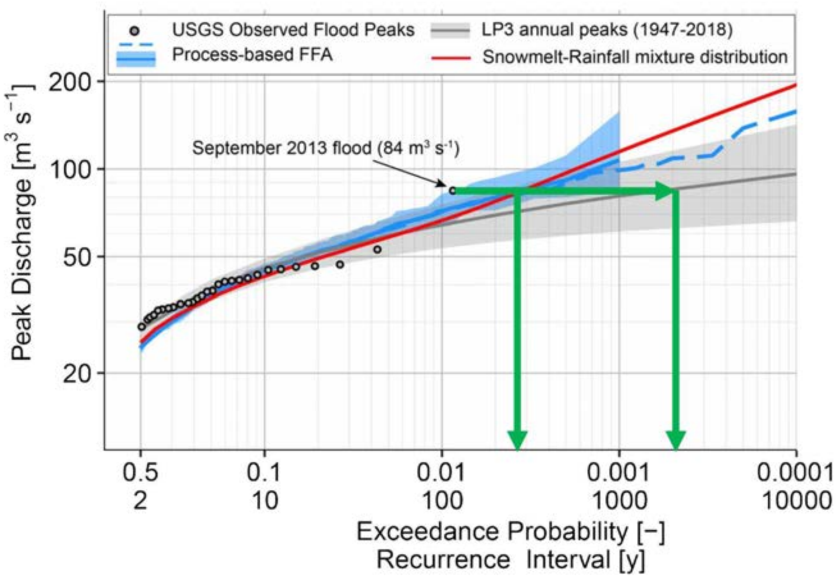
Yu et al., Connecting Hydrometeorological Processes to Low-Probability Floods in the Mountainous Colorado Front Range, in review, *WRR*

Two very different flood recipes



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

Example 2: Big Thompson River, CO



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

SUMMARY

- We've made major advances in understanding floods, as well as how to observe and model them
- Gridded precipitation data, Stochastic Storm Transposition, and physics-based/process-based models can translate these advances into flood frequency estimates, without requiring lots of assumptions
- Process-based methods have strengths for understanding and handling complex hydroclimatologic regimes and nonstationarities

Additional Info

- Holman et al., Stochastic Storm Transposition for Physically-Based Rainfall and Flood Hazard Analyses, Final Report No. ST-2020-1735-1, US Bureau of Reclamation, 2020.
- 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.
- Wright et al.,Six Decades of Rainfall and Flood Frequency Analysis Using Stochastic Storm Transposition: Review, Progress, and Prospects. *Journal of Hydrology*, 2020.
- Yu et al., Process-Based Flood Frequency Analysis in an Agricultural Watershed Exhibiting Nonstationary Flood Seasonality. *Hydrol. Earth Syst. Sci.* 2019.
- Perez et al., Using Physically-Based Streamflow Simulations to Assess Local and Regional Flood Frequency Analysis Methods, *Water Resources Research,* 2019.
- Wright et al.. A remote sensing-based tool for assessing rainfall-driven hazards, *Environmental Modelling & Software*, 2017.

- RainyDay source code: https://github.com/danielbwright/RainyDay2
- RainyDay online demo version and tutorial videos: https://her.cee.wisc.edu/rainyday-rainfall-for-modern-flood-hazard-assessment/
- More coming soon!

3.4.1.3 Questions and Answers

Question:
How can we handle the base flow caused by groundwater?

Daniel Wright:
In the presentation, I didn't go into details on how we create initial conditions for our flood scenarios. After model calibration and validation, we run a long-term continuous simulation, in this study about 35 years. We save the watershed states, including baseflow, every day. Those model states then serve as a "database" that we can sample from to provide initial conditions for our flood event simulations. We do it in a way to preserve realistic seasonality in those initial conditions. So, as long as the model can do a good job simulating baseflow conditions, we should be able to represent its role pretty well in our flood frequency analyses.

Question:
For Turkey River, the spread/variability is increasing dramatically with time. Any comment about that?

Daniel Wright:
There are two things going on:

1. There has been a decrease in the prevalence of springtime snowmelt and rain-on-snow flooding. This is likely due primarily to earlier snowmelt due to higher air temperatures. The earlier melt tends to "decouple" snowmelt from springtime rains, lowering the likelihood of springtime rain-on-snow floods. If you stare at the flood timeseries, you can

actually see a decrease in the magnitude of the mean flood over time, which is backed up by a (slightly) negative trend in the annual flood peaks.
2. There has been quite a large number of major summertime convective storms, in recent years, including those that produced catastrophic Midwest flooding in 2008. Presumably that increase is linked to climate warming, though that is beyond the scope of our work. The earlier period prior to about 1990 didn't really see many of those sorts of storms. So that explains the uptick since 1990 in the biggest floods.

Question:
When we use historical data for frequency of floods, we need to consider the change of land use, precipitation, topography etc. Can you comment on that?

Daniel Wright:
I mostly agree with that statement, at least when there is evidence for relatively large changes in these variables. I believe that the process-based methods that we presented here are really well suited to incorporating these changes into flood frequency analyses, since it is relatively straightforward to feed certain changes (e.g. land use, topography) into our hydrologic models, while stochastic storm transposition or other sorts of stochastic rainfall methods can be run in such a way to reflect current precipitation conditions, past conditions, and, with care, potential future conditions.

Question:
How can one account for topographic influences when applying stochastic storm transposition? What metrics are used to determine transposition limits?

Daniel Wright:
This is a very important question, and we are still working to solve it. That said, lots of prior work has been done on defining homogeneous regions for rainfall frequency analysis, and those can be useful for stochastic storm transposition as well. The most well-known are regional L moments approaches-specifically the H statistic and Discordancy statistic. In our Big Thompson work, we applied those methods to verify that the domain that we're using is approximately homogeneous, which it is. We also verified this against prior rainfall frequency studies in Colorado. However, we are also working to develop our own approach to define the storm transposition limits using methods of our own, though drawing inspiration from the regional L moment approach.

Question:
On a 10000-year time scale, how do single events like tributary capture get factored in?

Daniel Wright:
It is really important to remember that the purpose of flood frequency analysis (at least how it is typically conceived) is not to develop predictions of the future, whether it is 100 years from now or 10,000 years from now. Instead, it is to estimate the probability distribution of floods subject to the conditions laid out in the analysis. So, while the role of abrupt geomorphic changes like stream capture in flood frequency is certainly an interesting question (in fact, I am pursuing some research in that direction now—not stream capture but other more subtle geomorphic effects), it is outside the scope of typical analyses because those analyses are not concerned about what are generally thought of as long time-scale processes.

Question:
Again, for the Turkey River, apart from the shift of the snowmelt regime linked to air temperature, which of the accounted processes leads to more severe or more rare floods?

Daniel Wright:
As mentioned in question 2, the second process (aside from snowmelt changes) is the apparent increase in the number of major summertime convective storms, in recent years, including those that produced catastrophic Midwest flooding in 2008. Presumably that increase is linked to climate warming, though that is beyond the scope of our work. The earlier period prior to about 1990 didn't really see many of those sorts of storms. So that explains the uptick since 1990 in the biggest floods.

Question:
How did you calibrate your model to extreme floods?

Daniel Wright:
This depends a bit on one's definition of "extreme floods". We calibrate our models to a variety of things, including annual-scale evapotranspiration vs. runoff partitioning, snow water equivalent, soil moisture, and high flows, low flows, and everything in between. We also check the results against observed annual maxima (and if necessary adjust the model), and, in the case of the Big Thompson study, check annual maximum volumes as well. So in addition to other calibration targets, we are calibrating to the range of observed floods—whether that is the same as calibrating "to extreme floods" is perhaps somewhat subjective.

3.4.2 Presentation 2A-2: Probabilistic Flood Hazard Assessment for a Small Watershed in Eastern Tennessee: Methodology and Lessons Learned

Authors: Periandros Samothrakis, Craig Talbot, Kit Ng, Stewart Taylor, Bechtel Corporation

Speaker: Periandros Samothrakis

3.4.2.1 Abstract

In recent years, there is a growing interest in the U. S. and abroad to perform probabilistic flood hazard assessments (PFHAs) instead of traditional deterministic flood assessments. This presentation discusses the methodology developed and lessons learned performing a PFHA study for a small (~1 square mile), partially developed watershed in eastern Tennessee. A first step in performing a PFHA is to classify the uncertainty of the input parameters into two categories: aleatoric (or uncertainty due to chance) and epistemic (or uncertainty due to lack of knowledge). The characteristics of the design storms –durations, depths, and temporal patterns – and antecedent moisture conditions (based on the seasonality of the storms), are selected as having aleatoric uncertainty. To model the rainfall-runoff process, the Green-Ampt methodology is applied to estimate infiltration losses, and the SCS unit hydrograph method is used to transform the computed sub-basin runoff into flow hydrographs, with the associated input parameters having epistemic uncertainty. A climate change factor for rainfall intensities is considered for the study area, with epistemic uncertainty. Two sets of computations or “loops,” one nested inside the other, are incorporated in selecting model parameters. For each set of epistemic parameter computations (outer loop), a series of aleatoric parameter computations (inner loop) are performed. The outer loop consists of 20 different sets of input variables that are selected with the Latin hypercube sampling approach. The selection of the input variables (5000 sets) for the inner loop is performed by using a stratified sampling approach. After the input variables are selected, flood flows are estimated with HEC-HMS and flood levels are estimated with HEC-RAS. The probabilistic flood hazard curves for different locations within the watershed are estimated from the model results using the total probability theorem.

3.4.2.2 Presentation (ADAMS Accession No. ML21064A429)

Probabilistic Flood Hazard Assessment for a Small Watershed in Eastern Tennessee: Methodology and Lessons Learned

6th Annual NRC PFHA Research Workshop

February 22-25, 2021

Periandros Samothrakis, Engineering Specialist
Craig Talbot, Principal Hydraulics & Hydrology Engineer
Kit Ng, Hydraulics & Hydrology Manager
Stewart Taylor, Corporate G&HES Manager

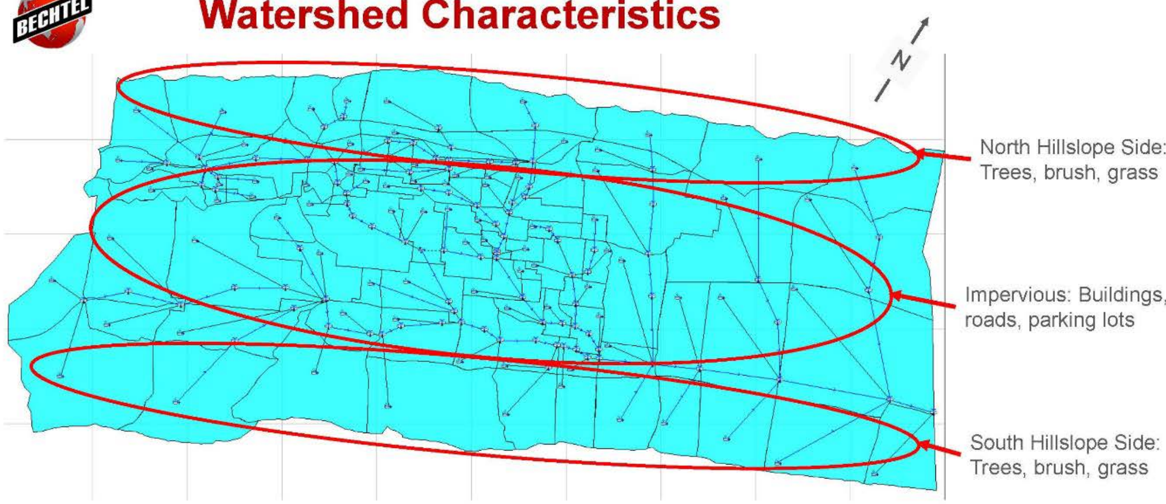
Presentation Outline

- Study Objectives
- Site Characteristics
- Regulatory Requirements
- Technical Approach
- Input Analysis
- Results
- Summary/Conclusions

Study Objectives

- Objectives of study:
  - Develop probabilistic flood hazard curves for locations within watershed
  - Determine design flood levels at buildings of interest within watershed
- Previously, a similar flood study was performed at the same watershed, which included some probabilistic elements.
  - Previous study was peer-reviewed
  - Peer-review team provided recommendations for additional probabilistic elements
- Three separate studies are prepared for determining design flood levels.
  - Precipitation (completed), Runoff (on-going), Hydraulic (on-going).

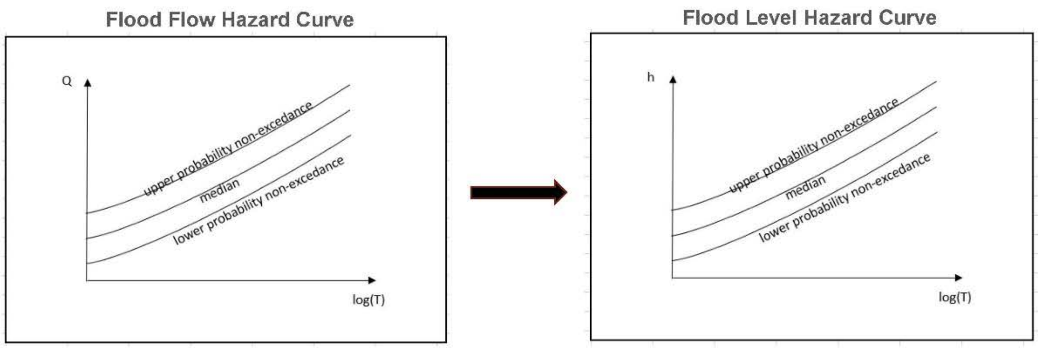
Watershed Characteristics



- Urban land use
- 1.126 mi^2 drainage area
- Humid climate

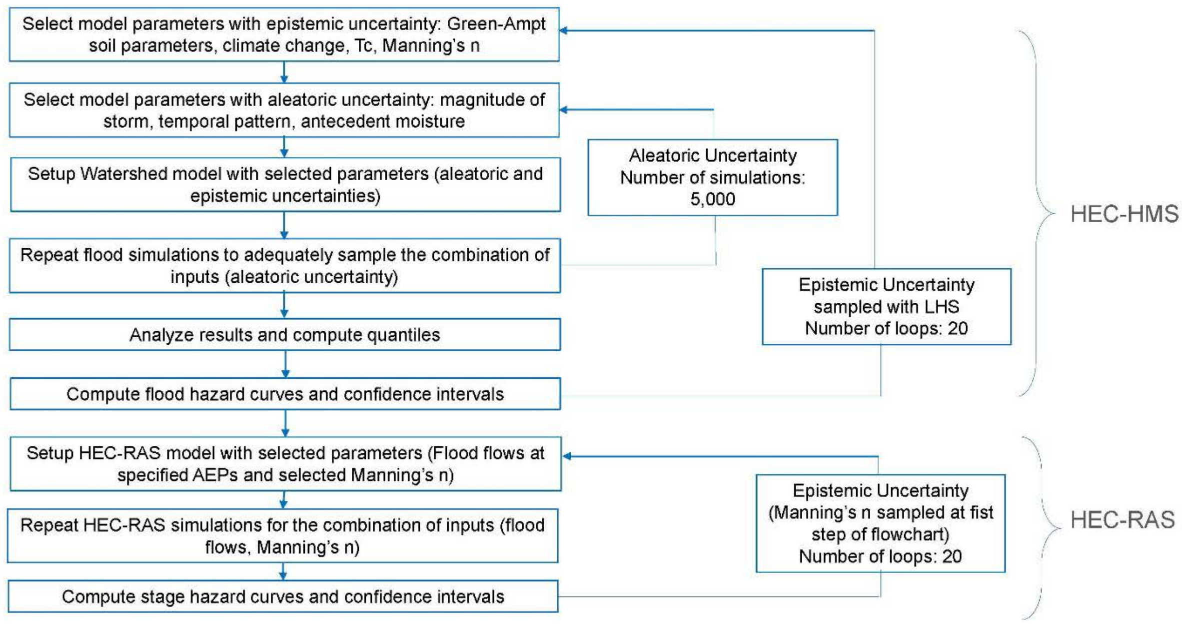
Regulatory Requirements

- Satisfy DOE-STD-1020-2016 "Natural Phenomena Hazards Analysis and Design Criteria for DOE Facilities" requirements:
  - Probabilistic approach that represents the flood/precipitation hazard as a function of the return period
  - Considers and propagates the uncertainties in the parameters used to estimate the flood levels



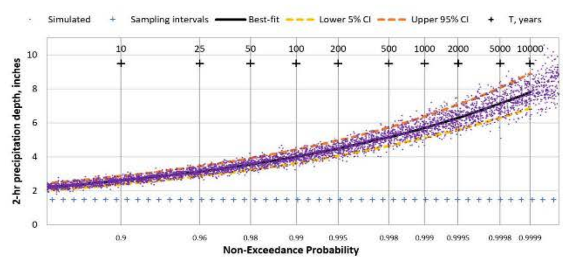
Uncertainty in Input Variables

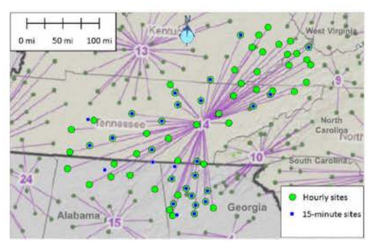
- Aleatoric uncertainty: due to chance
  1. Rainfall duration
  2. Total rainfall depth
  3. Temporal pattern (hyetograph) of rainfall
  4. Day of occurrence of rainfall, which sets the initial water content of the soil
- Epistemic uncertainty: due to lack of knowledge
  1. Climate change adjustment factor for rainfall
  2. Sheet flow length
  3. Manning's n for calculating travel time of sheet flow
  4. Peaking factor for adjusting lag time
  5. Soil hydraulic parameters for Green-Ampt (hydraulic conductivity, wetting front suction head, porosity)
  6. Manning's n for the hydraulic analysis and M-C routing



Precipitation Input - Aleatoric Uncertainty

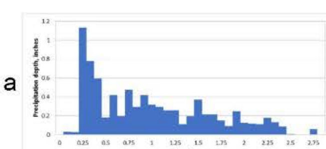
- GEV distribution parameters estimated using L-moments.
- 64 stations with hourly precipitation records and 28 stations with 15-minute records are used.
- Example of 2-hr precipitation-frequency curve.
- Probability space is divided into 50 equal width intervals. 100 values are simulated within each interval.





Sites selected for the regional frequency analysis (background shows regional groupings of hourly stations from NOAA (2006) Atlas 14 Volume 2).

- A group of scalable dimensionless hyetograph patterns was developed.
- The dimensionless hyetograph patterns were applied in a stochastic model that generated probabilistic storm sequences.



Run-off model: Green-Ampt

- Input parameters to G-A: Hydraulic conductivity, K, Water front suction head, S_f, Soil Porosity, φ
- Estimation of G-A parameters is based on regression equations (Saxton & Rawls, 2006).
- Regression equations use the composition of the soil in terms of percentage of sand, silt, clay and organic matter.
- USDA soil reports provide the composition of soils in sand, silt, clay, organic matter for the area.

	Symbol	Units	Area	Distribution	Minimum	Maximum
Sand	S	(%)	NORTH SIDE	uniform	5.0	40.0
Clay	C	(%)		uniform	8.0	27.0
Organic Matter	OM	(%)		uniform	0.5	1.0
Sand	S	(%)	SOUTH SIDE	uniform	10.0	50.0
Clay	C	(%)		uniform	10.0	27.0
Organic Matter	OM	(%)		uniform	0.5	2.0

- Soil composition is treated as epistemic uncertainty (LHS sampling).
- After the soil composition is selected for each epistemic loop, the regression equations are used to estimate the G-A parameters for the North and South Hillslope areas.
- Middle part of watershed is impervious.

Lesson Learned

- Green-Ampt Parameters selection.
- Hydraulic conductivity (K), Water front suction head (S_f) are inversely correlated.
- Different approaches:
  1. Used textbook values based on soil texture class to fit distributions and then sample. Correlation not preserved.
  2. USDA soil reports provide the composition of soils in sand, silt, clay, organic matter for the site. Stochastically sample the soil composition. Use regression equations to estimate Green-Ampt parameters. Fit distributions and then sample (LHS). Correlation not preserved.
  3. Same as No. 2 but first sample the soil composition as having epistemic uncertainty (LHS). Use regression equations to estimate Green-Ampt parameters. Correlation is preserved.

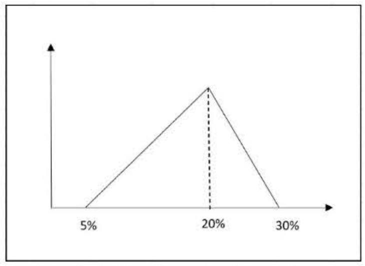
TABLE 5.5.5 USDA Soil Texture Green-Ampt Infiltration Parameters

Soil texture class	Porosity ϕ	Wetting front soil suction head S_f, cm	Saturated hydraulic conductivity K_s,* cm/h
Sand	0.437 (0.374–0.500)	4.95 (0.97–25.36)	23.56
Loamy sand	0.437 (0.363–0.506)	6.13 (1.35–27.94)	5.98
Sandy loam	0.453 (0.351–0.555)	11.01 (2.67–45.47)	2.18
Loam	0.463 (0.375–0.551)	8.89 (1.33–59.38)	1.32
Silt loam	0.501 (0.420–0.582)	16.68 (2.92–95.39)	0.68
Sandy clay loam	0.398 (0.332–0.464)	21.85 (4.42–108.0)	0.30
Clay loam	0.464 (0.409–0.519)	20.88 (4.79–91.10)	0.20
Silty clay loam	0.471 (0.418–0.524)	27.30 (5.67–131.50)	0.20
Sandy clay	0.430 (0.370–0.490)	23.90 (4.08–140.2)	0.12
Silty clay	0.479 (0.425–0.533)	29.22 (6.13–139.4)	0.10
Clay	0.475 (0.427–0.523)	31.63 (6.39–156.5)	0.06

Source: Rawls, W.J., L.R. Ahuja, D.L. Brakensiek, and A. Shirmohammadi, (1993). "Infiltration and soil water movement," Chapter 5 in Handbook of Hydrology McGraw-Hill.

Climate change adjustment factor

- From literature review: a range of different estimates of future changes to precipitation extremes as a result of climate change.
- Model the climate change adjustment factor using a triangular probability density function (pdf) having a lower bound of +5%, an upper bound of +30%, and a mode at +20%.



Probability Density Function for Climate Change Adjustment Factor

Reach Routing / Time of Concentration

- Reach Routing:
  - Reach routing accounts for the effects of reach storage on the runoff hydrographs as the flood flow moves through a reach.
  - The Muskingum-Cunge (M-C) method is a more theoretically detailed routing method.
  - Uses physical characteristics of the reach (reach length, slope, Manning's n and cross section shape) rather than empirical approaches.
  - Manning's n is treated probabilistic (epistemic uncertainty).

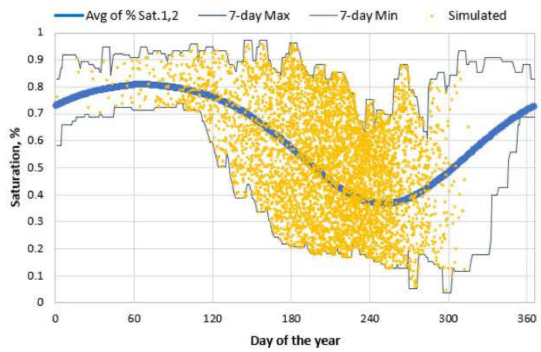
- Time of Concentration:
  - SCS unit hydrograph method is used.
  - Primary uncertainty is in the sheet flow portion:
    - Length of the sheet flow.
    - Sheet flow Manning's n, (different from Manning's n in M-C routing).
    - 2-year, 24-hour rainfall (climate change factor is incorporated).
  - These three parameters are varied within a certain range.
  - A range of minimum/maximum time of concentration is generated for each sub-basin.
  - Part of epistemic uncertainty (sample by LHS).

Antecedent Moisture Conditions

- Soil water content measurements at two depths (5 cm and 10 cm) from a nearby station, were converted to relative salutation with the following equation:

$$S_i = \frac{\theta_i - \theta_r}{\phi - \theta_r}$$

where, S_i = relative saturation, θ_i = initial moisture content, θ_r = residual moisture content, ϕ = total porosity of soil



- 5,000 simulated saturation values, S_i, distributed based on the seasonality of occurrence of heavy rainfall and uniform probability distribution of saturation.
- Initial soil moisture content for each storm (note that θ_r = residual moisture content and ϕ = total porosity of soil have an epistemic uncertainty):

$$\theta_i = \theta_r + S_i(\phi - \theta_r)$$

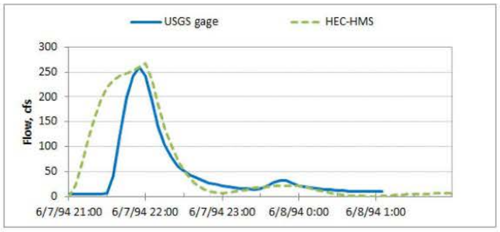
Summary of Inputs with Epistemic Uncertainty

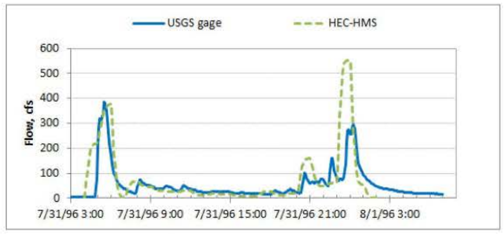
	Input Variable/Parameter to Epistemic Loos													
	Climate Change Adjustment Factor for Rainfall	Manning's n roughness coefficient		Soil Parameters (for Green-Ampt methodology) – For Pervious Sub-basins										
				North Side – Sub-basins					South Side – Sun-basins					
Epistemic Loop		Concrete	Short Grass	K_s (in/hr)	S_f (in)	ϕ (-)	ϕ_e Note 1 (-)	θ_r Note 1 (-)	K_s (in/hr)	S_f (in)	ϕ (-)	ϕ_e Note 1 (-)	θ_r Note 1 (-)
1	10.6%	0.0178	0.0270	0.0777	13.261	0.4779	0.3984	0.0795	0.3815	6.159	0.452	0.3931	0.059
2	22.5%	0.0159	0.0259	0.1222	13.143	0.4767	0.4301	0.0466	0.0833	15.97	0.4344	0.3536	0.0809
3	15.2%	0.0173	0.0283	0.0631	16.809	0.4687	0.3953	0.0733	0.06	20.279	0.432	0.347	0.085
4	18.1%	0.0196	0.0288	0.0674	15.09	0.4658	0.3818	0.084	0.0598	18.386	0.44	0.3512	0.0887
5	19.2%	0.0192	0.0300	0.0824	10.589	0.4567	0.3635	0.0932	0.1346	14.816	0.428	0.3699	0.0581
6	25.2%	0.0151	0.0333	0.0453	21.036	0.4624	0.3796	0.0828	0.0506	25.337	0.4224	0.3457	0.0767
7	12.6%	0.0180	0.0328	0.1587	10.291	0.484	0.428	0.056	0.1494	7.024	0.4449	0.3565	0.0884
8	21.0%	0.0189	0.0338	0.1212	11.83	0.4701	0.4048	0.0653	0.3832	7.872	0.4163	0.3597	0.0567
9	17.0%	0.0170	0.0323	0.1557	8.537	0.4814	0.41	0.0714	0.1263	11.702	0.4507	0.378	0.0727
10	24.3%	0.0139	0.0250	0.0473	16.878	0.4891	0.3999	0.0893	0.1866	10.765	0.4245	0.3561	0.0685
11	8.0%	0.0167	0.0261	0.1187	6.925	0.4868	0.3979	0.0889	0.1343	10.438	0.4245	0.3407	0.0838
12	16.2%	0.0136	0.0292	0.0506	20.575	0.4546	0.3883	0.0663	0.3055	5.837	0.4434	0.3722	0.0712
13	19.4%	0.0150	0.0302	0.2656	9.849	0.4629	0.4206	0.0423	0.1549	11.148	0.4331	0.361	0.0721
14	26.9%	0.0157	0.0267	0.1292	10.969	0.4886	0.429	0.0596	0.1987	8.537	0.4387	0.3654	0.0732
15	23.8%	0.0185	0.0313	0.0546	18.548	0.4677	0.4211	0.0466	0.1875	7.82	0.4374	0.3581	0.0793
16	22.0%	0.0199	0.0318	0.3204	7.086	0.4822	0.4313	0.0509	0.0584	22.201	0.4294	0.3593	0.0701
17	17.5%	0.0162	0.0347	0.1249	10.553	0.4729	0.4013	0.0716	0.0592	22.719	0.42	0.3385	0.0815
18	12.4%	0.0144	0.0342	0.0888	15.451	0.4752	0.4348	0.0404	0.0521	20.731	0.4466	0.3608	0.0858
19	20.3%	0.0131	0.0280	0.2047	8.501	0.4568	0.3899	0.0669	0.2025	10.441	0.4489	0.3919	0.057
20	13.7%	0.0145	0.0305	0.0672	16.724	0.4594	0.3825	0.0769	0.1672	13.765	0.4183	0.3605	0.0578

- Time of concentration not shown (different for each of the sub-basins)

HEC-HMS Model – Observed Events Performance

- Observed rainfall events are used for the verification of the HEC-HMS model
- Historical USGS gaging station within the study area is used for the observed events.
- For input parameters, the expected values (averages) are used.
- Buried stormwater drains, culverts, and passages beneath bridges, are not included in the HEC-HMS model (only overland flow).
- Not a calibration. To demonstrate the performance of model with observed events.





- Model results are reasonable compared to the observed events

HEC-HMS Model

- HEC-HMS 4.1 is used to perform the 100,000 simulations.
- HEC-HMS uses text files for reading input variables, for where to save results etc.
- Fortran codes where use to create the text files.
- Results are saved in *.dss files.
- Python script is used to extract the peak discharge of each hydrologic element for each simulation.

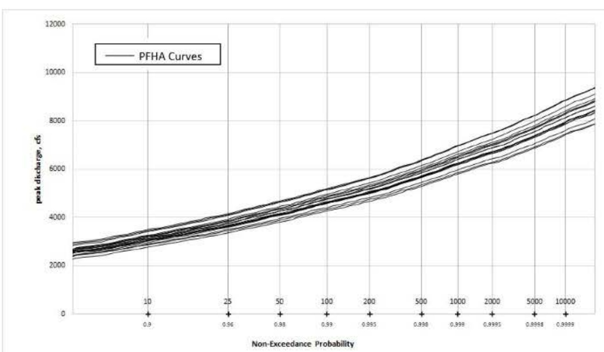
Post Processing

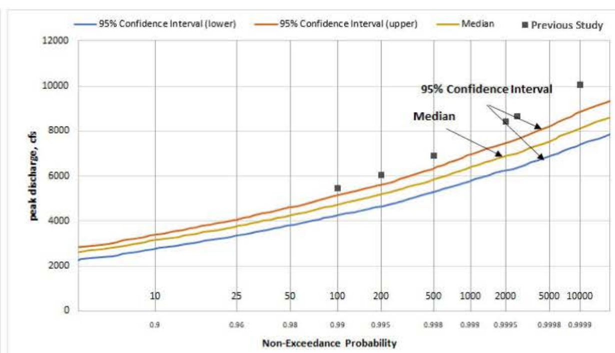
- For one epistemic loop, 5000 peak discharges, *Q*, are estimated for a location of interest.
- Total probability theorem is used to yield expected probability estimates of the flood frequency curve.
- The expected probability that a peak discharge *Q* exceeds a particular flow value *q*, is calculated from the total probability theorem as follows:

$$p(Q > q) = \sum_i p[Q > q|R_i] * p[R_i]$$

- where *i* is the number of the stratified probability interval (50 is the total number of intervals in the current study), $p[R_i]$ represents the probability that the design storm occurs within the interval *i*.

Results – at downstream end of watershed

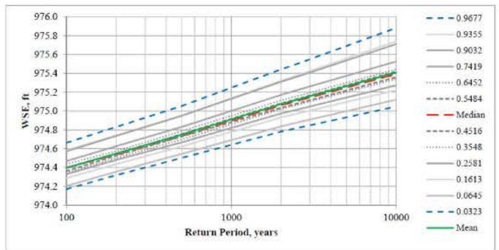




- Reduction of the peak discharges compared to previous study at the downstream end is in the order of 20% (2,000-yr return period).

Next step – Estimate Flood Levels

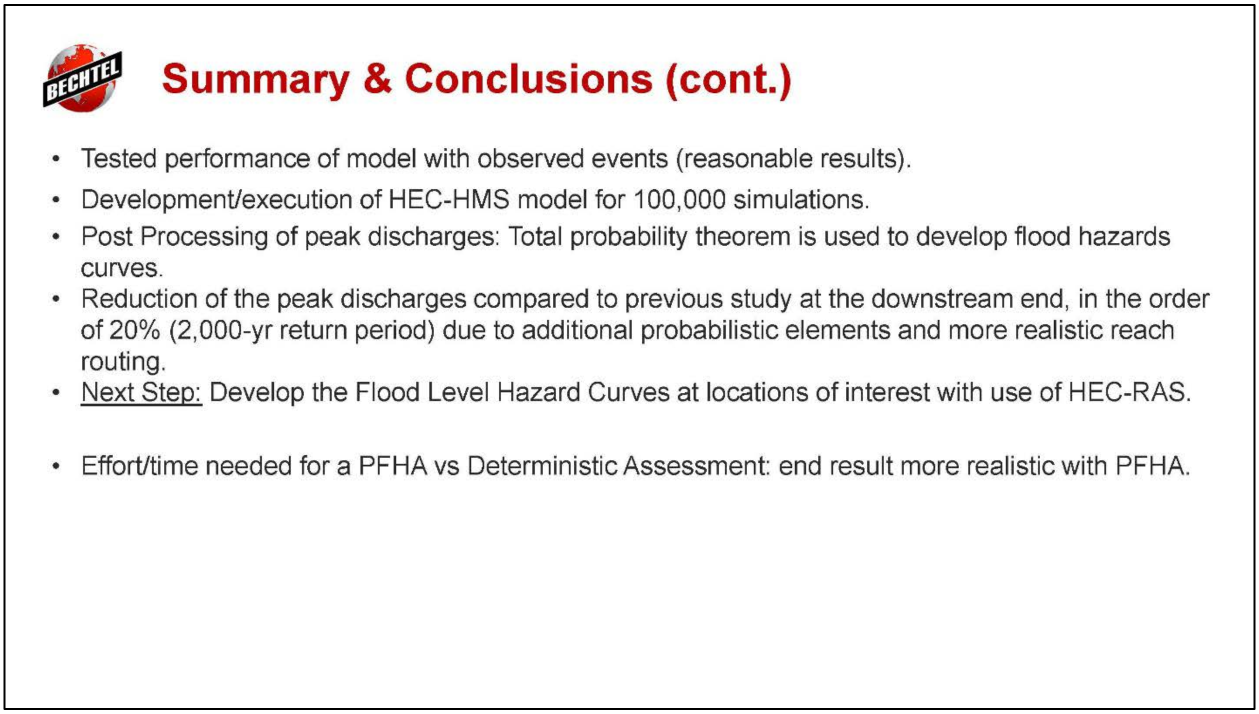
- Extract the peak discharges at different return periods (i.e. 10-, 100-, 200-, 1000-, 2000-, 5000-yr).
- 20 epistemic loops with HEC-RAS model and the extracted peak discharges.
- Additional probabilistic input variable: Manning's n roughness coefficient.
- Use Steady State to complete runs.
- Extract flood levels from results.
- Develop the Flood Level Hazard Curves at buildings of interest with use of a plotting position (i.e Weibull).
- Example of Flood Level Hazard Curve from previous study



Flood Level Hazard Curve

Summary & Conclusions

- Development of a Probabilistic Flood Hazzard Assessment for a watershed.
- Epistemic, aleatoric uncertainty of input variables:
  - LHS sampling for variables with epistemic uncertainty.
  - Stratified sampling for variables with aleatoric uncertainty.
- Different components of the hydrologic model:
  - Loss method: Green-Ampt
  - Reach Routing method: Muskingum-Cunge
  - Rainfall-Runoff model: SCS Unit Hydrograph
  - Climate Change Adjustment Factor for Rainfall
  - Antecedent Moisture Conditions
- Performing the simulations:
  - Outer loop for epistemic uncertainty
  - Inner loop for aleatoric uncertainty



3.4.2.3 Questions and Answers

Question:
Did you consider antecedent and or pre-storm conditions stochastically in your flood frequency and uncertainty analysis?

Periandros Samothrakis: No, not pre-storm. But we do consider the antecedent moisture condition with the approach I presented. Basically, we used the soil water content from a nearby station and that was converted to a relative saturation. Based on the relative saturation that we developed, we sampled stochastically with 5000 storms from the relative saturation values that we had.

Question: Why specifically do you think the addition of probabilistic representations reduce the overall flood frequency estimates? For example, was antecedent soil moisture being overemphasized in the earlier analysis?

Periandros Samothrakis: In the previous study, we used the outline block method in developing the hydrograph, and now we're using more realistic hydrographs from nearby stations that were developed with the stochastic approach. That was one big difference. In addition, we previously did not consider this approach of aleatory and epistemic uncertainty. We only focused on having epistemic uncertainties from a Latin hypercube sampling approach. So, we didn't really consider exactly the antecedent moisture conditions in terms of the actual day of the storm and the relative saturation in the area. These primarily are the two reasons that explain the difference in the results. Also, there's a difference in how we developed the original frequency analysis of the rainfall inputs in terms of the sub-hourly estimates, but I'm not very familiar with that portion of the study, so I will leave it there.

3.4.3 Presentation 2A-3: Probabilistic Assessment of Multi-mechanism Floods in Inland Watersheds Due to Snowmelt-Influenced Streamflow Events

Authors: Shih-Chieh Kao[1], Scott T. DeNeale[1], Michelle Bensi[2], Somayeh Mohammadi[2], Elena Yegorova[3], Joseph Kanney[3], Meredith L. Carr[4], [1]Oak Ridge National Laboratory, [2]University of Maryland, [3]U.S. Nuclear Regulatory Commission, [4]U.S. Army Corps of Engineers, Engineer Research and Development Center, Coastal and Hydraulics Laboratory

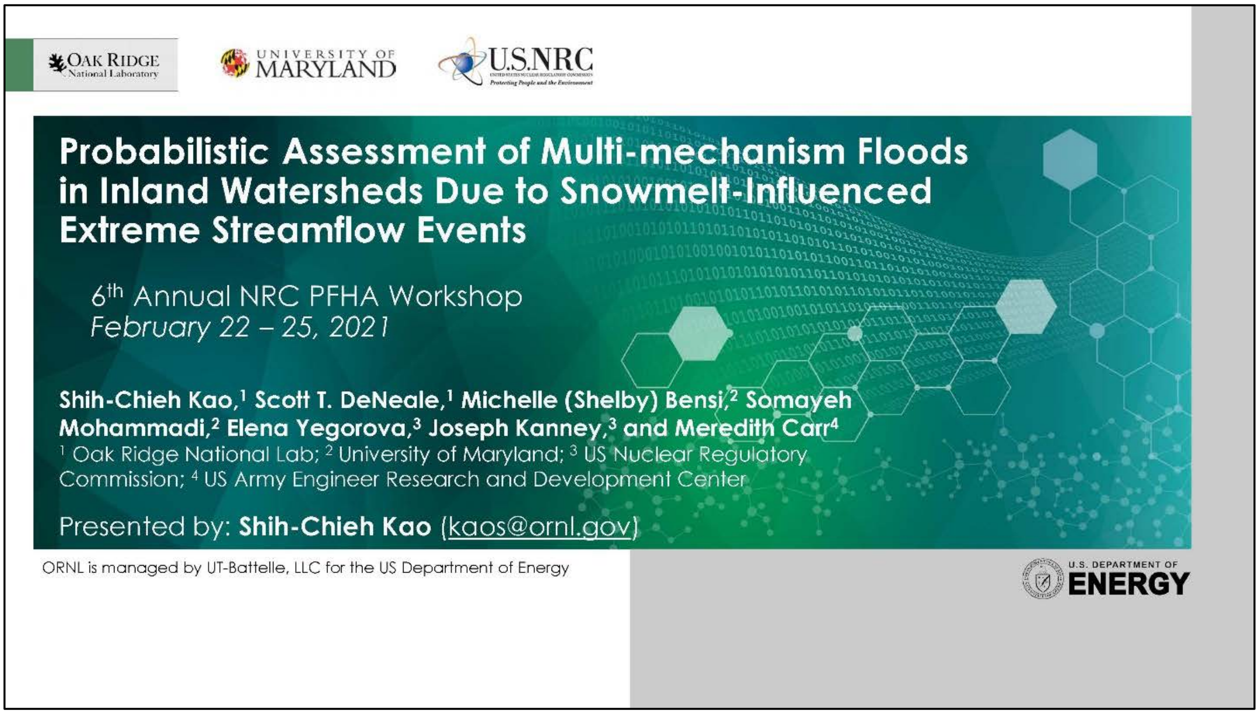
Speaker: Shih-Chieh Kao

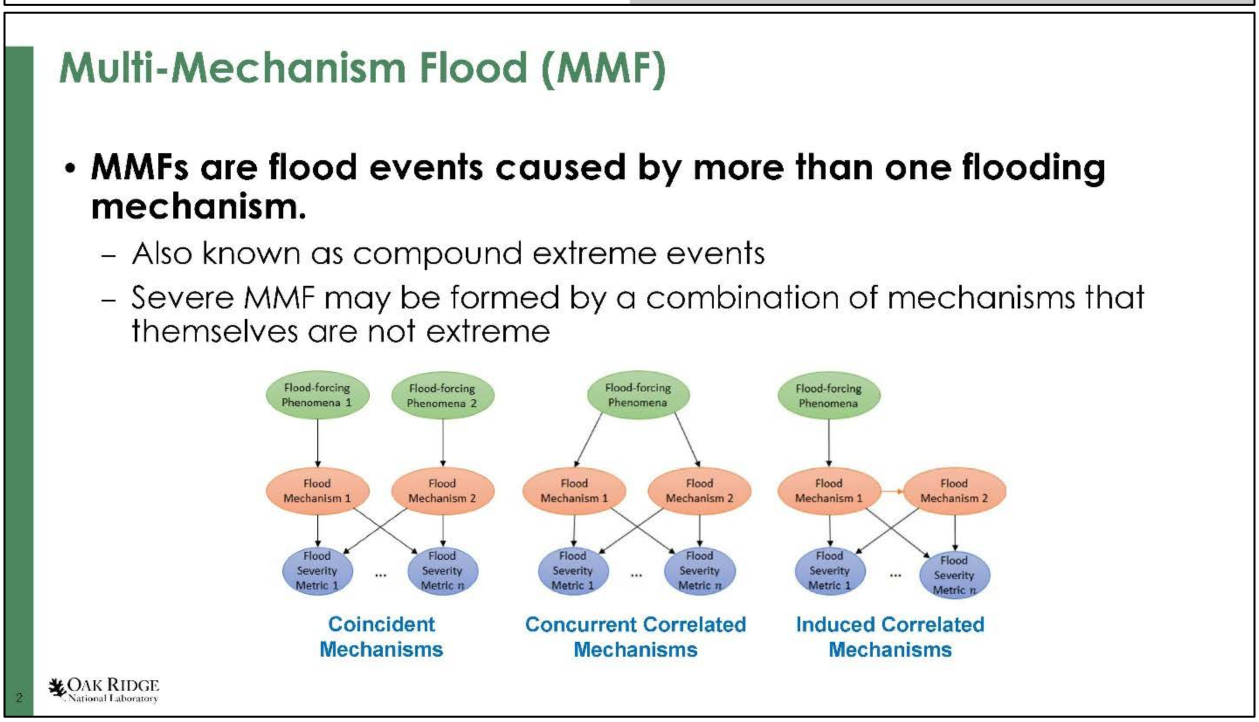
3.4.3.1 Abstract

Multi-mechanism flood (MMF) refers to flood hazard due to a combination of coincident and/or correlated mechanisms, such as extreme precipitation, snowmelt, and streamflow. While traditional probabilistic flood hazard assessment (PFHA) typically focuses on the extreme behavior of a single flood mechanism, severe MMF may form by a combination of mechanisms that themselves are moderate but lead to greater impacts when combined. Possible methods that can be used to construct joint distributions to support PFHA for MMF include the direct application of parametric multivariable distributions, copula-based approaches, and Bayesian-motivated approaches.

This study focuses on the use of copulas for the probabilistic MMF assessment in inland watersheds due to snowmelt-influenced extreme streamflow events. With the trend of earlier and larger snowmelt events in the recent decades, there is an interest to understand how peak streamflow estimates and the corresponding hazard curves may be affected due to the co-occurrence of major streamflow and snowmelt events. As opposed to the conventional univariate analysis that only analyzes the timeseries of streamflow to derive hazard curves, we used copulas to construct joint distributions that unite multiple variables (e.g., streamflow, precipitation, temperature, and snowmelt) for the derivation of conditional hazard curves. We selected three watersheds from the community Catchment Attributes and Meteorology for Large-sample Studies (CAMELS) dataset and also leveraged an existing hydrologic model with acceptable performance to simulate the snow processes in the watersheds. We tested several ways in identifying maximum events, selecting marginal distributions and copula functions, and comparing their difference in terms of conditional hazard curves. This inland case study serves as an example of copula-based analysis, which can be expanded for much broader MMF analyses in a variety of PFHA applications.

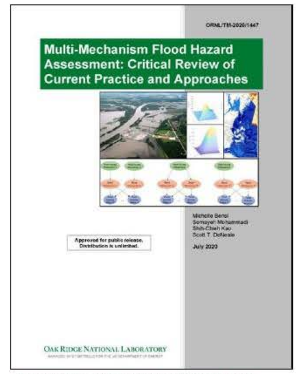
3.4.3.2 Presentation (ADAMS Accession No. ML21064A430)





MMF for Probabilistic Flood Hazard Assessment (PFHA)

- **A two-stage study to help better understand MMF for PFHA.**
  - Stage 1: Review of current concepts and methods
    - Bensi et al. (2020), Multi-Mechanism Flood Hazard Assessment: Critical Review of Current Practice and Approaches, doi:10.2172/1637939.
  - Stage 2: Development of example case studies
    - **Case 1: Inland study focusing on snowmelt-influenced events using copulas**
    - Case 2: Coastal study focusing on hurricane-induced storm surge and precipitation-induced river discharge using a Bayesian-motivated approach



https://www.osti.gov/biblio/1637939-multi-mechanism-flood-hazard-assessment-critical-review-current-practice-approaches

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Objectives of This Case Study

- **We plan to demonstrate:**
  - General procedures to construct multivariate joint distributions using copulas
  - Identification of extreme samples for multivariate frequency analysis
  - Selection of suitable marginal distributions and copula functions
  - Applications of copula-derived joint distributions in PFHA
  - Strengths and limitations of the copula-based MMF assessment approach
- **Focus on inland snowmelt-influenced peak streamflow events**

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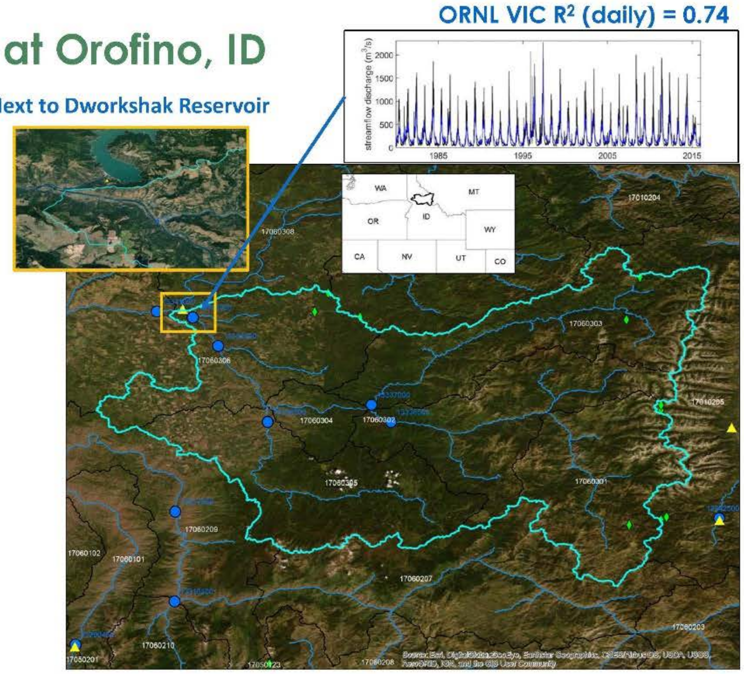
Study Areas

- **Selection considerations**
  - Long-term historic streamflow observations should be available at the watershed outlet to support model validation and frequency analysis.
  - Existing hydrologic model with acceptable performance should be available to simulate snow and other hydrologic processes.
  - The watershed should be large but not under strong flow regulation (e.g., presence of major dams). A headwater basin is preferred.
  - Significant snowpack should be presented to enable the assessment of snowmelt-influenced events.
- **Selected sites**
  - 3 sites meeting the above criteria from the NCAR CAMELS Dataset

S1: Clearwater River at Orofino, ID

ORNL VIC R^2 (daily) = 0.74

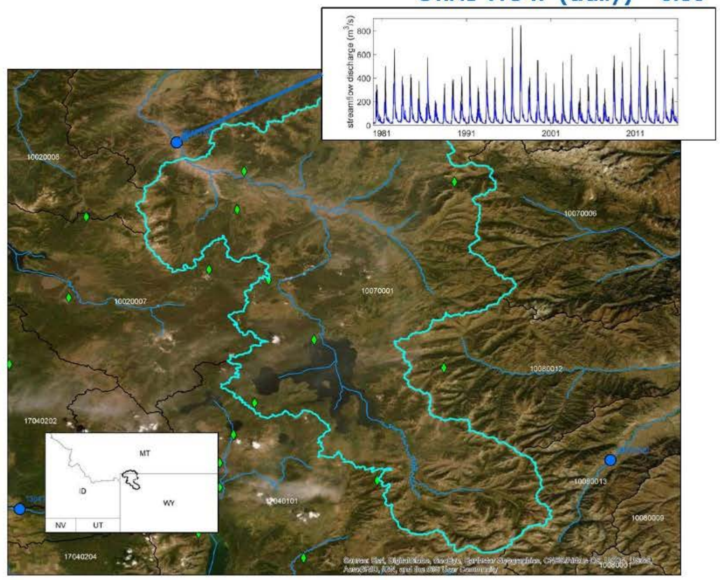
- **HUC08**
  - 17060301–17060306
- **Outlet USGS Station**
  - 13340000
  - 1965–present
  - 247.2 m^3/s
  - 14263 km^2
- **Elevation (m)**
  - min: 338
  - mean: 1451
  - max: 2602



S2: Yellowstone River at Corwin Springs, MT

ORNL VIC R^2 (daily) = 0.80

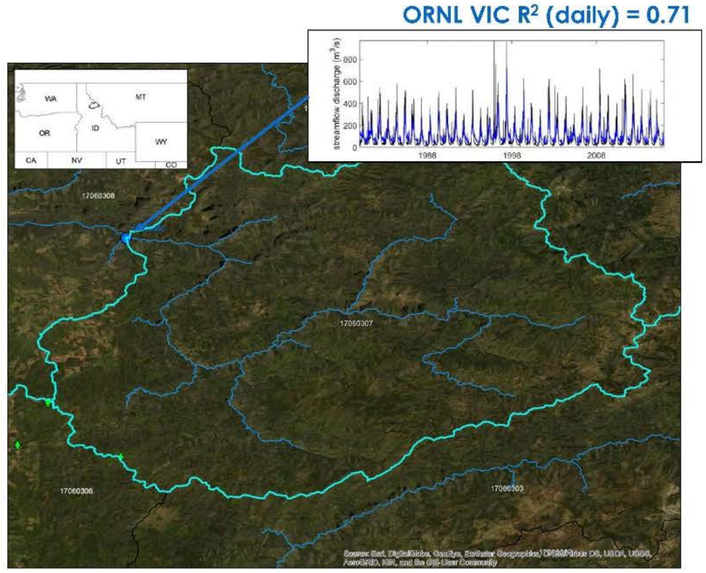
- **HUC08**
  - 10070001
- **Outlet USGS Station**
  - 06191500
  - 1911–present
  - 88.6 m^3/s
  - 3706.27 km^2
- **Elevation (m)**
  - min: 1560
  - mean: 2542
  - max: 3473



S3: NF Clearwater River NR Canyon Ranger Station, ID

ORNL VIC R^2 (daily) = 0.71

- **HUC08**
  - 17060307
- **Outlet USGS Station**
  - 13340600
  - 1967–present
  - 98.2 m^3/s
  - 3356.6 km^2
- **Elevation (m)**
  - min: 1448
  - mean: 569
  - max: 2241



Summary of Available Data

- **Observation**
  - USGS daily streamflow (Q_{obs})
  - 1980–2015 Daymet precipitation (P_{obs}) and temperature (T_{obs})
- **Observation-driven hydrologic model outputs**
  - 1980–2015 streamflow (Q_{VIC}) and change in snow water equivalent ($dSWE_{VIC}$)
- **We focus on the following variables in this case study**
  - Q_{dy}: Daily streamflow (m^3/s)
  - P_{3d}: 3-day precipitation (mm)
  - T_{3d}: 3-day temperature (°C)
  - dS_{3d}: 3-day change in SWE (mm)

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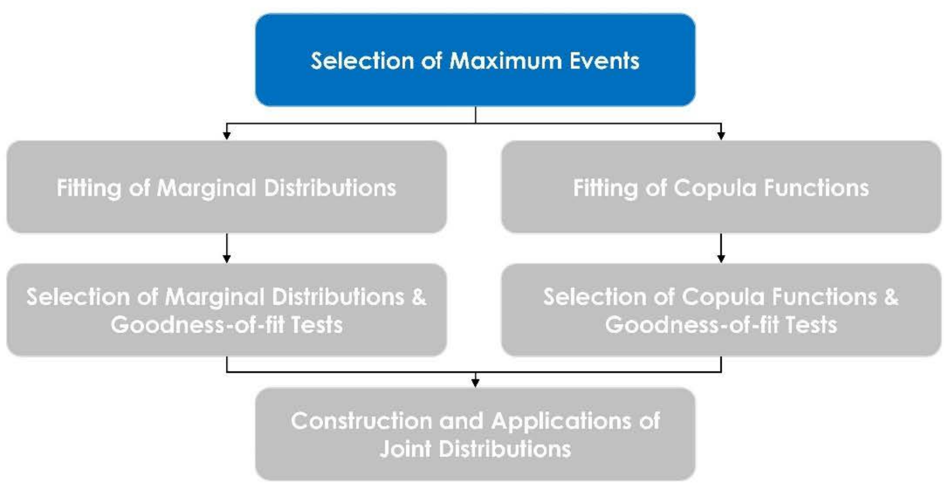
Assessment Procedures



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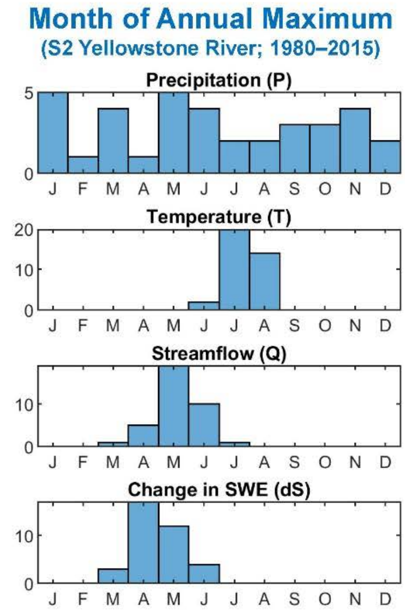
Selection of Maximum Events

- **Samples for multivariate frequency analysis should have consistent timing**
  - $(P_{t1}, T_{t1}, Q_{t1}, dS_{t1})$
- **The conventional annual maximum approach cannot work directly**
  - $(P_{t1}, T_{t2}, Q_{t3}, dS_{t4})$
- **In this study, we**
  - select maximum events during April–June
  - compare three different ways in selecting maximum events



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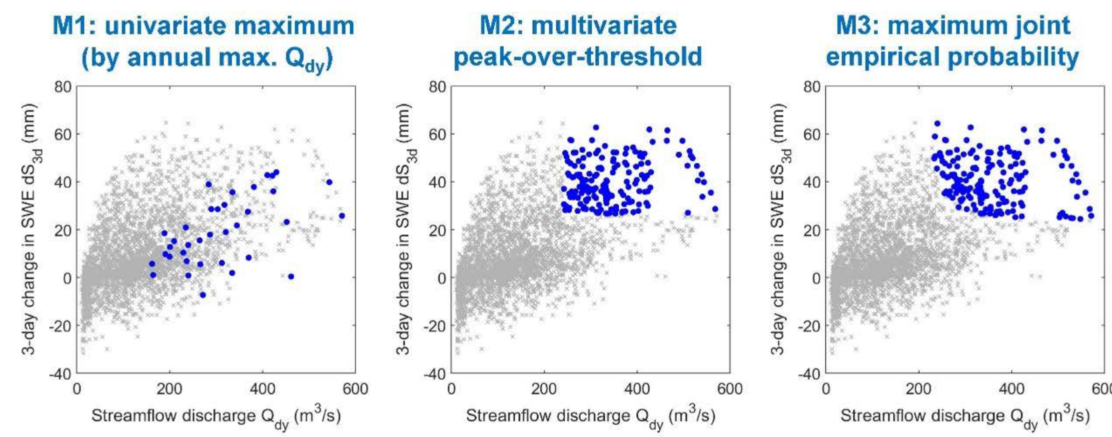
Compare Three Ways to Select Maximum Events



Bivariate example – S2 (Yellowstone River)

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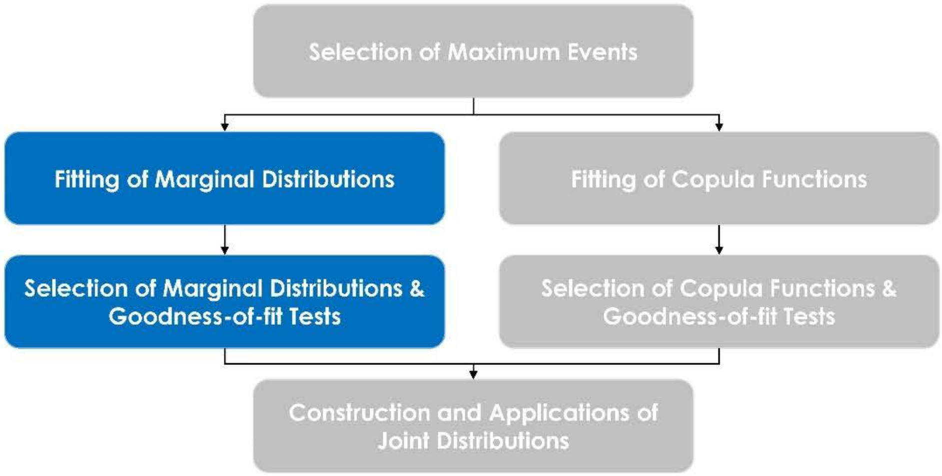
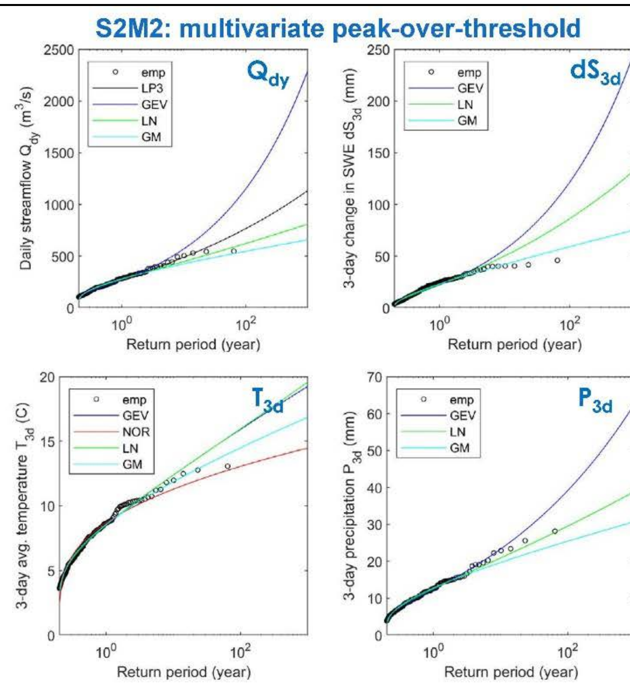
Assessment Procedures



Marginal Distribution

- **Tested distributions**
  - Log Pearson Type III (LP3)
  - General. Extreme Value (GEV)
  - Log-normal (LN)
  - Gamma (GM)
  - Normal (NOR)
- **Parameter estimation**
  - Maximum likelihood
- **Goodness-of-fit**
  - Kolmogorov-Smirnov (KS)
  - Cramer-Von Mises (CM)
  - Akaike Information Criterion (AIC)
  - Bayesian Information Criterion (BIC)



Distribution Selection Using AIC & BIC

S2M2 – Yellowstone river with multivariate peak-over-threshold

- **Select distribution with smaller AIC & BIC values**
  - AIC = −2*(*log-likelihood*)+2*(*numParam*).
  - BIC = −2*(*log-likelihood*)+*numParam*∗log(*numObs*)

	Streamflow (Q_{dy})		Change in SWE (dS_{3d})		Temperature (T_{3d})		Precipitation (P_{3d})	
	AIC	BIC	AIC	BIC	AIC	BIC	AIC	BIC
LP3	3362.2	3371.8	--	--	--	--	--	--
GEV	3362.0	3371.6	1298.4	1308.0	770.9	780.5	985.7	995.3
NOR	--	--	--	--	787.6	794.0	--	--
LN	3368.9	3375.2	1286.9	1293.3	767.9	774.3	985.4	991.8
GM	3382.2	3388.6	1289.2	1295.6	770.3	776.7	996.6	1003.0

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Selected Marginal Distributions

Variables	S1M2 Clearwater, Multivariate Peak-over-threshold	S2M2 Yellowstone, Multivariate Peak-over-threshold	S2M3 Yellowstone, Max. Joint Empirical Probability	S3M2 NF Clearwater, Multivariate Peak-over-threshold
Streamflow (Q_{dy})	LP3	LP3	LP3	LP3
Precipitation (P_{3d})	LN	LN	LN	LN
Temperature (T_{3d})	LN	LN	GEV	GEV
SWE Change (dS_{3d})	LN	GM	GM	GM

- **The best distributions varied by variables, maximum events, and sites.**
- **Maximum event searching approaches seem to have more profound impacts than different sites.**
  - M1 (univariate maximum) is more different than M2 and M3.
  - **M1 (univariate maximum) is NOT considered further due to the limited sample size.**

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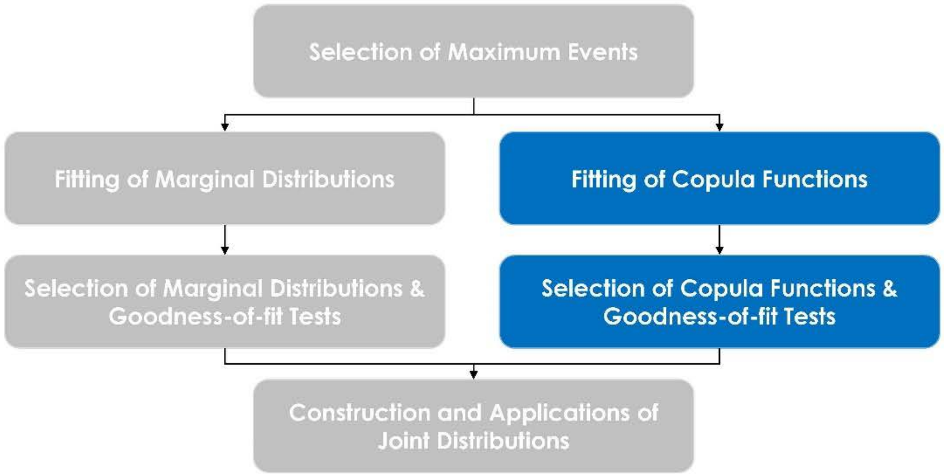
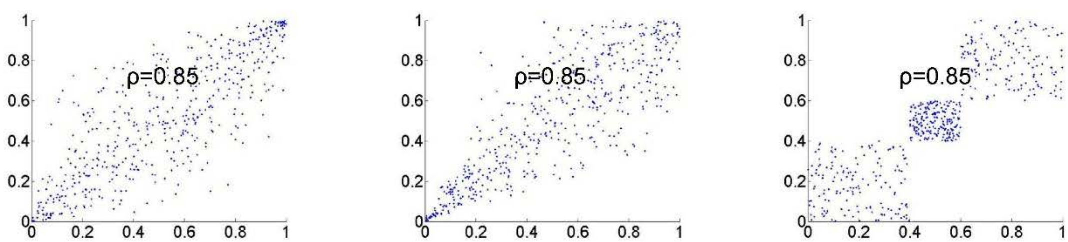
Assessment Procedures



Correlation and Dependence Structure

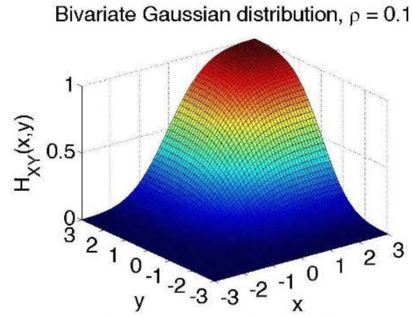
- **Can Pearson's linear correlation coefficient ρ fully characterize the relationship between variables?**
  - $\rho_{XY} = E[(X-\bar{x})(Y-\bar{y})]/Std[X]Std[Y]$

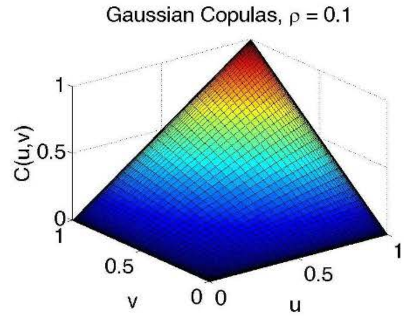


  - Only valid for Gaussian (or elliptic) distributions
- **Dependence structure provides a more comprehensive characterization than the correlation coefficient**

Copulas

- **Transformation of joint cumulative distribution**
  - $H_{XY}(x,y) = C_{UV}(u,v)$
    marginals: $u = F_X(x)$, $v = F_Y(y)$
  - Sklar (1959) proved that the transformation is unique for continuous r.v.s
- **Use copulas to construct joint distributions**
  - Marginal distributions => selecting suitable PDFs
  - Dependence structure => selecting suitable copulas
- **Together they form the joint distribution**

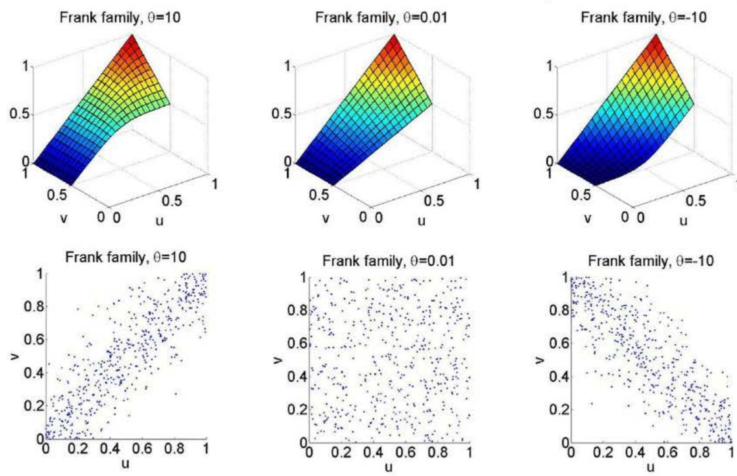




Example of Copulas – Frank Family

- **Frank family of Archimedean copulas**

$$C_{Frank}(u,v) = -\frac{1}{\theta}\ln\left(1+\frac{\left(e^{-\theta u}-1\right)\left(e^{-\theta v}-1\right)}{e^{-\theta}-1}\right)$$



Copula Functions

- **Tested copulas**
  - Gaussian (GAU)
  - T, degree of freedom = 2 (TD2)
  - Frank (FRK)
  - Clayton (CLT)
  - Gumbel (GUM)
- **Parameter estimation**
  - Inference Functions for Margins (IFM), using fitted marginals
  - Canonical Maximum Likelihood (CML), using empirical marginals
- **Goodness-of-fit**
  - Multivariate Kolmogorov-Smirnov (KS)
  - Akaike Information Criterion (AIC)
  - Bayesian Information Criterion (BIC)

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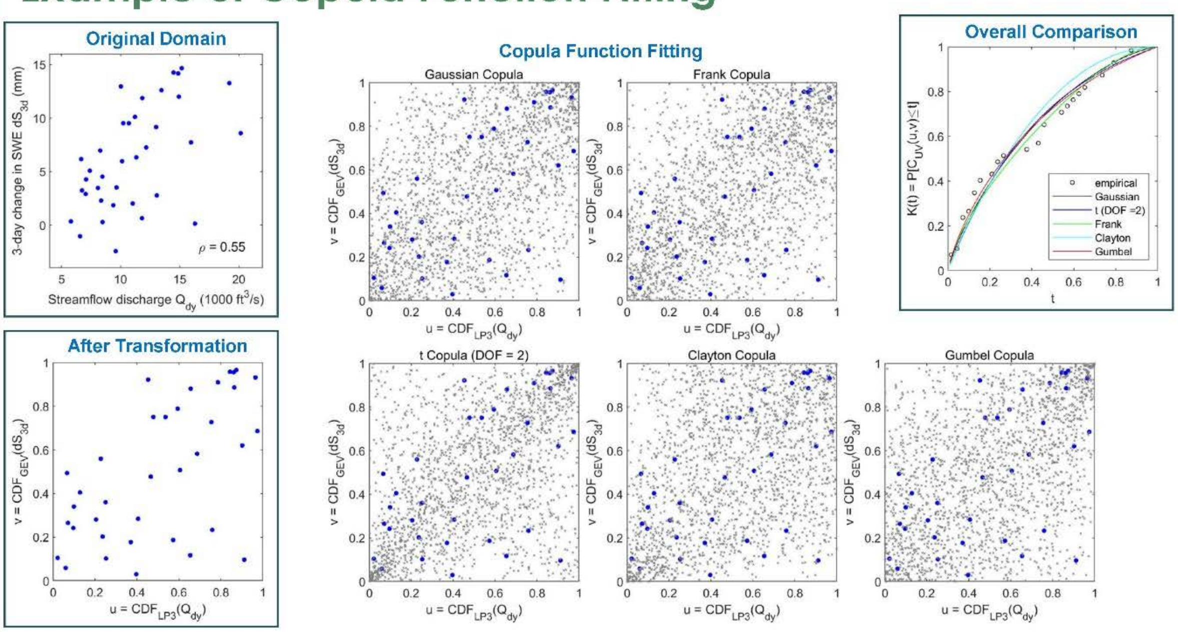
Example of Copula Function Fitting



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Variables	Correlation coefficient (ρ)	Kendall's τ	Selected copula function	Copula parameter
S1M2 (Clearwater River at Orofino, ID; Multivariate Peak-over-threshold)				
Q_{dy} & P_{3d}	0.1537	0.0606	GUM	1.0697
Q_{dy} & T_{3d}	-0.0455	-0.0077	FRK	-0.0933
Q_{dy} & dS_{3d}	0.3828	0.4045	FRK	4.0447
S2M2 (Yellowstone River at Corwin Springs, MT; Multivariate Peak-over-threshold)				
Q_{dy} & P_{3d}	0.2381	0.1387	GUM	1.1793
Q_{dy} & T_{3d}	0.2311	0.1762	CLT	0.3145
Q_{dy} & dS_{3d}	0.4555	0.3112	GAU	0.4461
S2M3 (Yellowstone River at Corwin Springs, MT; Maximum Joint Empirical Probability)				
Q_{dy} & P_{3d}	-0.1256	-0.0906	GAU	-0.1637
Q_{dy} & T_{3d}	0.2428	0.1351	GUM	1.1398
Q_{dy} & dS_{3d}	0.4287	0.2852	GAU	0.4247
S3M2 (NF Clearwater River NR Canyon Ranger Station, ID; Multivariate Peak-over-threshold)				
Q_{dy} & P_{3d}	0.1071	0.0673	FRK	0.6349
Q_{dy} & T_{3d}	0.0049	0.0026	CLT	0.0368
Q_{dy} & dS_{3d}	0.5273	0.4438	GAU	0.6124

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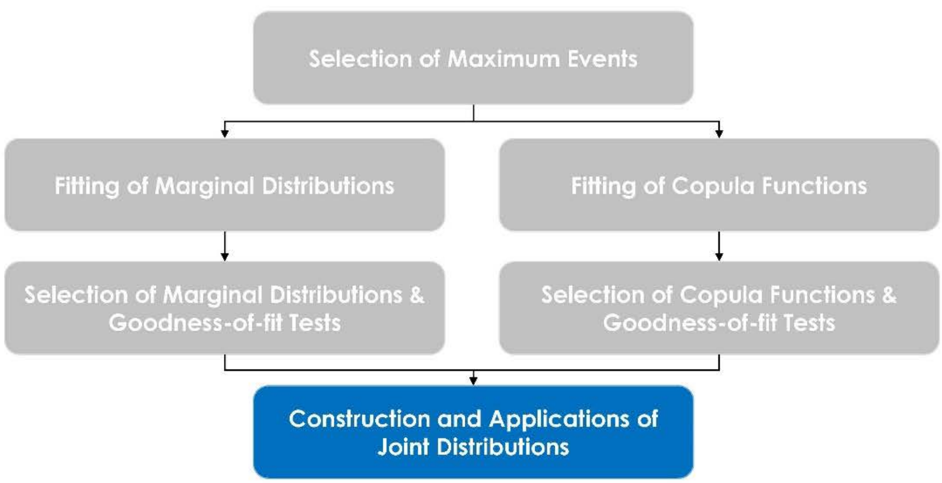
Assessment Procedures



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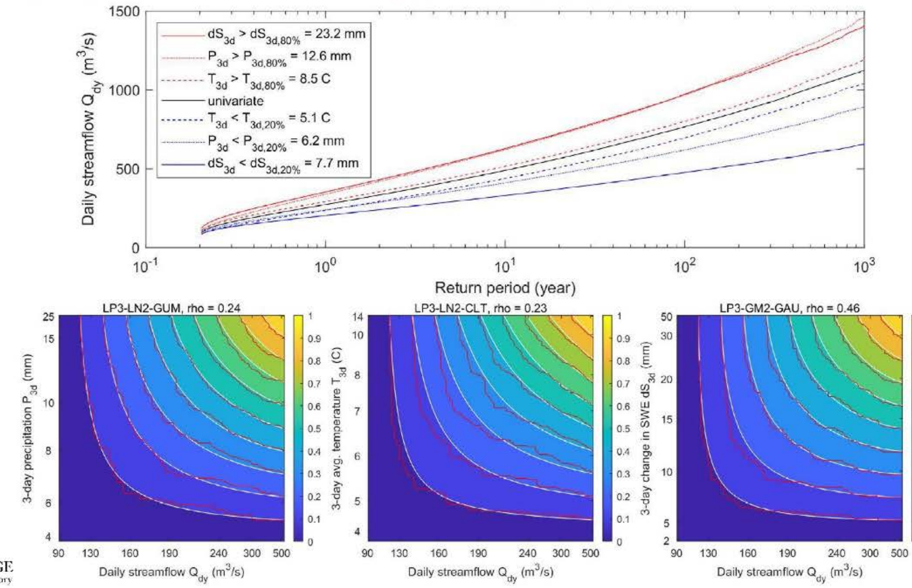
Bivariate Joint Distributions

S2M2 – Yellowstone River with multivariate peak-over-threshold



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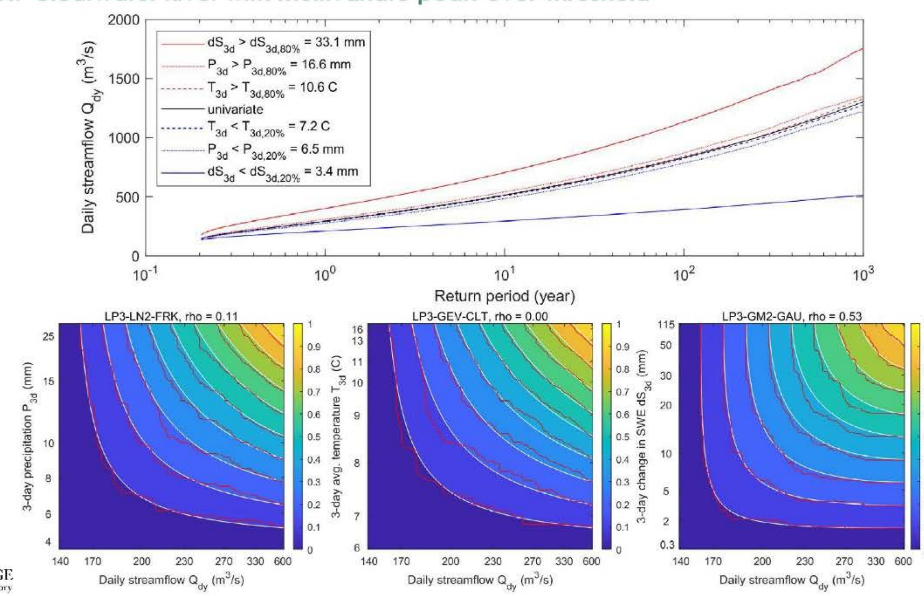
Bivariate Joint Distributions

S3M2 – NF Clearwater River with multivariate peak-over-threshold



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Summary and Next Steps

- **Copulas offer a natural way to extend our conventional univariate frequency analysis to multiple dimensions**
  - Can be applied to a variety of different MMF applications for PFHA
- **However, there are new issues to be considered**
  - Definition of maximum events
  - Data availability
  - Challenges in higher dimensions
- **Further exploration is needed to identify the best practice of applications**

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Thank you!

- Shih-Chieh Kao (kaos@ornl.gov)

3.4.3.3 Questions and Answers

No Questions.

3.4.4 Presentation 2A-4: Updating Design Flood Estimates at Sites with Changing Variability

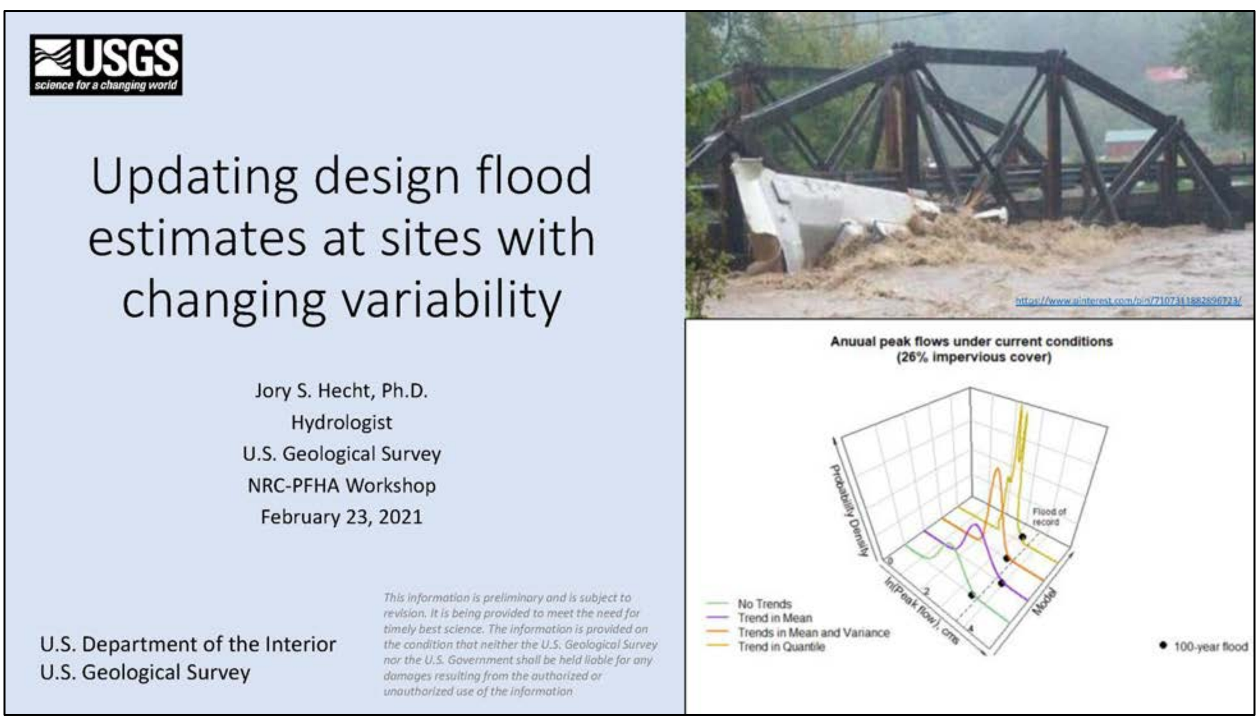
Author: Jory S. Hecht, Nancy A. Barth, Karen R. Ryberg, Angela E. Gregory, U.S. Geological Survey

Speaker: Jory S. Hecht

3.4.4.1 Abstract

While research on nonstationary flood frequency analysis (NSFFA) has proliferated, few continental-scale studies have compared the performance of NSFFA methods for updating design flood events to reflect current conditions. Moreover, practitioners have little guidance for considering the inherent biases and uncertainties of these methods and for assessing their goodness-of-fit to observed annual peak flows series. First, to compare the inherent biases and uncertainties of NSFFA methods, we parametrize a Monte Carlo experiment using distribution properties and trends in the central tendency and variability observed in annual peak flow series throughout the conterminous United States. We then identify trend magnitude thresholds above which modeling changes in central tendency and variability is warranted based on fractional root mean squared errors. Through a case study of an urbanizing watershed in suburban Detroit, we examine the extent to which Monte Carlo simulation experiments and goodness-of-fit analyses can, together, inform NSFFA model selection. We discuss the advantages and disadvantages of competing approaches, challenges in modeling changes in variability in hydroclimatic time series, and prospects for extending these methods to estimate rare design flood events needed for protecting critical infrastructure.

3.4.4.2 Presentation (ADAMS Accession No. ML21064A431)



Flood Frequency Estimation for Hydraulic Design

In cooperation with U.S. Department of Transportation Federal Highway Administration

Detection	Attribution	Adjustment
Where is change happening? How are floods changing?	What is causing the change?	How to adjust flood frequencies for change?

Research team and collaborators

Presentation overview

- Approaches for adjusting design peak flows to reflect current conditions in a basin
- Monte Carlo experiments based on observed peak flow changes in conterminous US (CONUS)
- Selecting design peak flow adjustments for an urbanizing basin
- Toward estimating current and future extreme events for critical infrastructure protection

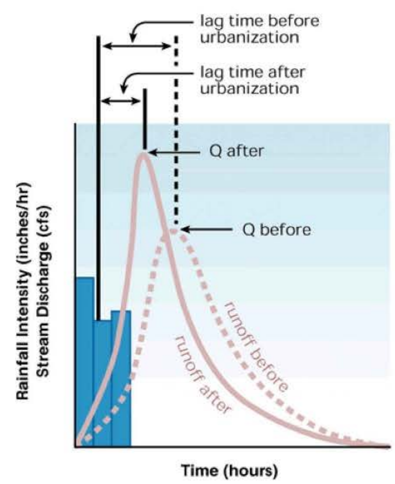


Figure: U.S. Environmental Protection Agency

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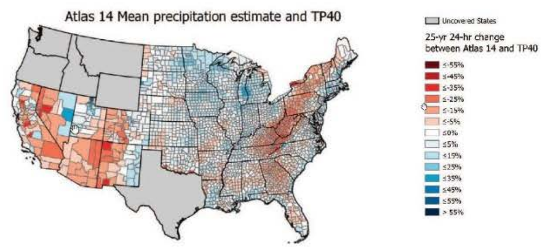
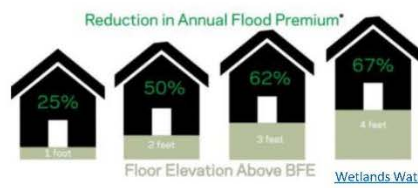
Some existing practices for addressing changes in design floods

- Safety factors
- Updating hydrometeorological data or removing data from unrepresentative period
- Simulate hydrologic responses of historic events under current land use
- Trends in mean annual flood (NCHRP, 2019)
- Bulletin 17C does not provide specific guidance on this topic



López-Cantu and Samaras (2018)



Wetlands Watch

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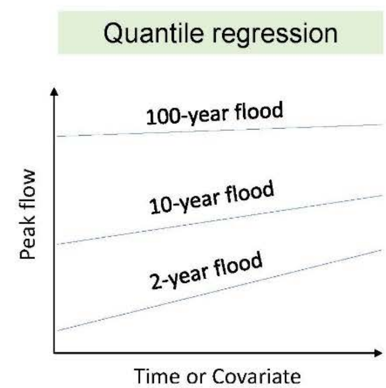
Comparing trend models

Method	Linear trend in mean	Exponential trend in variance	Direct quantile estimate
No trend			
Trend in mean (OLS regression)	X		
Trend in mean and variance (IWLS-GLM)	X	X	
Trend in quantile (Quantile regression)			X

All models fit to natural-log transformed annual instantaneous peak flows



Monte Carlo experiments for evaluating NSFFA methods

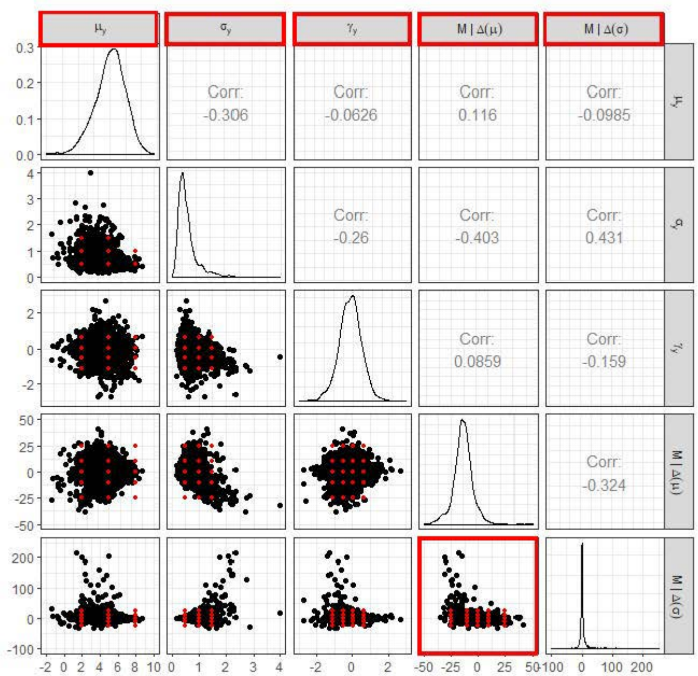
- Goal: Find best methods for estimating design floods that reflect current conditions
  - When is it worthwhile to model trends in the mean? Trends in the mean and variance?
- Trends and sample moments of synthetic records based on observed annual peak flows
- Modeling trends in mean and s.d. warranted under realistic conditions based on fRMSE
- Quantile regression outperforms distribution-based methods when peak flows have a strong negative skew
- Regression-based models are relatively robust to distribution mis-specification

Monte Carlo experiments

Based on observed sample moments and trends

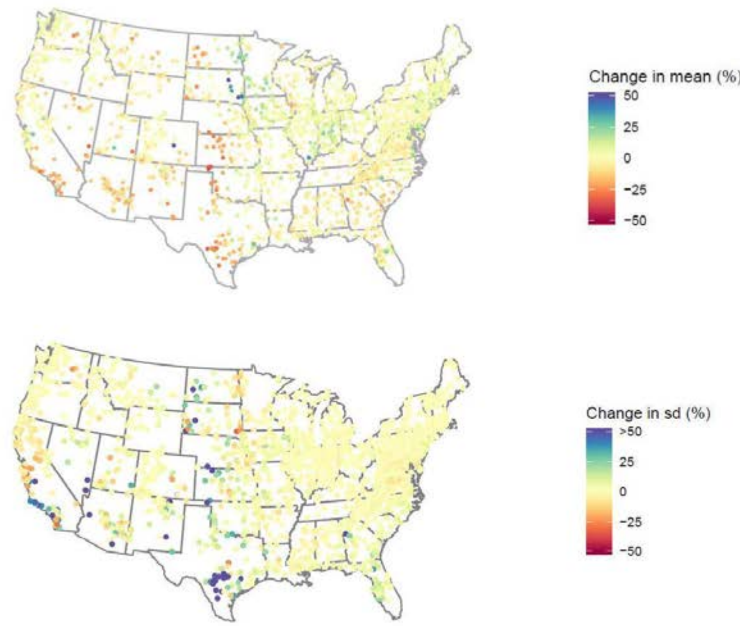
1,898 unregulated CONUS sites

50-year records 1966-2015 (Dudley *et al.* 2019)



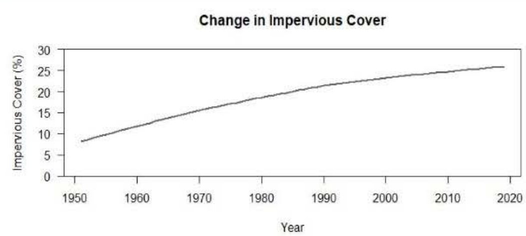
Decadal changes in mean and standard deviation of log-transformed annual peak flows

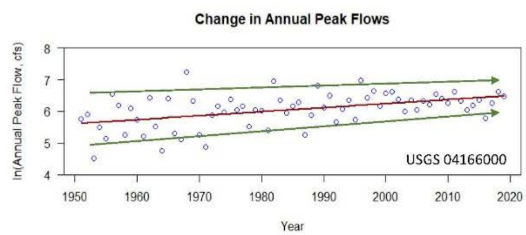
(1966-2015)



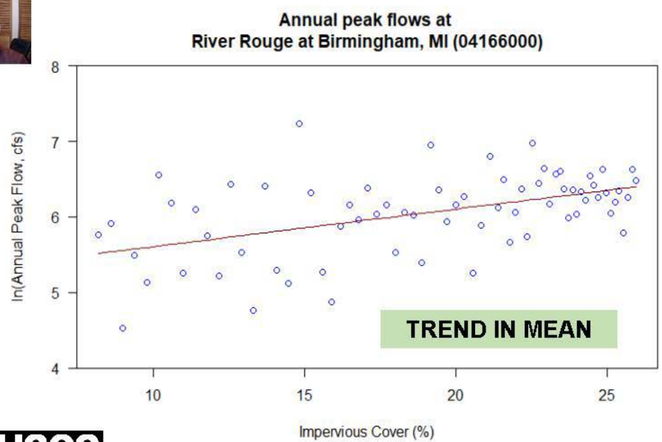
Case study: River Rouge at Birmingham, MI (33.3 sq mi)

- Impervious cover (IC) has increased from 8% in 1950 to 26% in 2010
- Increasing trend in annual peak flows
- Urbanizing basins tend to magnify small peak flows more than large ones
- No major flood-control reservoirs





'Current' design flood estimates using trends in mean and variance of log-transformed peak flows



Step 1: Log-transform peak flows

$$Y_{IC} \sim \ln(Q_{IC})$$

Step 2: Trend in mean

$$\hat{\mu}_{y|IC} = \hat{\beta}_{\mu}(IC - \hat{\mu}_{IC})$$

Step 3: Trend in variance

$$\hat{\sigma}^2_{y|IC} = \hat{\sigma}^2_{\varepsilon} \exp[\hat{\beta}_{\sigma^2}(IC - \hat{\mu}_{IC})]$$

Step 4: Estimate design flood with exceedance probability *p*

$$\hat{Q}_{p|IC} = \exp(\hat{\mu}_{y|IC} + z_{1-p}\hat{\sigma}_{y|IC})$$

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Key questions for nonstationary FFA model selection

- Question 1:
  - Which theoretical probability distribution should we select? Or should we employ an empirical approach?
- Question 2:
  - Is trend modeling worthwhile or will it just introduce more error into our design flood estimates?
- Question 3:
  - Are modeled flood change trajectories the same in calibration (in-sample) and validation (out-of-sample) periods?

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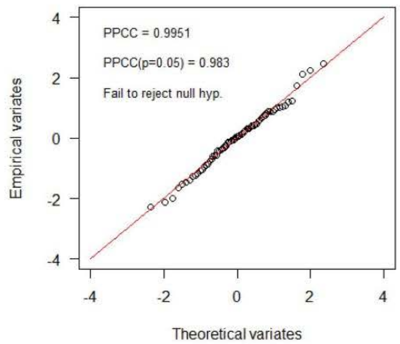
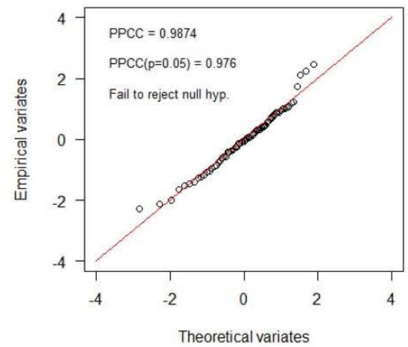
Q1: Evaluate nonstationary distribution fit

LN2



LP3



Nonstationary PPCC test (Serago and Vogel, 2018)

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Q2: Will trend modeling make our estimates too uncertain?

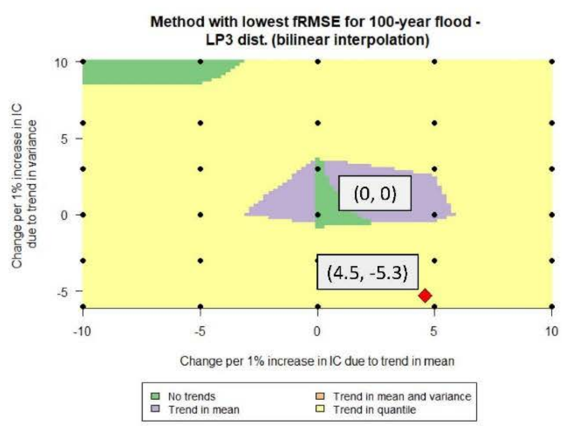
- How much does a 1% increase in impervious cover (IC) change floods:
  - 4.5% increase in 100-year flood due to trend in mean (IWLS-GLM model)
  - 5.3% decrease in 100-year flood due to trend in variance (IWLS-GLM model)
- Monte Carlo simulations show bias reduction vs. uncertainty tradeoff

Higher bias, lower uncertainty

Lower bias, higher uncertainty

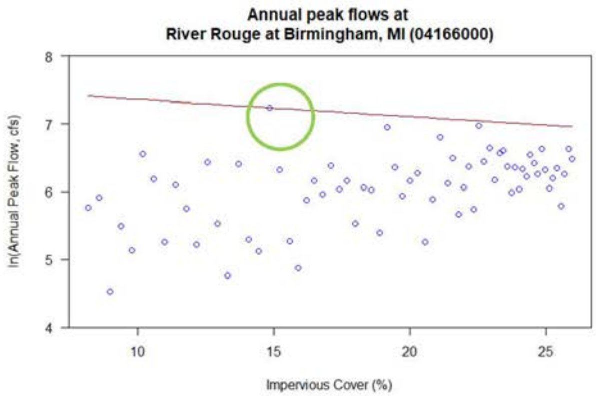
$RL = 69\ yrs$ $\sigma_y = 0.54\ m^3/s$

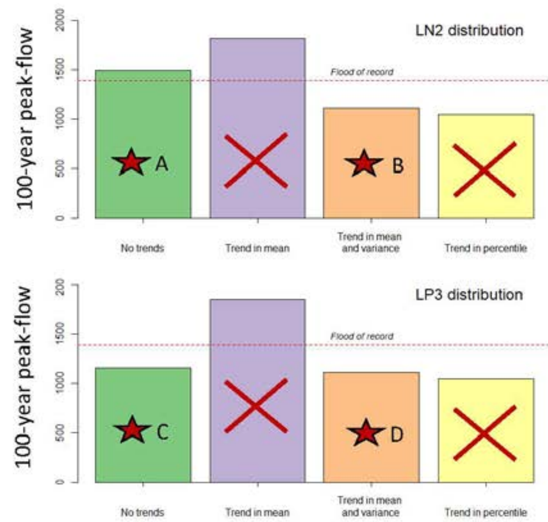
$\mu_y = 2.49\ m^3/s$ $\gamma_{y|BC} = -0.71$



'Current' 100-year floods

'Trend in mean' estimates too high





Which design flood estimate would you select?

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Concluding remarks

- Changes in annual peak-flow variability affect design floods
  - Critical in other urbanizing basins (Hecht and Vogel, 2020)
  - Many other factors to consider in urbanizing basins
- Assessment reveals model strengths and weaknesses
  - Asymmetric changes in variability hamper urban adjustments
  - Quantile regression sensitive to outliers
  - Need to compare nonstationary methods for regional frequency analyses
- Goodness-of-fit assessments complement Monte Carlo studies
- Climate-based adjustments to current conditions more complicated
- Critical infrastructure protection motivates further research

National Weather Service

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Thank you!

Jory Hecht (jhecht@usgs.gov)

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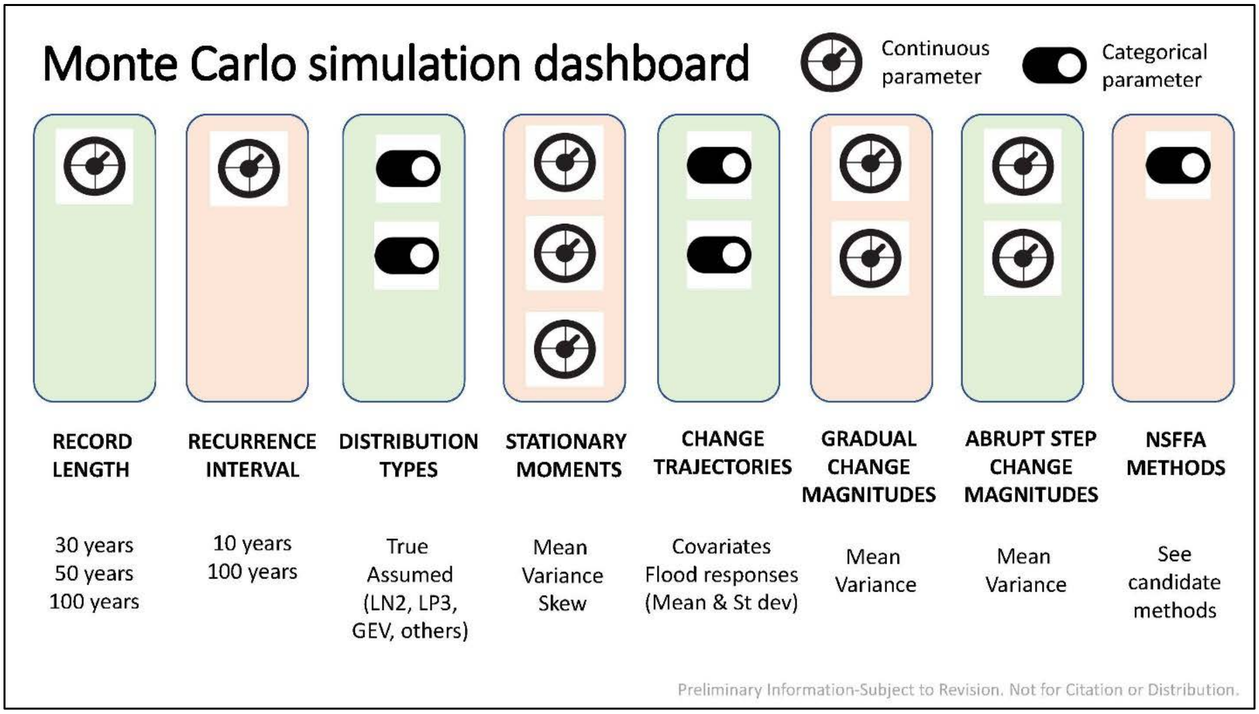
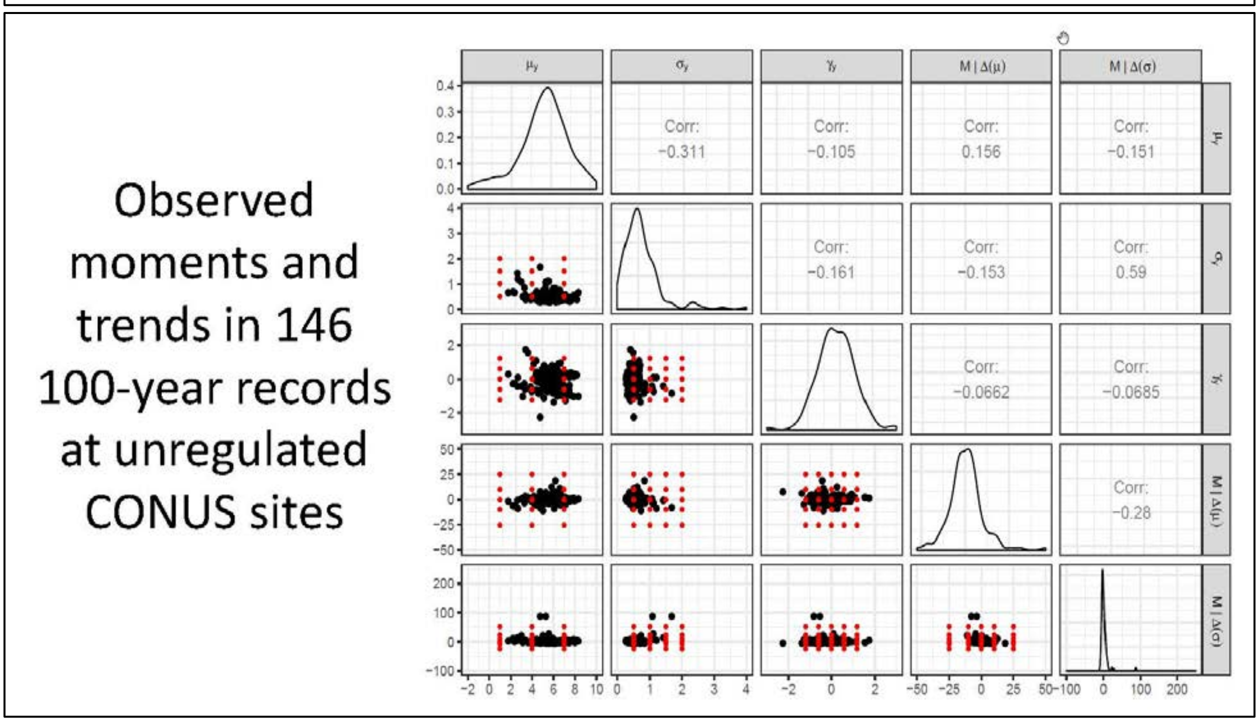
EXTRA SLIDES


Monte Carlo simulation dashboard
Continuous parameter
Categorical parameter
RECORD LENGTH
30 years
50 years
100 years
RECURRENCE INTERVAL
10 years
100 years
DISTRIBUTION TYPES
True
Assumed (LN2, LP3, GEV, others)
STATIONARY MOMENTS
Mean
Variance
Skew
CHANGE TRAJECTORIES
Covariates
Flood responses (Mean & St dev)
GRADUAL CHANGE MAGNITUDES
Mean
Variance
ABRUPT STEP CHANGE MAGNITUDES
Mean
Variance
NSFFA METHODS
See candidate methods
Preliminary Information-Subject to Revision. Not for Citation or Distribution.


Observed moments and trends in 146 100-year records at unregulated CONUS sites
Corr: -0.311
Corr: -0.105
Corr: 0.156
Corr: -0.151
Corr: -0.161
Corr: -0.153
Corr: 0.59
Corr: -0.0662
Corr: -0.0685
Corr: -0.28

3.4.4.3 Questions and Answers

Question:
Based on your study of 100-year floods, how do the Monte Carlo experiments performed for extreme flood events apply in nuclear safety analysis (i.e., in estimating the 10^{-6} frequency floods)?

Jory Hecht:
It's definitely going to be really, hard to have a lot of confidence in anything that has such a long return period. What's going to happen in the Monte Carlo experiments, is that the estimation errors are going to be greater and greater as your recurrence interval widens, when you just look at trends in variability and trends in the mean. What also concerns me about these extrapolation exercises, aside from just the basic nature of extrapolation, is that the variance change that you might see at a site, not only urban sites but any site, might be asymmetric. As I showed with this more straightforward urban example, you might have a larger change in the smaller floods or in the larger floods or even vice versa. Some of you have spent a lot more time with this than I have, with estimating really large return interval floods, but I suspect that you can't just let the tails speak for themselves because when it comes to extremely high floods, a distribution that works well for the 100-year floods might yield a really implausible one for the million-year flood. Conversely, one problem with the LP3 distribution is that, if there's a negative skew, which can happen often when you use log transformed data, the distribution will have an upper bound and that might give you a million-year flood that's just way too low. So, I would say that the results we have shown today offer a lot of food for thought, for how we might want to continue researching probabilistic flood hazard assessment. But it's not a recipe to necessarily provide for the estimation of floods of much longer return intervals.

Question:
Aside from urbanizing basins, is the team moving towards addressing climate variability issues, especially in North Dakota and South Dakota?

Jory Hecht:
When you say the team, I assume that you are referring to myself and my coauthors as well as possibly the USGS in general. Yes, it is something that we have been investigating. We have done some experimental work looking at the Palmer hydrological drought index as a covariate that relates to the magnitude of flooding in the Dakotas. This work is still in process, but we definitely think that using a lot of climatic covariates is really important. And one thing that we're working on is addressing these added challenges regarding the stochastic nature of climate, or climatic covariates, that I briefly alluded to in the in the concluding remarks that I gave. There are a lot of issues. First, you need to extract the deterministic trend from the stochastic variable mathematically. Not only that, you also have to really do some heavy thinking, incorporating numerous lines of evidence including paleohydrology, climate models for the future, etc., to really get a good sense of whether the trends in variability that you're seeing are truly sustained. It's easier to justify that they are sustained in an urbanizing setting. But when you're dealing with climatic covariates, you're going to really need to be on top of whether this is truly a trend over the design period that you're interested in and that it is being modeled as a deterministic trend, or if it's really just part of a cycle or an oscillation. The variability might be trending downward instead of upward during the period for which you want to design some infrastructure.

3.4.5 Presentation 2A-5: Historical and Paleoflood Analyses for Probabilistic Flood Hazard Assessments—Approaches and Review Guidelines

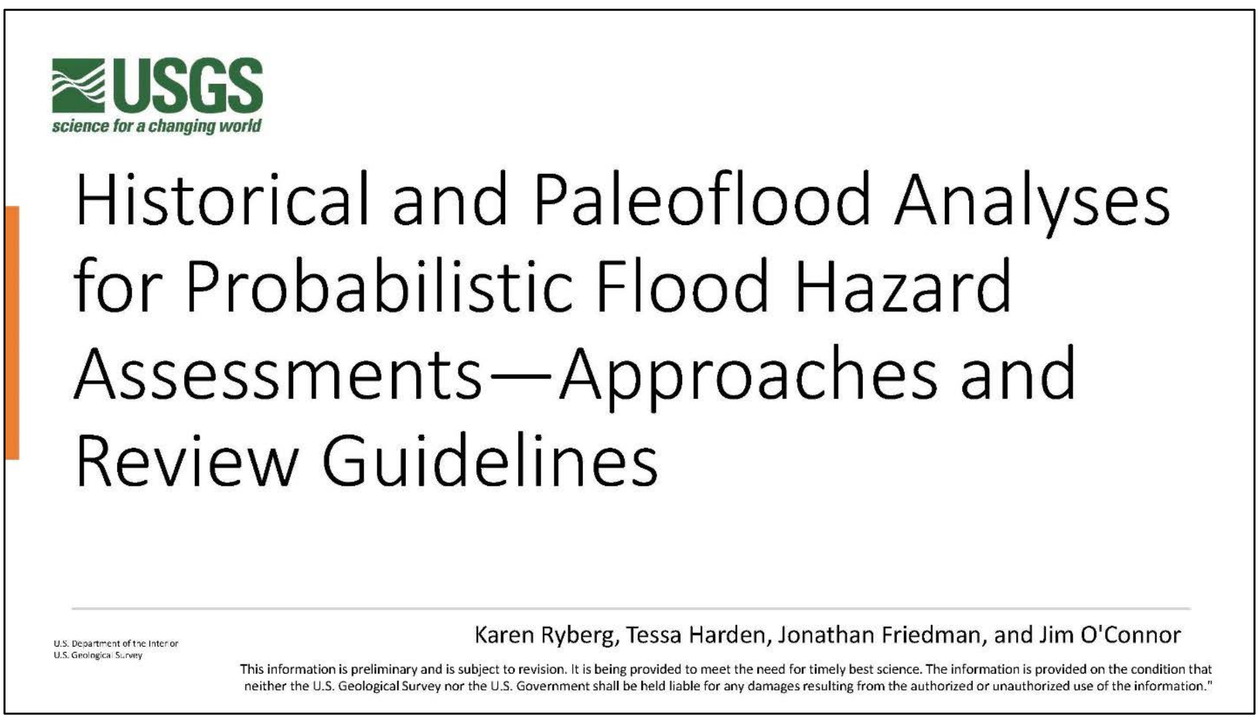
Authors: Karen Ryberg, Tessa Harden, Jonathan Friedman, Jim O'Connor, U.S. Geological Survey

Speaker: Karen Ryberg

3.4.5.1 Abstract

Paleoflood studies are an effective means of providing specific information on the recurrence and magnitude of rare and large floods. These studies can be combined with systematic records to improve flood-frequency analyses and the calibration of rainfall-runoff models, especially for extreme flood events. Paleoflood data also provide valuable information about the linkages among climate, land use, flood hazard assessments, and channel morphology. The U.S. Geological Survey in cooperation with the Nuclear Regulatory Agency have developed a USGS Techniques and Methods report describing typical standards of practice for developing historical and paleoflood data and incorporating such data into flood-frequency analyses. We discuss geological and botanical evidence of floods, geochronologic techniques, and hydraulic analysis methods and flood-frequency analysis. Three levels of paleoflood analysis and review are identified, ranging from scoping or reconnaissance (Level 1) to intermediate (Level 2) to comprehensive (Level 3). These levels are chosen to meet project objectives including the risk criteria and management goals of the project. This new USGS Techniques and Methods report also summarizes strategies for assessing and mitigating uncertainties and provides guidelines on appropriate technical review of paleoflood analyses.

3.4.5.2 Presentation (ADAMS Accession No. ML21064A432)



Project Funded by the U.S. Nuclear Regulatory Commission

- Will be published as a USGS Techniques and Methods Report.
- Has had extensive review by
  - NRC staff,
  - academic experts in flood geomorphology and tree rings, and
  - a Surface-Water Specialist in the USGS Hydrologic Networks Branch
- Currently being edited
- Hope to have it published by end of 2021

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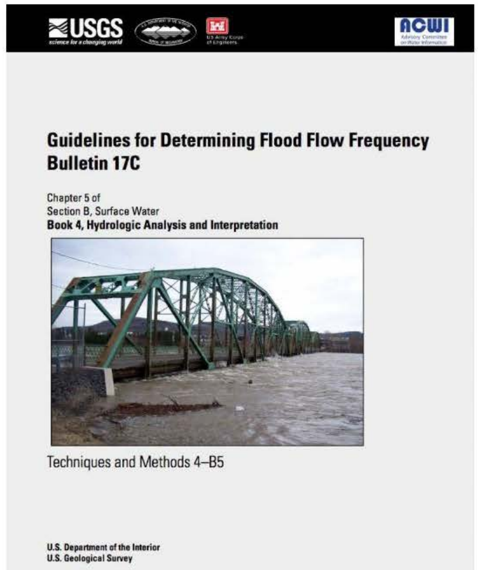
Motivation for Report and Related Workshop

- Paleoflood hydrology studies are an increasingly import tool for design and safer operation of critical infrastructure.
  - Extending the effective flood record
  - Informing estimates of the magnitude and frequency of flooding hazards
- Standards of practice for conducting and reviewing such studies are lacking.
  - Inhibits effective use in regulatory decision making

USGS

Bulletin 17C

Federal agencies are requested to use these Guidelines in all planning activities involving water and related land resources. State, local, and private organizations are encouraged to use these Guidelines to assure uniformity in the flood frequency estimates that all agencies concerned with flood risk should use for Federal planning decisions.



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England and others, 2018

ENGLAND AND OTHERS, 2018, p. 125

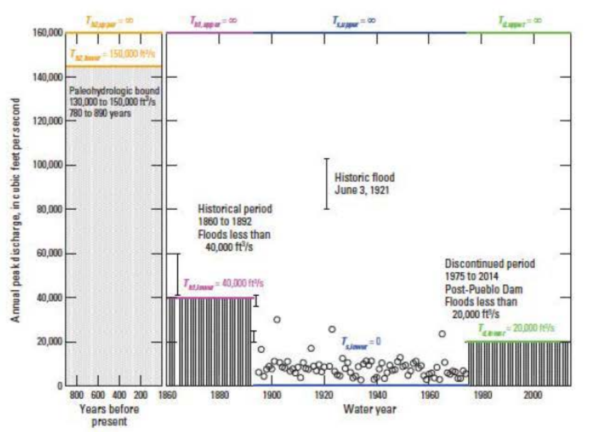

Figure 10–8. Graph showing peak discharge, historical and paleoflood estimates, Arkansas River at Pueblo State Park. A scale break is used to separate the gage and historical data from the longer paleoflood record. Flood intervals are shown as black vertical bars with caps that represent lower and upper flow estimates, including unobserved estimates in the historical period and historical floods in 1864, 1893, 1894 and 1921. The gray shaded areas represents floods of unknown magnitude less than the perception thresholds for the paleoflood period $T_{h2,lower}$, the historical period $T_{h1,lower}$, and the discontinued period $T_{d,lower}$. Perception threshold ranges in cubic feet per second (ft³/s) are shown as orange lines for the paleoflood period, magenta lines for the historical period, blue lines for the systematic period, and green lines for the discontinued period.

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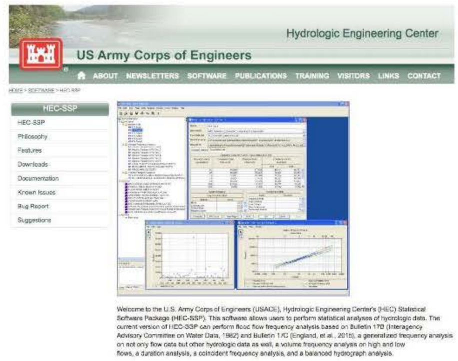
Software

- Software incorporates ability to use perception thresholds and interval estimates.
- Can account for the inherent greater uncertainty in historical and paleofloods.



USGS

Veilleux and others, 2014

https://www.hec.usace.army.mil/software/hec-ssp/

	Documentation Type	Description
Paleoflood Study Attributes	Site Information	Level 1: location and description of study area, map of area, simplistic description of hydrology, geomorphology and geology of study area; stream/river length, slope, sinuosity; location (survey or GPS), photo or site sketch, comments. If using previously published regional paleoflood information, not all information may be available. Level 2: Basin level: location and description of study area, maps, lidar, existing inundation maps/models, land use maps, soil maps, general description of hydrology, geomorphology and geology of study Reach Level: reach location, photos, stream information (width, confined or unconfined, slope, etc.), general description of local geomorphology and geology Site level: location data, surveying of landmark to link to lidar or aerial photography, aspect, land cover, photos, site sketch or annotated map, comments or observations Level 3: similar to Level 2, except for multiple basins and sites. Documentation may need to be standardized across many field teams and simplified for tabulation.

Preliminary Information-Subject to Revision. Not for Citation or Distribution.

Paleoflood Study Attributes	Documentation Type	Description
	Stratigraphy	Level 1: Study area: Photos and maps of site locations, major landmarks, etc. Sites: locations, schematic diagrams, photos, number of units in the stratigraphic sequence, method used to expose stratigraphy; Stratigraphic descriptions for each unit: thickness, color, texture grainsize estimate, degree of sorting, moisture content, amount of organic material, type of fluvial structures (such as laminations or cross bedding), dip, degree of bioturbation, nature of contact between the units. Level 2 and 3: Similar to Level 1 but includes more sites and basins (Level 3). May include samples for grain size or geochemical analyses.

Paleoflood Study Attributes	Documentation Type	Description
	Botanical	Level 1: *Trees:* species, condition, record of locations, scar location and height; may include limited cores or slabs at chest height, observations and locations for recent HWMs, notes Level 2 and 3: *Trees:* species, condition, sketches, photos or annotated maps and locations of geomorphic and geographic positions (distance from trees to locations with respect to the thalweg, channel, bank, floodplain; straight reaches, inside or outside bend; exposure), equipment and precision for distances and elevation, description of geological characteristics, observations and locations for recent HWMs, notes *Indicator:* scar or damage height, description, description of observed debris (boulders, woody), skeleton plots; tilt description, aspect, angle to river; wedge, cross-section or core location and elevation, photo, equipment used, comments *Burial study information:* sediment depth, description, excavation method and details, tree species, condition, slab locations, elevations and methods, method to link information with stratigraphic exposure, stratigraphic information from exposure as above

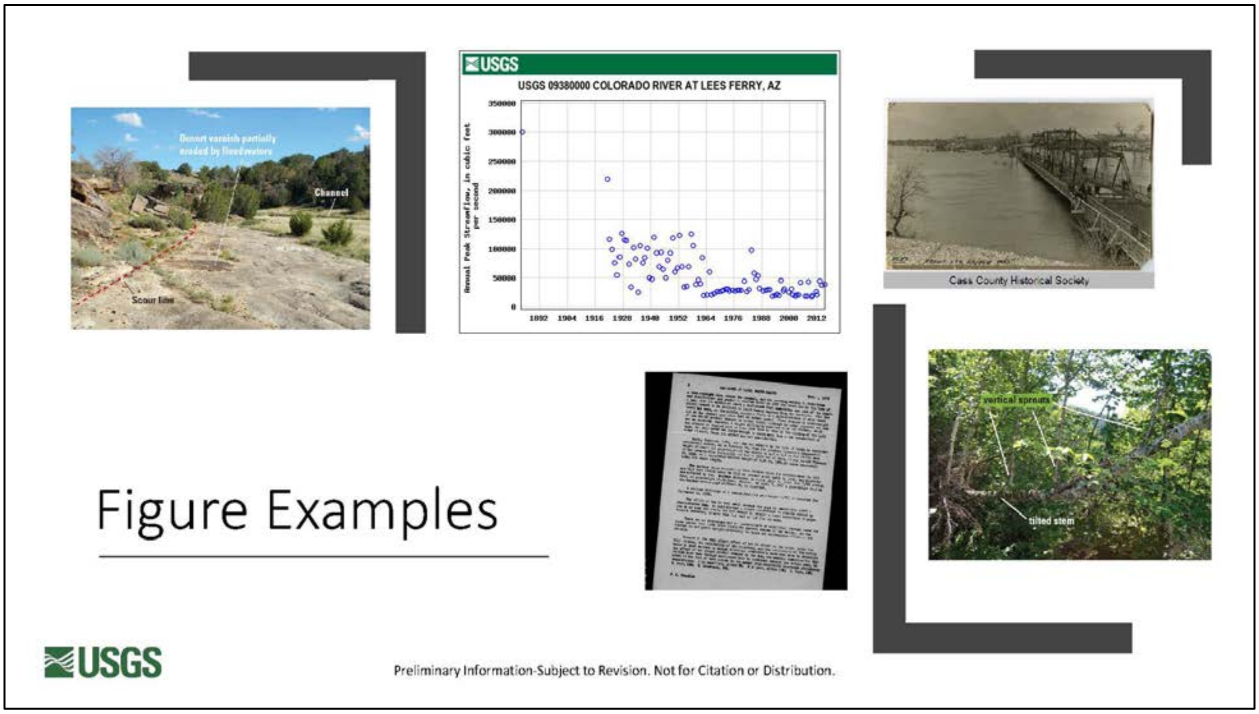
	Documentation Type	Description
Paleoflood Study Attributes	Geochronology	All Levels: All samples: Dating method, sample location, photo, schematic diagram with sample location in exposure or core, stratigraphic unit; depth below surface, material, key observations and comments, lab results, uncertainty Soil Development: note characteristic soils and structures similar to nearby quantitatively dated studies, record: trimlines, soil characteristics, desert pavement, physical weathering of rocks and terraces, and vegetation. Dating anthropogenic evidence, unusual geologic evidence. Tree rings: preparation methods, equipment, techniques, skeleton plots, criteria for, description of and measurements of growth anomalies, method of statistical evaluation of cross-dating with other samples/trees, software version, inputs and outputs, photographs, uncertainty estimates Radiocarbon: organic material description, photo, sample location and sampling collection method and storage, dating technique (AMS or conventional), results, corrections, uncertainties

Also Address Levels of Review In These Areas

- Source Information for Systematic, Historic and Paleoflood Data
- Flow Estimation Methods
- Flood-Frequency (Hydraulic Hazard Analysis) Methods
- Uncertainty and Non-Stationarity Records and Methods
- Comparison with Other Analyses

USGS

Preliminary Information-Subject to Revision. Not for Citation or Distribution.



3.4.5.3 Questions and Answers

Moderator:
I see a nice comment in the chat from John England which I will read: "*This is a tremendous contribution, that is invaluable for the flood hazard community. And for your information, the Corps of Engineers published guidance in an ETL from September 2020: https://www.publications.usace.army.mil/Portals/76/Users/182/86/2486/ETL%201100-2-4.pdf?ver=BCMmEL8FwycdUYzawIYlQQ%3d%3d*"

Karen Ryberg:
We saw that published guidance. I know Tess got it and she initially thought that the Corps of Engineers stole our thunder. Looking at it more closely, we don't think they did. The two guidance publications have different purposes and ours is going to be more exgtensive. But we are definitely aware of the Corps publication. It came out well after all the reviews and the writing of our report, so I'd have to go back and look and see if we actually referenced it or not. But we did see it and it's good for others to be aware of it.

Question:
How do you correlate the full sweep of geomorphology, cut, fill, terraces, etc. to the contemporary stream organization without more detailed geochronology, such as cosmogenic radionuclide dating. I am referring to changes in base level or stream capture.

Karen Ryberg:
That would be a question for Tess Harden or Jim O'Connor who are experts in the geomorphology part of it. They are not online right now. I am certainly not an expert on that. I was on the project because I'm a statistician and have done work looking at the effects of flood frequency estimates when you incorporate paleoflood and historical flood estimates. So that is really a question for Tess or Jim.

Question:
What would be the most bare-bones analysis you could do to get in the ballpark for paleo-flood?

Karen Ryberg:
That is another question that Tess would do a better job of answering. She has done what we designated as level one studies which are more of a reconnaissance study. It will, of course, depend on the setting. We had a workshop that gathered information for this report and one of the talks was by Scott St George at the University of Minnesota who used to work for the Geological Survey of Canada. He's done estimates of large floods on the Red River at Winnipeg, Manitoba, based on tree rings. He talked about how they got to the tree ring analysis after trying everything else. The Red River setting, a very flat basin and a lake floodplain, was not conducive to methods that determine floods through geomorphology. That is why they tried tree rings with success. So it is highly dependent on the setting. But you would start out with some reconnaissance studies, for example looking to see if there are terraces in the floodplains such that you might have terraces deposits in a cave, or for forested areas with old trees. Age of trees was another issue for the Red River at Winnipeg. Prairie and plains trees aren't as long lived as trees in some other areas. So, it would very much depend on the setting.

Question:
Do you have a handle on when that report will be available?

Karen Ryberg:
It is in the USGS publishing network for editing which has been slower during the pandemic. Because, as we all know, scientists are traveling less and, in some cases, working longer hours because they're not going anywhere. Our publishing network has really been inundated with more reports than normal. She thinks will probably see it back from editing in May. We will update it very quickly. And then it still has to go through layout process, but that's usually much quicker than editing. I hope that will be published this federal fiscal year.

3.4.6 Riverine Flooding Panel Discussion

Moderator: Mark Fuhrmann, NRC/RES/DRA

Panelists:

Daniel Wright, University of Wisconsin-Madison
Periandros Samothrakis, Bechtel Corporation
Shih-Chieh Kao, Oak Ridge National Laboratory
Jory S Hecht, U.S. Geological Survey (USGS)
Karen Ryberg, U.S. Geological Survey (USGS)

Question (to Panel):
There are obviously a lot of challenges to doing probabilistic modeling for riverine flooding but what are the most difficult issues to resolve? What gives the biggest gain for the effort?

Periandros Samothrakis:
I could go first on this question. I mentioned in my conclusions that there's substantial effort needed to analyze all the uncertainty that exists in the input variables and how to better decipher and implement them in the model. So that's one challenge. Substantial time is needed to perform these kinds of analyses. For specific input variables we also perform a partial rank correlation coefficient estimation in our analysis. I didn't present the results of that because of time. Basically, we compare the ranking of the input variables having epistemic uncertainty against the ranking of flood flows and we see which input variable has the higher correlation. What we found is that for the specific study watershed, the climate change factor has the highest correlation with the results. I believe that this will be an area of further investigation, since at this specific site it has the highest Impact. There are many global climate models that take into account different emission scenarios. How do we transfer the results of these global models to our specific site? We have a small water shed in eastern Tennessee, about one square mile. How can we better estimate the climate change adjustment factor for the rainfall. I think that's an area that we need to further look into and have an understanding on the uncertainty on this input variable.

Daniel Wright:
I could add to that. I would also like to say “Hi” to Peri. He taught me numerical methods back in 2003, so it's nice to see you again here. I totally agree with what Peri said. Climate change and other sorts of changes like land use are certainly big issues. But I would even make this a little bit broader. What I see as one of the big challenges, is understanding how all the different pieces that make floods end up fitting together. If you look at a series of annual maxima flood peaks for example, it doesn't really tell you a lot about processes, right? And so that's what's really driven my interest in taking more numerical and stochastic-based modeling approaches to look at this. I think you have to end up turning to model approaches to deal with that question of variability because we just don't have enough observations of soil moisture, distributed snowpack properties and all of that sort of stuff. I think that is really important, particularly when you start thinking about the real extreme tail of floods because that's certainly going to be under-observed. Certainly, in the context of climate change as well. Because it's not that flood peaks themselves are somehow changing. It's that the processes that drive floods forward are changing. There are interactions there that need to be understood to be properly represented and reflected in our flood quantile estimates.

Jory Hecht:
I'd like to just build off of what Daniel was saying. I think that it would be wonderful to do some Monte Carlo experiments with stochastic models like the ones that he's been using in this framework. Provided that there is control being placed on the correlations of different input

variables, which I'm sure there would be. In addition, I think it would be really interesting to work toward a set of experiments that really could evaluate both traditional statistical approaches as well as process-based approaches with different modeling platforms. It would be interesting to see how well each of these approaches are doing in predicting extreme events that are useful for various applications, ranging from designing a culvert to more critical infrastructure applications.

Daniel Wright:
Stay tuned. We have some papers in review right now that looks at least some of those. But yeah, I definitely agree that there's a lot of fertile ground there to work on.

Jory Hecht: Yeah, definitely! Is that the paper on the Front Range or is that a different one?

Daniel Wright:
There are a couple of them. The Front Range paper one is. But we've also done some work using results from our process-based methods to test the robustness of at-site or regional flood frequency analysis methods. I wasn't ready to show that yet today, but I'll just tease you by saying that the results are sobering. I'm sure that you could poke holes in some of the things that we did, but nonetheless I think there are some potentially valuable findings there.

Karen Ryberg:
From my perspective, I think Jory answered that question really well. I agree that there's huge opportunity for Monte Carlo experiments, some process-based experiments. For the USGS, it's a matter of finding time and funding as it is for others and academics too. But I think Jory answered it well.

Question (to Panel):
Given the modeling tools available, how good of a handle do you think we have on flood timing? That question comes in two senses. One is in terms of warning times, but maybe a lot more important, especially for NRC, is the duration of flood conditions. As you know, we see a lot more damage occur when we have long, protracted flooding conditions, as opposed to a short period of inundation.

Karen Ryberg:
It's certainly something a lot of people are talking about. The duration issue is really fascinating, and I'm sure the Corps of Engineers has a lot to say on that. It's one thing to build infrastructure to hold back a massive flood of a short duration, but it's a whole other thing for that flood to last months and months. That makes me think of flooding in recent years along the Missouri River in the Omaha area. Also, along the Red River of North, from Fargo and Grand Forks up to Canada, and where Interstate 29 is essentially acting as a dam in many places. We occasionally hear the per-mile cost of interstate highways. It's astronomical and those are not designed to be dams. This is something the Federal Highway Administration has been talking about. It is something we've been talking about in the USGS. Also, seasonality. In snow climates we are seeing a lot more flooding in summer and fall than we traditionally have. On the James River, a tributary to the Missouri, two stream gauges South Dakota were above flood stage for over a year, ending in September of 2020. That just brings up existential philosophical questions. What even is a flood when your stream gauges are above flood stage for a year? So, we have a project where we are doing work on seasonality. I don't know of any current USGS large scale efforts looking at duration, but I know it's something certainly being talked about.

Jory Hecht:
Yeah, it's been an increasingly touched upon topic in the literature. Going back to literature, there have been a few papers, at least one in Nature by Naresh Devineni and others from Hunter College. So, it is not just lingering on the sidelines of our field anymore. I think there's a

lot more room to do research on it, especially given the breadth of applications for which it's relevant. In addition to critical infrastructure applications, there's also a lot of studies on bank erosion, floodplain inundation in ecosystems, etc., for which it would be really valuable. I think to move that field forward in practice, it might be really useful to do some brainstorming as to all the different types of applications for which duration modeling could be beneficial and think about ways to forge collaborations with those diverse stakeholders who would be interested in having better information about flood duration.

Periandros Samothrakis:
In our case we're looking at a small water shed. We have some buildings of interest and we're planning to calculate flood durations at specific locations around these buildings. We're planning to do that with the use of HEC-RAS. We haven't completed that portion of the study yet, but it's our goal. Basically, we will look at the flood hazard curves, and our focus will be the median flood hazard curve. From that we will look at which hydrographs produce this flood level and see if we can deduce the flood duration at the lowest levels above a certain elevation. So, it's in our plan to investigate duration for buildings of interest in this watershed and hopefully we can present some results at the next workshop.

Shih-Chieh Kao:
In a way, it is about the sample size. Usually when one goes to longer duration and larger scale, you will have a smaller sample size which lower your ability to fit a distribution and that's generally a challenge. I think I also received some questions about my session related to the size of the sample that would be sufficient for copula-based analysis. What we are thinking right now is that maybe we should not rely only on data. I think we will need to be flexible, to think about ways we can use a modeling to expand our simple size. That way we can have a larger sample size to evaluate the frequency of these longer duration or larger scale events.

Question (to Panel):
In the chat we have a kind of long question. Let me read it:

> "*The goal to have a handle on 10,000 recurrence intervals (including rare events) is very difficult problem to solve. There has been innovative and good work presented. I would argue that long term changes (past and contemporary steam organization such as tributary capture or base level fall) influence the capabilities of a fluvial system. In my view, this would need to be reconciled for a 10,000-year history before overlaying climate and parameterizing past scenarios (wet and dry periods, historical extreme events, etc.). After stream organization and climate correlations are built, you could then project forward under different climate scenarios to have a better understanding of future flood potential. In short, although geomorphic data is incomplete and sparse, the observation history needs to match the temporal scale of projection.*"

What the questioner is driving at here is that, for very long-term projections, enough changes in geomorphology may occur that may have a much more substantial impact than a lot of other affects that we typically are concerned with.

Jory Hecht:
I think you've raised a lot of really good points about looking at very extreme events, but when we design a lot of critical infrastructure (and I'm just going to forget about the really long term issues with nuclear sites) that require protection against extreme floods, one important thing to keep in mind is that the design horizon is not the same as the recurrence interval of interest in a lot of cases. We might be interested in designing a bridge or a wastewater treatment plant for 100 years and we're going to want to protect that infrastructure against the flood that has a recurrence interval of much more than 100 years. So, I think it's important to keep track of that

distinction when we talk about this problem. If we're interested in looking at the 10,000-year flood for a damn that might have 100-year useful life, what might be worthwhile to do is to conduct an extreme probabilistic analysis based on a relatively narrow range of geomorphological conditions, if it's appropriate for a site. So, for instance, like not having drastic changes in base level or stream capture be included.

Daniel Wright:
I would echo what when Jory said. I would push back against the notion that we need 10,000 years of data. We should keep in mind the definition of recurrence interval for one thing. It's the recurrence interval of specific site. If we have methods, whether it's regional frequency analysis or storm transposition methods that can sample from across a larger region, it's very conceivable that you're pulling in historical events, observed events that have unknown recurrence intervals that are on the order of thousands of years. That, combined with the fact that our planning horizon is not 10,000 years in the future, I would agree that we shouldn't undersell our ability to answer these types of questions. I guess there are lots of difficulties, but we can make some smart moves and lots of people have been doing that for a long time.

Karen Ryberg:
I agree with Daniel's comments. I did a report for the Nuclear Regulatory Commission where we calculated magnitudes of floods with recurrence intervals of 10,000 years and beyond. You can get your brain wrapped up in this in a number of ways. If it's a million year flood, is the river even going to be there in a million years? You start wondering about the whole enterprise. I think Daniel described it very well, especially if you look at this in a regional context. What are those extraordinarily rare events that could generate massive flooding? We need to get a sense of our risk for those. No statistical analysis should be done totally disregarding hydrologic processes. You would combine that information about the physics of the generating mechanisms and guesses about future climate and the topography of the area using multiple lines of evidence approach. But I think we should, for long term protection of certain assets, be able to think about what the really massive flood that may be out there.

Periandros Samothrakis:
I agree with what the previous speaker said. The 10,000-year flood could happen tomorrow, just the probability is very low. To give a small example close to where we are in Maryland. Ellicott City, I believe, had two flood events of about 800 years return period within two to three years. So, it can happen at any time within the project life, which is typically 100 years. So as the previous speaker said, we're doing a good job looking into this 10,000-year event as it's required by the regulation.

Question (to Panel):
That brings up another topic which is the issue of land-use change and how to deal with that. Yesterday we heard a talk where they used a very detailed land-use maps for small areas. I'm kind of wondering if for riverine flooding the same sort of detail is needed from the point of view of actual land-use maps. How necessary is that? We saw with one of your talks, that in fact the 1% change makes some difference. This is an issue that speaks back to that Ellicott City problem.

Jory Hecht:
Land-use mapping is a very good tool to have with which to associate changes in floods. But when we look at current impacts of urbanization, it's also important to consider what we're doing to mitigate against these increases, such as stormwater detention as well as different decisions made with sewering and whatnot. One thing that I found in my recent work is that it is relatively easy to get some impervious cover data and establish a statistical relationship between the change of impervious cover and flooding. It is a lot harder to find some other data, such as data

about sewers or detention ponds. I think conducting some sort of more detailed study on a number of urban areas that include providing these types of data could shed further light on how urbanization is affecting flooding and how its impact on flooding might not be the same today as it was 40 years ago when there are far fewer stormwater ordinances.

Karen Ryberg:
I think Jory spoke well about the challenge of getting good ancillary data. Certainly, where people have done LIDAR data assessments, where there are good estimates of impervious cover, that's really beneficial when you start thinking about other landscape-level changes. This is an ongoing issue in water quantity and water quality studies. It's a big topic in best management practices in agriculture. But it's difficult to get good data as Jory described. It depends on what the practice is. Some take several years to reach maximum efficiency because it involves disturbing the soil and you need cover to grow back. So, you don't reach maximum efficiency for a few years. Maybe other practices lose efficiency overtime, so the effect of whatever you're looking at is not the same year after year. So, it's a challenge just to get any data to begin with, to say nothing of these other details about what exactly is the management method and how has it been maintained. It's a big challenge to do causal assessments or better understand how human impacts affect these processes. We need more and better ancillary data.

Daniel Wright:
I agree with what's been said, in terms of the need for that data, that's oftentimes quite hard to find. These process-based approaches, like you saw from Peri or from myself, are well suited to building in those data directly to flood estimation. There are lots of modeling software that can simulate the effects of stormwater detention or storm water transmission, for example. So, I think that is a promising direction going forward.

Question (to Panel):
Karen told us about the paleoflood guidance that USGS is in the process of publishing. How can we establish national guidelines for accounting for non-stationarity in flood estimation? Is it a topic that's ripe for something like that? Or is it too soon? What do you think?

Karen Ryberg:
I just spoke to an internal group yesterday where this came up. At the risk of getting too much into politics, there used to be a Hydrologic Frequency Working Group (HFWG) and numerous other water-related committees related to sediment and water quality that brought together multiple agencies, people from academia, and others to wrestle with these issues. That’s how Bulletin 17C came about. In late 2019, HFWG and other water-related committees were disbanded because there was a sense in the federal government that there were there were too many of these federal committees taking up too many resources. I don't disagree with the idea that some of these things need to be re-examined every once in a while, to see if they are still serving a purpose. But I would like to see something like that come back. We need a Bulletin 17D and there needs to be some type of umbrella organization organizing the effort.

Question (to Panel):
Shouldn't one get the latest and greatest conditions to ensure basin characteristics are properly calibrated? For example, with the potential debris flow, would one try to ascertain the geomorphological changes from https://landslides.usgs.gov/hazards/postfire_debrisflow/. And how do you project forward on these types of wildfire/ debris flows/ sediment erosion changes? Particularly for geomorphological changes, could you use paleo to get a handle on to project forward?

Karen Ryberg:
A lot of this would depend on the setting. If you're in a riverine system that's scoured down to the bedrock and has been for a very long time, paleo could be very useful. If it's a dynamic system that's undergoing a lot of change, incorporating paleoflood data, and historical peaks, brings up a lot of questions and maybe it's not appropriate for trying to determine future conditions. Again, it really varies with the setting.

3.5 Day 2: Session 2B – Coastal Flooding

Session Chair: Meredith Carr, USACE/ERDC/CHL

3.5.1 Presentation 2B-1 (KEYNOTE): A Risk Analysis Framework for Tropical Cyclones (RAFT)

Authors: Karthik Balaguru, Wenwei Xu, David Judi, Lai-Yung (Ruby) Leung, Pacific Northwest National Laboratory

Speaker: Karthik Balaguru

3.5.1.1 Abstract

Tropical Cyclones (TCs) are the most destructive and persistent natural hazards in the global tropics and subtropics, including in the US. The impacts from a TC on the coastal region manifests in various forms, such as coastal storm surge, inland flooding, and damages from high winds. However, quantifying risks from TCs using observations is challenging, in part due to the short length of the record during the satellite era. To address this, we have developed a Risk Analysis Framework for Tropical Cyclones (RAFT) to model the physical behavior of TCs and their impacts on the nation's critical infrastructure. TC tracks are initially generated based on the 'beta-advection' method. Subsequently, a deep neural network approach is used to produce along-track intensities. Results reveal that the model well-reproduces the observed distribution of TC track locations, intensities and landfall probabilities. Next, a physics-based rainfall model is combined with TC tracks to produce precipitation at various TC locations. Further, the TC tracks are combined with storm surge, population, electric power, and infrastructure assessment models. Taken together, the RAFT is a unified framework to quantify the risk associated with TCs for the US East and Gulf coasts.

3.5.1.2 Presentation (ADAMS Accession No. ML21064A433)

Pacific Northwest
NATIONAL LABORATORY

A Risk Analysis Framework for Tropical Cyclones (RAFT)

NRC PFHA Annual Workshop,
Feb 23rd 2021

Karthik Balaguru
Wenwei Xu
L. Ruby Leung
David R. Judi

U.S. DEPARTMENT OF ENERGY BATTELLE

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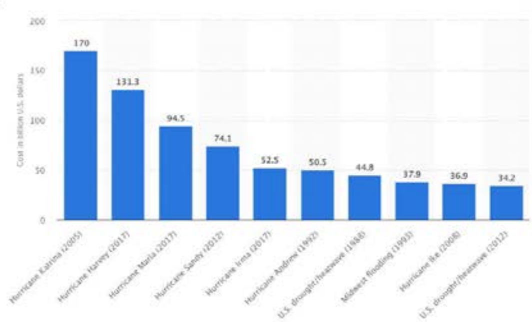
Quantifying the risk from Tropical Cyclones

- Tropical Cyclones (TCs) or hurricanes are the deadliest and costliest natural disasters, including in the US.
- On average, 1-2 hurricanes make landfall over continental US each year, the number of historical landfall events during the satellite era is not sufficient to derive probabilistic hurricane risk.
- Using high-resolution dynamical models is computationally expensive.
- To address this, we are developing a Risk Analysis Framework for Tropical Cyclones (RAFT)

Costliest natural disasters in the US



Source: statista

Top 5, 7 in top 10 are hurricanes

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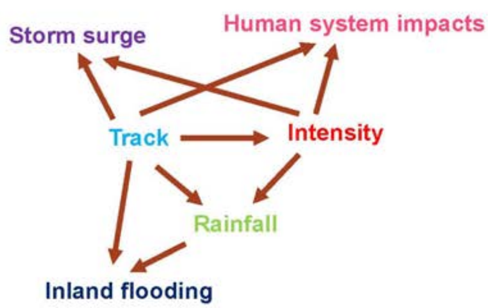
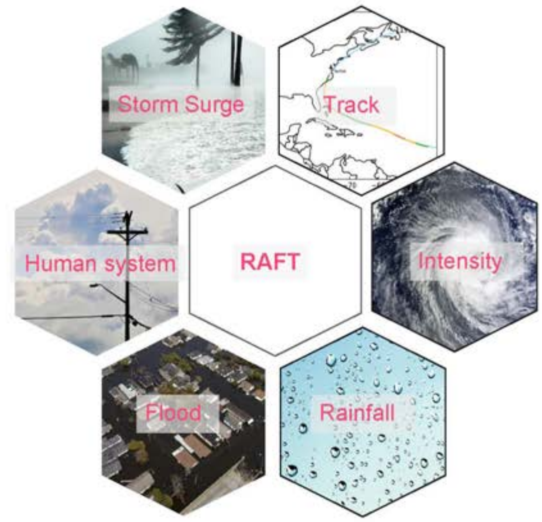
RAFT: A Risk Analysis Framework for Tropical Cyclones





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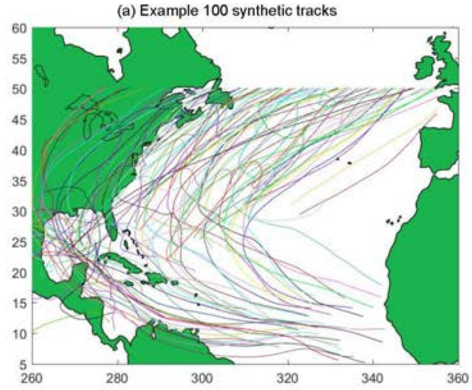
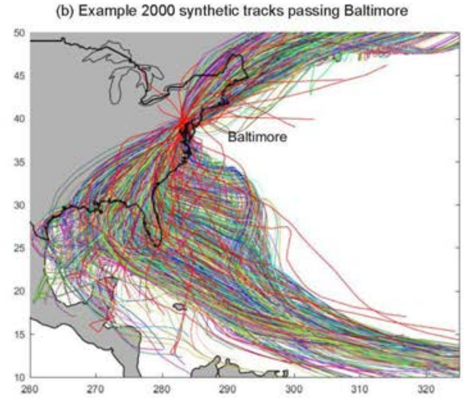
Physics-based synthetic TC Track Model

- Tracks propagate according to large scale wind and a beta-drift (Emanuel et al. 2006)
- Modified the method to use a spatially varying beta-drift, improved the model's ability to represent TC landfall (Kelly et al. 2018)

(a) Example 100 synthetic tracks



(b) Example 2000 synthetic tracks passing Baltimore



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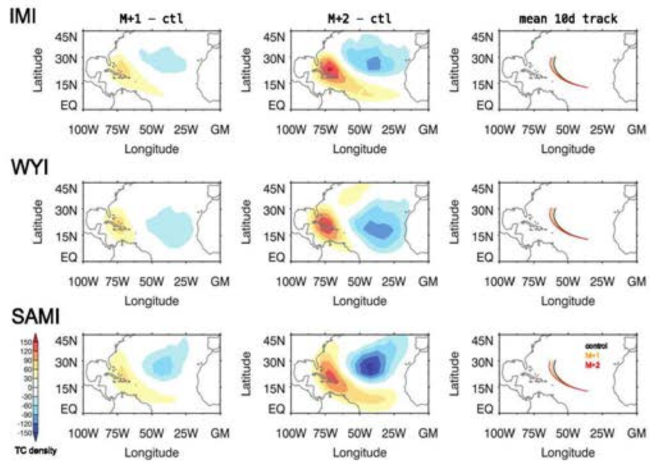
Track model application

- Kelly et al. GRL, 2018
- Realistic track shift with stronger Indian Monsoon
  - Strong Indian Monsoon -> Stronger Subtropical High -> More landfalling hurricanes
- Track shift generated with 7,000 TCs seeded in MDR



Track model TC density difference for experiment minus control where experiment is +1 (left column) and +2 (middle column) standard deviation of the indicated monsoon index (rows) and mean 10-day track for the control and monsoon perturbation experiments (right column).

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Neural Network based Intensity Model

- Xu et al. *WAF (under review)*
- Multilayer Perceptron Model (MLP) with automated architecture and hyperparameter search
- Trained using global Statistical Hurricane Intensity Prediction Scheme (SHIPS) predictors from 1982–2018
- Two versions:
  - 24-hour model for operational forecast, which consistently outperformed SHIPS, DSHP, and LGEM
  - 6-hourly model for climate studies (with 9 environmental variables as inputs)

24-hour MLP model evaluated in the North Atlantic basin

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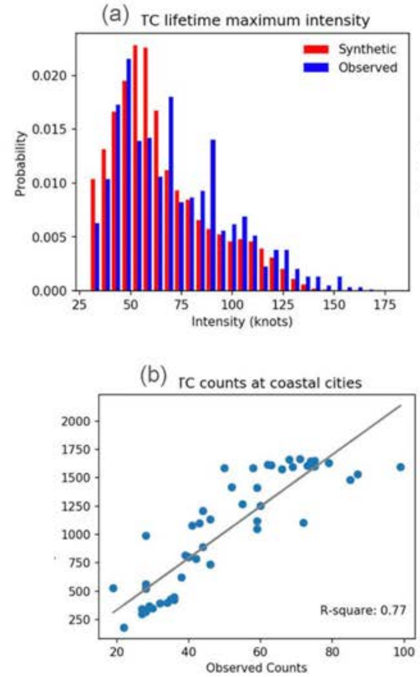
Coupling track model with 6-hourly intensity model

- Generated realistic intensities along synthetic tracks
- Reasonable TC lifetime maximum intensity distribution (a), the most intense synthetic event reaches Category 5 strength.
- The landfall probability based on synthetic TCs for 51 selected US coastal cities is well-correlated with the observed (b).



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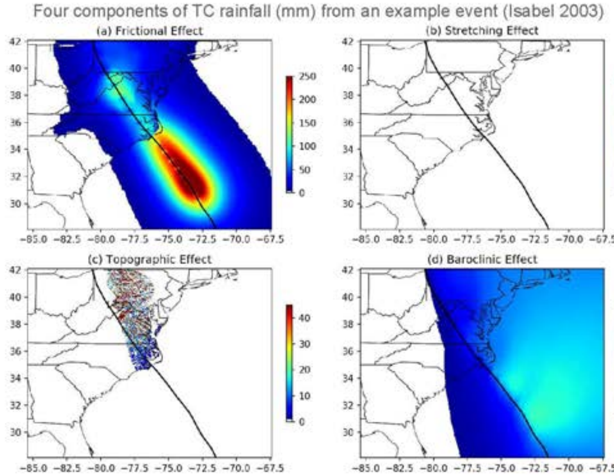
TC rainfall model

- Physics-based TC rainfall model (Zhu et al. GRL, 2013; Lu et al. JAS, 2018)
- TC rainfall is proportional to the upward vapor flux, estimated as the product of saturation specific humidity and the vertical velocity.
- The vertical velocity has 4 components to it
  a) Frictional effect
  b) Stretching effect
  c) Topographic effect
  d) Baroclinic effect

Four components of TC rainfall (mm) from an example event (Isabel 2003)



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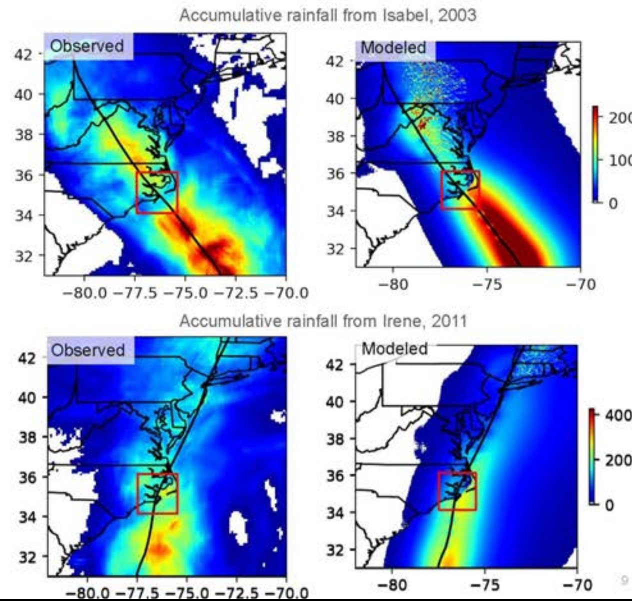
Reproducing historical TC rainfall events

- Model inputs: Track, intensity, RMW, wind shear, topography, and saturation specific humidity
- Wind profiles are generated from Holland (2010)
- Grid resolution: 0.04 x 0.04 degree, 6-houly
- Observed rainfall from IMERG since June 2000
- Model generates realistic accumulative rainfall compared to observation



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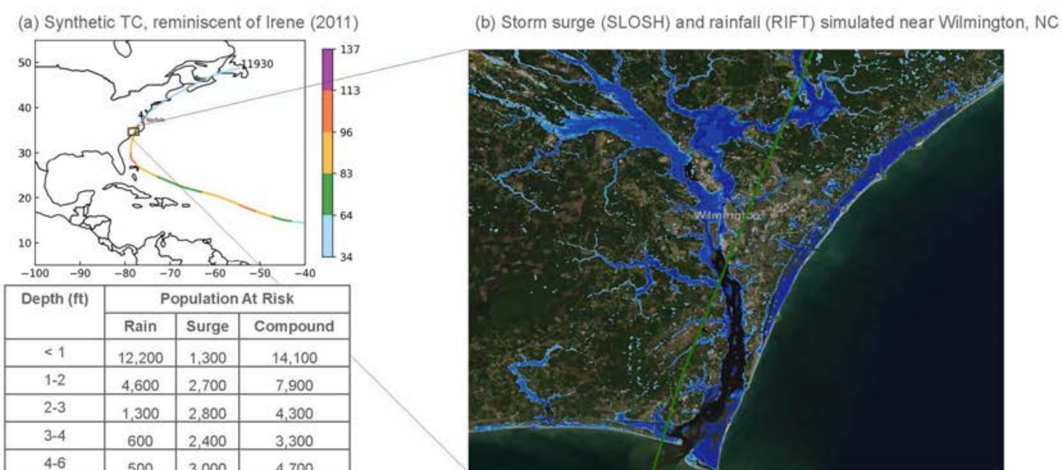
Compound Flood Simulation Example



Depth (ft)	Population At Risk		
	Rain	Surge	Compound
< 1	12,200	1,300	14,100
1-2	4,600	2,700	7,900
2-3	1,300	2,800	4,300
3-4	600	2,400	3,300
4-6	500	3,000	4,700
6-8	300	1,400	2,000
8-12	200	400	400
Total	19,700	14,000	36,700

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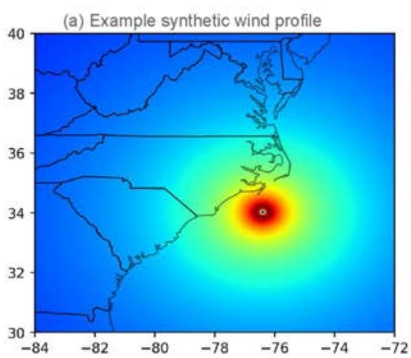
Individual components of flooding

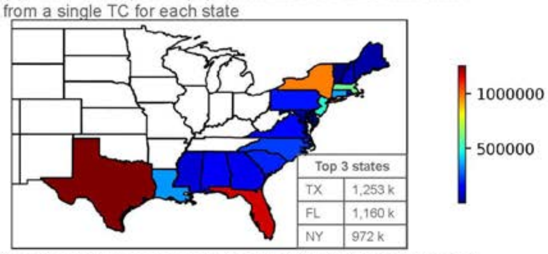
Storm Surge + Rainfall = Compound

Human systems impact – Wind hazard

- Analytical wind field: Holland (2010)
- GIS based analysis on wind hazard impact.
- Wind hazard risk map generated from 50,000 synthetic TCs (b and c). 58 knots: threshold of power line destruction from wind.



(b) The mean expected population under 58-knot wind band from a single TC for each state



(c) The worst-case-scenario of population under 58-knot wind band from a single TC for each state

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Summary

- The RAFT, a framework to quantify risk associated with TCs.
- The framework can realistically represent TC tracks, along-track intensities and rainfall.
- The framework can be used to ascertain storm surge, inland flooding and their net effect (compound flooding).
- Human system impacts can also be derived, such as risk for electric power disruption.
- RAFT can also be applied to climate model output to determine the impact of climate change on TC characteristics and environment, and consequently the risk associated with them.

New Orleans after Katrina, 2005

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Thank you!

Contact: ***Karthik.Balaguru@pnnl.gov***

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3.5.1.3 Questions and Answers

Question:
How are SLOSH and RAFT combined? Is the over land flow from SLOSH simply added to the pluvial depth from RAFT or does RAFT do both riverine discharge and pluvial flooding?

Karthik Balagru:
For now, we simply adding it as a pluvial depth, like an initial condition. It is not evolving in time. We take the maximum extent of the storm surge from SLOSH and prescribe it. The only thing that is evolving in time is the hurricane rainfall. But we do have plans to consider making the storm surge as something that evolves with time along with the hurricane.

Question:
You said you used SHIPS for your training set. How many storms were in that training set?

Karthik Balagru:
On an average you have approximately 80 storms globally per year. The period we have used for training is 1982 to 2017, close to 35 years. So that would mean anywhere between 2500 to 3000 storms.

3.5.2 Presentation 2B-2: Storm Surge Model Uncertainty

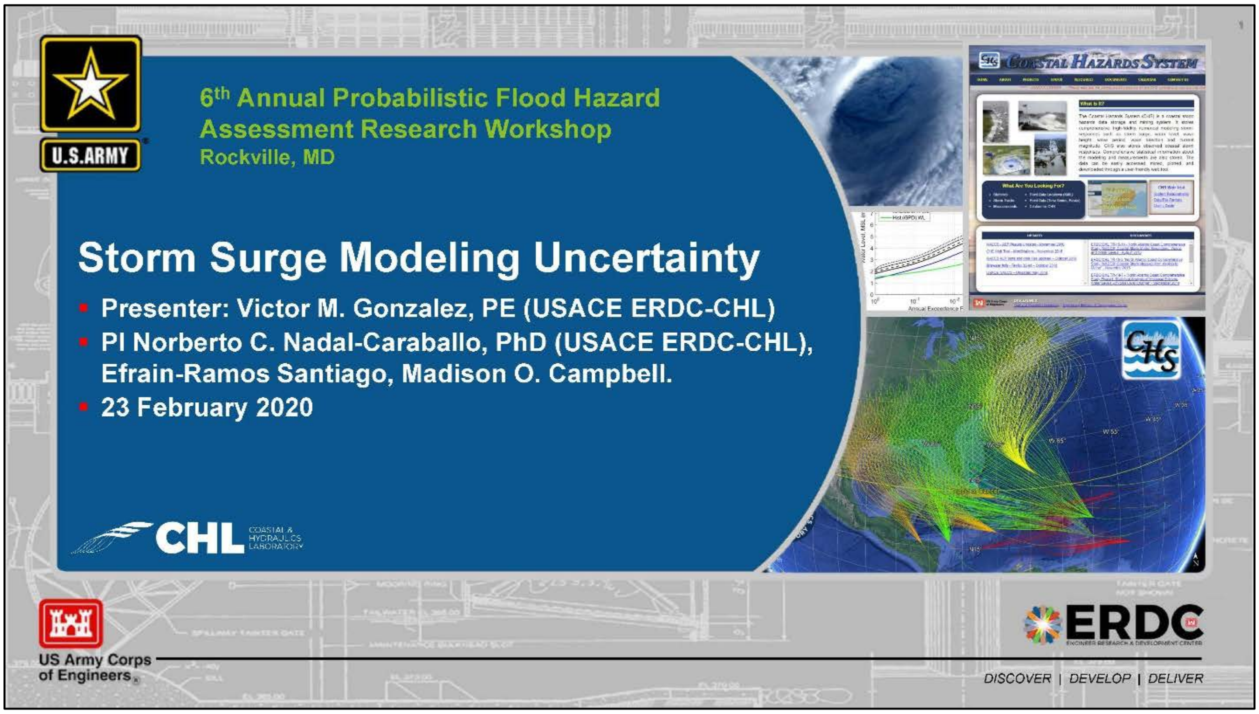
Authors: Victor M. Gonzalez and Norberto C. Nadal-Caraballo, U.S. Army Corps of Engineers, Engineer Research & Development Center, Coastal and Hydraulics Laboratory (USACE/ERDC/CHL)

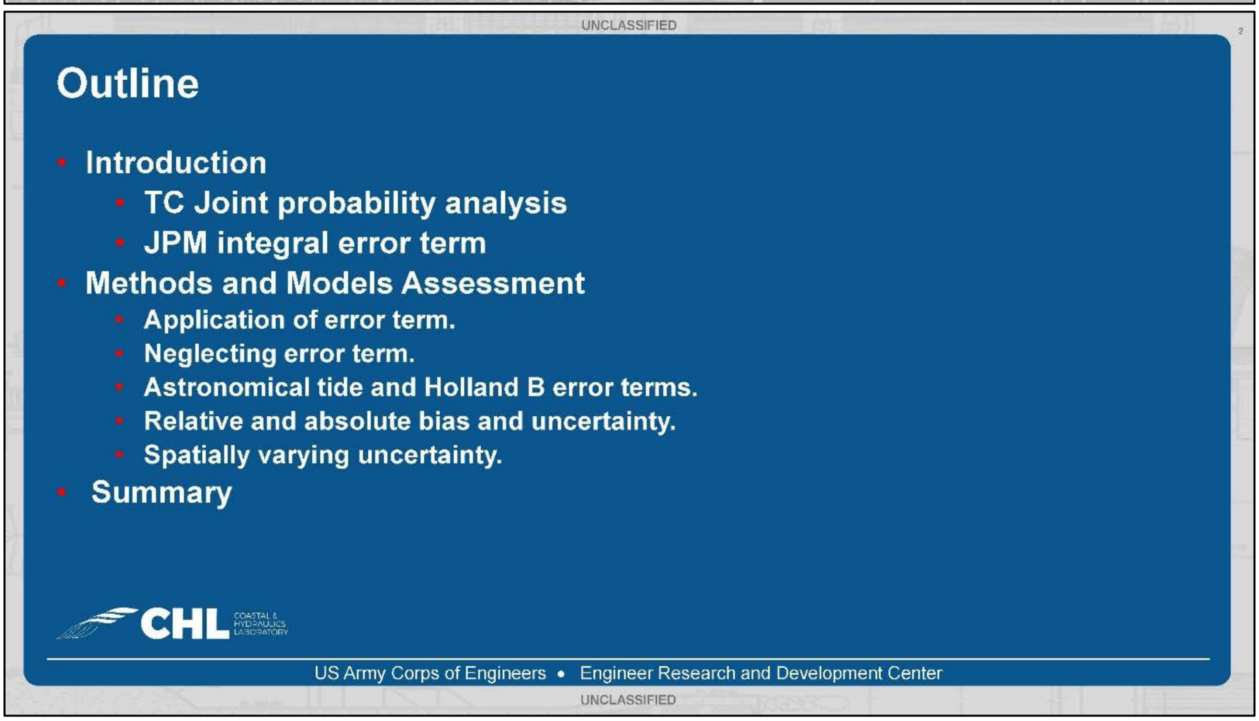
Speaker: Victor M. Gonzalez

3.5.2.1 Abstract

Quantification of coastal hazards is probabilistic in nature and as such requires estimating uncertainties associated with the data, models, and methods used. Specifically, these approaches require an understanding of the sources of errors related to the numerical modeling of meteorological and hydrodynamic processes and the simplifications in the conceptualization of the elements that drive the hazards. The uncertainty associated with the ability of models and data to represent real systems is typically considered by comparing model performance with historical measurements through metrics such as bias and standard deviation or spread of errors. Quantification of uncertainty in areas impacted by tropical cyclones requires the development of a joint probability model of tropical cyclone (TC) atmospheric parameters. In this case, uncertainty quantification needs to account for the reduced dimensionality in the representation of TCs and the uncertainty is treated as an error term either added in the hazard integration process central to the Joint Probability Method (JPM) used for quantifying TC hazard or conveyed through confidence intervals. Specific errors quantified include modeling errors, variations in the TC wind and pressure fields and, where applicable, astronomical tide. Numerical experiments were performed to investigate how approaches for quantifying and incorporating the error term affects storm surge estimates and associated uncertainties. Topics include methods for distributing the error term in the JPM integral, and approaches used for estimating errors and characterizing uncertainty. This investigation was performed as part of USNRC-sponsored study “Quantification of Uncertainties in Probabilistic Storm Surge Models”.

3.5.2.2 Presentation (ADAMS Accession No. ML21064A434)





Introduction

- Main objective: evaluate sources of aleatory and epistemic uncertainty in probabilistic modeling of numerical surge simulation errors.
- Work conducted as part of "Quantification of Uncertainties in Probabilistic Storm Surge Models" study within U.S. NRC's Probabilistic Flood Hazard Assessment (PFHA) research plan.
- General approach
  - Develop hazard curves with uncertainty represented through confidence limit curves.
  - Epistemic uncertainty obtained through the evaluation of alternate data, models, and methods used in probabilistic storm surge models.
  - Consider AEPs that go beyond traditional state-of-practice for non-nuclear facilities (e.g., 10^{-4} to 10^{-6}).

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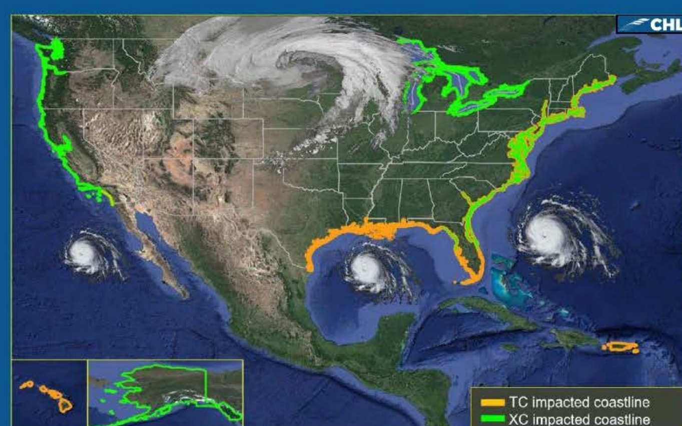
Probabilistic storm surge modeling

- Approach for quantification of coastal storm hazards (e.g. surge) dependent on type of cyclonic exposure.
  - Tropical cyclones (TC).
  - Extratropical cyclones (XC).
- Probabilistic coastal hazard analysis for hurricane exposed coastlines requires → Joint probability analysis of TC forcing parameters.
  - Development of synthetic TCs through sampling joint distribution of TC parameters.
  - Atmospheric modeling of TCs wind and pressure fields and hydrodynamic modeling of water levels and waves.



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Focus: Probabilistic storm surge modeling uncertainty

US Army Corps of Engineers • Engineer Research and Development Center
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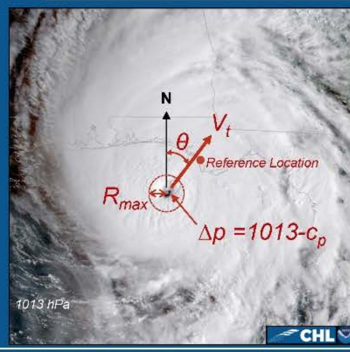
TCs JPA approach

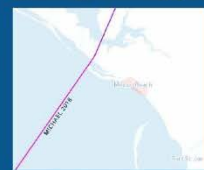
- Why JPA approach with synthetic storms?
  - TC hazard is spatially and temporally underrepresented in historical record.
- Joint probability method (JPM) is the standard JPA model approach for TCs.
  - JPM-OS
  - USACE PCHA (Nadal-Caraballo et al. 2020).
- Standard TC Forcing Parameters.
  - Track 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.
- TCs with Michael's characteristics can be represented within JPM probability space.

Mexico Beach, Florida

From 1842-2017 (176 years):
19 hurricanes within 50 km radius
- **Only three category 3.**

2018:
Hurricane Michael
- **Category 5 at landfall**
- **Measured storm tide 15.5 ft, HWMs ~ 19 ft (USGS).**





NOAA Historical Tracks https://coast.noaa.gov/hurricanes

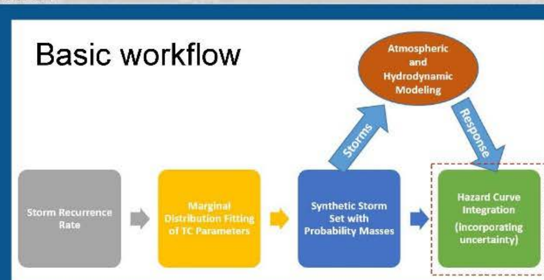
Joint probability method

JPM Integral

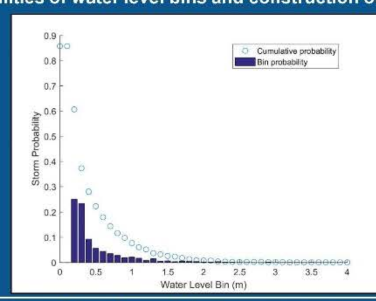
$$\lambda_{r(\hat{x})>R} = \lambda \int P[r(\hat{x}) + \varepsilon > r|\hat{x}, \varepsilon] f_{\hat{x}}(\hat{x}) f_{\varepsilon}(\varepsilon) d\hat{x} d\varepsilon$$

$$\approx \sum_i^n \lambda_i P[r(\hat{x}) + \varepsilon > r|\hat{x}, \varepsilon]$$

where:
$\lambda_{r(\hat{x})>R}$ = AEF of TC response R due to forcing vector $\hat{x}$
$\hat{x} = f(x_o, \theta, \Delta p, R_{max}, V_t)$
λ = SRR (storms/yr/km)
$\hat{\lambda}_i$ = probability mass (storms/yr) or λp_i, with p_i=product of discrete probability and TC track spacing (km)
$P[r(\hat{x}) + \varepsilon > r|\hat{x}, \varepsilon]$ conditional probability that storm i with parameters $\hat{x}_i$ generates a response larger than r
ε = unbiased error or aleatory uncertainty of r



Probabilities of water level bins and construction of AEF curve.



The error term "ε"

- Error term components
  - Hydrodynamic modeling errors.
    - Unresolved physical processes.
    - Inadequate resolution/topo bathy errors.
  - Meteorological modeling errors.
    - Simplified wind and pressure fields representation.
  - Holland B.
  - Tide (Gulf coast)
- Assumption of normality and application of central limit theorem.
  - Combined error represented as a Gaussian distribution with mean zero.
  - Errors are unbiased → If present, correct bias.
  - Standard deviation of error, σ_ε, represents uncertainty.

Total bias from summation of individual biases

$$\mu_\varepsilon = \mu_{\varepsilon 1} + \mu_{\varepsilon 2} + \cdots + \mu_{\varepsilon n}$$

where μ_ε = bias (mean of the error).

Total uncertainty

$$\sigma_\varepsilon = \sqrt{\sigma_{\varepsilon 1}^2 + \sigma_{\varepsilon 2}^2 + \cdots + \sigma_{\varepsilon i}^2}$$

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Methods and Models Assessment

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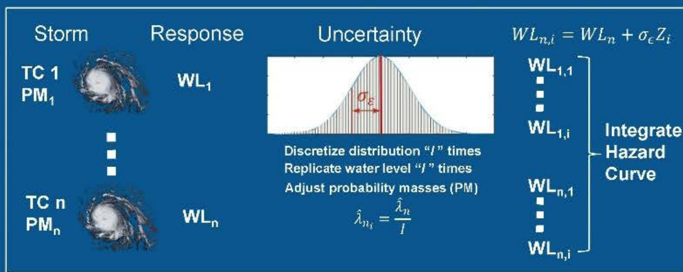
Application of the error term "ε"

- Distribution of error inside JPM integral (e.g. FEMA)



- Uncertainty allocation between integral and confidence limits).

$$\sigma_\varepsilon = \sqrt{\sigma_{int}^2 + \sigma_{CL}^2}$$

Confident Limit, CL:
$$CL = WL + Z * WL * \sigma_{CL}$$

- Completely within confidence limits.
  - Requires a very large number of storms for proper characterization of mean hazard curve.
  - No smoothing required.
  - Applied in USACE PCHA using augmented storm suite developed with surrogate modeling (Nadal-Caraballo et al. 2020)

Main limitations
- Inside integral – No confidence limits
- Inside Integral and confidence limit – No consensus allocation.
- Confidence limits only – requires thousands of storms.

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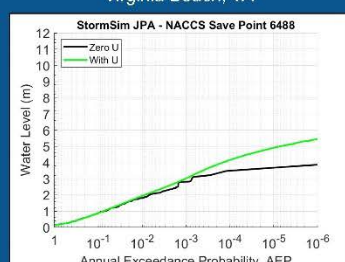
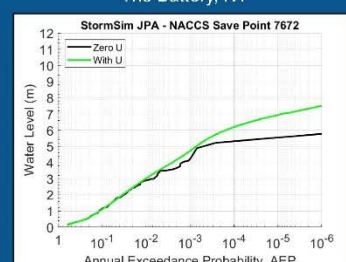
Neglecting the error term

- What are the effects of the non-inclusion of the error term in the integral?
- Underestimation of the hazard.
  - Hazard curves start diverging within the 10^{-2} to 10^{-3} AEP range.
  - Underestimation of 20-30% for 10^{-6} AEP (range of interest to Nuclear Power Plants)
- No smoothing effect in the hazard curve.

Virginia Beach, VA



The Battery, NY



Location	Error Term	AEP – Water Levels (m)					
		1X10-2	0.2X10-3	1X10-3	1X10-4	1X10-5	1X10-6
The Battery, NY	Without	1.81	2.37	2.81	3.50	3.68	3.87
	With	1.94	2.67	3.02	4.16	4.91	5.46
	Difference (%)	-6.46	-10.91	-6.89	-15.86	-25.04	-29.16
Virginia Beach, VA	Without	2.88	3.66	4.21	5.31	5.54	5.77
	With	3.01	4.17	4.71	6.18	6.93	7.50
	Difference (%)	-4.23	-12.23	-10.66	-14.08	-20.08	-23.10

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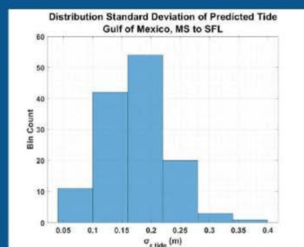
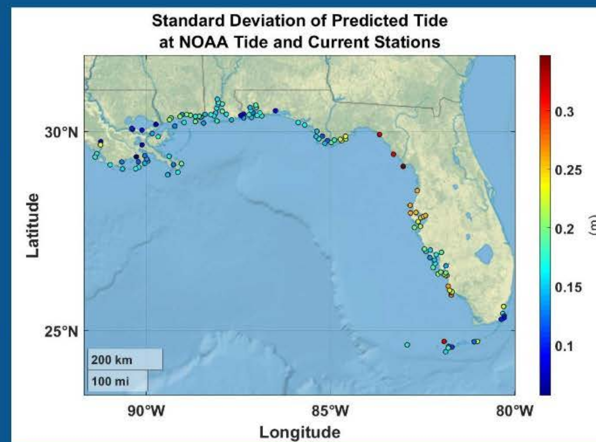
Astronomical tide as secondary TC parameter.

- Treated as secondary TC parameter at locations with small tidal range.
- Incorporated statistically within the error term of the JPM equation ($\sigma_{\epsilon tide}$).
- Computed from tide gage data as the deviation from a random tide phase and the zero tide level.





Median SD = 0.17 m
90% Percentile SD = 0.25 m
10% Percentile SD = 0.11 m

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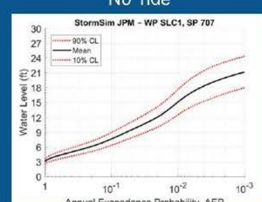
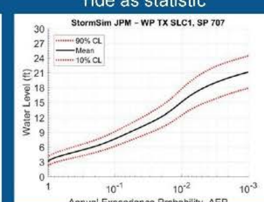
Astronomical tide as secondary TC parameter (cont.)

- Adequacy of incorporating tide as an error term.
- Assessment by Melby et al. (2020) for the Texas Gulf coast.
  - Used synthetic TC and modeling data from Texas Coastal Study (Nadal-Caraballo et al. 2018).
  - Tidal statistics obtained from a 5 year sample from NOAA tide and currents station 877570 Sabine Pass North.
- Compared still water levels hazard curves using three methods:
  - No tide.
  - Tide as a statistic (secondary JPM parameter).
  - Historical tides sampled using Monte Carlo Simulation using linear superposition.
- Tides can be included as statistic.

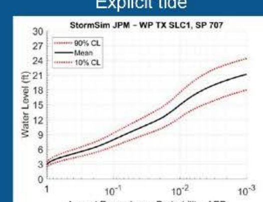
No Tide



Tide as statistic



Explicit tide



No significant impacts on results

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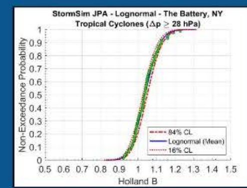
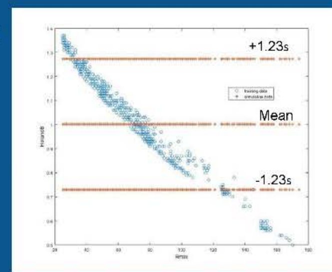
Holland B

- Synthetic TCs wind radial profiles are defined by Holland B parameter (Holland 1980).
- The error term accounts for the variation of Holland B with respect to the values modeled in the synthetic TCs.
- Approaches for incorporating Holland B.
  - As secondary parameter.
    - Uniform Holland B values for all TCs with three along track variations used with respect to landfall.
    - Consideration of Holland B variation using statistical models of the parameter (e.g. Vickery and Wadhera 2008). Holland B is computed individually for each storm.
  - As primary JPM parameter (error term set to zero), estimated with statistical model.
    - Considerations:
      - Additional parameter discretization increases computational burden.
      - High correlation to R_{max} might limit information gained.
- Holland B might not provide significant additional information. It's an empirical function of Δp, R_{max} *and location.*



Lognormal marginal distribution fit of Holland B



Three discretizations of Holland B

Holland B. Estimated, highly correlated to other parameters, specially R_{max}

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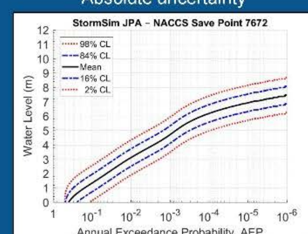
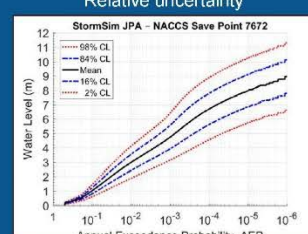
Model bias and uncertainty

- Quantification of model errors are necessary for calibration and validation of model performance.
- Two main components of error relate to accuracy and precision.
  - Systematic error (bias) – mean of the error.
  - Spread (uncertainty) – standard deviation of the error.
- Quantified by comparing model performance with measurements.
- Computed based on high water marks and gage readings.
- Two types can be computed:
  - Absolute bias and uncertainty (dimensional).
  - Relative bias and uncertainty (non-dimensional).
- Issues related to the application of these types of uncertainties.
  - Absolute: for small surge values, the uncertainty could be the same order of magnitude as the surge.
  - Relative: if computation based on small measured values, it could result in unrealistic errors for large values of surge.

Absolute uncertainty



Relative uncertainty



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Combination of absolute and relative uncertainty

- **Alternatives for combining uncertainty**
  - **Use absolute uncertainty to constrain the relative uncertainty.**

$$\sigma_{constrained} = Z \times \min\{ WL * \sigma_{rel}, \sigma_{abs}\}$$

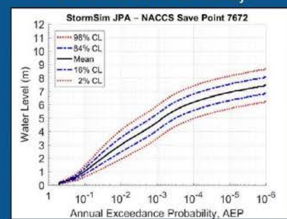
  - **Combine through the use of weighting factor (w).**

$$\sigma_w = w * Z * \sigma_{abs} + (1 - w) * Z * WL * \sigma_{rel}$$

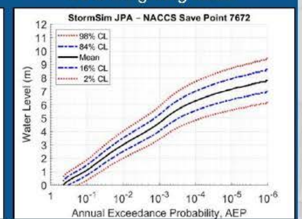
  - **Combination approach based on data assimilation error statistic described in Gao et al. (2012).**

$$c = \frac{1}{\sqrt{\frac{1}{a^2}+\frac{1}{r^2}}};$$ where c =combined uncertainty, a=absolute uncertainty r =relative uncertainty

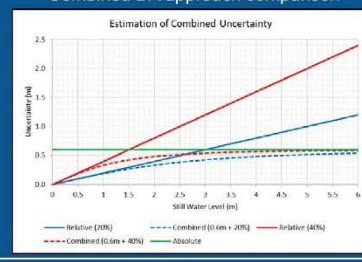
Constrained uncertainty



50% weighting factor



Combined DA approach comparison



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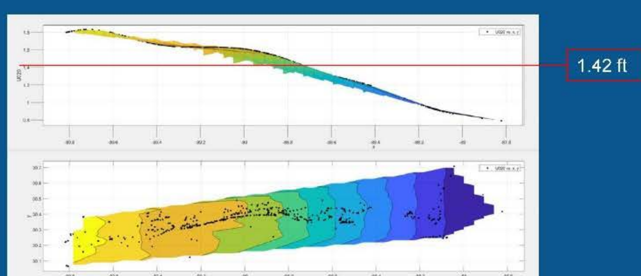
Spatially-varying modeling error

Modeling error: has a direct effect on hazard curve shape and confidence limits.

- **Gaussian kernel surface (GKS) approach**
- **Global uncertainty: 1.42 ft.**
- **Spatially varying uncertainty:**



Method applies Gaussian kernel function (GKF) to obtain distance adjusted weights at a water level measurement location with respect to other water level measurements locations.

$$w(d_i) = \frac{1}{\sqrt{2\pi}h_d} exp\left[-\frac{1}{2}\left(\frac{d_i}{h_d}\right)^2\right]$$

where $w(d_i)$ = distance-adjusted weights from the Gaussian probability density function (PDF); d_i = distance from location of interest to other measurement location points (kilometers); h_d = optimal kernel size (kilometers).

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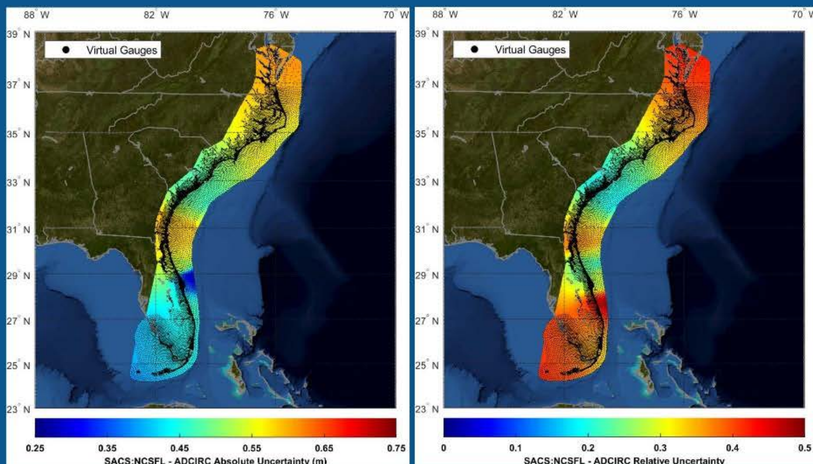
Spatially-Varying relative and absolute uncertainty

- South Atlantic Coastal Study Example (Nadal-Caraballo et al. 2021)



Numerical Model	Average Uncertainty	
	Absolute (m)	Relative
ADCIRC	0.4998	0.3119
PBL	0.2027	0.2683
Total (ADCIRC & PBL)	0.5420	0.4148
Numerical Model	Absolute (m)	Relative
STWAVE (H_{mo})	1.512	0.3126

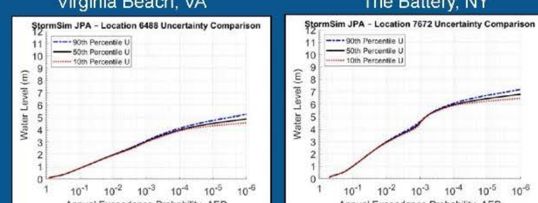
Impact of spatial variation of model error

- Spatially-varying hydrodynamic model uncertainty was computed for the North Atlantic Coast Comprehensive Study.
- Effect on hazard tested by comparing 10th 50th and 90th percentile errors.
- Combined uncertainty using constrained approach.
- The difference between 10th and 90th percentile uncertainty values small.
- Impact observed at very low AEPs.

Select statistics for spatially varying model uncertainty

Statistic	Uncertainty (m)	Relative Uncertainty
Mean	0.36	0.16
Median	0.34	0.16
90th percentile	0.50	0.19
10th percentile	0.24	0.13

Virginia Beach, VA — The Battery, NY



Location	Applied uncertainty statistics	AEP – Water Levels (m)					
		1X10⁻²	0.2X10⁻²	1X10⁻³	1X10⁻⁴	1X10⁻⁵	1X10⁻⁶
The Battery, NY	90th	2.99	4.06	4.61	6.07	6.72	7.19
	Median	2.96	3.93	4.53	5.95	6.45	6.81
	10th	2.91	3.84	4.45	5.89	6.25	6.48
	Difference (%)	2.8	5.5	3.5	3.0	7.3	10.5
Virginia Beach, VA	90th	1.96	2.70	3.06	4.00	4.53	4.89
	Median	1.96	2.70	3.06	4.00	4.53	4.89
	10th	1.94	2.63	3.01	3.93	4.34	4.58
	Difference (%)	0.7	2.5	1.6	1.6	4.3	6.3

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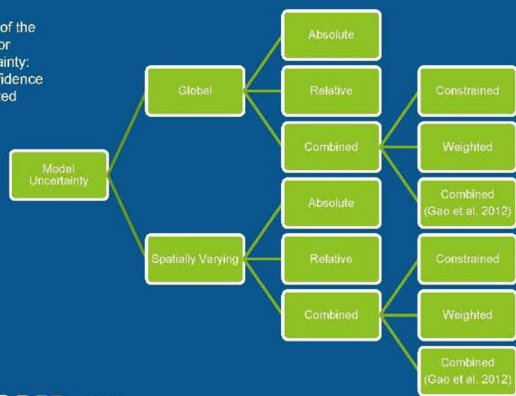
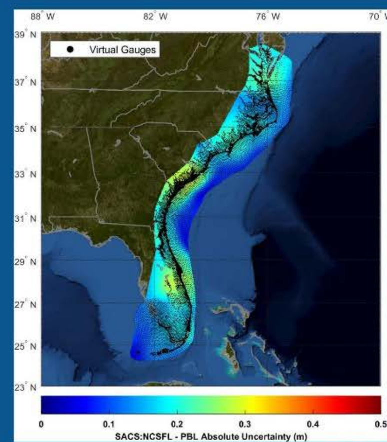
Probabilistic surge modeling uncertainty branches

- Multiple paths can be used to compute meteorological and hydrodynamic modeling uncertainty.

Applies to each of the three methods for applying uncertainty: To integral, confidence limit, and allocated between both.





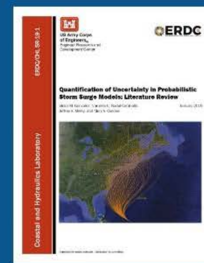
(Nadal-Caraballo et al. 2021)

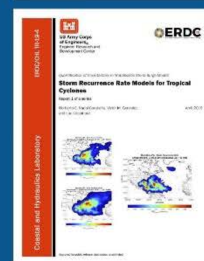
Summary

- Several approaches for characterizing and modeling of errors storm surge modeling were evaluated.
- Aleatory uncertainty in probabilistic storm surge modeling accounted for in "error" term of JPM integral.
- Epistemic uncertainty can be characterized from the consideration of these approaches:
  - Manner of incorporating uncertainty in JPM integral.
  - Characterization of bias and uncertainty.
  - Consideration or not of spatially-varying uncertainty.
- Use of absolute and relative uncertainties, as well methods for combining them, have a significant impact on the computed hazard.
- Availability of measured water level data has a significant impact on the quantification of the numerical modeling bias uncertainty. Historic measurement data is typically limited in terms of quantity and quality.
- Spatially-varying bias and uncertainty has an effect in the quantification of the hazard compared with use of global uncertainty, in particular for smaller AEPs.

Reports

- Gonzalez V.M., N.C. Nadal-Caraballo, J.A. Melby, and M.A. Cialone. 2019. *Quantification of Uncertainty in Probabilistic Storm Surge Models: Literature Review*. ERDC/CHL SR-19-1.
- Nadal-Caraballo, N.C., V.M. Gonzalez, and L. Chouinard. 2019. *Quantification of Uncertainties in Probabilistic Storm Surge Models: Storm Recurrence Rate Models for Tropical Cyclones*, ERDC-CHL TR-19-4. Vicksburg, MS: U.S. Army Engineer Research and Development Center.
- Nadal-Caraballo, N.C., V.M. Gonzalez, E. Ramos-Santiago, and M.O. Campbell. *Data, Models, and Methods for Defining Joint Probability of Storm Parameters and Generating Synthetic Storm Simulation Sets*. ERDC/CHL TR-20-X (In Review)





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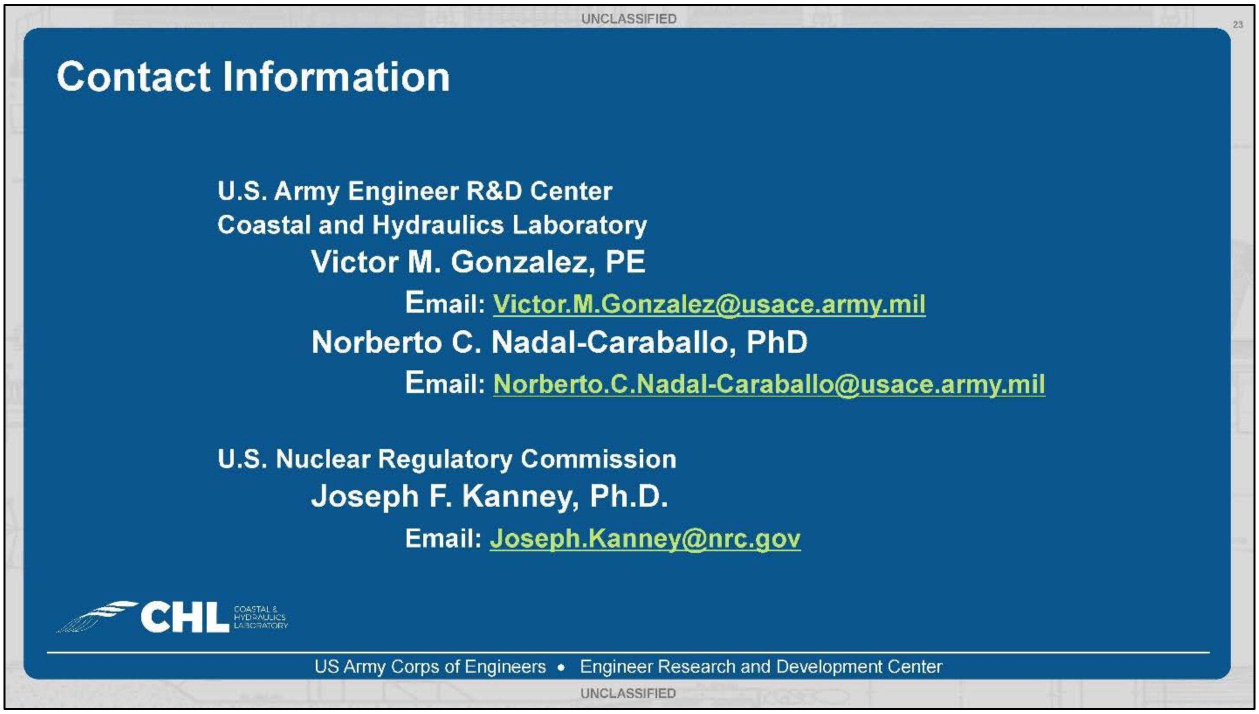

3.5.2.3 Questions and Answers

Question:
You talked about some uncertainties that could be substantial. Do you have approaches you're looking into to reduce those uncertainties? Such as the Holland B issue?

Victor Gonzalez:
Yes, but I think the main thing to do is to make sure that it is quantified. In the general approach we're using for the study, which is using logic trees to capture that epistemic uncertainty, it's important that the uncertainty is captured. In terms of reducing uncertainty, I think one of the most important issues is just the availability of high-water marks, and other data to be able to quantify the modelling uncertainty.

Question:
How can you consider situations such as changes in the shoreline caused by Hurricane Katrina?
Victor Gonzalez:
These types of studies are regional in nature. You do the hydrodynamic modeling for a wide area at high resolution. Typically, the intent is to have this [shoreline] data be used for a period of time and you can always update the statistics and probabilities associated with events with new historical data. If an event like Katrina occurs and you're interested in analyzing a particular area, you would have to incorporate the new bathymetry into the study. One of the things that can be done that lowers the effort is that you can optimize selection of storms using a design of experiments approach. Instead of having to use a full suite of storms which could be as large as 600-1000 storms, you can bring that down to 150 storms and be able to do the hydrodynamic modeling for just those storms. In this way, a particular problem such as the changes in the shoreline in a particular area due to a storm can be addressed.

Question:
Could you clarify what is the definition of “standard deviation of predicted tides”?

Victor Gonzalez:
That is just taking the predicted tide signal and then computing the standard deviation of that signal. We can use that as an uncertainty incorporated into the JPM integral.

3.5.3 Presentation 2B-3: Coastal Flooding PFHA Pilot Study

Authors: Karlie Wells, Victor M. Gonzalez, Norberto C. Nadal-Caraballo, U.S. Army Corps of Engineers, Engineer Research and Development Center, Coastal and Hydraulics Laboratory

Speaker: Karlie Wells

3.5.3.1 Abstract

Flooding hazards in coastal settings are produced by storm surge and waves. These are often exacerbated by excessive rainfall and associated runoff, including riverine flooding. Inundation due to these hazards can produce widespread damage to coastal infrastructure. Proper characterization of compound flooding hazards is necessary to fully address risk in a costal setting, especially for critical infrastructure such as nuclear power plants (NPPs). A coastal flooding probabilistic flood hazard assessment (PFHA) pilot study is being conducted to demonstrate the application of PFHA to external flooding at a hypothetical nuclear power plant (NPP). Consideration of factors such as model availability, watershed characteristics, and Nuclear Regulatory Commission (NRC) guidance for siting NPPs were used to select a site on the Lower Neches River watershed in Texas. Compound flooding hazards being assessed in this study include storm surge, astronomical tide, waves, rainfall, and coincident riverine flooding along with associated uncertainties. The assessment requires the characterization of storm climatology for tropical cyclones (TCs) using the U.S. Army Corps of Engineers' (USACE) Coastal Hazards System (CHS) and its Probabilistic Coastal Hazard Analysis (PCHA) framework, both developed by the Engineer Research and Development Center, Coastal and Hydraulics Laboratory (ERDC-CHL). Simulation of both coastal and riverine processes driven by TCs and extra-tropical cyclones (XCs) will be completed using hydrologic, hydraulic, and hydrodynamic models. Rainfall is generated for synthetic TCs using a physics-based parameterized tropical cyclone rainfall (TCR) model that estimates spatial rainfall along the storm track. The TCR model will be applied to a HEC-HMS model of the Neches River basin. A genetic algorithm-based Design of Experiments (DoE) approach is applied to subsample TCs from the 660 synthetic storms suite developed for the USACE Coastal Texas Study. The compound hazards will be quantified through the application of a loosely-coupled HEC-RAS and ADCIRC modeling framework.

3.5.3.2 Presentation (ML21064A435)

Coastal Flooding PFHA Pilot Study

- Presenter: Karlie Wells (USACE ERDC-CHL)
- PI: Victor Gonzalez, PE (USACE ERDC-CHL)
- Norberto C. Nadal Caraballo, PhD, Meredith L. Carr PhD, Madison O. Campbell, Efrain Ramos-Santiago;

Coastal and Hydraulics Laboratory

- Ning Lin, Dazhi Xi

Princeton University

23 February 2021

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Presentation Outline

- Project Objectives and Site Selection
  - Existing Site Information
- Compound Coastal-Inland PCHA Development
- Synthetic Tropical Cyclone Rainfall Assessment
  - Bias Correction
- Synthetic Tropical Cyclone (TC) Selection
- Next Steps

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Project Goals and Site Selection

- Goal: Develop compound flood hazard curves for a hypothetical nuclear power plant (NPP) located in a coastal setting
  - Use the Coastal Hazards System's (CHS) Probabilistic Coastal Hazard Analysis (PCHA) framework developed by ERDC-CHL
  - Extended to include precipitation-induced riverine flooding
- Leverage existing data and models characterizing the hydrology, hydraulics, and hydrodynamics of the region
- Primary region: Texas Coast
  - Available H&H data and models offered through SWG
  - CTXCS results through ERDC-CHL

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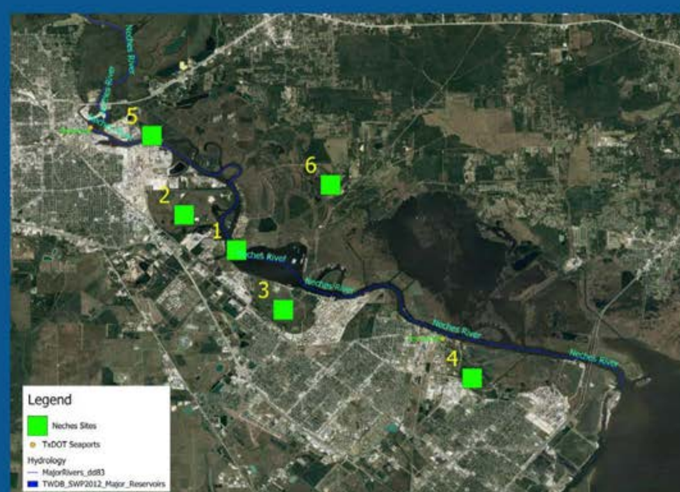
Lower Neches River

- Six potential locations identified
- Surge levels vary from
  - 1×10^{-2} AEP ~10 ft
  - 1×10^{-6} AEP: ~20 ft
- Developed area, industrial (petrochemical) and residential zones
- All locations affected by riverine and storm surge flooding
- All within HH model and hydrodynamic modeling domains



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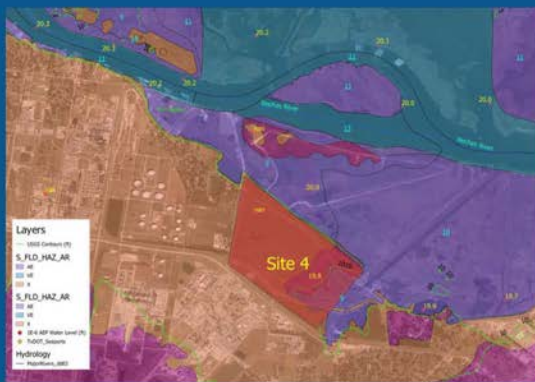
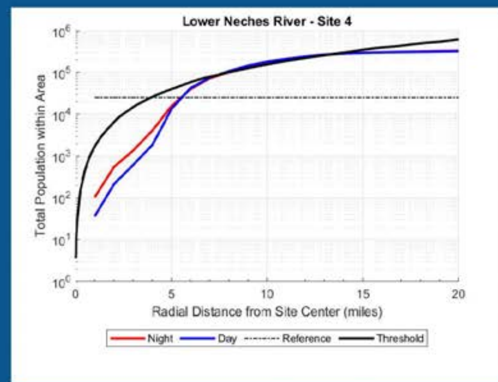
Lower Neches River – Site 4

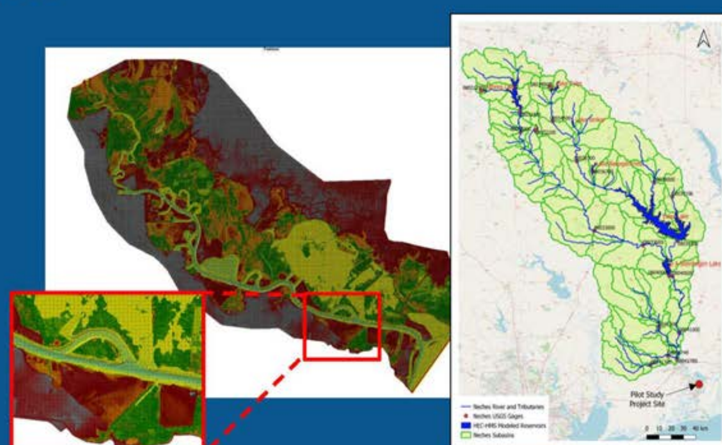




- **Characteristics:**
  - **Outside FEMA AE Zone**
  - **Location closest to Sabine Lake**

Existing Site Information

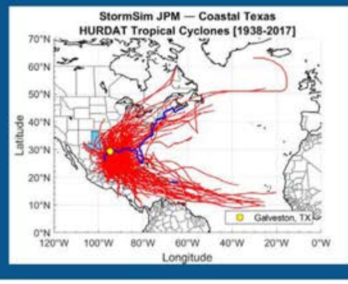
- **LiDAR Topography**
  - **70 cm resolution (SWG)**
- **2019: Fort Worth District completed the Lower Neches Riverine Flooding Analyses (LNRFA) (Mosser et al. 2019)**
  - **Evaluation of riverine flooding along both Sabine and Neches Rivers**
- **HEC-HMS and HEC-RAS models have been made available to ERDC-CHL through the SWG**

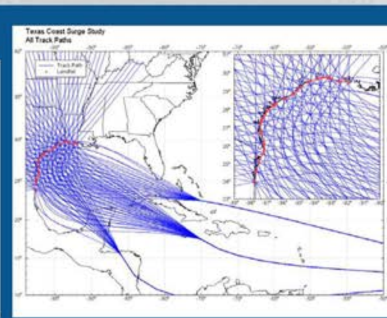


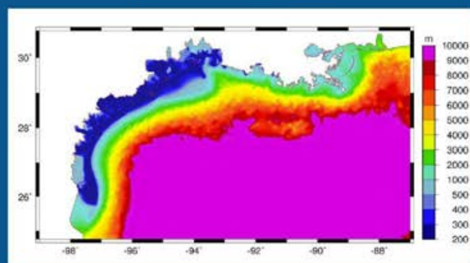
Coastal Texas Study

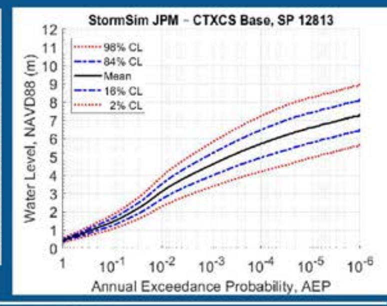
Storm response and statistical analysis for entire coastal Texas region

- Characterization of storm climate
- 660 unique storms
- High-fidelity storm surge and wave computations
  - 18,000 savepoints
- AEP and average recurrence interval









Compound PCHA Development

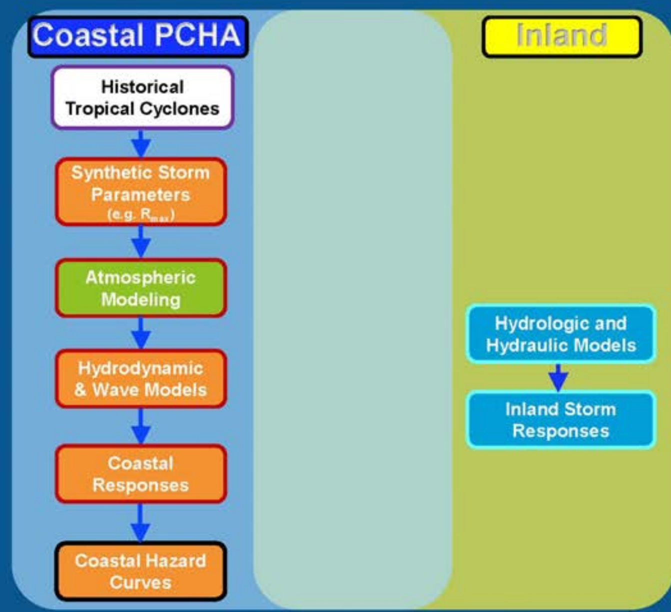
Compound PCHA

Existing Models & Data

- PCHA based on Coastal Texas results
  - Many elements not shown such as atmospheric parameter correlations, metamodel-augmented storm suite, storm probability masses, etc.
- ADCIRC and STWAVE models
- HEC-HMS & HEC-RAS inland models

Link by Joint Effects

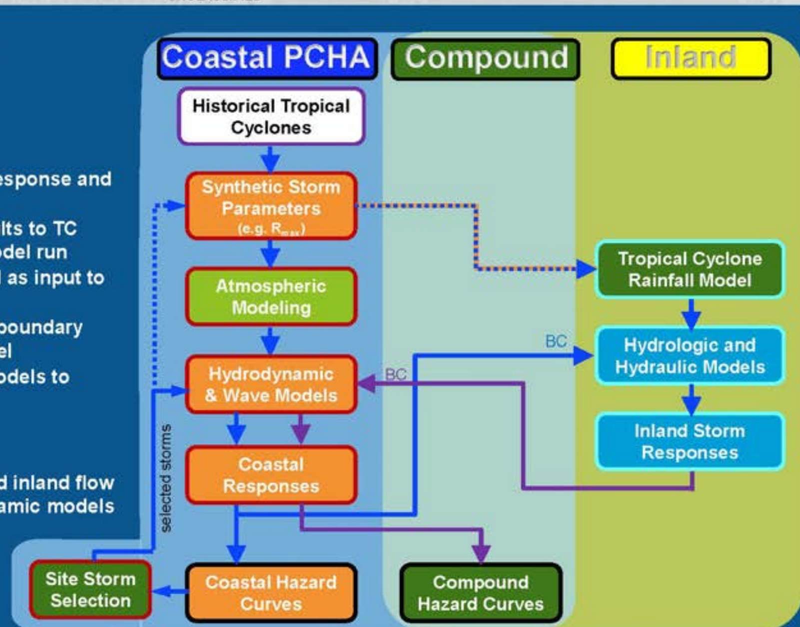
- Tropical Cyclone Rainfall (TRC) Model (Lu et al. 2018) using synthetic TC parameters
- Boundary conditions for inland hydraulic and coastal hydrodynamic models
- Synthetic TC selection for site



Compound PCHA

Loose Coupling under Review

- 1st Loop in BLUE
  - Step through PCHA to Coastal Response and Hazard Curves
  - Storm selection from PCHA Results to TC Rainfall Model and next surge model run
  - Synthetic storm parameters used as input to TC Rainfall Model
  - Coastal Response elevations as boundary condition (BC) for hydraulic model
  - Step through TC Rainfall, H&H Models to Inland Response
- 2nd Loop in PURPLE
  - From hydraulic model, distributed inland flow used as BC for coastal hydrodynamic models
  - Coastal responses:
    - Used to develop compound hazard curves (or):
    - Coupling can be repeated



Tropical Cyclone Rainfall (TCR) Analysis

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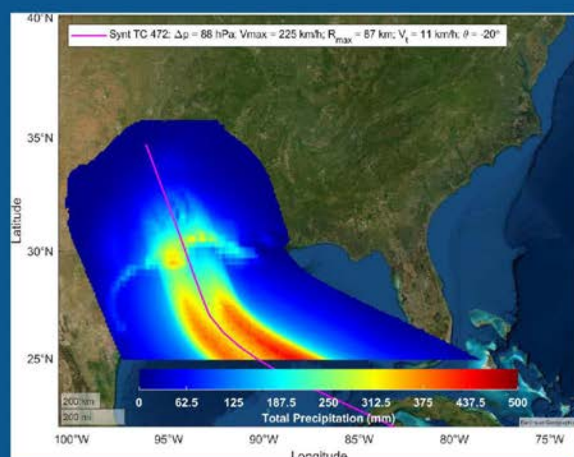
Synthetic TCR Description

- Parametric Tropical Cyclone Rainfall (TRC) Model (Lu et al. 2018)
  - Collaboration with Princeton University (Dr. Ning Lin, Dazhi Xi)
  - Physics-based
  - Developed for 660 synthetic storms from Coastal Texas Study
- Spatial rainfall estimates along storm tracks
  - Time-series (1-hr) based on evolution of synthetic storm parameters (Wmax, Rmax, lat/lon)
  - 0.1 x 0.1 degree resolution



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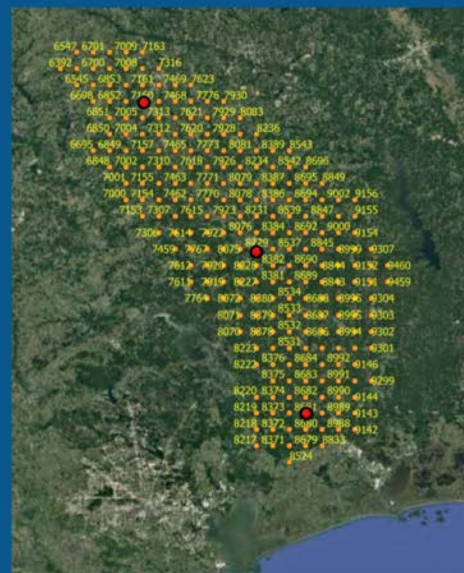
TCR Frequency Assessment

- Compare 24-hr and 48-hr precipitation hazard curves from synthetic TC rainfall to NOAA Atlas 14 Vol. 11v2 precipitation frequency estimates
- IMPORTANT: NOAA Atlas 14 uses precipitation from all sources (mixed storm populations)
- Comparison at select grid point locations within the Neches River watershed representative of lower, middle and upland areas



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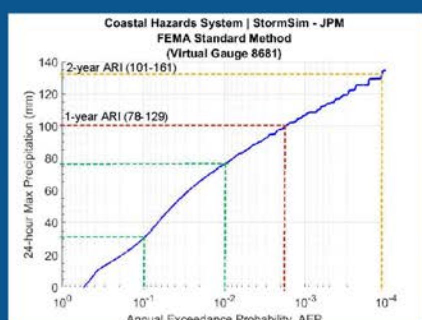
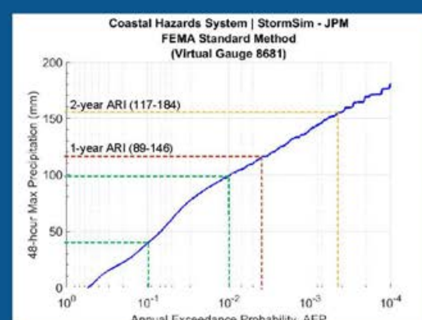
Comparing to NOAA Atlas-14 – Lower Neches River Watershed

- Grid Point 8681





PDS-based precipitation frequency estimates with 90% confidence intervals (in millimeters)

Duration	Average recurrence interval (years)									
	1	2	5	10	25	50	100	200	500	1000
24-hr	100 (78-129)	133 (101-161)	179 139-226)	223 (172-289)	291 (218-390)	350 (255-482)	420 (296-590)	501 (343-722)	626 (413-935)	733 (472-1121)
2-day	114 (89-146)	154 (117-184)	209 (163-262)	263 (204-339)	347 (262-463)	422 (309-578)	510 (361-711)	611 (419-873)	764 (506-1133)	895 (578-1357)

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Historical TC and NOAA Atlas 14 Rainfall Comparison

	Lower Neches	Middle Neches	Upper Neches
Rank TC Event	Max. 24-hr Precip Synthetic TCs (mm)		
1	145.66	74.66	37.12
2	139.10	74.65	37.02
3	123.38	70.34	36.98
4	120.45	69.23	34.24

	Lower Neches	Middle Neches	Upper Neches			
NCDC Station	Kountze	Nacogdoches	New Summerfield	Swan	Henderson	Jacksonville
Rank TC event	Max 24-hr Precip Historical TCs (mm)					
1	327.406	149.86	216.66	63.5	191.01	157.48
2	112.268	129.54	135.38	48.26	133.35	142.49
3	58.42	104.14	93.98	35.56	92.96	76.2
4	36.83	93.98	47.498	35.56	92.71	58.92

	Lower Neches	Middle Neches	Upper Neches
Rank TC Event	NOAA Atlas 14 ARI range for Synthetic 24-HR TC rainfall (years)		
1	2-5	<1	<1
2	2-5	<1	<1
3	1-2	<1	<1
4	1-2	<1	<1

	Lower Neches	Middle Neches	Upper Neches			
NCDC Station	Kountze	Nacogdoches	New Summerfield	Swan	Henderson	Jacksonville
Rank TC event	NOAA Atlas 14 ARI range for historical 24-HR TC rainfall (years)					
1	25-50	5-10	25-50	<1	10-25	5-10
2	1-2	2-5	5-10	<1	2-5	5-10
3	<1	1-2	1-2	<1	1-2	<1
4	<1	1	<1	<1	1-2	<1

- 24-hr TCR for top-rainfall producing TCs higher in historical record compared to synthetics
- Historical ARIs can be as high as 25-50
- ARIs for synthetics are less than 5 years
  - All have less than 1 year ARI for middle and upper Neches

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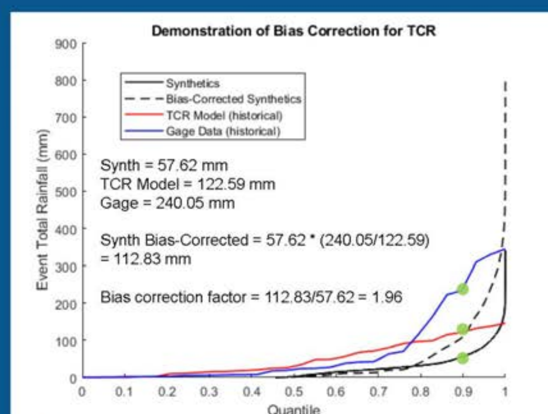
Bias Correction of TC Rainfall

- Remove precipitation > 300km from the track of each storm
  - Adjust probability masses accordingly
- Use Quantile Delta Mapping (QDM) to bias-correct the event total rainfall (ETR)
  - Starting with Beaumont, TX
  - Rain gage data and TCRM output for 37 historical storms (1979-2014)
- Multiply the bias correction factor with the rainfall value at each time step
- Calculate the 24-hour and 48-hour maximum totals for each storm
- Run StormSim-JPM to produce hazard curves



$$Rain_{bias-corrected} = Rain^{Q}_{synthetics} * \frac{Rain^{Q}_{Gage,hist}}{Rain^{Q}_{TCRM,hist}}$$

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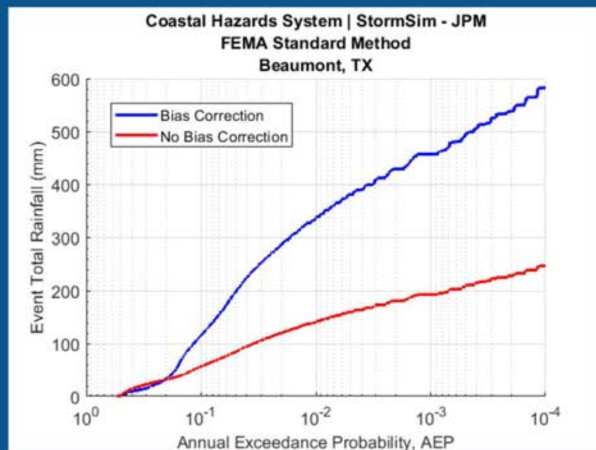
Results of Bias Correction



Event Total Rainfall

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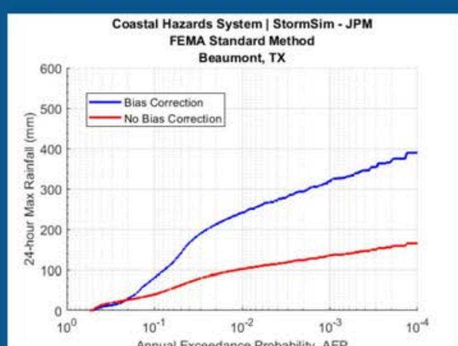
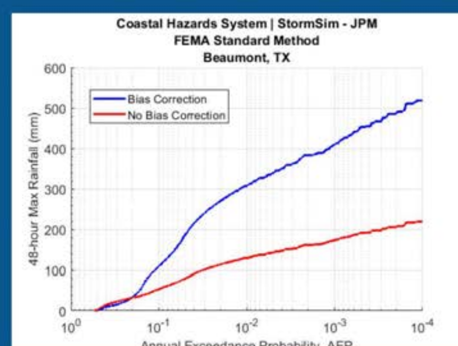
Results of Bias Correction



24-hour



48-hour

PDS-based precipitation frequency estimates with 90% confidence intervals (in millimeters)

Duration	Average recurrence interval (years)									
	1	2	5	10	25	50	100	200	500	1000
24-hr	103 (81-131)	138 (105-164)	186 (146-231)	233 (181-297)	305 (230-403)	368 (270-501)	442 (313-616)	530 (364-757)	666 (440-989)	783 (504-1191)
2-day	117 (93-147)	158 (122-185)	215 (171-265)	271 (213-343)	358 (273-470)	436 (322-589)	527 (375-727)	634 (437-897)	798 (530-1174)	939 (607-1416)

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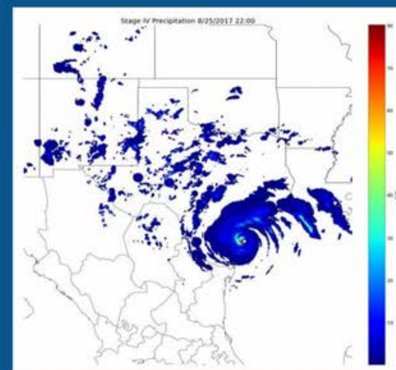
Next Steps for TCR Bias Correction

- Use NCEP Stage IV precipitation data as secondary source to compare against gage data
- Compute quantiles for observed precipitation based on an established distribution rather than using the empirical (rank-based) distribution



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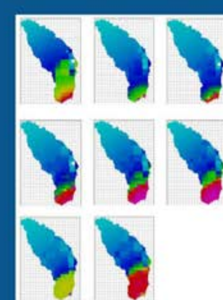
TC Rainfall into HEC-HMS

- NetCDF rainfall files -> ASCII
- Using ArcToolbox (python script)
  - ASCII -> Raster (resampled to 2,000 m cell size)
    - Align with ModClark grid
  - USA Contiguous Albers Equal Area Conic USGS version (HEC-HMS projection in existing model)
  - Raster -> ASCII
- Using HEC-DSS
  - ASCII -> precipitation DSS grids
- Loaded to HEC-HMS



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Storm Selection

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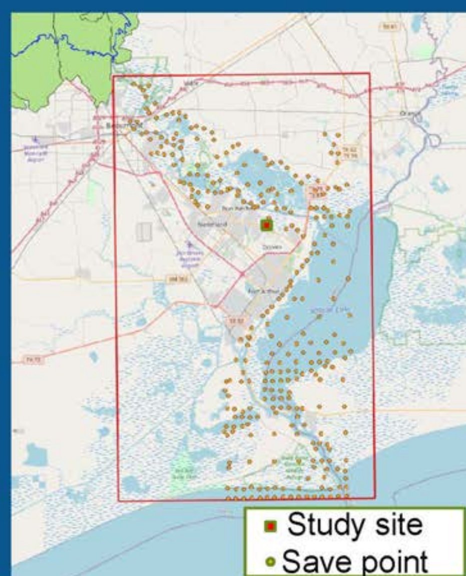
Storm Selection

- Objective: select a subsample of ~150 storms from the full suite of 660 synthetic TCs developed for Coastal Texas
- Genetic algorithm-based Design of Experiments (DoE) approach
- Optimization performed at select save point locations to match hazard curves
- 292 save points selected (5% of TCs producing response)



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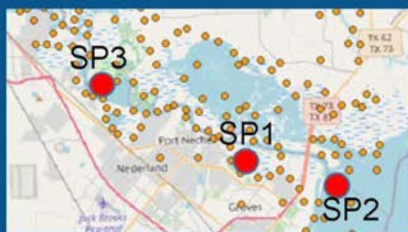
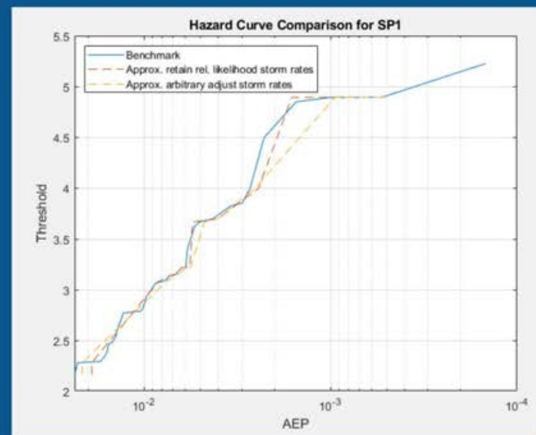
Hazard curve comparison for 150 storms





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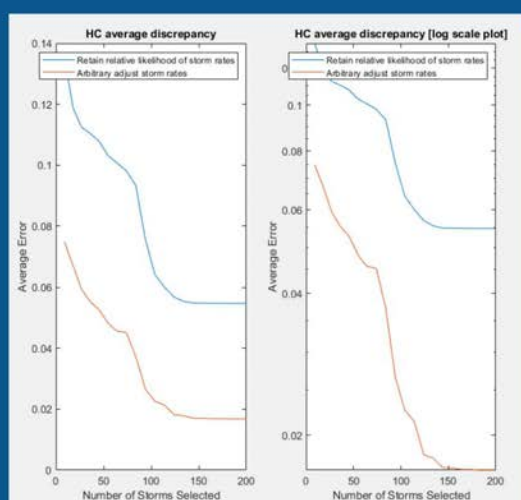
Number of storms vs average error



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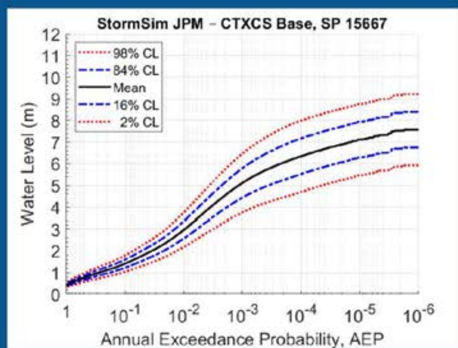
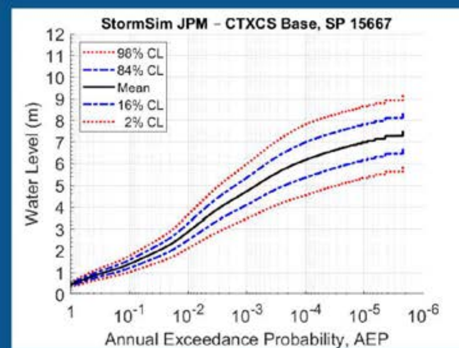
Preliminary hazard curve comparisons



Full 660 storm suite



150 TCs

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Next Steps

- Apply hydrologic modeling with subset of storms
  - Generate flow for each synthetic storm
- Run flows through hydraulic model
- Execute “loosely-coupled” framework with hydrodynamic model
- Compute combined hazard curves

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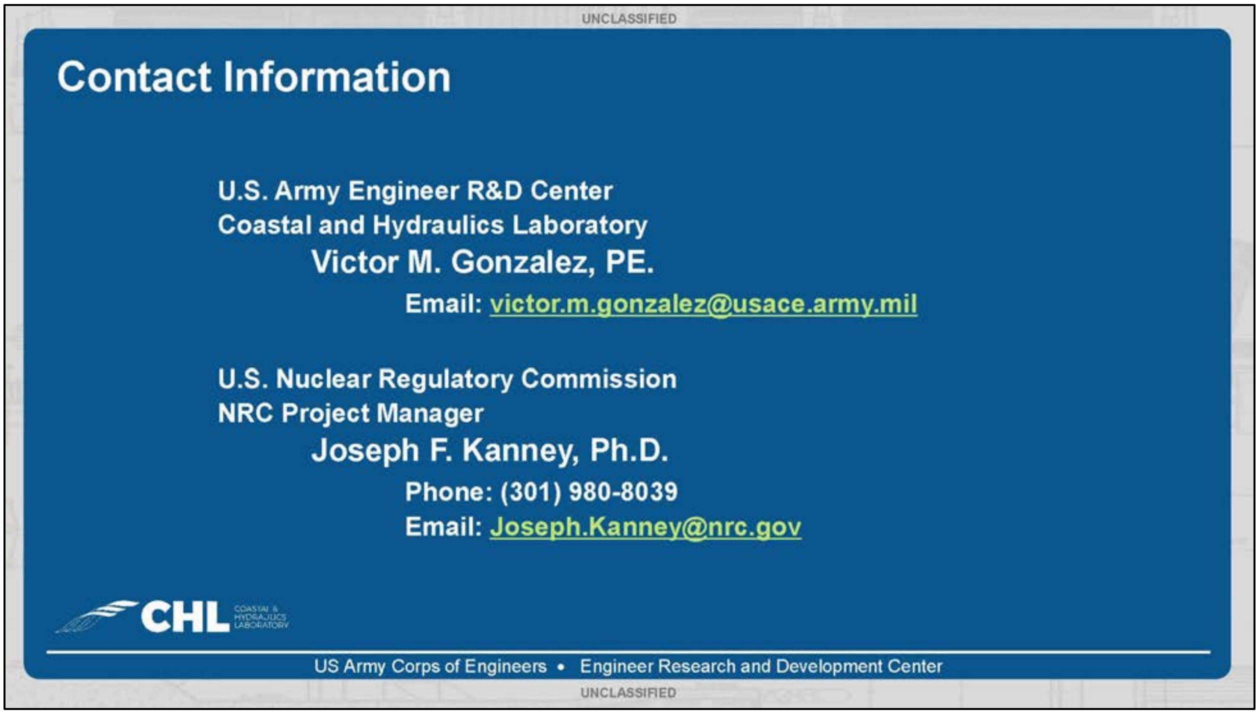


3.5.3.3 Questions and Answers

Question:
What are the possible reasons for the TCR bias? Are there specific rainfall mechanisms not being well captured by the model?

Karlie Wells:
That's something that we're currently investigating with our collaborators at Princeton University. Some ideas that I have off the top of my head are that the TCRM doesn't account for storm rain bands or interactions with other meteorological systems. For example, short-term heavy rainfall may be less common, as that model output, which could lead to an underestimation. Other sources that we have looked at also indicate that the problem in Texas could be due to complex terrain. That's a known problem that the TCR model struggles with as well. Other things that we're planning on doing to try to look at the output from our bias correction is trying to narrow down those tables from NOAA Atlas 14 to pull out specific events related to just TC-induced rainfall to see how close are we actually getting with doing that bias correction. But yeah, that's something that we're actively looking into.

Question:
Do you happen to know how sensitive the design of experiment approach performance is to the probabilistic assumptions? Is it pretty robust to changes in that those assumptions?

Karlie Wells:
The person that did the most work on that was Victor Gonzalez, and I think he's here on the call. Victor, do you mind giving your thoughts on that question?

Victor Gonzalez:
In terms of the probabilistic assumptions, the design of experiments approach uses as a benchmark the probability masses of the full suite of storms. So, if there is a significant change in the probability masses of the full suite, you might have to redo the analysis, but it should not

be too sensitive to smaller or mild changes in the probability masses. It shouldn't affect the storm selection. In other words, if you've selected your subsample storms and no dramatic change occurs that affects the probability masses significantly, you should be good to go.

3.5.4 Presentation 2B-4: Probabilistic Assessment of Multi-Mechanism Floods in Coastal Areas Due to Hurricane-Induced Storm Surge and River Flow

Authors: Somayeh Mohammadi[1], Michelle Bensi[1], Shih-Chieh Kao[2], Scott DeNeale[2], Elena Yegorova[3], Joseph Kanney[3], [1]University of Maryland, [2]Oak Ridge National Laboratory, [3]U.S. Nuclear Regulatory Commission

Speaker: Somayeh Mohammadi

3.5.4.1 Abstract

Flood mechanisms are physical processes that can cause water accumulation on a site. Site flooding can occur due to the occurrence of a single flooding mechanism or from a combination of flooding mechanisms. Traditional probabilistic flood hazard assessment (PFHA) typically focuses on one flooding mechanism. However, multi-mechanism floods (MMFs) can be more severe or differing in characteristics than single-mechanism floods. Therefore, PFHAs that consider only a single mechanism may underestimate or mischaracterize a site's flood hazard. This issue is notable in coastal areas exposed to the simultaneous occurrence of hurricane-induced flood mechanisms (e.g., surge, precipitation, river floods, tides, and waves). A challenging aspect in PFHAs of MMFs is the construction of joint distributions over the involved random variables. In the current literature, three methods have been used to construct joint distributions to support PFHAs for MMFs: the direct estimation of joint distributions (e.g., using parametric multi-variable distributions), copula-based approaches, and Bayesian motivated approaches. This use case study develops a conceptual framework for the PFHA of MMF hazards in a coastal area using a Bayesian-motivated approach. Flood mechanisms analyzed in this study include hurricane-induced storm surge and precipitation-induced runoff along with concurrent factors (e.g., river flow and tides). This study develops a probabilistic model of the hazards resulting from the simultaneous occurrence of these flood mechanisms and then structures the probabilistic model using a Bayesian network. To facilitate calculations, this study develops or leverages a series of surrogate and empirical predictive models for estimating hurricane-induced surge height, precipitation, precipitation-induced runoff, and changes in river discharge. This study ultimately develops a hazard curve to present the frequency of exceedance for river discharge.

3.5.4.2 Presentation (ADAMS Accession No. ML21064A436)

Probabilistic Assessment of Multi-Mechanism Floods in Coastal Areas Due to Hurricane Induced Storm Surge, precipitation and River Flow

Somayeh Mohammadi[1], Michelle Bensi[1], Shih-Chieh Kao[2], Scott DeNeale[2], Elena Yegorova[3], Joseph Kanney[3] and Meredith L Carr[4]

(1) University of Maryland College Park, Department of Civil and Environmental Engineering, College Park, MD, United States
(2) Oak Ridge National Laboratory, Environmental Sciences Division, Oak Ridge, TN, United States
(3) Nuclear Regulatory Commission, Rockville, MD, United States
(4) U.S. Army Corps of Engineers, ERDC/CHL, Vicksburg, MS, United States

6th Annual NRC PFHA Research Workshop
Online (Feb 22-25, 2021)

Topics addressed

- Research objective
- Challenges for multi-mechanism flood (MMF) hazard
- MMF hazard estimate in this study
- Probabilistic model (Bayesian motivated approach)
- Predictive models
- Next steps

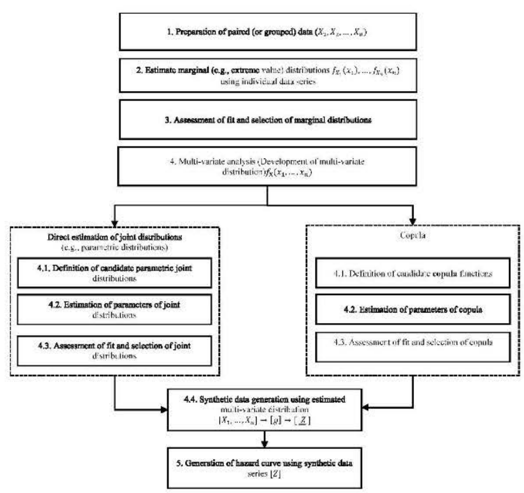
1

Research objective

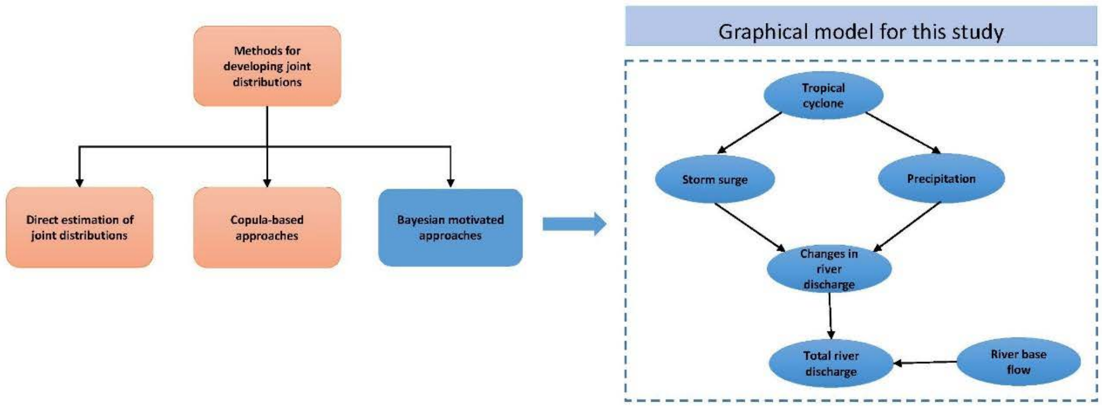
Estimating flood hazard due to simultaneous occurrence of storm surge, precipitation, and river flow in coastal areas

Challenges in Analyzing Multi-Mechanism Floods

1. Capturing dependency structure
   - Statistical approaches
     - Copula
     - Direct estimation of joint distributions
   - Bayesian approaches
2. Capturing the interaction between the flood mechanisms
   - Computationally expensive models



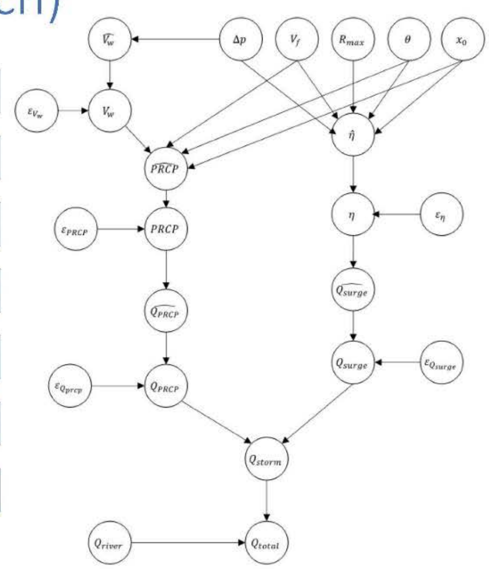
MMF analysis in this study



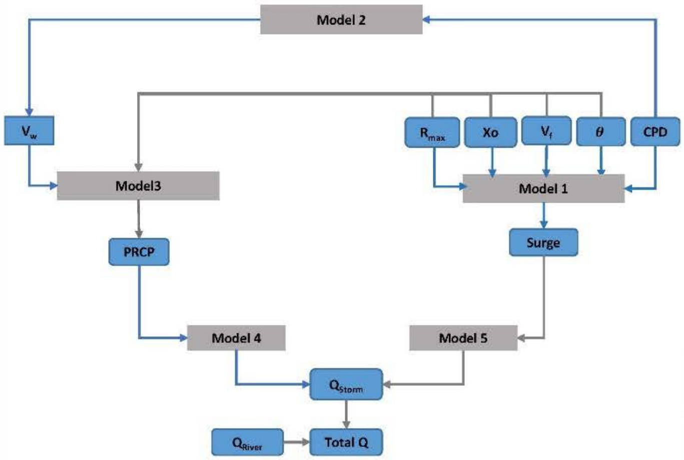
$$f_{\mathbf{X}}(x_1, \dots, x_n)$$
$$= f_{X_n|X_1 \dots X_{n-1}}(x_n|x_1, \dots x_{n-1}) f_{X_{n-1}|X_1 \dots X_{n-2}}(x_{n-1}|x_1, \dots x_{n-2}) \dots f_{X_2|X_1}(x_2|x_1) f_{X_1}(x_1)$$

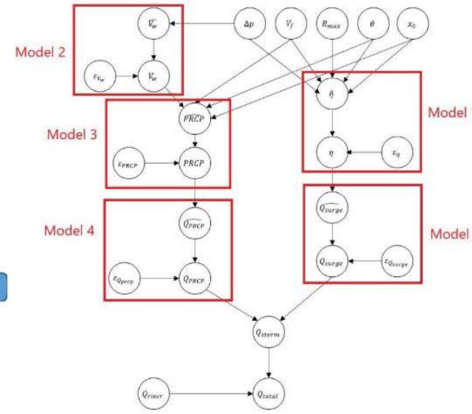
Probabilistic Model (Bayesian Motivated Approach)

- Determine physical relationships between involved variables
- Fit distributions to input variables and discretizing them
- Develop numerical, surrogate or analytical models to predict response variable and conditional distributions
- Discretize the distributions
- Discretizing the error of each model and correcting response variables
- Calculate joint probability for different combination of discretized values by considering dependency between variables and conditional probabilities
- Estimate probability of exceedance for different values of target response variable and generation of hazard curve



Predictive models





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Predictive models

- Model 1 (Surge model)
  - Surrogate model for predicting surge height using hurricane parameters
- Model 2 (Wind model)
  - Statistical model for predicting maximum wind velocity using central pressure deficit
- Model 3 (Precipitation model)
  - Statistical and empirical model for predicting hurricane induced precipitation
- Model 4 (Precipitation-induced Discharge Model)
  - Statistical model for predicting precipitation induced discharge
- Model 5 (Surge-induced Discharge Model)
  - Statistical model for predicting surge induced river discharge

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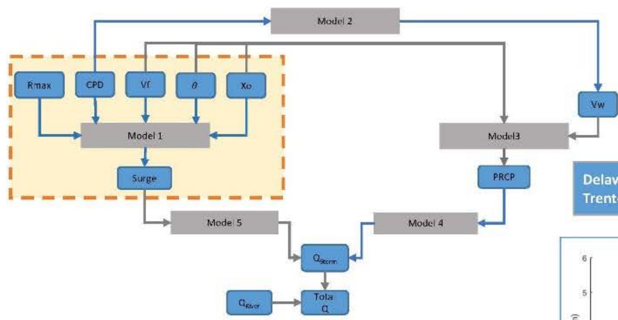
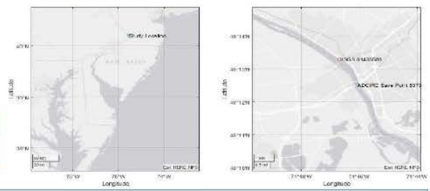
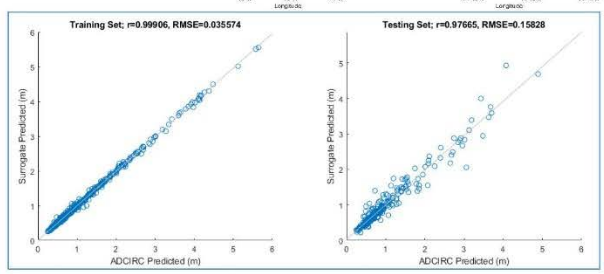
Model 1: Surge Model



Predictive (X) variables V_f, CPD, X, θ, $Rmax$	Model 1 →	Response (Y) variable Surge height

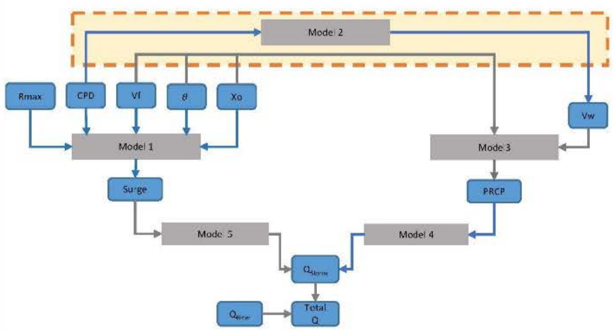
Delaware River at Trenton





Data source: https://chswebtool.erdc.dren.mil/
Save point: 5373

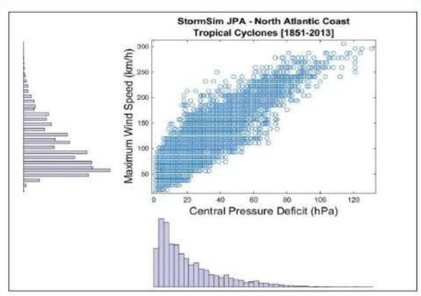
Model 2: Wind model



Predictive (X) variable Central pressure deficit	Model 2 →	Response (Y) variable Max wind speed

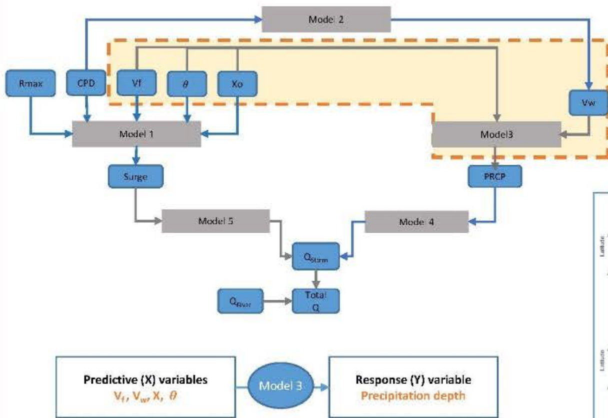
$$V_w = 42.4807 - 0.0084CPD^2 + 2.9752CPD$$

$$\sigma_{V_w} = 18.66$$

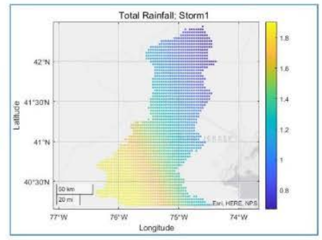


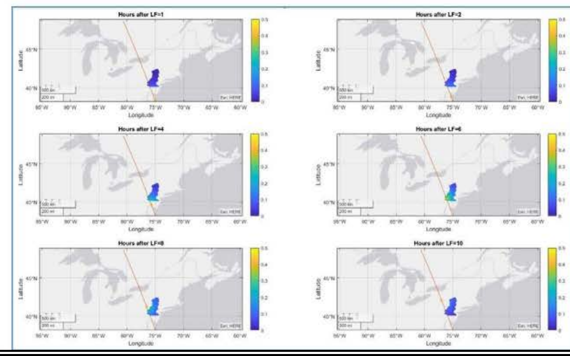
Source: North Atlantic Coast Comprehensive Study (NACCS), Nadal-Caraballo et al. 2015

Model 3: Precipitation Model



Basin Average daily rainfall





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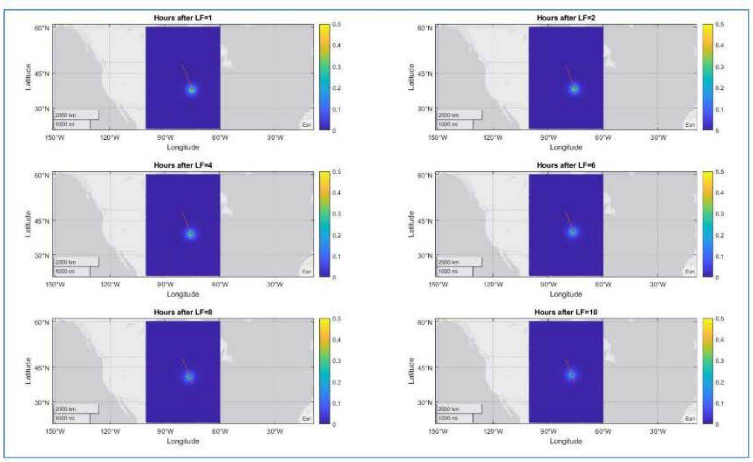
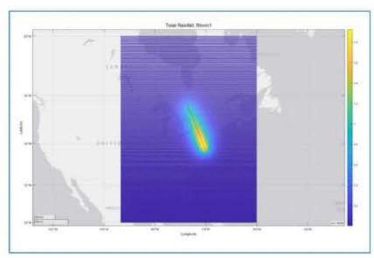
Along-Track precipitation

Along-track precipitation at different hours after landfall





Total daily along-track precipitation

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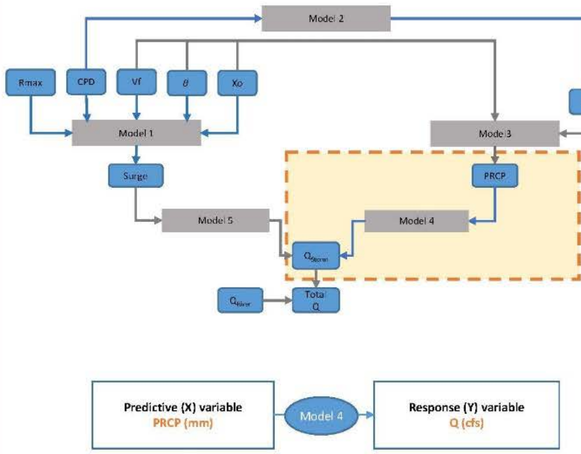
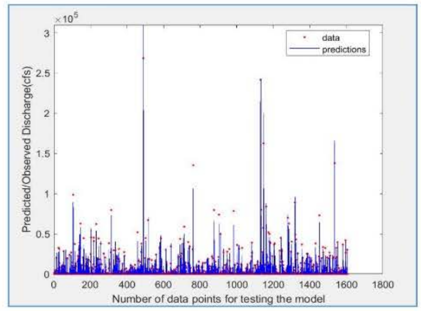
Model 4: Precipitation-Induced Discharge



Data :

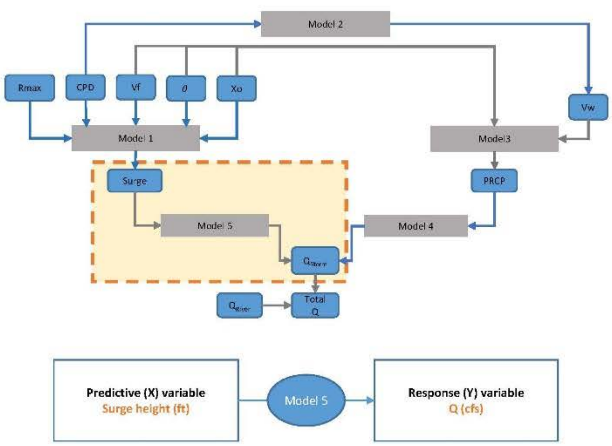
Simulated daily streamflow, runoff and precipitation data from 1980-2015 (Rapid-VIC model)



Correlation = 0.9831; RMSE_Test = 3.0915e+03 (cfs)

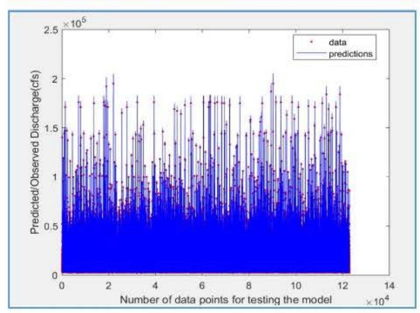
12

Model 5: Surge induced discharge



Data:

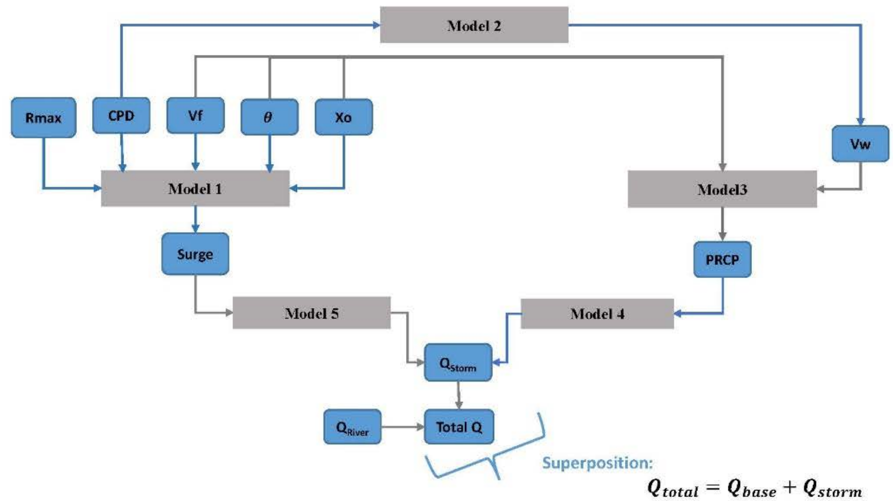
15 minute data from USGS (Discharge and Water Level)
Station number: 01463500



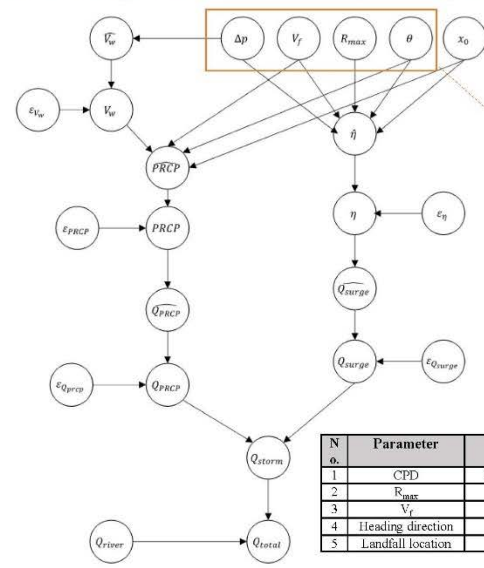
Correlation = 0.9831; RMSE_Test = 3.0915e+03 (cfs)

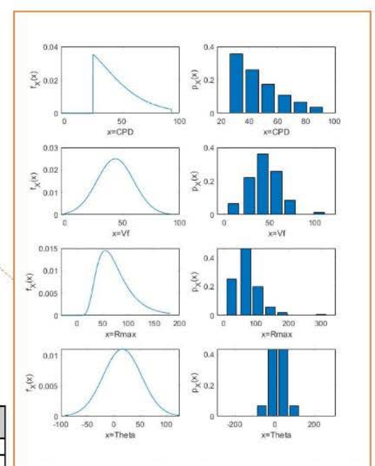
13

Computing Total Discharge (Q)



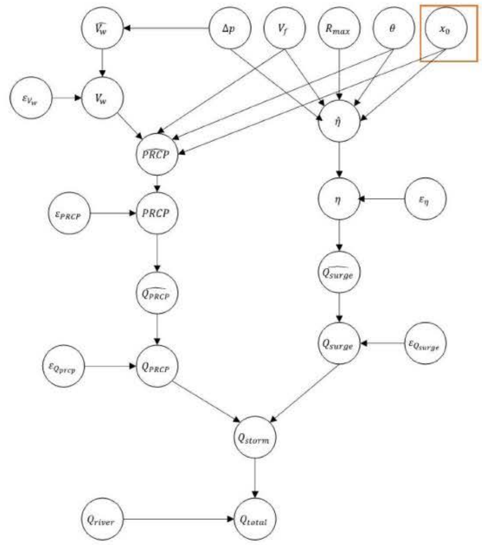
Defining model input parameters

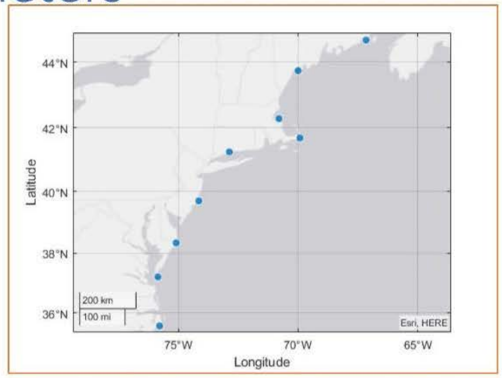


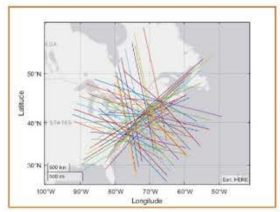


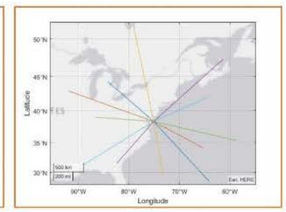
No.	Parameter	Distribution type
1	CPD	Doubly truncated Weibull distribution
2	R_{max}	Lognormal distribution
3	V_f	Normal distribution
4	Heading direction	Normal distribution
5	Landfall location	Uniform distribution

Defining input model parameters









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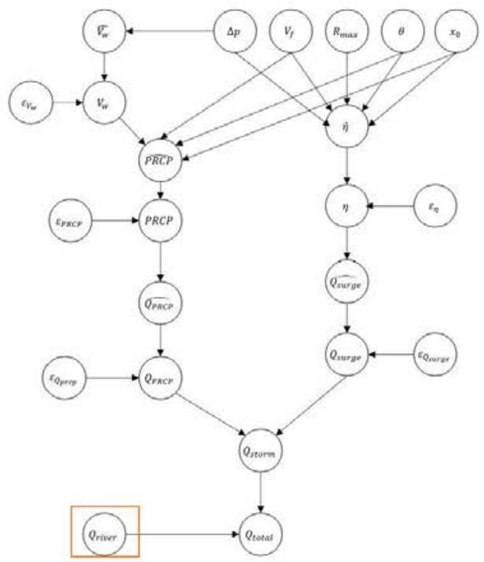
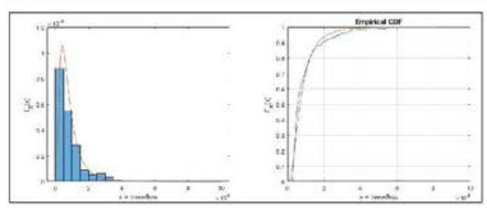
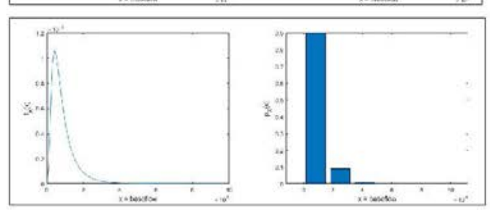
Statistical analysis of baseflow



- Gathering daily discharge time-series
- Removing hurricane event dates from record
- Randomly sampling a subset of data
- Performing statistical assessment to define distribution
- Lognormal distribution as the best fit distribution





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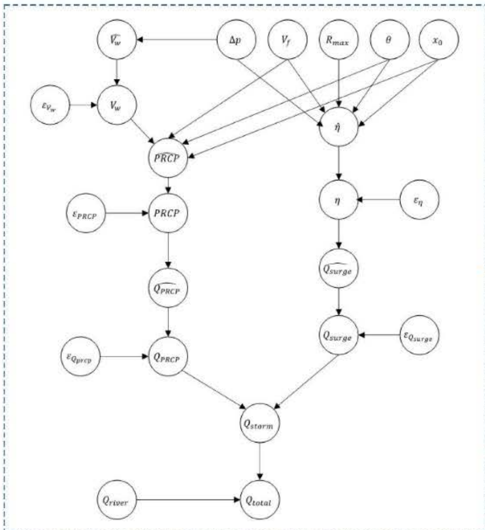
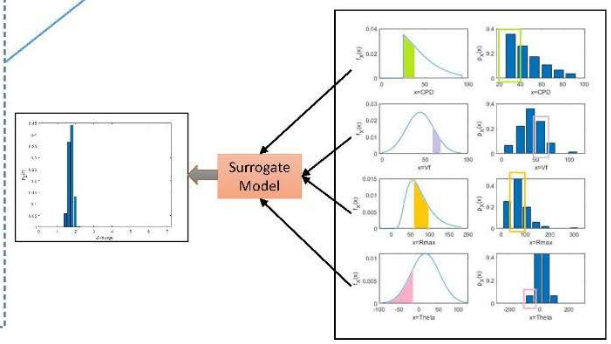
Decreasing discretization error

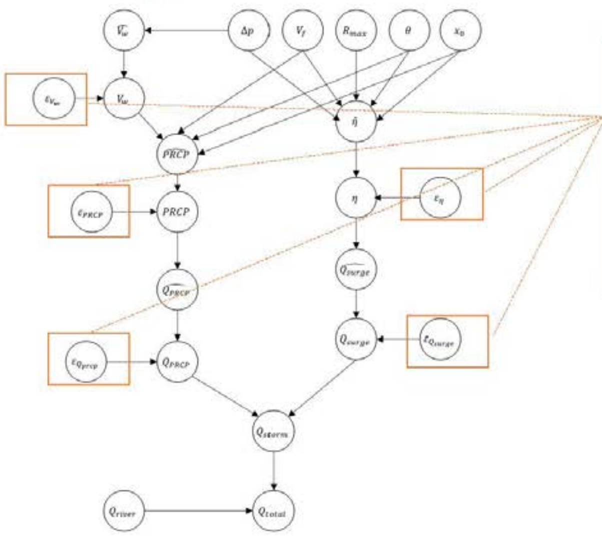


Monte Carlo simulation

- **Generating conditional probability tables (CPTs)**
- **Reducing the impact of discretization error**



Inclusion of modeling error (epistemic uncertainty)



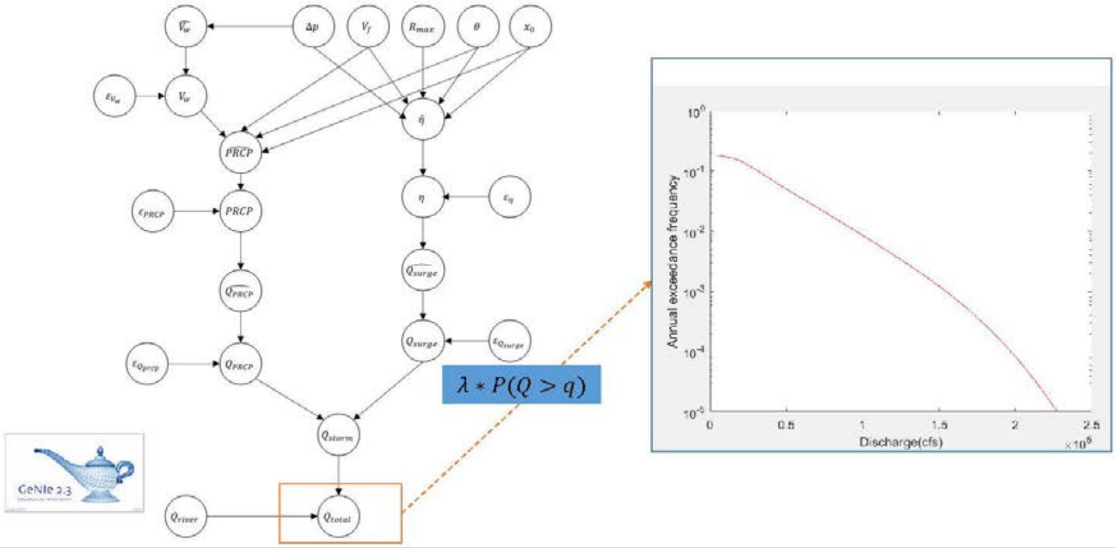
For all models:

- **Normal distribution assumed for error**
- **Error discretized in to 9 bins**

Correcting predicted response variables:

$$X = X_{pred} + \epsilon_X$$

Estimating annual exceedance frequency



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Next steps

- Considering the non-linearity between surge induced and precipitation induced discharge in the analysis
- Inclusion of the tides in the analysis
- Conducting the analysis using other methods (for comparison)
  - Copula based
  - Direct estimation of the joint distribution

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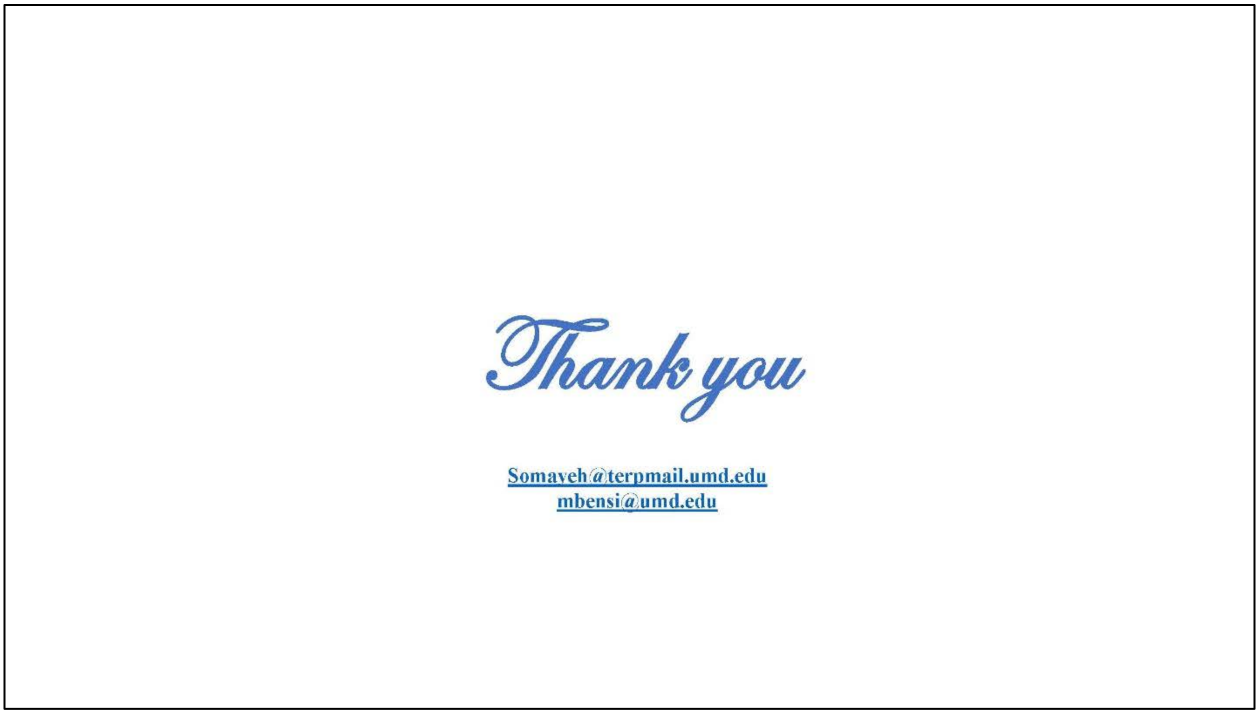


3.5.4.3 Questions and Answers

Question:

I think you did address this somewhat in your talk, but how can the model be fully validated?

Somayeh Mohammadi:
Yes, as I mentioned, for each part of the model we did validation. We usually had testing sets. The other thing that we are still working on is validation of the big model. We consider that validation of each of these predictive sub-models can guarantee that the overall model is working well. However, we are still working on calibration of the big model. I mean we are working on some earlier storms that have occurred in the area. Given those extra parameters and river discharge at the time, we are working on analyzing the result. But this is something that we are still working on.

Question:
You mentioned that you were looking at just the peak, sort of the worst case of the event. I've been looking a lot into duration and lag time in these sorts of situations and also the issue of wave lag time. Have you done any work on that or looked at how to deal with that in your next steps?

Somayeh Mohammadi:
No, not yet. But it's a good suggestion to consider as this is still an ongoing project.

3.5.5 Coastal Flooding Panel Discussion

Moderator: Meredith Carr, U.S. Army Corps of Engineers

Panelists:

Karthik Balaguru, Pacific Northwest National Laboratory
Victor Gonzalez, U.S. Army Corps of Engineers
Karlie Wells, U.S. Army Corps of Engineers
Somayeh Mohammadi, University of Maryland

Question (to Panel):
Can the panel comment on the recent concern with increase of rapid intensification right before hurricane makes landfall, for example, Harvey and Michael? Is this a trend which should be considered in estimating storm surges? I was thinking our first speaker might want to talk about that because of your work with the rainfall.

Karthik Balaguru:
Rapid intensification is almost like the Holy Grail of intensity prediction. If you look at the operational forecasts related to it, they tend to struggle with accurately predicting the rapid intensification. It's like a different beast. It's not like normal intensification of the hurricane. It's so difficult because it depends on a lot of small-scale processes in the atmosphere and ocean. And when rapid intensification happens close to the coast, makes it even more challenging because you don't have much of a response time. So, improving our ability to simulate rapid intensification is very important. We have done some work in the past and we're continuing to work on it. Some of the things we've been looking at are: (1) what are the parameters in the ocean and atmosphere that people are currently incorporating in prediction models and (2) what parameters are not there that could actually help improve the prediction. For instance, one of the things we're looking at is the role of ocean salinity. That is typically neglected in most models used for hurricane intensity prediction and we have found is it plays pretty important role. So, documenting the role of upper ocean stratification and heat content and so on may be important. The other important thing with rapid intensification is the ability to predict it. Statistical models typically have a hard time predicting rapid intensification, and it's also the case with most dynamical models. That has motivated us try using the neural network-based method. We have found that, compared to other models, the neural network approach seems to be particularly good with respect to predicting rapid intensification.

Moderator:
There are a couple follow ups on that. One question I had, specifically for those of you who are using TC rainfall models. Are these type models capable of responding to rapid intensification?

Karthik Balaguru:
When it comes to rainfall, one of the main factors that controls rainfall is intensity. So that ties in with the model ability to simulate rapid intensification. A lot of the presentations here today are using simple models to predict rainfall. The more complex thing is the intensity. Based on that, my opinion is that the complexity lies more with the intensity of the storm rather than the rainfall. There could be other things related to rainfall. For instance, the environmental moisture and so on.

Somayeh Mohammadi:
I just wanted to say that I agree. Intensity is the most important thing in the model that I have used, which was a combination of TRR model and a statistical model for tropical rainfall. In this model rainfall is a function of maximum velocity and hurricane storm intensity. The other model

was an empirical model for wind decay. But yes, I agree that the most important thing for capturing precipitation is storm intensity.

Question (to Panel):
Is rapid intensification more of an issue for forecasting versus hazard assessment?

Victor Gonzalez:
I think it's more of an issue for forecasting in the sense that hazard assessment depends, by definition, on looking at the historical data. Once an event like Michael occurs, whatever parameters Michael had at landfall are going to be incorporated in the next assessment that we do. It’s going to affect the probability mass for the recurrence rate of hurricanes of that certain intensity. We might look into the impact of that rapid intensification, if that's something that we want to consider, in the synthetic tracks. The time history as the storm is coming to shore may have an influence on the surge response at the coast. That that might be an area that probably should be looked at. But in general, I feel that if they happen, they will be a be part of the next coastal hazard assessment.

Karthik Balaguru:
I just want to add that rapid intensification is typically like 5 to 10% of the total number of hurricane situations. In terms of sample size, it's actually very, very small. So, if you're going to be using a statistical model that's based on historical data, you're going to struggle with generating rapid intensification in your synthetic tropical cyclones because you run into sample size issues, especially when you're using a linear statistical approach.

Question (to Panel):
We have a question on the translational speed of tropical cyclones its dependance on SST. How do you consider this kind of phenomenon for evaluating PFHA?

Karthik Balaguru:
The translation speed of tropical cyclones is typically dependent on the large-scale winds, so I don't think they depend too much on SST directly. The more direct connection is with the winds. If you look at the way our framework works, we use the winds to generate the tracks. We also use the same winds to generate windshear, which affects intensity. Windshear can also affect rainfall. So, in that sense, the slowness or the fastness of the storm is taken care of when you use the winds for various characteristics.

Question (to Panel):
This question is related to the whole issue of compound flooding. Have you considered the temporal interactions between the surge and precipitation rather than the superposition of one static result on top of the other? I was speaking earlier about lag time, thinking about peaks and also the peaks of waves as the third part of the compound. Right at that interface, how do you consider uncertainties that are different between the two systems? Any ideas people have about that, or how it's come up in the projects they're working on? Or how their projects deal with that temporal interaction.

Karthik Balaguru:
In our case, we have mostly used the static field from the storm surge model to couple with the flood model. We are basically prescribing it as a boundary condition in the initial time step. But this is something ongoing that we're working on. Eventually we hope to have the time evolution in both storm surge as well as the component related to rainfall.

Somayeh Mohammadi:

In the model that we use, we simply added them. We didn't consider interaction between surge and participation in change of our river discharge.

Victor Gonzalez:
We're going to investigate it. We want to use hydrographs, but that's something that we're still looking at how to implement.

Question (to Panel):
Does the panel want to share your opinions on where to put resources in terms of PFHA for compound hazards? We've seen several approaches with effort placed in different areas: (1) focusing on numerical modeling, (2) probabilistic dependencies, (3) a river problem with a surge boundary, and (4) a surge problem with the river boundary.

Victor Gonzalez:
I'll start on practical considerations. If this is something that we want to consider and more widely analyze, the preferable approach would be to look at it as a river problem with a surge boundary. So perhaps we should be concentrating on trying to find out how far can we get with this. How accurate can we get with this approach? I'm thinking more in terms of engineering practice than in research.

Moderator:
In the work that we've been doing at CHL, in which Karlie's project is one element, we are looking at different frameworks to try to have a way for different users to address what level of need they have. You might have an area where you only need to look at the surge coming in and the rainfall is not as significant, or vice versa. So, site specific, and try to build it so that it can be used for the purpose that's needed for that specific user.

Karthik Balaguru:
I have the similar sentiments when it comes to this.

Question (to Panel):
Does the panel have a comment in terms of the duration of the compound flooding in addition to the intensity or the extent?

Karthik Balaguru:
This duration aspect of it is partly related to the question on translation speed or forward speed of the storm that we talked about it a bit earlier. Definitely this is something very important. If you are using a physics-based model which accounts for the forward motion of the storm based on the large-scale winds, I would assume that this part of the question would have been addressed by using that approach.

Question (to Panel):
Can the panelists talk about how climate change impacts could be incorporated into their respective model frameworks? Are the models able to respond to changes in TC characteristics induced by climate warming? For the statistics-based models, can they be extrapolated to future climates?

Karthik Balaguru:
In terms of the impact of climate change, if your framework takes into account the large-scale environment that governs the intensification of the storm, then you pretty much include it. For instance, if your framework is using the ocean and atmosphere from, say, a reanalysis or something from the current climate, then you could easily use future projections of the climate system from the CMIP suite of models and apply those as the conditions to model tropical cyclones. That's one way to take into account climate change.

Somayeh Mohammadi:
I think the hurricane recurrence rate is something that may be affected by climate change. Another thing is the effects on sea level rise that we can incorporate into our models. Also, the intensity of these storms. In these three ways, our model can consider the effects of climate change.

Victor Gonzalez:
In order to incorporate climate change, storm recurrence rate is key. And those can be modified to account for any documented future changes. For example, if we expect more intense tropical cyclones, that's where you will do the adjustment. As we do the analysis now, we separately do the statistics for different partitions based on intensity. So, if we were to include the effects of climate change, we will do it through that storm recurrence rate. And of course we already incorporate sea level change in our projects. It’s a requirement for us to do projections of water levels into the future for projects that are done within the Corps of Engineers.

Question (to Panel):
It seems like most of these are event-based models, but do any of your approaches include multiple storms in succession?

Karthik Balaguru:
While the results that we have shown in our talk today are mostly based on synthetic storms, we're also doing another study where we're looking at sequential storms. But that is more based on a case study because in the synthetic approach it's all random and you don't actually control for the timing of the storms or anything like that. It just occurs naturally, but we are doing a case study type of approach to look at sequential storms, which I think is a really important aspect of flooding that is not typically looked at.

Moderator:
I did want to say that the project that Karlie is working in doesn't directly look at sequential storms, but it does look at antecedent moisture conditions, which could be caused by prior storms. I believe we are trying to look at a way to represent that, not just deterministically, but as part of the model. It's not likely tropical storms but you get those moisture conditions in there from previous events.

3.6 <u>Day 3: Session 3A – Modeling Frameworks</u>

Session Chair: Thomas Nicholson, NRC Office of Nuclear Regulatory Research

3.6.1 Presentation 3A-1 (KEYNOTE): Stochastic Hydrology in the Tennessee Valley

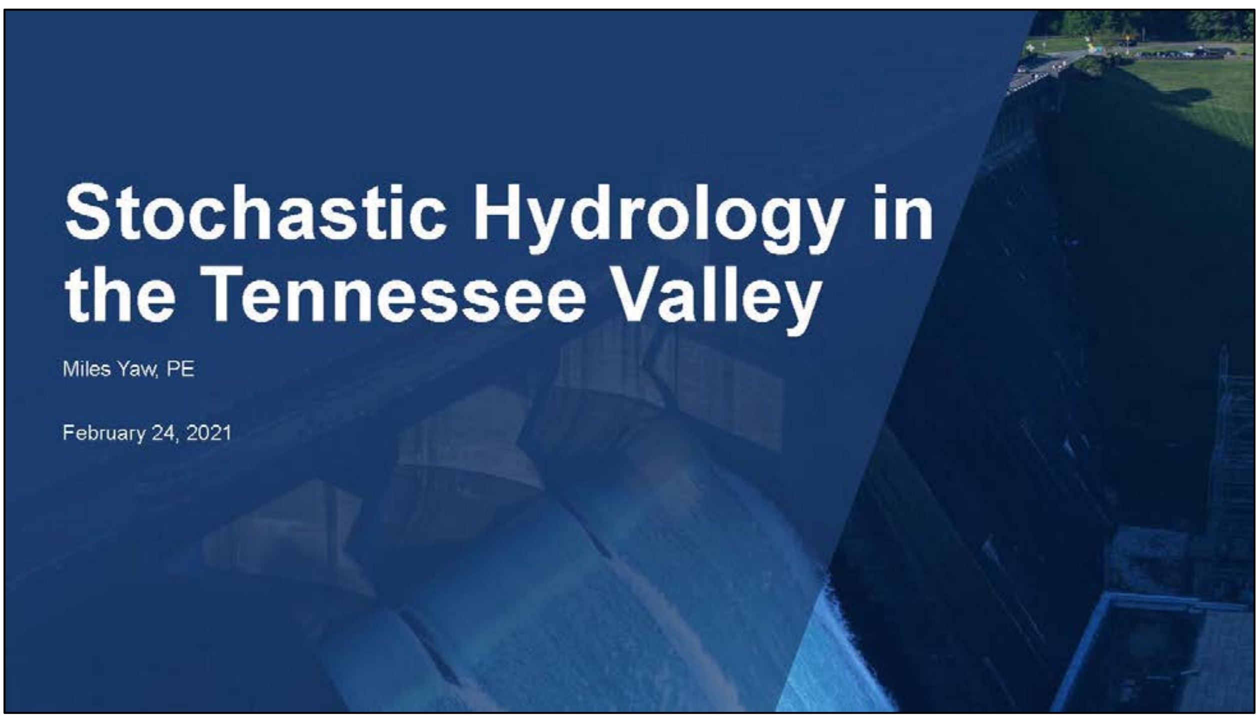
Authors: Miles Yaw, Tennessee Valley Authority (TVA)

Speaker: Miles Yaw

3.6.1.1 Abstract

In 2014, the Tennessee Valley Authority began development of a modeling framework for evaluating hydrologic hazards across its entire portfolio of dams. Seven years into the program, TVA has evaluated hydrologic hazards at 19 projects. Many of the hydrologic hazard analyses have been applied to dam safety risk assessments, which are a critical piece of TVA's Risk Informed Decision Making (RIDM) process. During the course of the analyses, TVA has identified, implemented, and planned program, process, and framework improvements to better inform the risk quantification process. Critically, as the program moves from a developmental phase into production, the incorporation of paleoflood and dendrochronology analyses will provide a more complete picture of hydrologic risk. This presentation will provide a brief overview of the TVA PFHA model and how probabilistic hydrology supports TVA's RIDM framework. The presenter will share lessons learned from probabilistic analyses, ongoing enhancements to the program and framework, and future areas of research and application, both to Dam Safety and TVA's broader essential mission.

3.6.1.2 Presentation (ADAMS Accession No. ML21064A437)



Agenda

Some History

PFHA and Dam Safety

Where are we?

What do we do?

How do we use it?

What have we learned?

Where are we going?

TVA's Statutory Responsibility

An Act to provide for :

1. Improved navigability
2. Flood control
3. Reforestation and proper use of marginal lands
4. Agricultural and industrial development of the valley
5. National defense
6. "other purposes"

The TVA Reservoir System

4

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TVA Dam Safety – It's all about Risk

Risk is everywhere. Risk is fine. But you MUST:

RIDM allows dam safety to prioritize investments across the portfolio to those projects that provide the greatest risk benefit.

We need to understand *probabilities* of extreme loadings

We need a method that is consistent and repeatable

5

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PFHA Program – Where we are

PHASE 1: Development	PHASE 2: Implementation	PHASE 3: Production
FY14 – FY16	FY17 ~FY21	~FY22 and Beyond
Project Inception Storm Typing Regional Point Precipitation Frequency Analysis Detailed Watershed Studies Storm Transposition Tool Development RiverWare Model Development	First Pilot Studies for Risk Assessment (FY17) Framework Peer Review Site-specific Study Independent Review Incorporation of Paleoflood Data Incorporation of Dendrochronology Data Enhancements to Front end/Back end Application of PFHA to Interim Risk Reduction Measures Evaluation of Policy Alternatives with PFHA	Mature Product Routine studies and updates Expansion of PFHA into other operational areas Ongoing routine maintenance

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The TVA Framework

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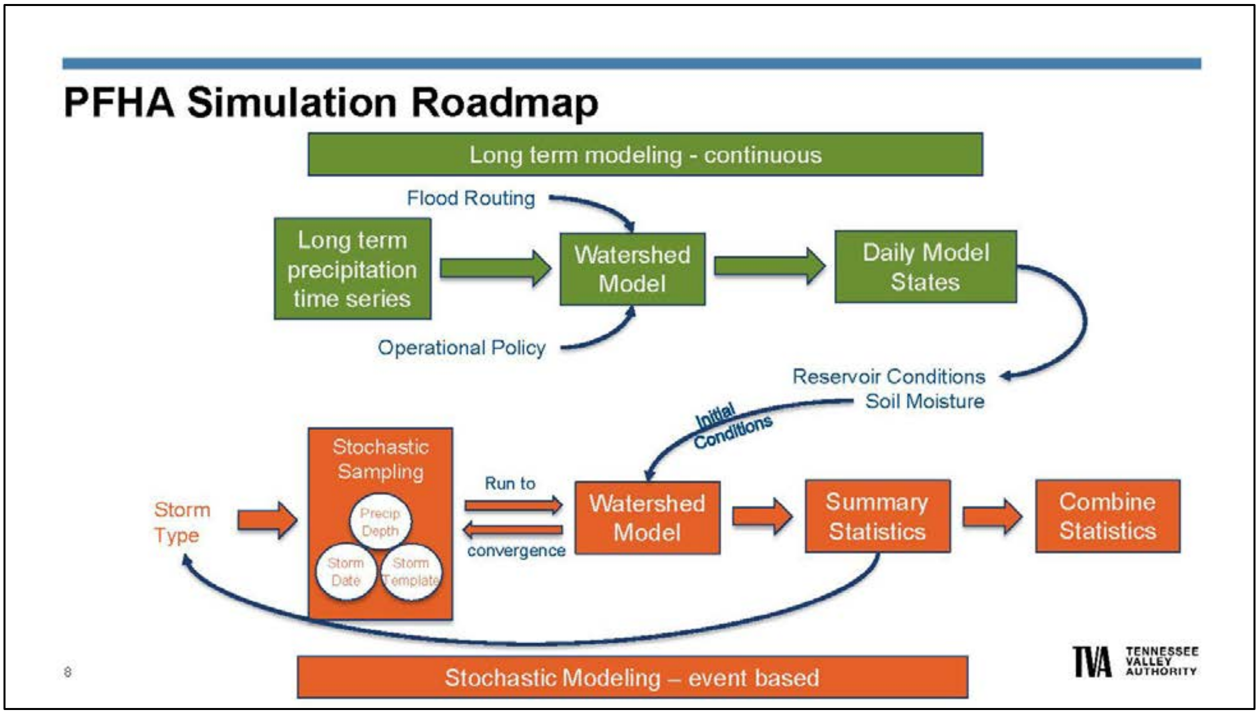
PFHA Simulation Roadmap
Long term modeling - continuous
Flood Routing
Long term precipitation time series
Watershed Model
Daily Model States
Operational Policy
Reservoir Conditions
Soil Moisture
Initial Conditions
Stochastic Sampling
Precip Depth
Storm Date
Storm Template
Storm Type
Run to
convergence
Watershed Model
Summary Statistics
Combine Statistics
8
Stochastic Modeling – event based
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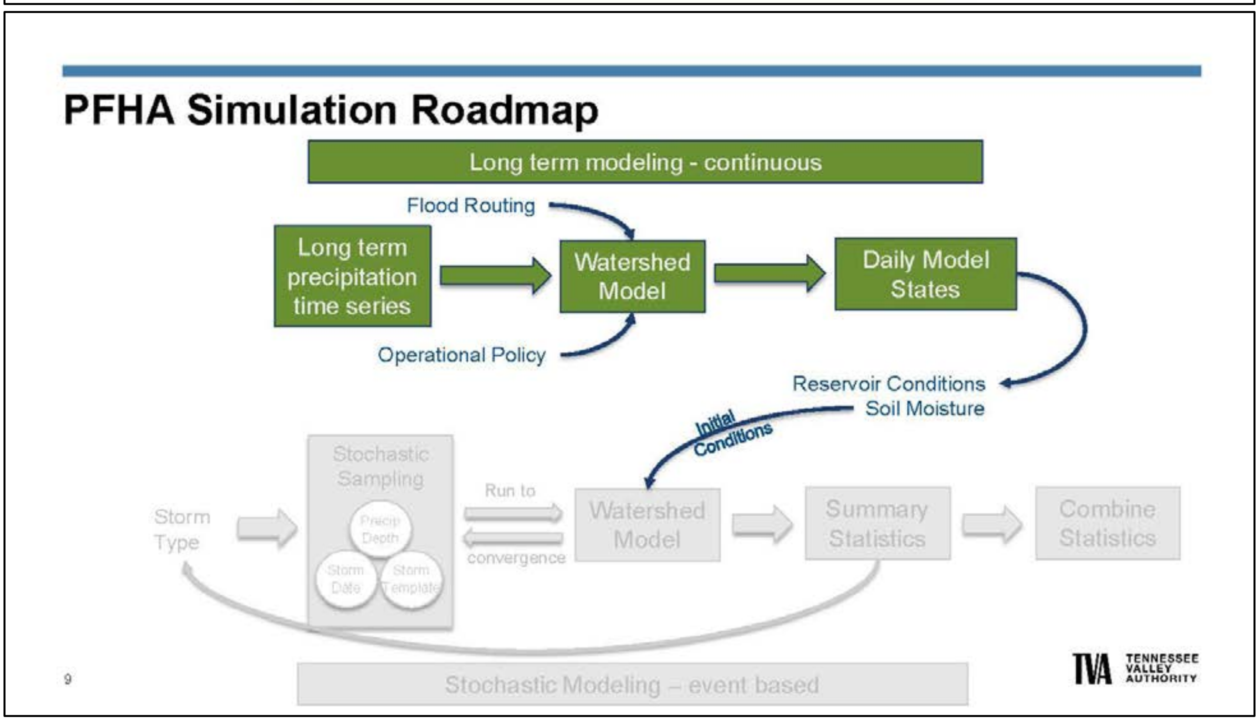
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Storm Template
Storm Type
Run to
convergence
Watershed Model
Summary Statistics
Combine Statistics
9
Stochastic Modeling – event based
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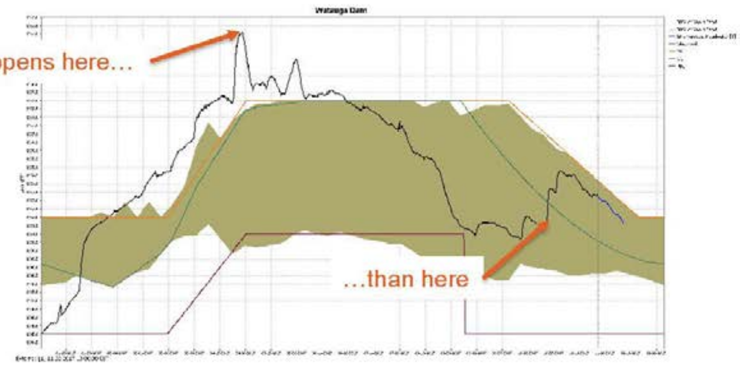
Long term simulation

The Goal:

To provide a representative range of initial watershed conditions for stochastic events.

To represent sequences of storms that may cause flooding issues.

The worst case scenario may not be an exceptionally rare storm, but an unfortunately timed storm of moderate intensity



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Long term simulation

The Solution:

Simulate a long term watershed and reservoir model using resampled historical precipitation

But… resampled historical precip may not provide sufficient variability of wetter and drier periods

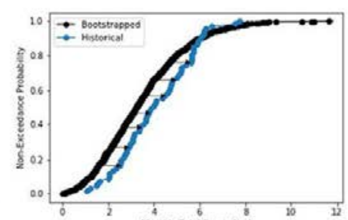
Use an Alternating Renewal Method:

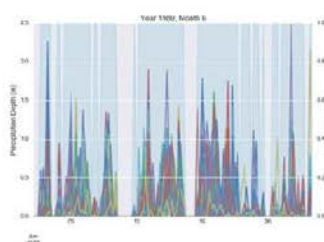
Fit distributions to seasonal rainfall statistics (depth, duration, etc.)

Resample the distributions to capture distribution tails

Synthesize a 1,000 year precipitation time series

Bias correct the middle 90% of the data





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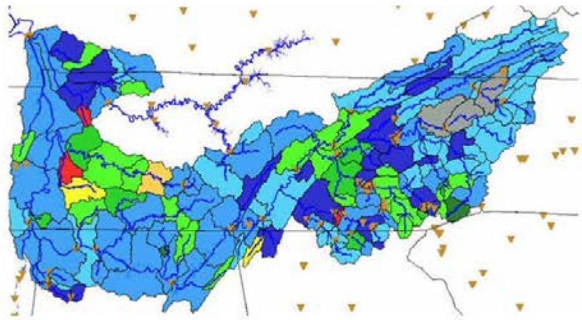
Long term simulation

Watershed Modeling:

Drop the rainfall on the TVA Operational forecast model

- 127 auto-calibrated basins, used in daily operations
- Runoff modeling using SAC-SMA

Route the runoff to RiverWare control points



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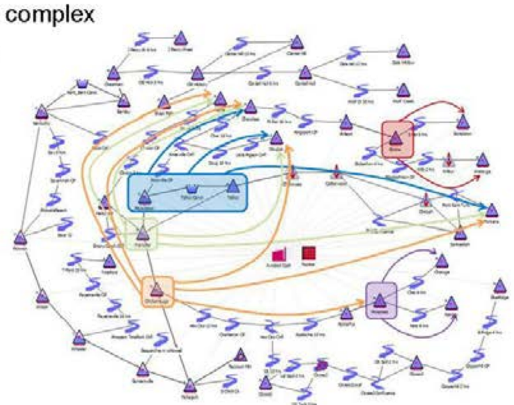
Long term simulation

Operations Modeling:

Simulate the entire reservoir system using RiverWare

- Flood operations and routine daily operations are complex
- RiverWare rules based simulation approximates:
  - *Turbine releases*
  - *Environmental releases*
  - *System operating guide constraints*
  - *Flood operations*
  - *Tieback operations*
- There are 79 rules and hundreds of functions

Record the model states – these provide initial conditions for the stochastic sampling



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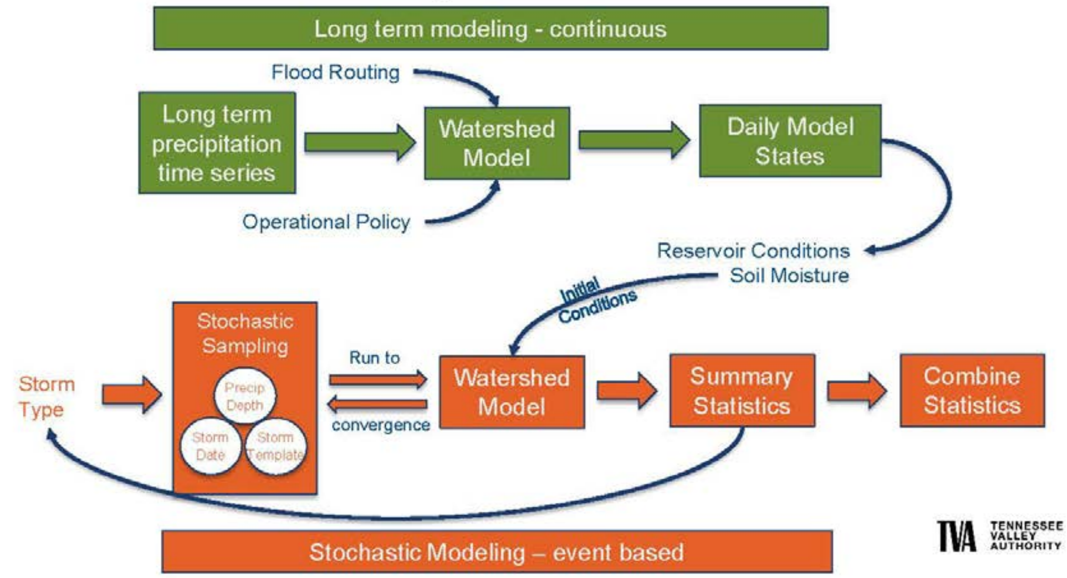
PFHA Simulation Roadmap



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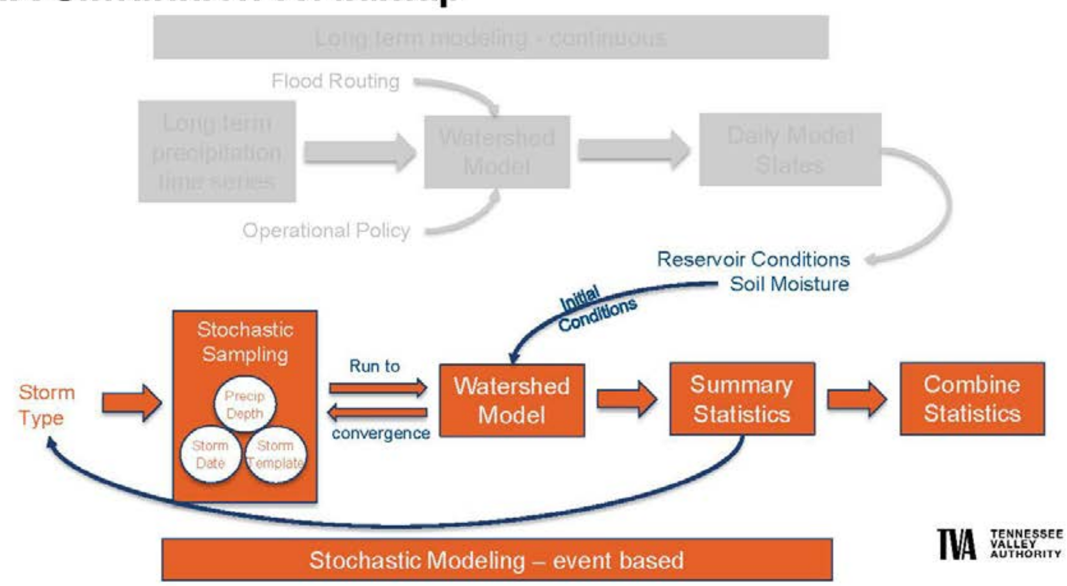
PFHA Simulation Roadmap



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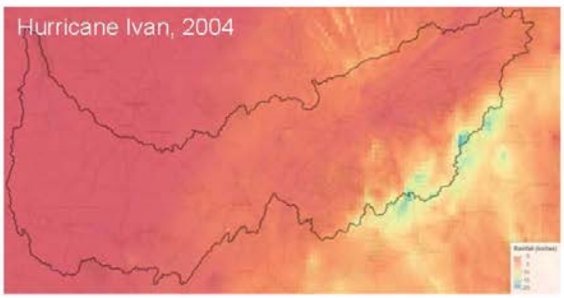
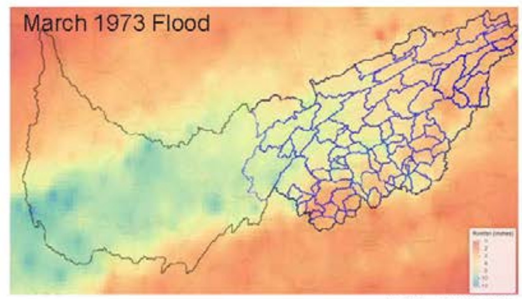
Storm Typing

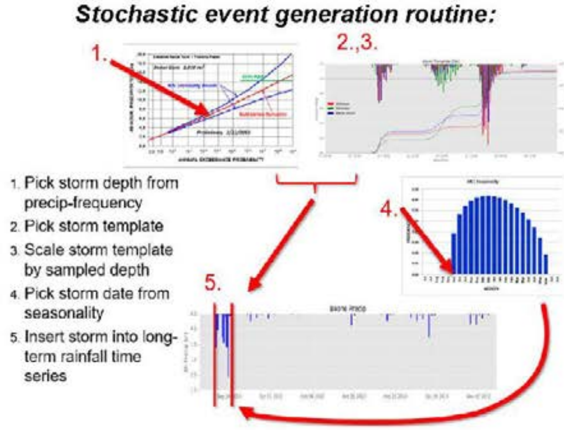
- The Tennessee Valley is subject to mixed populations of storms and floods
- Different types of storms have different spatial and temporal characteristics, which cause floods with differing impacts
- Separating the storm types reduces uncertainty in the PF relationships
- The tropical storm remnant PF analysis was the first ever conducted in the US specific to TSRs





Stochastic Simulation

Stochastic event generation routine:



- Simulate stochastic events until the headwater frequency curve converges
  - Intelligent sampling allocates additional samples to precipitation bins where it matters
- Simulate a stochastic event for each storm type
- Combine the frequency statistics for each of the three storm types into a single hazard curve

Current Work

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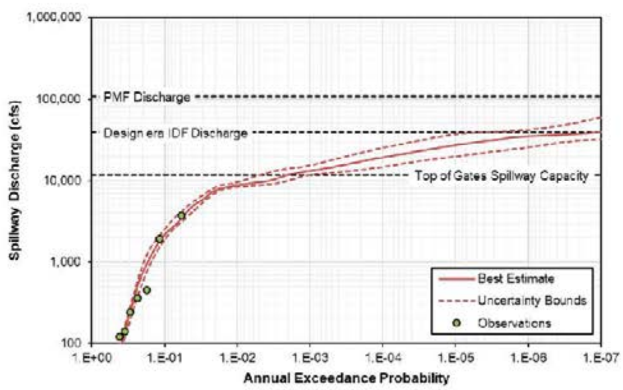
Practical Application – Dam A

The issue:

- Screening level analysis highlighted concerns with the spillway
- Baseline risk assessment identified an actionable level of risk
- The primary risk driving failure mode has a hydrologic loading
- Inflow hydrology is dominated by regional winter storms on the common end
- Summer thunderstorm complexes can be severe and drive risk for rare probabilities

The question:

- What can we do to modify our risk profile, and how much does it buy us?



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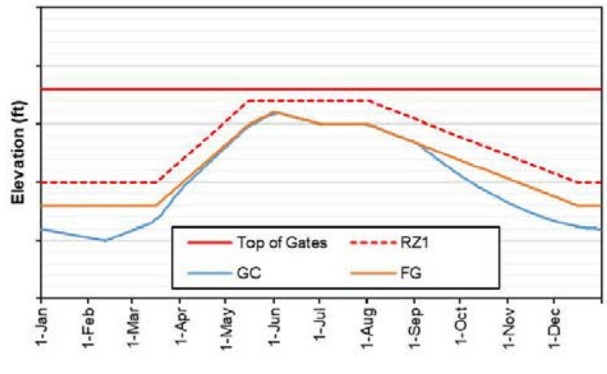
Dam A – operating policy

Operational Constraints:

- Limited pool control
- Turbines are not always available
- Discharges will be curtailed during rain events to help downstream
- Dam is tied in to operations downstream, and can be called on to change discharges
- Pool is low in the winter to control flooding
- Pool is high in the summer to facilitate recreation and water supply



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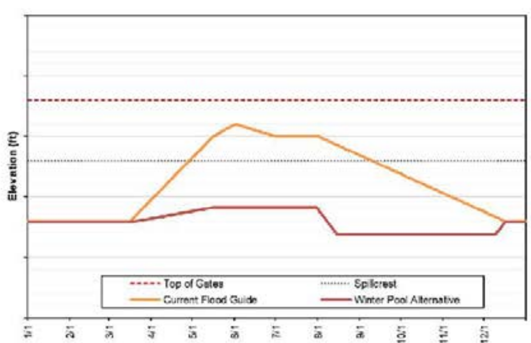
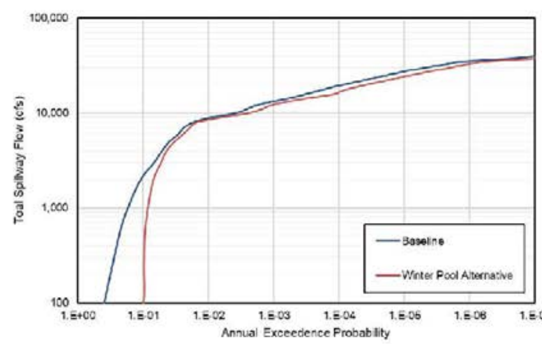
Dam A – operating policy

What if we just go to winter pool(ish) all year?





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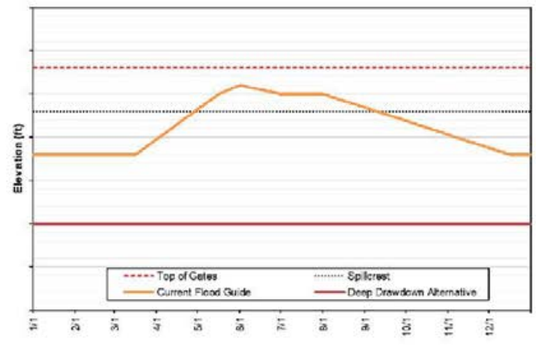
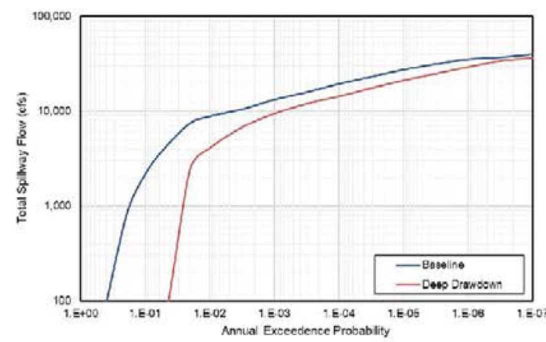
Dam A – operating policy

What if we draw down even further?





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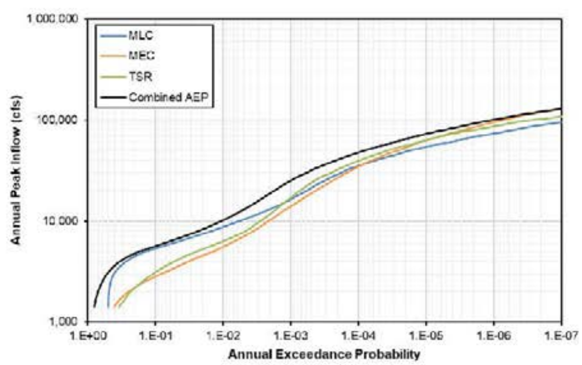
Practical Application – Dam B

The issue:

- Screening level analysis highlighted several potential risk drivers
- Risk analysis showed a secondary risk driver was due to hydrologic loads on the spillway
- Inflow hydrology can be dominated by different types of storms on different parts of the curve
- The auxiliary spillway may be more resilient than the primary, but requires a higher headwater to use

The questions:

- What can we do to modify our risk profile, and how much does it buy us?



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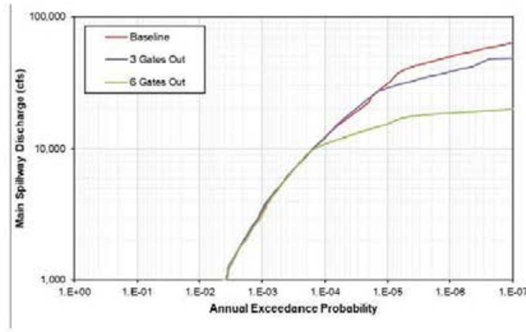
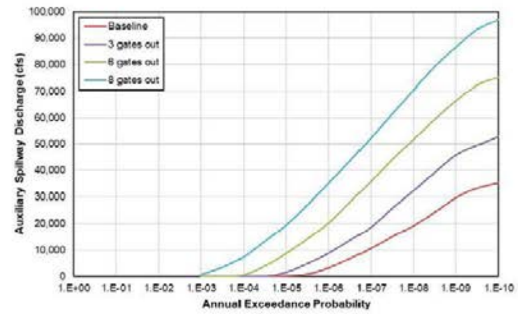
Dam B – Risk modification alternatives

Can we permanently tag out some of the main spill gates?





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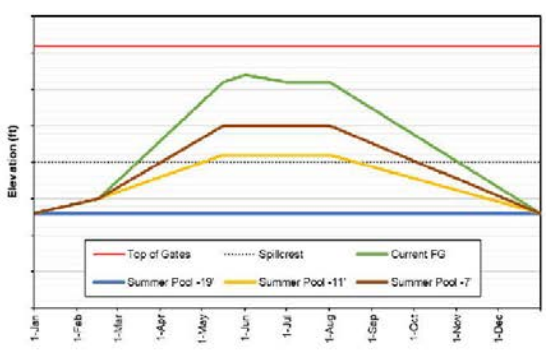
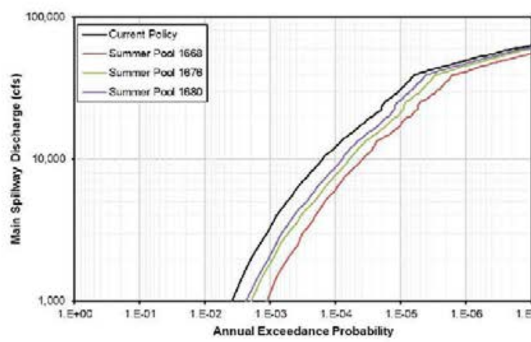
Dam B – Risk modification alternatives

What if we lower the pool?





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Lessons Learned

Lessons Learned

- Look at the data!
  - We have a black box. Black boxes are dangerous.
  - At Fontana Dam – 765,000 stochastic events, and they are all meaningful
  - How do you know you're right?
- Paleoflood and dendrochronology data is *indispensable*
- Solicit input from across the organization – don't work in a vacuum
- Let the questions drive the software development
- There is a huge range of potential applications

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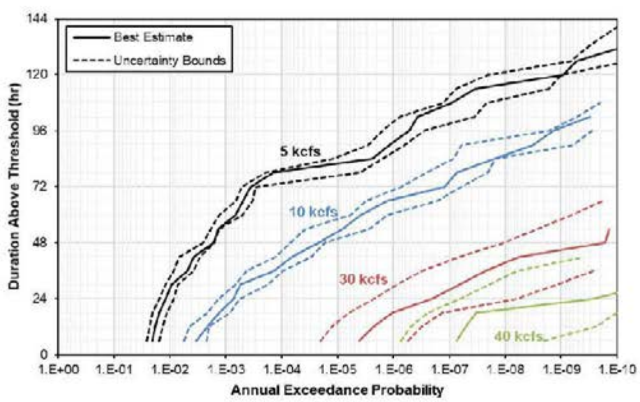
Future Work

Future Work

- Using the PFHA system to evaluate multivariate hydrologic frequency



Future Work

- Accounting for climate change and non-stationarity in the PF analysis
- Assessing transference of risk from one project to another
- Evaluating individual policy changes for River Management and communicating with stakeholders
- Optimizing system wide, multiple purpose operations

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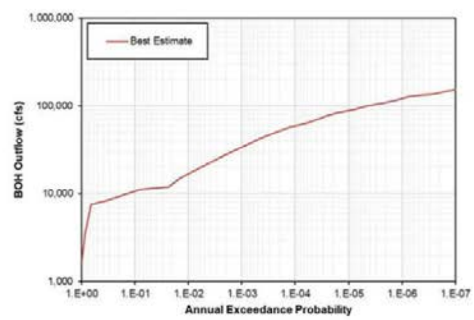
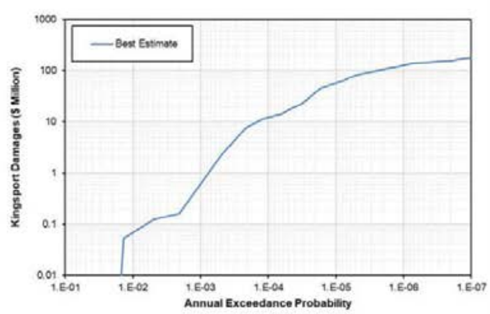
Future Work

- Leveraging PFHA in economic analyses
- Quantifying the economic benefit of the reservoir system compared to natural conditions





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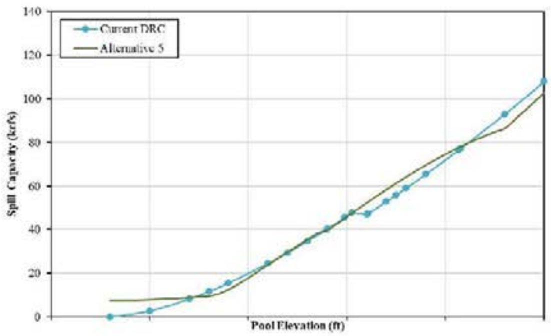
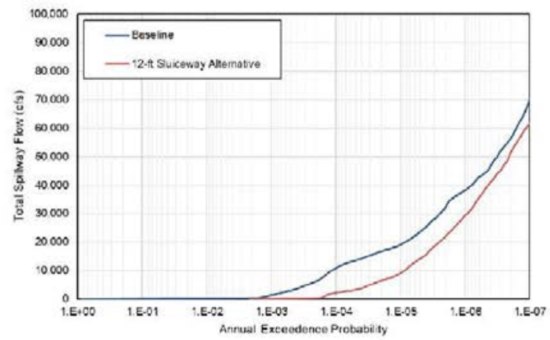
Future Work

- Using PFHA to inform the design process and evaluate infrastructure alternatives





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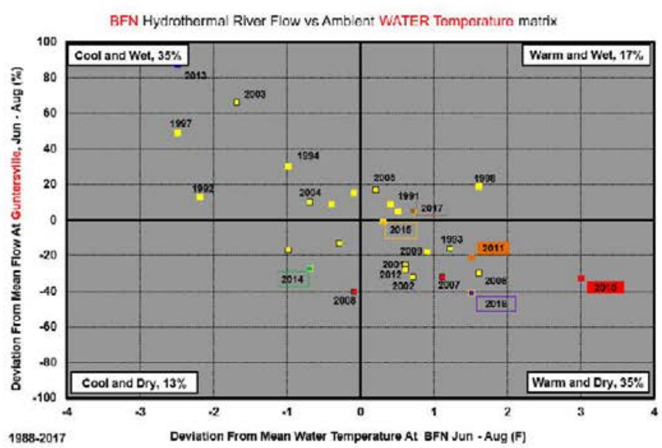
Future Work

- Using the PFHA framework and dendrochronology analysis to evaluate operational resiliency and quantify the economic benefit of water reliability.



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Future Work

- Incorporating *watershed scale* paleoflood data to better inform, refine, or validate PF relationships
  - FY19-20 – completed paleoflood studies immediately downstream from Guntersville Dam (big, main river project)
  - FY21 – Paleo study at Douglas Dam (French Broad River)
  - FY22 – Paleo study at Ocoee Dams 1&2 (Ocoee River)
  - FY23 – Paleo study at Norris Dam (Clinch River)
  - Go see Rachel Lombardi's presentation later today! Ask her lots of hard questions!

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Further Information

Miles Yaw
Tennessee Valley Authority
865.632.3786
myaw@tva.gov

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3.6.1.3 Questions and Answers

Question:
Can you provide more detail about the storm generation, the stochastic stage specifically, based on the historical storms catalog? How are they moved within the domain and their temporal dynamics modified to generate synthetic storms to feed the models?

<u>Miles Yaw:</u>
The stochastic storm generation is based on storm templates derived from historical storms that affected the Tennessee Valley service area. So, take the watershed and expand it a little bit. It was that catalog of historical storms. I think there were about 11,000 storms that went through the automated storm typing. The temporal and spatial characteristics of those storms were recorded and preserved. We have a 10-kilometer-spaced grid of transposition points upstream from the dams of interest. We take those historical storms and transpose them and center them over that suite of transposition points. The bigger the watershed, the more transition points we have. At Fontana Dam, for instance, we had eight or nine transposition points. We move those storms and put them on top of that point and then scale them according to the precipitation frequency (i.e., the sample depth for that event). So, the temporal and spatial characteristics don't change, but the intensity of the storm gets modified.

Question:
Could you please briefly discuss the computer hardware used and approximate simulation runtimes for your stochastic simulations?

<u>Miles Yaw:</u>
We use 6 cloud-based servers. Each one has 48 cores and, I think, they run at 2.5 GHz. The stochastic processes are all parallelized. As you sample these, you can put one RiverWare model and one weekly scheduling model on its own processor, so you get 48 of these things going at the same time. We do that across 6 servers. We typically will have nine simulations that are going: three best estimates for each storm type and uncertainty bound simulations. The

stochastic part of this process takes about four days total. It would be nice if we had a couple more servers. There isn’t a good way to parallelize the long-term simulation because it’s continuous hydrology. It's a 1000-year long simulation that also takes about four days. So, in terms of just pure compute time, it's roughly 8 days on 6 servers.

Question:
Are you also looking at different mitigation options such as modifications of spillways and embankments? It seems like the only parameter discussed in your presentation is normal pool elevations.

Miles Yaw:
We can get any hydrologic variable of interest we want out of the system if we know the need for that information in advance. Here we presented pool elevation and spill just for convenience of illustration. But we can look at whatever is wanted. There are two components in a dam safety analysis. There's the loading probability (hydrologic, seismic, etc.), and then there's also the system response. Things like spillway modification or embankment armoring would be characterized in the system response. The work I do specifically looks at the loading probabilities. Some of the things that we can look at are: what if we had a bigger spillway, or a deeper spillway? Those kinds of things. When you talk about hydraulic design, that can have a feedback mechanism to hydrologic risk on various variables. So, it's sort of two questions. We can consider risk modification actions that work on system response, and we can look at risk modification actions that look at hydrologic loading.

Question:
You said one of the most important lessons was to look at the data. What QA/QC do you do with your data before it's used in your RiverWare model.

Miles Yaw:
Our modeling system is built on a lot of products. There's the inflow forecasting model, the unit hydrographs, the SAC-SMA parameters, and all that kind of stuff. It's almost impossible for a single human to sit down and comprehend the whole thing altogether. So, each of the models the system is built on has been through a documented calibration and QC process. We had the system peer reviewed by John England and Jerry Stedinger back in, I think, 2017. Then the question became: Once the process has been peer-reviewed, can you now have a specific application to a specific dam peer reviewed to make sure that the system that we agree with is producing results that are reasonable? That's the process we're going through now. We have one of these studies going through an independent external review. But I don't think that will mean that we have QC’d it, we're done, and we never have to check it again. It's important to periodically come back and make sure we get more eyes on it. This is driving capital decisions worth millions of dollars. It must be right. So that's what we're doing there.

Question:
How far away from the Tennessee Valley can you take meteorological data such as rainfall or snowmelt? How far away from the Tennessee Valley are you importing and transpositioning data?

Miles Yaw:
The storm transpositioning domain was larger than the Tennessee Valley, but not substantially. Let's call it a rectangle that's maybe 50 miles wider on all the edges. The regional precipitation frequency analysis happened with rain gauges outside the Tennessee watershed too.

3.6.2 Presentation 3A-2: HEC-WAT as a Framework for PFHA

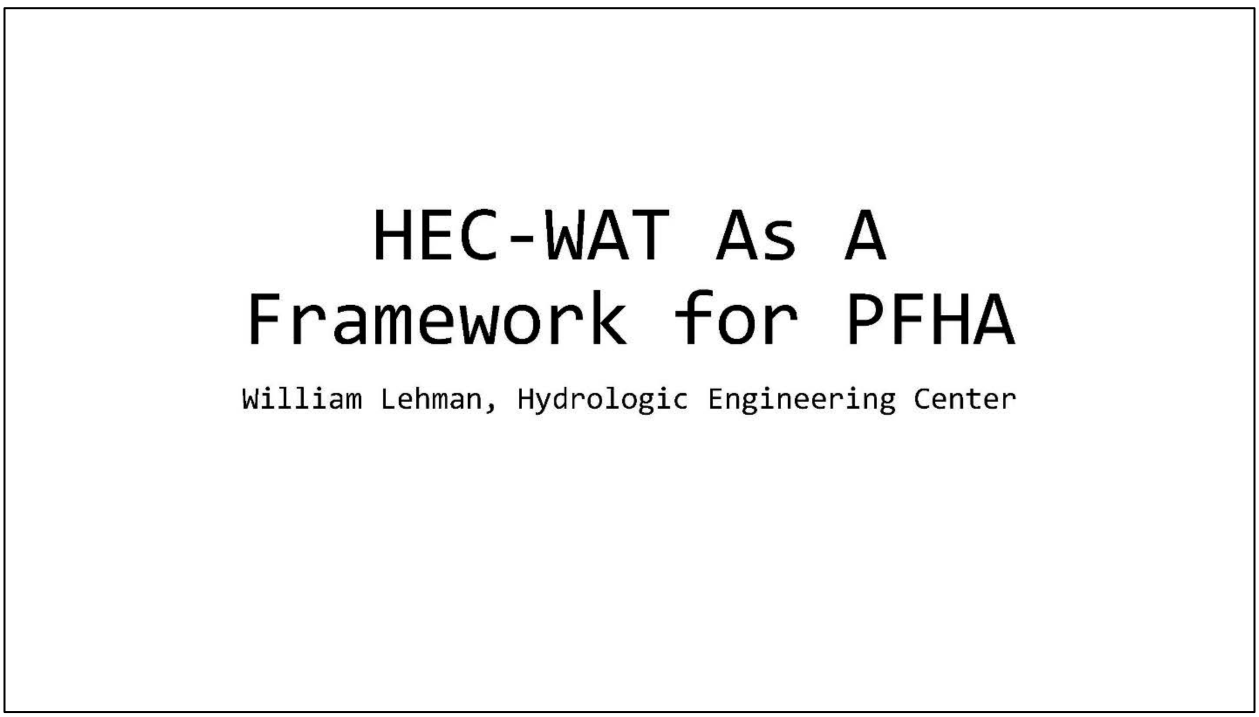
Authors: William Lehman, Sara O'Connell, Brennan Beam, David Ho, Leila Ostadrahimi, U.S. Army Corps of Engineers, Hydrologic Engineering Center

Speaker: William Lehman

3.6.2.1 Abstract

The Nuclear Regulatory Commission (NRC) requested HEC assistance with methods to include dam failure in their probabilistic flood hazard assessment (PFHA) process. Leveraging HEC's Watershed Analysis tool (HEC-WAT) the HEC project team is evaluating the impact of dam failures in the Trinity River watershed. The modeling includes evaluation of mixed population stochastic precipitation events. These weather events are input into HEC-HMS to convert precipitation into basin run-off which feed both HEC-ResSim and HEC-RAS. Randomized Dam failures impact the system response in HEC-ResSim operations and are routed through HEC-RAS to create the hydraulic hazard frequency curves. This presentation will focus on how the framework of HEC-WAT facilitates a Probabilistic Flood Hazard Assessment on the NRC riverine pilot project.

3.6.2.2 Presentation (ADAMS Accession No. ML21064A438)



HEC-WAT Mission and Vision

"Integrating Water Resource Management"

Mission

To provide a water resources tool that integrates engineering and consequence software to support a wide range of water resources applications, including watershed and systems based risk analysis.

Vision

Develop the primary integration tool for engineering and water resources studies.

2

HEC-WAT Goals

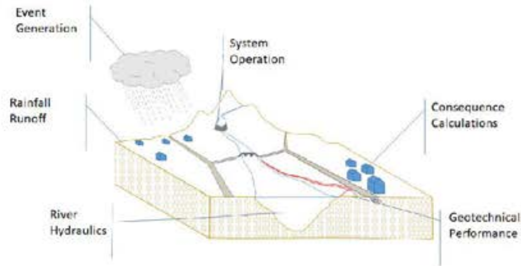
Goals

- An excellent user experience
- Provide innovative solutions to complex problems
- World class training and documentation
- Support field applications of HEC-WAT for real world problems
- Increase the combined capabilities of water resources software

3

Overview of HEC-WAT

Modeling a Watershed as a System

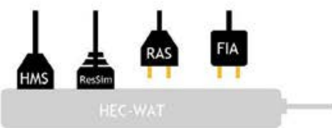


- **Plugin Architecture**
  - Supports Integration of any water resources software
- **Watershed Systems Approach**
  - Model Linking
- **Risk Analysis**
  - Nested Loops

1 outer loop B = a realization

inner loop A varies natural variability, computes Stage Frequency,

outer loop B varies knowledge uncertainty, computes distribution of Stage Frequency



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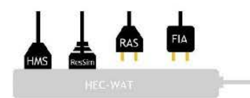
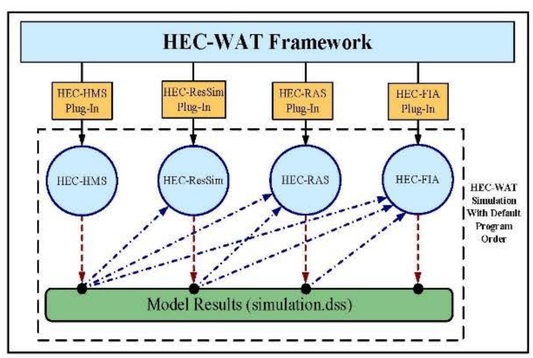
HEC-WAT Plugin Framework



Integrates Software

- Hydrology
- Reservoirs
- Hydraulics
- Consequences



Facilitates linking

- Inputs
- Outputs

Results Storage

5

Integrated Applications

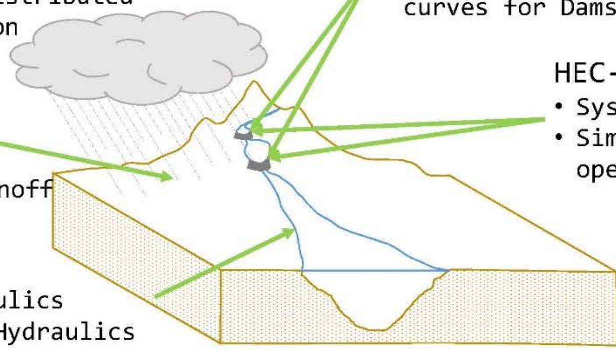
Weather Generator
- Stratified Stochastic Spatially distributed Precipitation hyetographs

Fragility Curve Editor
- Samples System Response curves for Dams

HEC-ResSim
- System Operations
- Simulate Post Dam breach operation

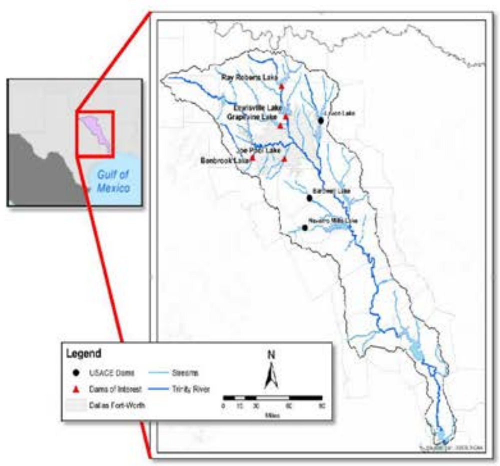
HEC-HMS
- Rainfall Runoff

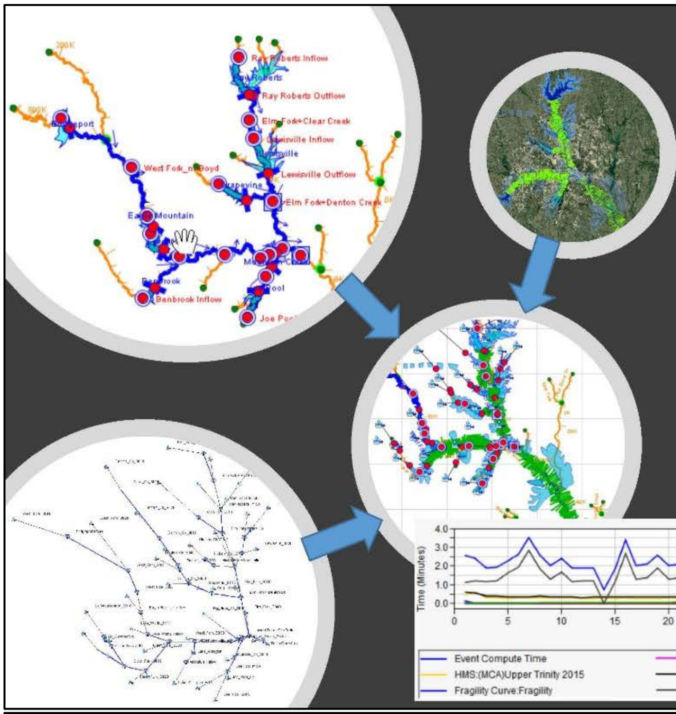
HEC-RAS
- River Hydraulics
- Dam Breach Hydraulics



Project Area

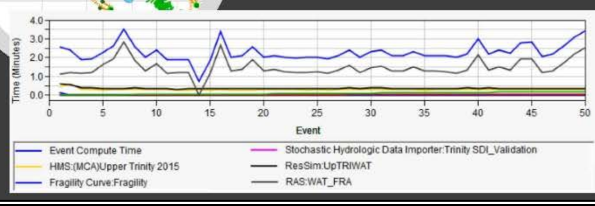
- Five Main USACE Dams
  - Ray Roberts
  - Lewisville
  - Grapevine
  - Joe Pool
  - Benbrook
- Weather Generator
- HEC-HMS
- HEC-ResSim
- HEC-RAS
- Other Plugins





Combining Watershed Processes in HEC-WAT

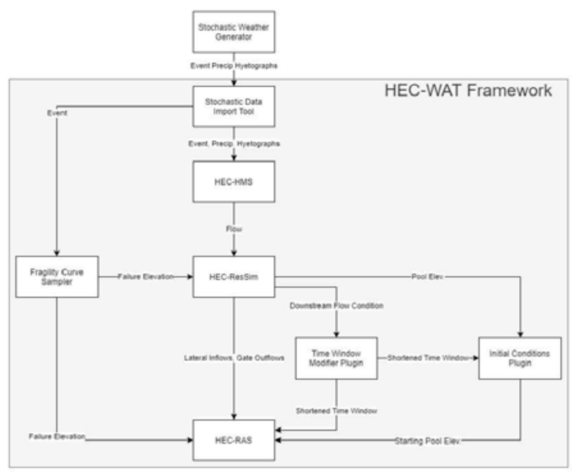
Application	Average Run time per event
HEC-HMS	~30 seconds
HEC-ResSim	~45 seconds
HEC-RAS	~90 seconds
Total (with all supporting plugins)	~175 seconds



Model Linking

Model Linking defines the flow of data

- Precipitation can be generated externally and imported
- Data can be consumed by multiple subsequent processes
- Simulation time windows can be shortened for computationally intensive components



HEC-WAT Flood Risk Analysis

Natural Variability (Aleatory)

Describing that things naturally vary

Knowledge Uncertainty (Epistemic)

Uncertainty describing what we do not know

10

HEC-WAT Flood Risk Analysis

Events

How we represent Natural Variability

Realizations

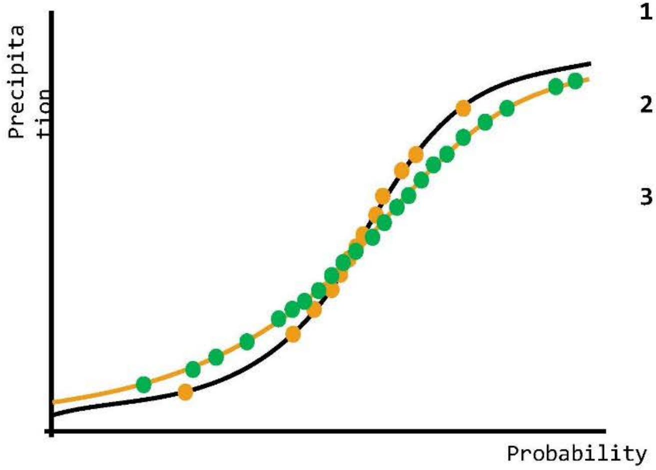
How we represent Knowledge Uncertainty

Simulation

Multiple Realizations of multiple Events

11

Events in a Realization



1. **Sample From Input Distribution**
   1. Use number of events in EYOR (ORANGE)
2. **Develop Analytical fit**
   1. Use same distribution type (ORANGE)
3. **Sample Events**
   1. Sample realization number of events (GREEN)

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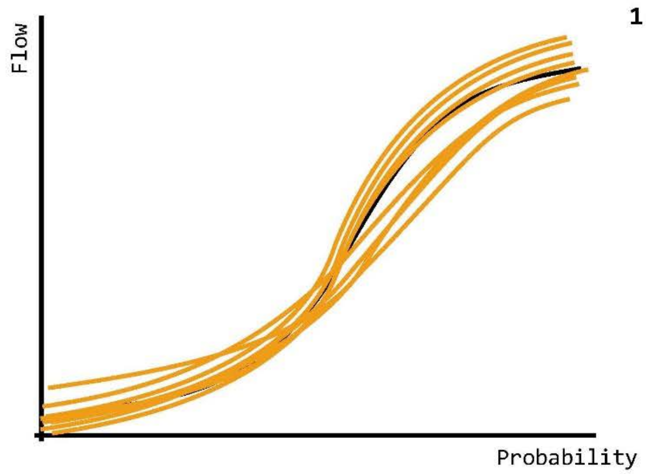
Realizations in a Simulation



1. **Repeat Process Many times**
   1. Realizations Reflect Knowledge Uncertainty due to EYOR (ORANGE)

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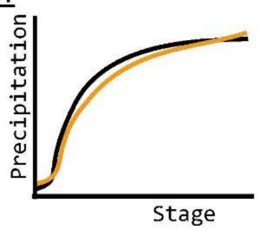
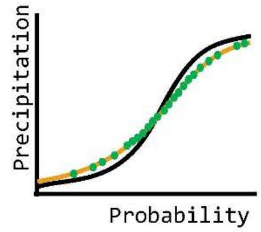
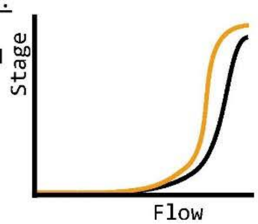
Precipitation to Hazard Frequency

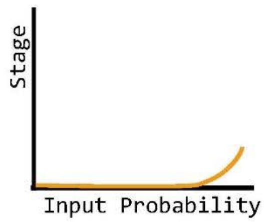
Uncertainties:
- Basin wetness
- Reservoir Operations





Uncertainties:
- Breaches
- Manning's N





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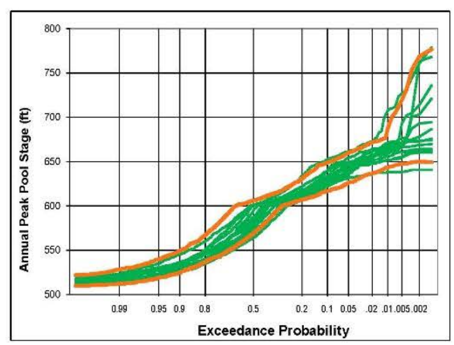
Pool Stage Example

sample of peak pool stage from **one realization**
(spans natural variability)
provides 1 estimate of peak frequency

sample of frequency curves from **all realizations**
(spans knowledge uncertainty)
provides distribution peak stage quantiles



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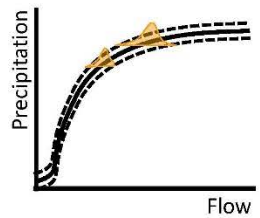
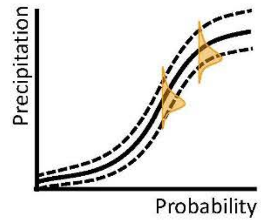
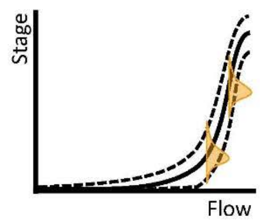
Knowledge Uncertainty Only?







What about Natural Variabilities other than Event Magnitude?
How does the WAT manage Natural Variabilities and Knowledge Uncertainties outside of precipitation or flow?

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Plugins Receive 2 Seeds Per Event

- A Natural Variability Seed and a Knowledge Uncertainty Seed

	Natural Variability	Knowledge Uncertainty
Flows	Annual Maximum Flow Snowmelt, Flow Forecasting	Flood Frequency Curve
Reservoir Modeling	Starting Storage / Elevation Demands (water, power)	Reservoir physical data: storage / elevation relation. release capacity
Channel Routing	Sedimentation Profile *Manning's n* Bridge Debris, Ice Thickness Dam/levee breeching	Weir, Gate, Bridge Coefficients Contract / Expans coefficients *Manning's n* Terrain Data

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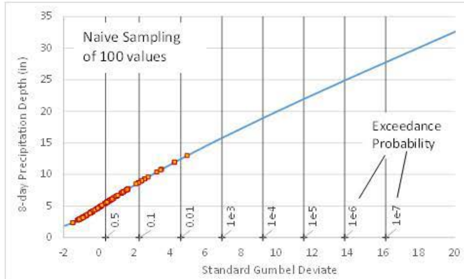
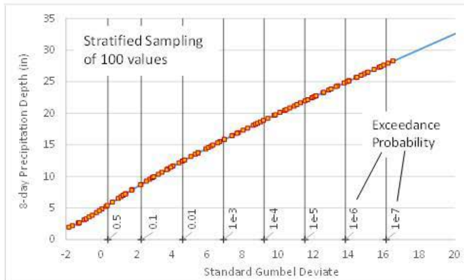
Stratification

- In order to achieve sufficient modeling samples we stratified the Natural variability loop





Conclusions

- HEC-WAT can produce Hazard Frequency curves that show the influence of dam failure.
- Stratified Sampling is necessary to reduce computational burdens
- HEC-WAT distributed computes need better error handling and system operation tooling
- It is difficult to link HEC-RAS and HEC-ResSim to properly account for flood wave volume and pool frequency.
- HEC-ResSim needs to be able to respect dam failure as part of the rule operations.

3.6.2.3 Questions and Answers

Question:
Do you need staff from the Hydrologic Engineering Center to run HEC-WAT, or can a user run HEC-WAT themselves?

William Lehman:

HEC-WAT is available for download from the HEC website (currently HEC-WAT Version 1.0) and anyone can download it. For the PFHA process presented here we're using version 1.1 internally. We can point to people who have successfully used it in the field, both within USACE and externally by contractors. We believe that anybody can use it, though it can get very complex. This system for the Trinity River is pretty complex and I don't foresee very many people using it at that level of complexity routinely until we provide better support on some of those features.

Question:
For the realization of events, what type of distributions are used?

William Lehman:
It depends upon the user's needs. For an unregulated system, if you're using a flow sampling technique, we would advise using a Log-Pearson Type 3 distribution as recommended in Bulletin 17 C. If you're modeling a regulated system, it should be an empirical distribution. We can support both of those within the hydrologic sampler plugin. In the Trinity River case, we were using the stochastic data importer to pull in data from precipitation developed by the weather generator. When considering precipitation, there's a lot of distributions that play from the Kappa to the normal distribution. So, it just depends upon the particular case and the particular application.

Question:
Another question is for dams in series. For instance, suppose you had two dams, A and B, for which you want to model a cascading failure scenario. Can the HEC-WAT model linkages be adjusted such that HEC-RAS-routed flows from A can be fed into HEC-ResSim for B in the HEC-WAT workflow?

William Lehman:
The answer is yes, but really the big question should be: is it appropriate? It depends upon the case. Programs are run sequentially in HEC-WAT; ResSim typically runs before RAS. You can add a second ResSim to operate based off the conditions of RAS to accommodate the type of workflow that you're saying. But that becomes kind of difficult. There's not a lot of feedback looping. We run these sequentially. One way to accommodate that is to put in systems within ResSim to operate based on what likely will happen within RAS. That's why we connected the fragility curve sampler to ResSim and RAS to feed the same information into them so they can operate as if A had failed and in the rule system we have under the condition of failure: how would ResSim operate and what would ResSim expect in terms of inflows?

Question:
Can you give a little more information on the weather generator? What time step is the weather generator run at? Is it a nonparametric bootstrap resampling or is it parametric? If parametric, how are you accounting for spatial correlation? What kind of run times are you looking at for running the weather generator?

William Lehman:
I'm an economist, so I'm going to pull my economist card. I don't know if I can answer every single question that you asked, but I can say that the output time step is hourly. It's being run in 50-year life cycles, so we're doing essentially continuous simulation for 50 years, sampled out of that. Of course, we're running a million total events, organized in realizations. Internally, the distributions are predominantly parametric, though there might be a few empirical ones in there. You will need to talk to Greg Karlovits for specifics on that. Spatial correlation is based on the historic storm datasets that were developed by MetStat. That would be controlling how those

storms are spatially distributed across the basin. Again, that would be another question for Greg. With respect to runtimes on the weather generator, for a million events it took us about 120 hours of compute time.

Question:
If you're interested in low frequency dam failure results, can you skew the sampling bias to reduce the computational effort?

William Lehman:
That's what we refer to as stratification. There's stratification and importance sampling, but we generally refer to that whole topic as stratification. We use a method very similar to what Rory Nathan wrote about a few years back. We do bias correct on the back end. For the Trinity, since it's being stratified external to WAT, we have a specialized plugin to de-stratify based off that technique. Within the WAT we also have native stratification techniques that operate through the hydrologic sampler and we have tools to automatically de-stratify there as well.

3.6.3 Presentation 3A-3: Structured Hazard Assessment Committee Process for Flooding (SHAC-F) for Probabilistic Flood Hazard Assessment (PFHA)

Authors: Rajiv Prasad[1], Philip Meyer[1], Kevin Coppersmith[2], Norberto C. Nadal-Caraballo[3], Victor M. Gonzalez[3], [1]Pacific Northwest National Laboratory, [2]Coppersmith Consulting, [3]U.S. Army Corps of Engineers, Engineer Research and Development Center, Coastal and Hydraulics Laboratory

Speaker: Rajiv Prasad

3.6.3.1 Abstract

The Pacific Northwest National Laboratory (PNNL), Coppersmith Consulting, and the U.S. Army Corps of Engineers Coastal and Hydraulics Laboratory (CHL) have completed the development of the structured hazard assessment committee process for flooding (SHAC-F). The process was developed to enable users to perform probabilistic flood hazard assessments (PFHAs) in a consistent, transparent, and reproducible manner, particularly with respect to the quantification and incorporation of uncertainties. The report focuses on three flooding mechanisms: (1) site-scale flooding from local intense precipitation (LIP), (2) riverine flooding, and (3) coastal flooding from storm surges.

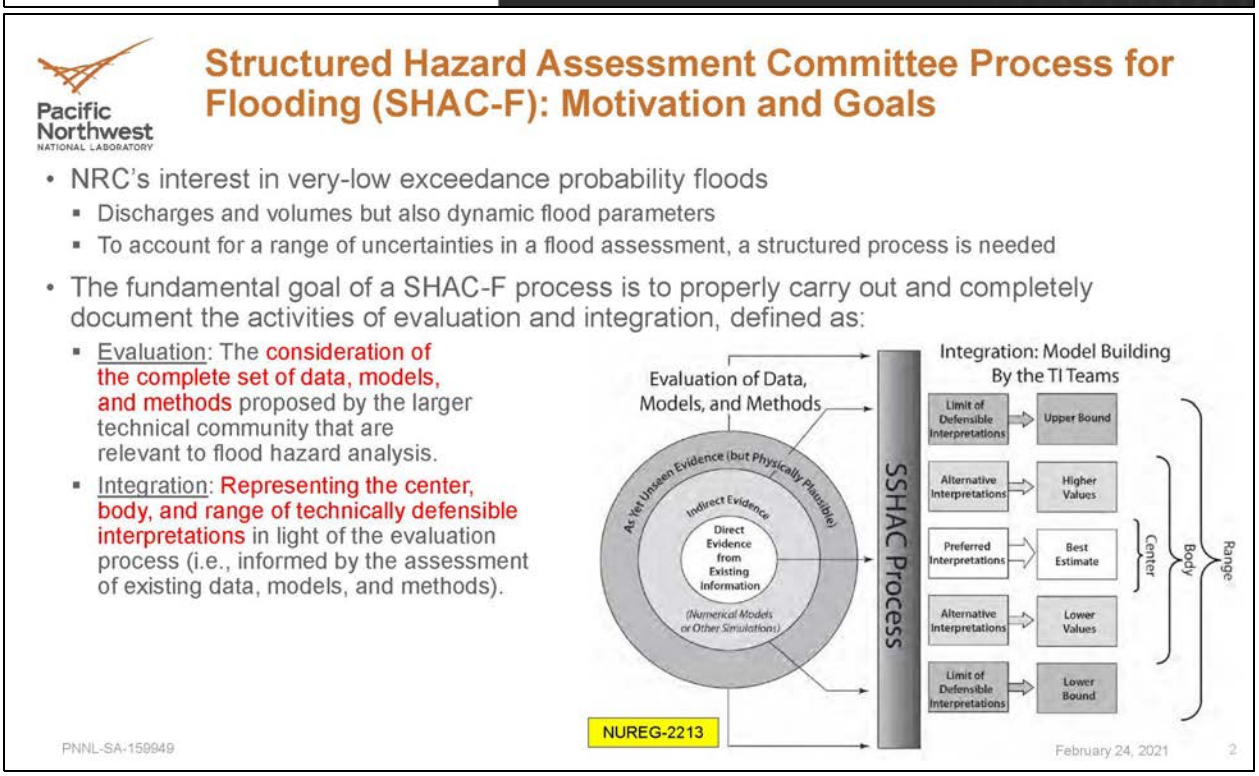
SHAC-F study levels are structured to explicitly support a variety of purposes. A Level 1 SHAC-F study is designed to support rapid decisions for screening and binning NPP structures, systems, and components (SSCs) into risk categories. A Level 2 SHAC-F study is designed to (a) replace a Level 1 SHAC-F study that did not adequately resolve screening and binning of SSCs of interest or (b) refine and/or update a Level 3 SHAC-F study with additional data, models, and methods. A Level 3 SHAC-F study is the most complex and is used to support external-flooding probabilistic risk assessments. All SHAC-F studies must capture the distribution of flood hazards, including both aleatory variability and epistemic uncertainty, that reflects the center, body, and range of technically defensible interpretations (CBR of TDIs).

In a Level 1 SHAC-F study, a frequency analysis using readily accessible data relevant to the flooding mechanism combined with a relatively simple site-scale hydraulic modeling may be performed by a small project technical team with expertise in statistical modeling, regional flooding, and site hydraulics. The participatory peer review panel (PPRP), a feature of the SHAC-F process, is also small and includes expertise in the relevant technical disciplines and uncertainty quantification. In a Level 2 SHAC-F study to replace a previous Level 1 study, additional data collection and model refinement in consultation with experts may be performed. The project team could consist of Technical Integration (TI) teams that consults with data and model experts. In a Level 2 SHAC-F study to refine and/or update a previous Level 3 study, the TI teams would evaluate and integrate additional data, models, and methods. Evaluation and integration may need consultation with data owners and model developers. In a Level 3 SHAC-F study, depending on the flooding mechanism, the project technical team consists of meteorology/probability and statistics/coastal modeling and hydrologic/hydraulic TI teams. The TI teams, led by a Project Technical Integrator, may need additional support for database and geographical information system management and specialty contractors for data collection or model simulations.

SHAC-F studies are thoroughly documented to (1) catalog all considered data, models, and methods; (2) describe the evaluation of data, models, and methods; (3) describe the technical bases of all models and methods; (4) describe the integration of data, models, and methods to

represent the CBR of the TDIs; (5) catalog all sensitivity analyses; and (6) provide the hazard results and instructions for their use.

3.6.3.2 Presentation (ADAMS Accession No. ML21064A439)



SHAC-F: Features

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- Five essential features provide regulatory confidence – that a hazard assessment has followed a sufficiently rigorous and transparent process that can be efficiently reviewed by the regulatory agency:
  1. **Clearly defined roles** for all participants, including the responsibilities and attributes associated with each role.
  2. **Objective evaluation** of all available data, models, and methods that could be relevant to the characterization of the hazard at the site. This will often include additional new data collected specifically for the hazard assessment. This process includes identifying the limits of the existing data, gaps in the existing data, and the resolution and uncertainties in the available data.
  3. **Integration** of the outcome of the evaluation process into models that reflect both the best estimate of each element of the hazard input with the current state of knowledge and the associated uncertainty. This distribution is referred to as the center, body, and range of technically defensible interpretations. This will generally involve the construction of hazard input models … that address both aleatory variability and epistemic uncertainties.
  4. **Documentation** of the study with sufficient detail to allow reproduction of the hazard analyses. The documentation must identify all the data, models, and methods considered in the evaluation, and justify in detail the technical interpretations that support the hazard input models.
  5. **Independent participatory peer review** is required to confirm that the evaluation considered relevant data, models, and methods, and that the evaluation was conducted objectively and without bias. The peer review is conducted following a "participatory" or continual process throughout the entire project.

NUREG-2213

SHAC-F: Levels

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- Three levels
- Levels address purposes of various NRC flood reviews
- Data, methods, project teams, and levels of effort commensurate with complexity of reviews
- Probabilistic flood assessment
- Incorporation of aleatory and epistemic uncertainties
- All three levels result in estimation of a family of flood hazard curves

Table 2.1. Delineation of SHAC-F studies.

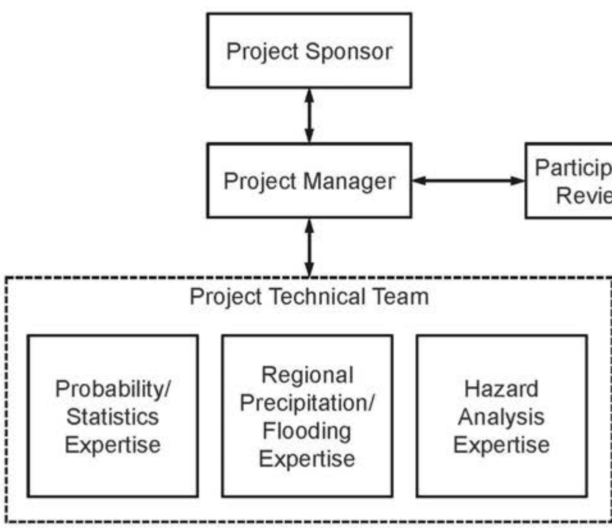
Study Aspects	Structured Hazard Assessment Committee Process for Flooding (SHAC-F) Levels		
	1	2	3
Purpose	Screening, decide to update or go to higher level Example: binning flood hazards in high- or low-risk categories	Replacing and updating and/or refining existing analyses Example: replacing a previously performed Level 1 study, updating and/or refining an existing Level 3 study	Supporting design and/or providing input to probabilistic risk assessment (PRA) Example: flood hazard assessment for new reactor applications
Expected Results	Family of hazard curves plus associated effects for a particular structure, system, and component (SSC) being analyzed	Family of hazard curves plus associated effects for multiple plant SSCs or locations	Family of hazard curves plus associated effects for sitewide hazards
Data	Readily accessible data relevant to the chosen assessment approach Example: existing topographic data, precipitation estimates, discharge measurements, stage-discharge relationships, tide data	More extensive effort to compile existing data, contact Resource Experts[a] for relevant data Example: more refined topographic data, site-specific precipitation, data to support site-specific simplified hydraulic/ hydrodynamic models	Consider collecting new data relevant to flood hazard assessment Example: Light Detection and Ranging (LIDAR) surveys, remote sensing, bathymetric surveys, site-specific precipitation, data to support refined hydrologic/hydraulic/ hydrodynamic models
Models and Methods	Statistical methods, at-site or regional precipitation-frequency analyses, simplified process-simulation models	Statistical and simplified process-simulation models, alternative frequency distributions, consider spatial variation in simulation models and nonstationarity	Alternative conceptual flood simulation models, coastal hydrodynamic models, spatial/temporal resolution to support PRA, sitewide hazards and associated effects, nonstationarity
Aleatory Variability Sources	Precipitation, tide data	Precipitation, storm parameters, initial conditions, streamflow	Precipitation, storm parameters, initial conditions, streamflow, boundary conditions
Epistemic Uncertainty Sources	Measurement uncertainty, alternative frequency distributions with parameter uncertainty, stage-discharge relationship uncertainty	Measurement uncertainty, alternative frequency distributions, model parameter uncertainty	Measurement uncertainty, alternative frequency distributions, model parameter uncertainty, alternative process representations
Technical Project Team	Small (e.g., two: one with expertise in flood-frequency modeling, one in regional hydrology/hydraulics)	Small to possibly multiple teams (for update and/or refinement of a Level 3 study)	Larger with Technical Integration[a] teams and a Project Technical Integrator[a]
Participatory Peer Review Panel	Small (e.g., two: one with expertise in flood-frequency modeling, one in regional hydrology/hydraulics modeling)	Two/more reviewers (e.g., one/more for flood frequency, one/more for regional analyses and simulation modeling)	Larger team of reviewers (e.g., precipitation and runoff experts, experts in use of runoff/hydraulic/hydrodynamic models, PRA expert)

(a) SHAC-F terminology is defined in Chapter 4.

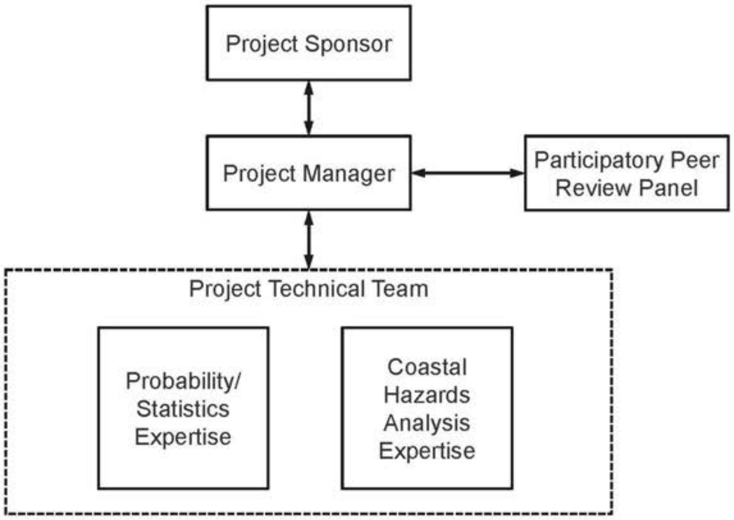
SHAC-F: Key Roles

- **Project Sponsor**: Has a need for PFHA; funds the SHAC-F study; owns the products
- **Project Manager**: Responsible for successful execution of the SHAC-F study
- **Project Technical Integrator**: Responsible for overall technical execution of the SHAC-F study
- **Technical Integration Lead and Team Members**: Responsible for technical performance of an aspect of the flood hazard assessment
- **Hazard Analyst and Specialty Contractor**: Responsible for analyses, calculations, and computations
- **Resource Expert**: Owners or custodians of data, models, and methods
- **Proponent Expert**: Advocates of models and methods relevant to the SHAC-F study
- **Participatory Peer Review Panel**: Responsible for ongoing, independent review of data, models, and methods; assures that the SHAC-F approach was followed

Level 1 SHAC-F Study – Project Team Structure (LIP and riverine flooding)



Level 1 SHAC-F Study – Project Team Structure (coastal flooding)



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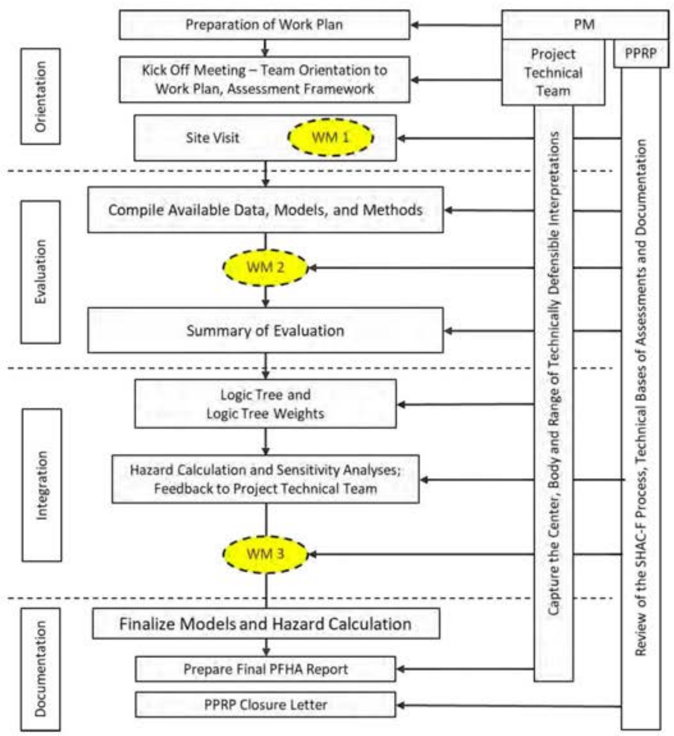
Level 1 SHAC-F Study: Workflow



WM: Working Meeting

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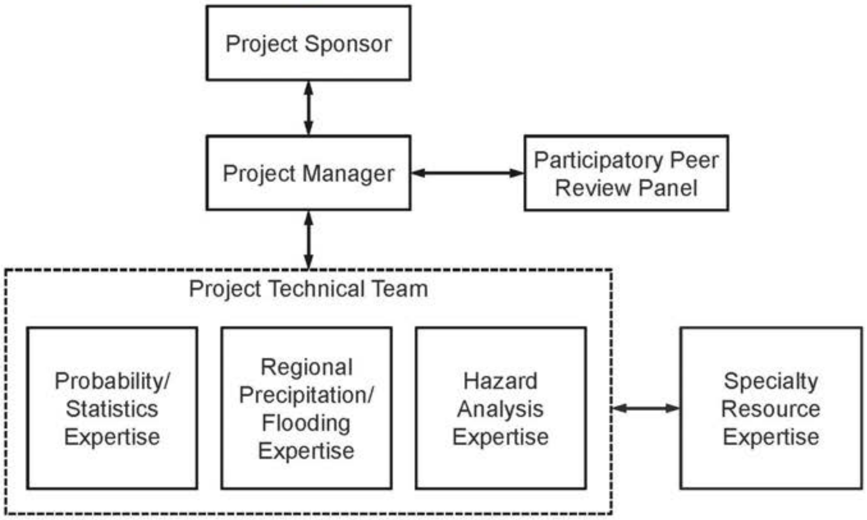
Level 2 SHAC-F Study – Project Team Structure for Replacement of a Level 1 Study (LIP and riverine flooding)



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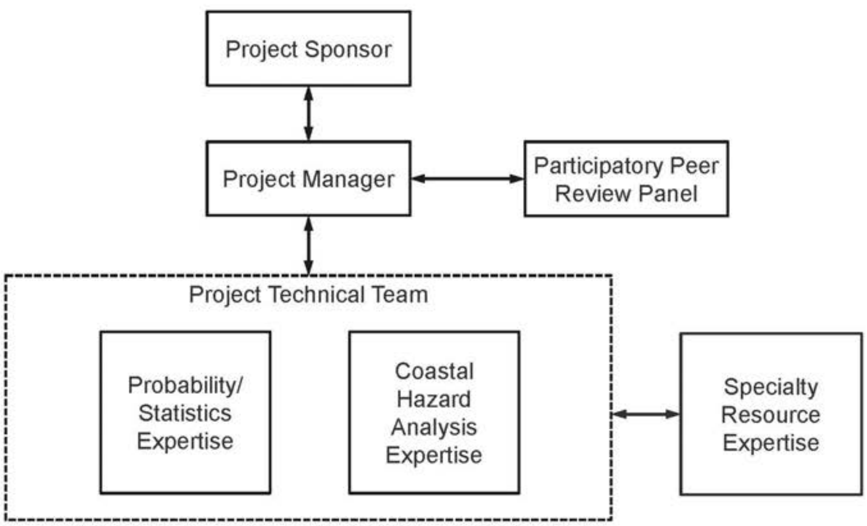
Level 2 SHAC-F Study – Project Team Structure for Replacement of a Level 1 Study (coastal flooding)



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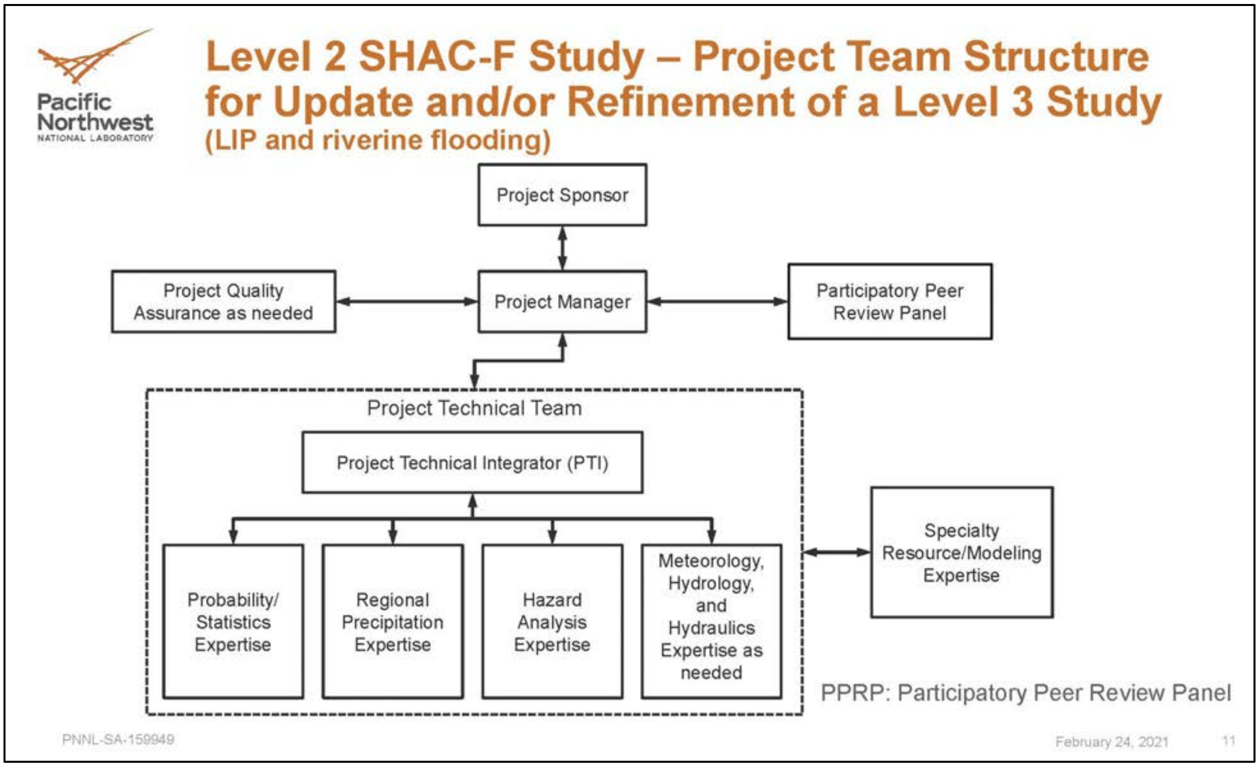
Pacific Northwest
NATIONAL LABORATORY
Level 2 SHAC-F Study – Project Team Structure for Update and/or Refinement of a Level 3 Study
(LIP and riverine flooding)
Project Sponsor
Project Quality Assurance as needed
Project Manager
Participatory Peer Review Panel
Project Technical Team
Project Technical Integrator (PTI)
Probability/ Statistics Expertise
Regional Precipitation Expertise
Hazard Analysis Expertise
Meteorology, Hydrology, and Hydraulics Expertise as needed
Specialty Resource/Modeling Expertise
PPRP: Participatory Peer Review Panel
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February 24, 2021
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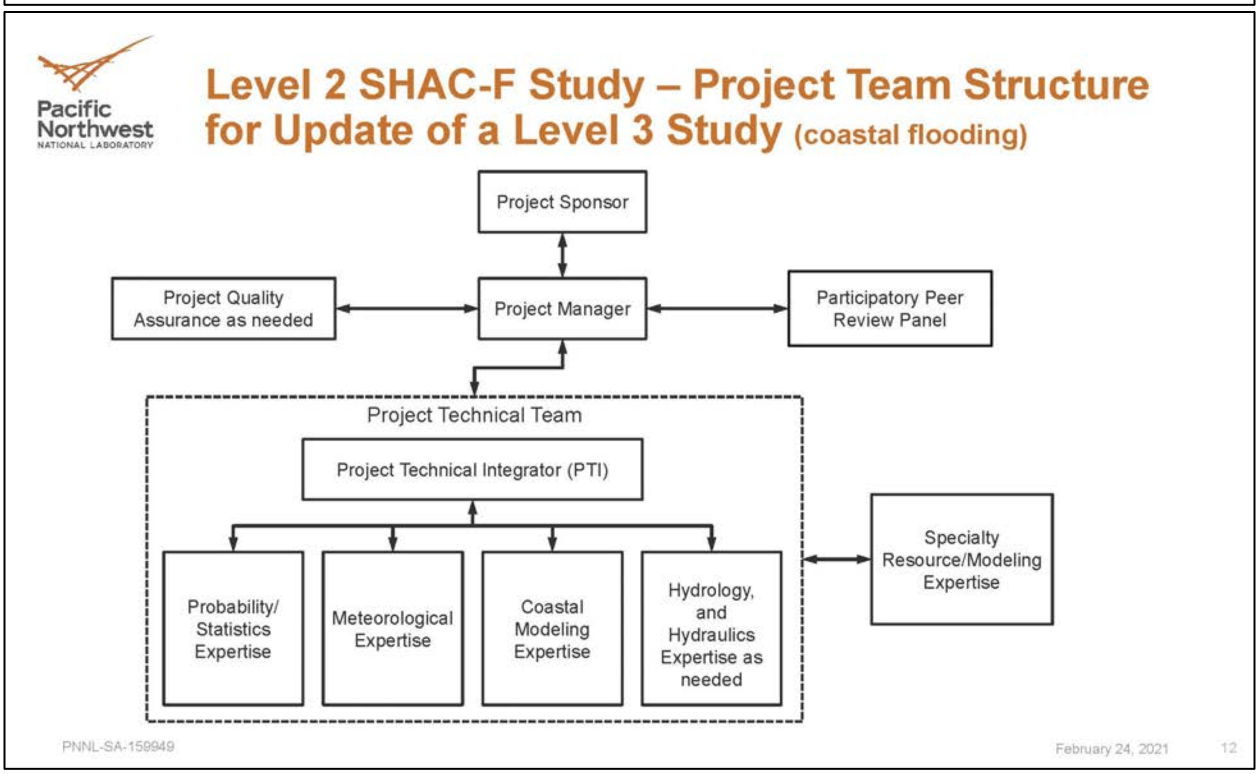
Pacific Northwest
NATIONAL LABORATORY
Level 2 SHAC-F Study – Project Team Structure for Update of a Level 3 Study (coastal flooding)
Project Sponsor
Project Quality Assurance as needed
Project Manager
Participatory Peer Review Panel
Project Technical Team
Project Technical Integrator (PTI)
Probability/ Statistics Expertise
Meteorological Expertise
Coastal Modeling Expertise
Hydrology, and Hydraulics Expertise as needed
Specialty Resource/Modeling Expertise
PNNL-SA-159949
February 24, 2021
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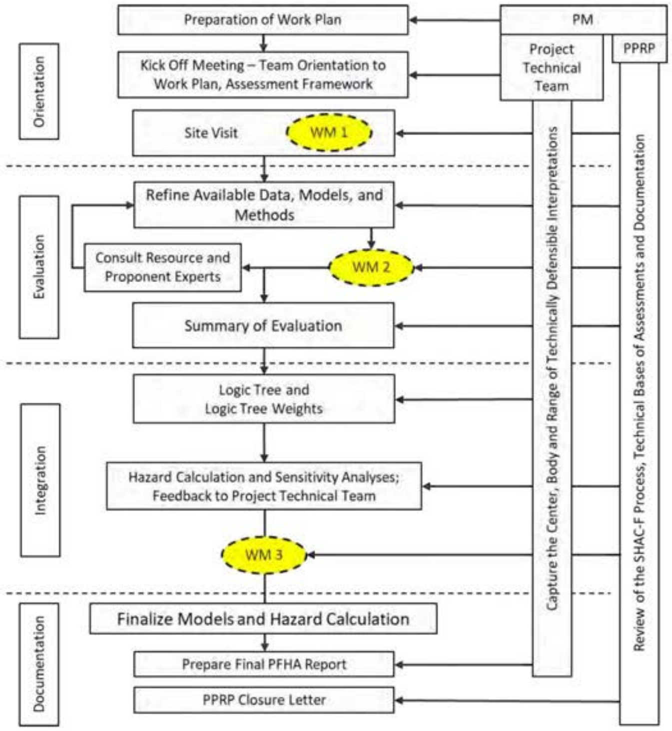
Level 2 SHAC-F Study: Workflow



WM: Working Meeting

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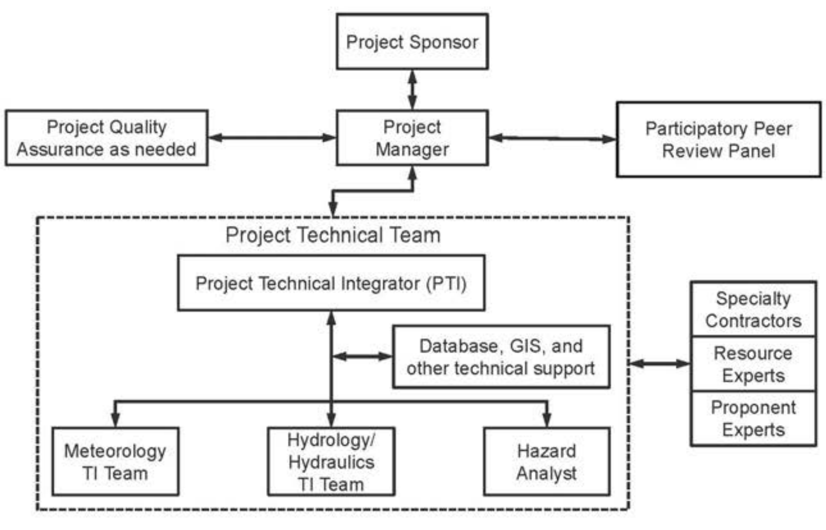
Level 3 SHAC-F Study – Project Team Structure

(LIP and riverine flooding)



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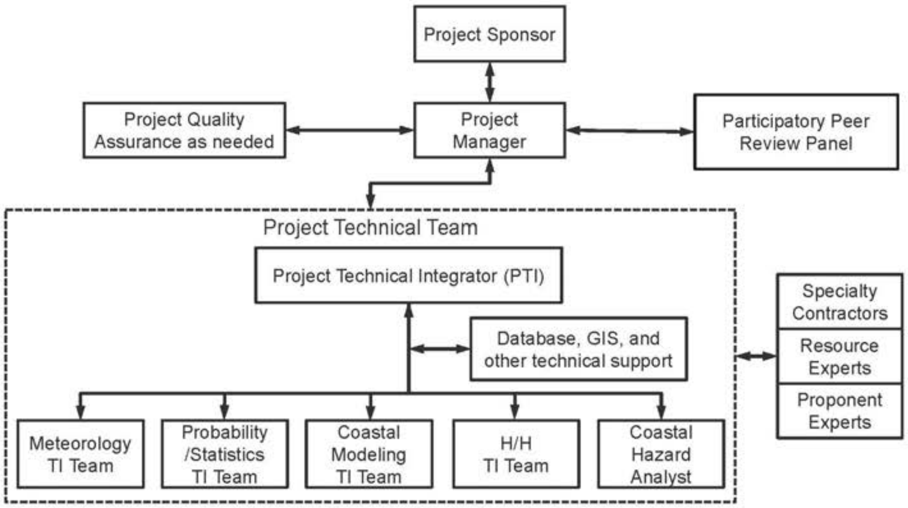
Level 3 SHAC-F Study – Project Team Structure
(coastal flooding)



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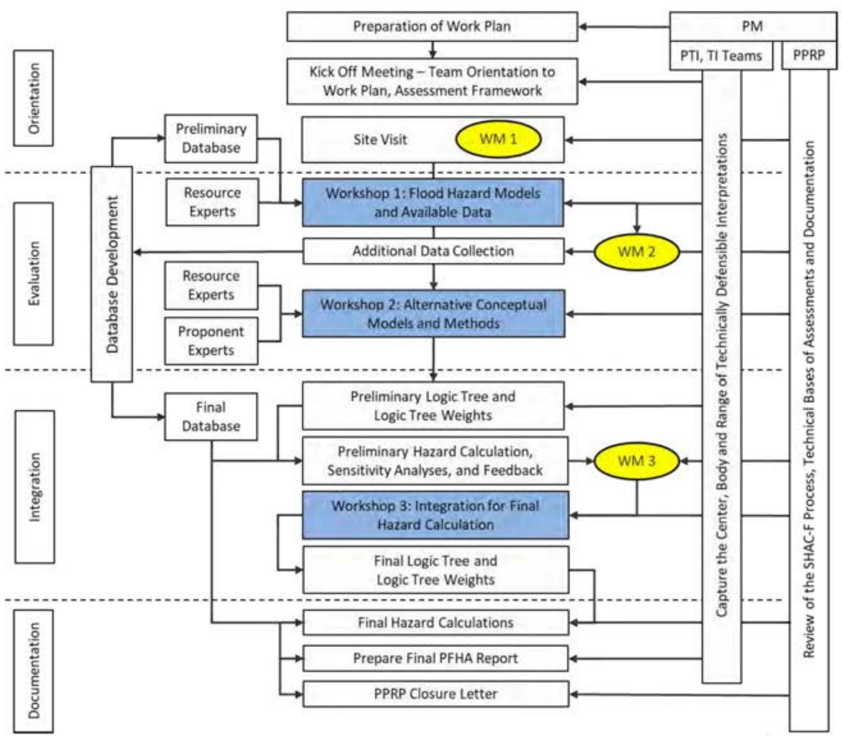
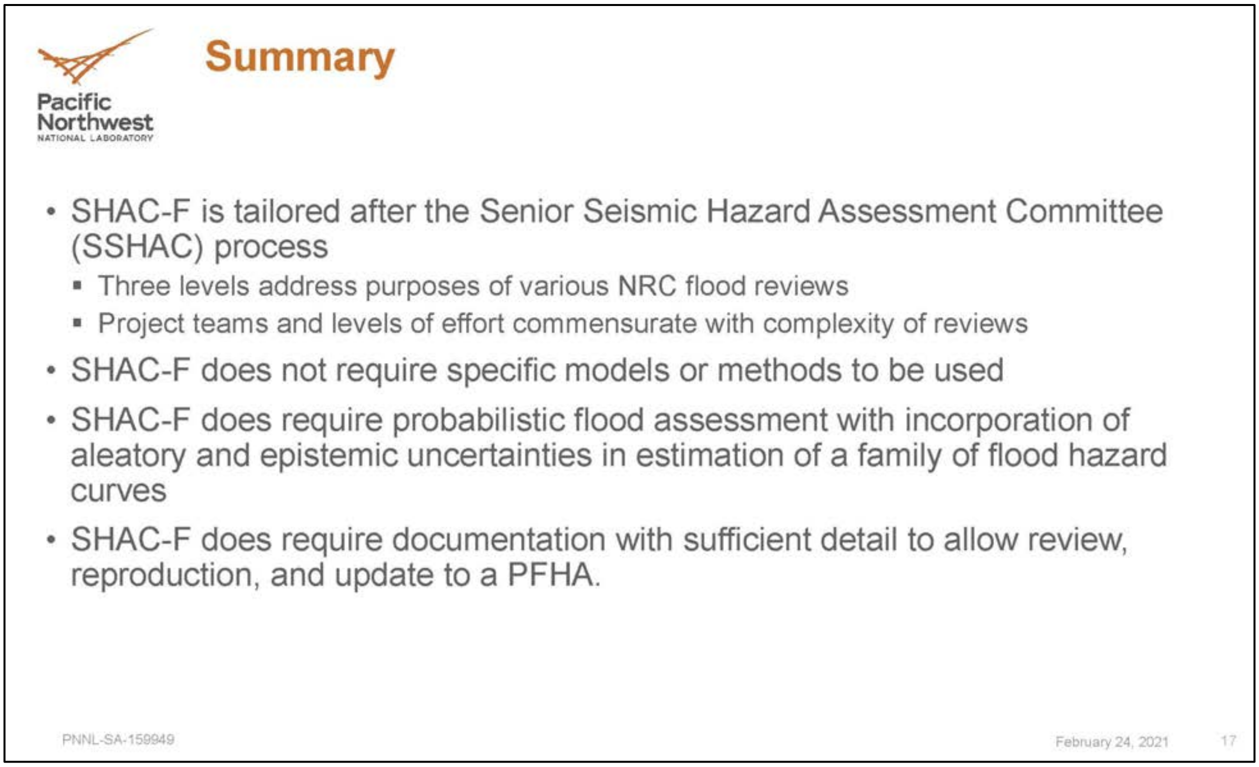
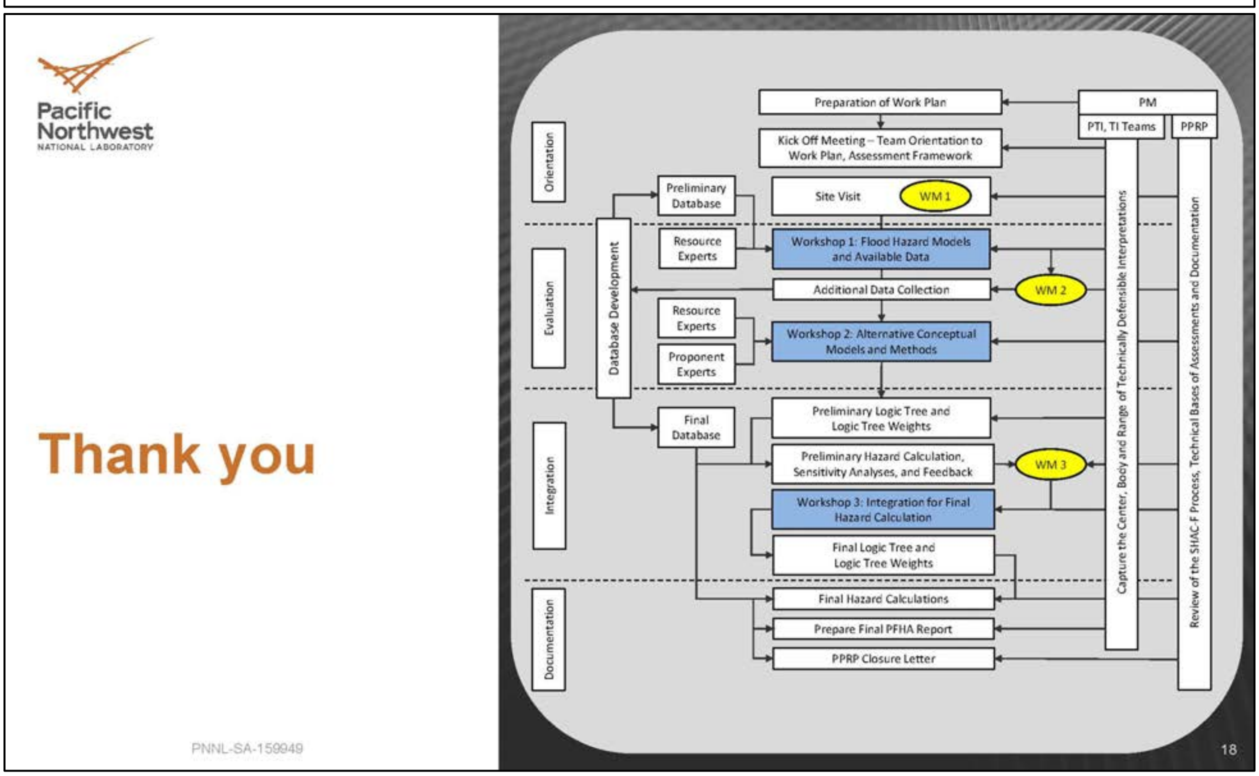
Level 3 SHAC-F Study: Workflow



WM: Working Meeting

PNNL-SA-159949 16





3.6.3.3 Questions and Answers

Question:

People are familiar with the SSHAC process for seismic hazard assessment. What are some significant differences between the SSHAC process for seismic hazard assessment and the SHAC-F process for flooding?

Rajiv Prasad:
When we were doing this project, there were a couple of things that stood out to us. One was that the SSHAC approach was not familiar to hydrologists. That is a significant difference when you bring flood analysis experts and hydrologist into this framework of performing PFHA's. You need to get them to alter their thinking a little. For example, if a team performs a PFHA, they go about their business collecting data and they usually have preferred sets of models and methods that they can apply to it. They can also consider aleatory and epistemic uncertainties, but that is from their own point of view. The central point of the SSHAC process is that you are trying to represent the center, body, and range of the technically defensible information (CBR of TDI), which goes beyond just one person or a team that does the analysis and tries to represent the complete range of technically defensible ways to approach the hazard assessment in the larger technical community. So that is one difference and we needed to explain that to the people that were participating in this study. The second thing that was very important to us was flipping around some of the ways in which SSHAC workshops are conducted and the purposes of those workshops, particularly at Level 3. In the seismic SSHAC process, you basically evaluate data, models, and methods first and then you build your own models to perform the analysis. From our point of view, in the way you perform flood hazard assessments, the model you use sort of drives the data that you need. So, if you go back and look at our first workshop, we wanted to put both data and models together and have a conversation about it to figure out what exactly are the appropriate models, what datasets would be needed to drive those models and then go forward from there. Those are two major differences between the seismic process and the flooding aspects of it.

Question:
Could you briefly mention costs, going from Level 1 to Level 2 to Level 3? Obviously, you have added complexity and additional tasks. What can you say in a relative sense as to the cost of going from Level 1 to Level 2 and from Level 2 to Level 3?

Rajiv Prasad:
That's a question that frequently comes up related to SHAC-F. The simple answer is we don't know yet. That said, if you look at the way that I described how these assessments would be done, Level 1 SHAC-F involves very small teams. The only part added to what is regularly performed today would be the addition of the participatory peer review process (PPRP). The PPRP would add to the cost of the study, but I don't think it adds a lot. So, in a relative sense, that is what I can offer for now. As you go to Level 2 and Level 3, it depends on the purpose of the study. Level 3 is obviously the most complicated, and I would expect that to be more expensive, in relative terms.

Question:
How does SHAC-F fit in with the current PRA peer review process which is required by the regulations? What is that relationship?

Rajiv Prasad:
The way I see SHAC-F is that it provides a consistent and transparent way to perform a probabilistic flood hazard assessment. What that flood hazard assessment would do is provide you the initiating mechanisms for the external flooding aspects of PRA. I know that some of these standards have been put in place now (are either in process of being reviewed or already published) that talk about external flooding providing input to the PRA process. So, the PRA

peer review process would be something that would happen in the PRA and the PFHA, if it is done using the SHAC-F process, has its own PPRP process that sort of maintains the consistency. If you were to perform these analyses at different sites for different plants and things like that. So, in my mind, the PPRP process that happens in the SHAC-F process is distinct and sort of self-contained within PFHAs and is in parallel to the PRA review.

3.6.4 Modeling Frameworks Panel Discussion

Moderator: Thomas Nicholson, NRC/RES/DRA

Panelists:

Miles Yaw, Tennessee Valley Authority (TVA)
William Lehman, U.S. Army Corps of Engineers (USACE)
Rajiv Prasad, Pacific Northwest National Laboratory (PNNL)

Question (to William Lehman):
There's a lot of interest in the scale of the applications of HEC-WAT. You showed us one example in the southwestern part United States. Have you tried it in other areas of the United States under different climatic conditions and different scales?

William Lehman:
One particularly large study has been performed to support the Columbia River Treaty. That study was conducted by the USACE Northwestern Division. It spans three states and includes the Columbia and Snake rivers. And of course, it has different climatic conditions. It's looking at snow melt, for instance. It's looking at long-term simulations on a large system. Another example is the Missouri River. There is a HEC-WAT model that spans the length of the Missouri River. That's a pretty big watershed. It's similar to the Columbia River in terms of its forcings, though that does change as it gets into the Midwest. They have a different strategy for their stochastic hydrology. We also did a really small one, less than 16 square miles, in Hawaii. A very different type of system altogether. So, I would say we span the gambit of large scale to small scale with WAT applications.

Question (to Rajiv Prasad):
One of the issues you brought up was the ability to characterize and get distributions for the center, body, and range for the flood hazards. How do you determine how much confidence you have that you've adequately characterized the center, body, and range? What steps to take to check to see if you have that confidence?

Rajiv Prasad:
That you have completely captured the distribution of the hazards in a particular study is a very difficult thing to prove; that you have the correct and complete distribution. Now, that said, the process that SHAC-F goes through gives you confidence that there have been multiple interactions, that the data models and methods have been adequately evaluated not only by the project team, but their interactions with both the PPRP and the larger technical community. You bring in resource experts (custodians of data) and you bring in proponent experts that tell you about the strengths and weaknesses of models. The SHAC-F documentation process gives confidence that this whole process has been performed transparently. So that's the only way to say that we did our best, we arrived at the CBR of TDI. If there is evidence later that these need to be updated, you can go back, look at all the justifications that were initially used, and then update them as necessary.

Question (to Miles Yaw):
Are you able to use the TVA's risk-informed decision-making approach to look at environmental aspects in addition to dam safety? For example, using it during a drought period to regulate operation of nuclear and coal-fired power plants in the Tennessee Valley (in addition to the dams/reservoirs). What are your thoughts?

Miles Yaw:
We can, although I have not been involved in that yet. Risk-informed decision making at TVA is relatively young, so it may just be a case of the opportunity hasn't arisen yet. We don't want to get in the box where we are only thinking about extreme floods because TVA's operations are at risk from severe and prolonged droughts. That's one of the reasons that we went through the dendrochronology analysis, trying to use long-term tree ring studies to look at how dry or wet can these periods get? It doesn't fit neatly in the PFHA system, at least in terms of the stochastic event sampling. But it does fit in the long-term synthetic hydrology. I showed that plot in my presentation, just as an example. There is a very clear correlation between how dry it gets and what the maximum ambient temperature is in the river, and that can threaten operations. You can also look at water supply reliability, in terms of economics and its impact on navigability. It also comes into play when we're looking at risk reduction alternatives at various projects. In Tennessee Valley, TVA operates 10 head-water reservoirs, and they have this equitable balancing scheme where waters are released late in the summer equitably between the reservoirs to meet minimum flow requirements on the lower mainstem of the river. If you were to have a risk reduction activity at one dam that takes storage out of the cumulative reservoir storage, you may have jeopardized your ability to meet minimum flow requirements downstream. So, the modeling system really allows us to balance all the objectives across the entire system to meet environmental or navigation, or any one of TVA's operations.

Question (to William Lehman):
I'm interested in the use of HEC-WAT by other agencies. For instance, yesterday we heard about the USGS doing a study in the Delaware River basin. Are you using any of your models to help the USGS do their study of that watershed?

William Lehman:
I'm not sure I know exactly which Delaware River study you're referencing (it gets studied a lot). I'm not aware of USGS using HEC-WAT on the Delaware. However, FEMA is considering a project to model the entire state of Delaware with HEC-WAT, which will include part of the Delaware River basin. We do work with other agencies when it's appropriate and would support that as far as it is fit for purpose.

Question (to William Lehman):
I'm interested in how to integrate external hydrologic events in HEC-WAT. How adaptable and how flexible is your modeling framework to bring those external events in?

William Lehman:
In general, that's why we developed the stochastic data import tool, to allow for any kind of externally developed hydrology to be imported into HEC-WAT. Our hydrologic sampler and other event-generator-type plugins also allow for the user to specify boundary conditions however they see fit. The hydrologic sampler is robust for precipitation and flow under a couple of different sampling schemes. We see it as a generic tool that could be applied pretty much anywhere, even internationally. It just depends upon the particular use case. Also, we are interested in supporting non-agency tools. For instance, there's a RiverWare plugin. If you don't want to use HEC-ResSim you can use RiverWare instead within our system.

Question (to Rajiv Prasad):
Has anyone attempted to use SHAC-F for a variety of situations? For instance, have you applied it or are other organizations trying to apply SHAC-F? What is your experience in applying it?

Rajiv Prasad:
The short answer to that is we have not yet. This study was funded by NRC and was looking particularly at NRC applications. We haven't done a study yet that uses SHAC-F in its entirety. There are certain aspects of SHAC-F that you could adopt in any probabilistic flood hazard assessment. But, for now we can’t point to one study that was performed using the whole SHAC-F process.

Question (to Rajiv Prasad):
Because you are with a Department of Energy (DOE) National Laboratory, I’m curious if you have thought about applying SHAC-F at the Savannah River Site or at Idaho National Laboratory. Have you talked to anyone at DOE looking at their requirements for flood assessment and moving towards a risk informed approach? What are your thoughts?

Rajiv Prasad:
Not yet. There are some modifications to DOE standards that have happened over the last few years. There is an appendix to a DOE Handbook that addresses performing probabilistic flood hazard analysis that reads very similar to the way SHAC-F might come across. But I'm not aware of anybody doing that. That handbook is not a requirement for DOE sites. DOE Standard 1020 is a requirement, but it doesn't really specify how you should go about doing a PFHA. That said, INL is currently performing an extreme precipitation analysis and they are moving ahead this year to an extreme flood analysis for their Advanced Test Reactor site. I am helping them a little bit on the review side of it. They may adopt some of the PFHA techniques, but I don't think they're doing SHAC-F yet.

Question (to Miles Yaw):
You seem to have a very complex modeling framework for the Tennessee Valley. You have many sub basins. The question I'm thinking about is forecasting. Do you do a weekly forecast? A monthly forecast? What do you do about being prepared? One of the issues the NRC is faced with is that industry says that they have what's called a FLEX approach, in which if something were to happen, they could respond quickly with regard to flood protection measures. How much lead time would TVA have given an approaching storm?

Miles Yaw:
That gets brought up a lot, but I'm going to caveat my answer because I am not a forecaster. TVA has a river forecast center that is manned 24/7. They look at rainfall of course. My impression is that forecasts are very uncertain. If you look at a 72- hour forecast in various basins, it will typically have a long-term bias, either under prediction or over prediction. TVA's general rule of normal daily operations is that we respond to rain on the ground. You don't want to lower the reservoir by a couple feet in the middle of your summer pool because you think that you're going to get a big storm event and then not get that storm event. That doesn't make people very happy. The reservoirs are, by and large, able to withstand and operate well for reasonably common storms or even relatively rare storms. It's when you get very extreme events that things really start to become a problem and you really need to hit the capacity of reservoirs. The other thing is that many of the tributary reservoirs have big pools with very little spigots at the bottom. If you can only get a few thousand cubic feet per second (CFS) out of your turbines and you have a million acre feet behind your damn, a two-day lead time on the forecast isn't going to be a large impact on reservoir storage. But as you work downstream that

becomes less and less true. We have bigger main-stem dams that have less storage and very large capacities and so you can start to buy yourself something there. For those reservoirs also, the storm hydrographs take a little bit more time to develop so that maybe is a roundabout way to tell you “It depends”.

3.7 Day 3: Session 3B – Flood Protection and Flooding Operating Experience

Session Chair: Thomas Aird, NRC/RES/DRA

3.7.1 Presentation 3B-1 (KEYNOTE): Modeling of the May 2020 Michigan Dam Breaches

Authors: John Edward Stowasser, Wesley Crosby, Christopher Warren, U.S. Army Corps of Engineers

Speaker: John Edward (Ed)Stowasser

3.7.1.1 Abstract

The USACE Modeling Mapping and Consequences Production Center (MMC) provides hydraulic modeling, mapping and consequence analysis for USACE dams in support of the USACE Dam Safety and Critical Infrastructure Protection and Resilience (CIPR) Programs. The MMC has developed processes, tools and standards for creating dam breach hydraulic models for use in emergency action plans (EAP), during real-time flood events, and in support of the Corps Dam Safety and Security programs. The MMC-developed standards have been used to provide dam failure modeling for over 550 USACE dams and multiple flood events, involving over 1000's of stream miles throughout the continental U.S. and Alaska. The MMC also provides Flood Inundation Modeling support during real-time flood events with its Flood Inundation Modeling Cadre (FIM). The mission of the FIM Cadre is to assist districts when called upon to run real-time hydraulic models, prepare forecast inundation maps, and develop consequence estimates for significant flood events. This presentation will provide information on the dam breach and consequence modeling that was conducted for the Sanford and Edenville Dams which failed in May 2020 outside of Midland, Michigan. In addition to these 2 failures, hypothetical breaches were also modeled for the 2 upstream dams of Smallwood and Secord and inundations were developed for forecasted rain events and the potential impacts of the downstream areas with the dams in their current breached state. The presentation will cover data collection, data limitations and assumptions to account for these limitations. The use of mapping during extreme events (floods, droughts, hurricanes, dam breaches, etc.) has provided, and continues to provide, critical situational, and real-time information for emergency responders, decision makers, and key stakeholders. This information is helpful not only to USACE, but also to federal, state, local, and emergency responder partners.

3.7.1.2 Presentation (ADAMS Accession No. ML21064A440)

1

MODELING OF THE MAY 2020 MICHIGAN DAM BREACHES

MMC PRODUCTION CENTER
Modeling | Mapping | Consequences

Prepared by:
Ed Stowasser

February 24, 2021

US Army Corps of Engineers

U.S. ARMY

2

TOPICS

- What is the MMC?
- Background
  - MMC-FIM Cadre Support Role
  - Event Description
- MMC Modeling Effort
  - Data Collection
  - Model Setup & Assumptions
  - Timeline
  - Results (Mapping & Consequences)
- Questions?

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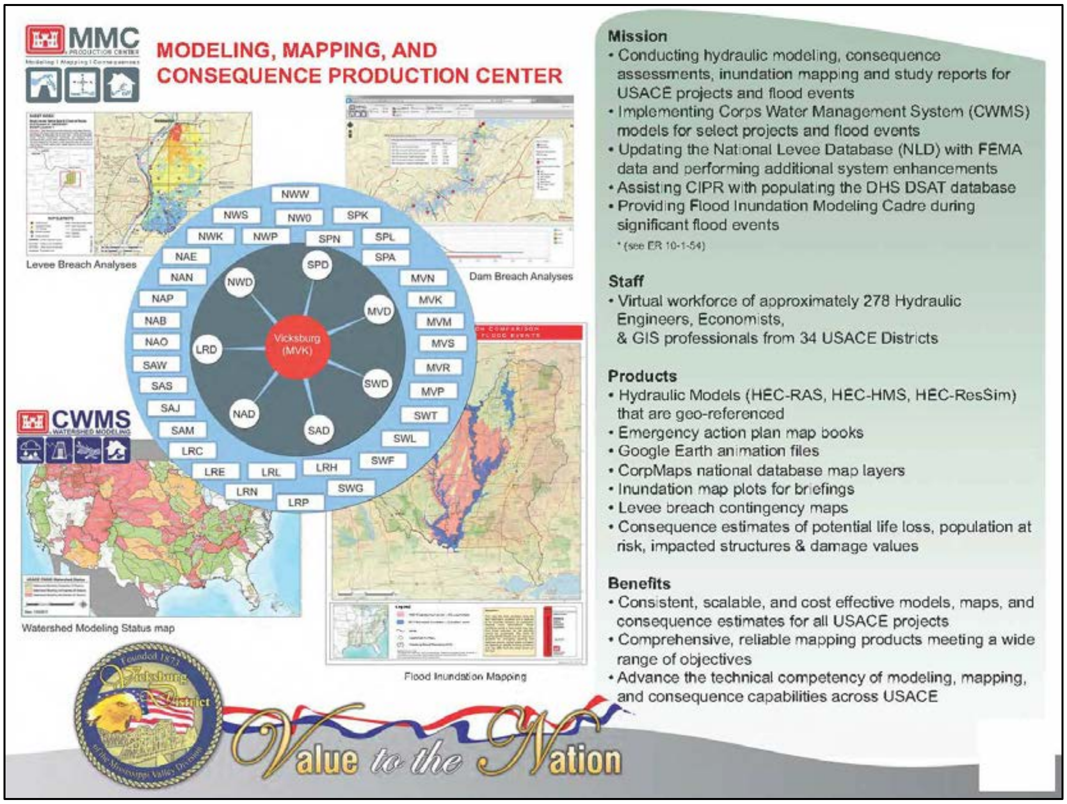
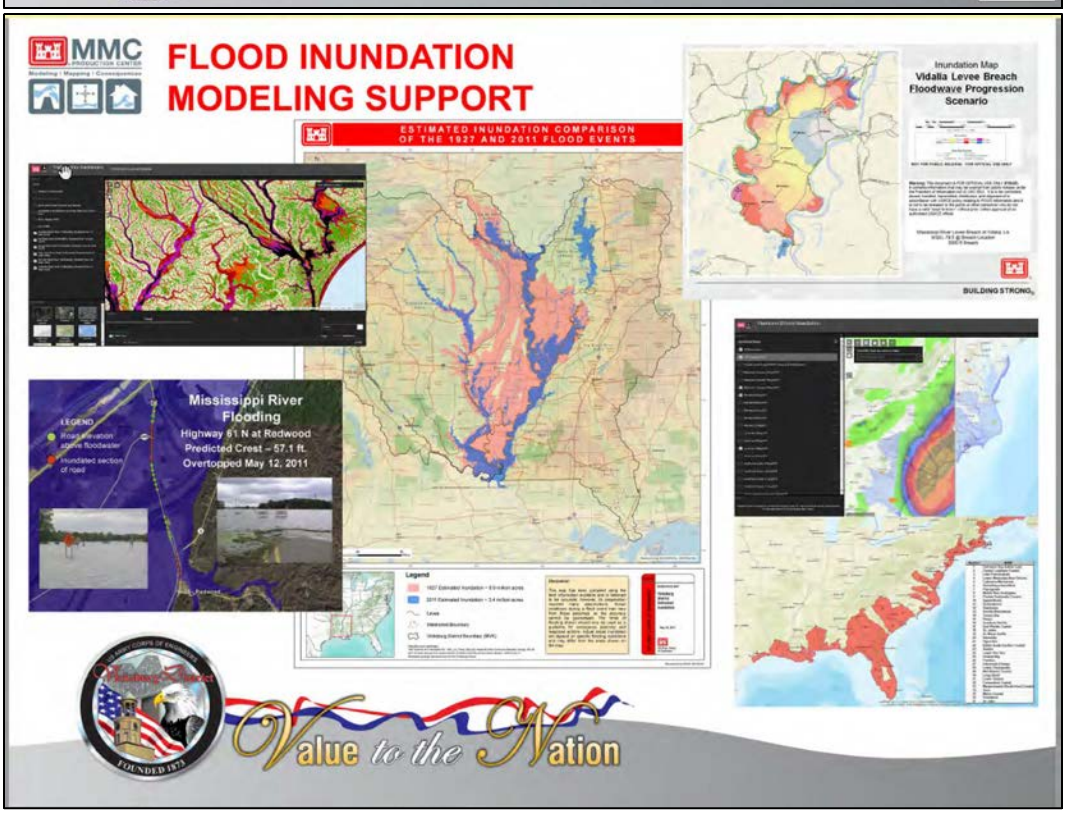
Modeling | Mapping | Consequences

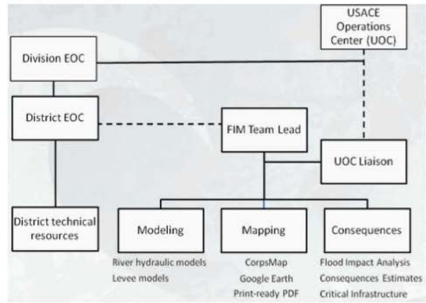

MMC
MODELING, MAPPING, AND CONSEQUENCE PRODUCTION CENTER
Levee Breach Analyses
Dam Breach Analyses
NWW
NWS
NWO
SPK
NWK
NWP
SPN
SPL
NAE
SPA
NAN
NWD
SPD
MVN
NAP
MVK
MVD
NAB
MVM
NAO
LRD
Vicksburg (MVK)
MVS
SAW
MVR
SAS
SWD
MVP
SAJ
NAD
SWT
SAM
SAD
SWL
LRC
SWF
LRE
LRL
LRH
LRN
SWG
LRP
CWMS
WATERSHED MODELING
Watershed Modeling Status map
Flood Inundation Mapping
Mission
• Conducting hydraulic modeling, consequence assessments, inundation mapping and study reports for USACE projects and flood events
• Implementing Corps Water Management System (CWMS) models for select projects and flood events
• Updating the National Levee Database (NLD) with FEMA data and performing additional system enhancements
• Assisting CIPR with populating the DHS DSAT database
• Providing Flood Inundation Modeling Cadre during significant flood events
* (see ER 10-1-54)
Staff
• Virtual workforce of approximately 278 Hydraulic Engineers, Economists, & GIS professionals from 34 USACE Districts
Products
• Hydraulic Models (HEC-RAS, HEC-HMS, HEC-ResSim) that are geo-referenced
• Emergency action plan map books
• Google Earth animation files
• CorpMaps national database map layers
• Inundation map plots for briefings
• Levee breach contingency maps
• Consequence estimates of potential life loss, population at risk, impacted structures & damage values
Benefits
• Consistent, scalable, and cost effective models, maps, and consequence estimates for all USACE projects
• Comprehensive, reliable mapping products meeting a wide range of objectives
• Advance the technical competency of modeling, mapping, and consequence capabilities across USACE
Value to the Nation


MMC
FLOOD INUNDATION MODELING SUPPORT
ESTIMATED INUNDATION COMPARISON OF THE 1927 AND 2011 FLOOD EVENTS
Inundation Map
Vidalia Levee Breach
Floodwave Progression
Scenario
BUILDING STRONG
Mississippi River Flooding
Highway 61 N at Redwood
Predicted Crest – 57.1 ft.
Overtopped May 12, 2011
LEGEND
Road elevation above floodwater
Inundated section of road
Value to the Nation

FLOOD INUNDATION MODELING (FIM) CADRE

Strategy

- A national team assisting district technical resources and supporting the districts' flood-fighting lead role
- Providing assistance through a national production center while utilizing staff from local districts
- Leveraging existing models from Corps Water Management System (CWMS), District H&H & other agencies
- In the future, establishing full CWMS flood inundation modeling teams at each USACE Division
- Leveraging available flood inundation mapping from NOAA, USGS, and other sources
- Enhancing flood risk information sharing and availability during significant flood events



Innovations

- National coverage and response teams
- Consistent, cost-effective, quality USACE flood inundation products
- Dynamic flood inundation modeling
- Advancements in the state of practice for national flood risk communication
- Heightened awareness of flood risks
- Same-day river stage forecast updates
- Recognition of USACE as a technical leader in the field of flood inundation modeling

Current Activation: Providing technical assistance to Texas, Memphis, New Orleans, and Vicksburg

Key Products

- Inundation maps in CorpsMap & Google Earth
- Print-ready maps for briefings
- Levee overtopping/breaching maps (*includes flood depths and arrival times*)

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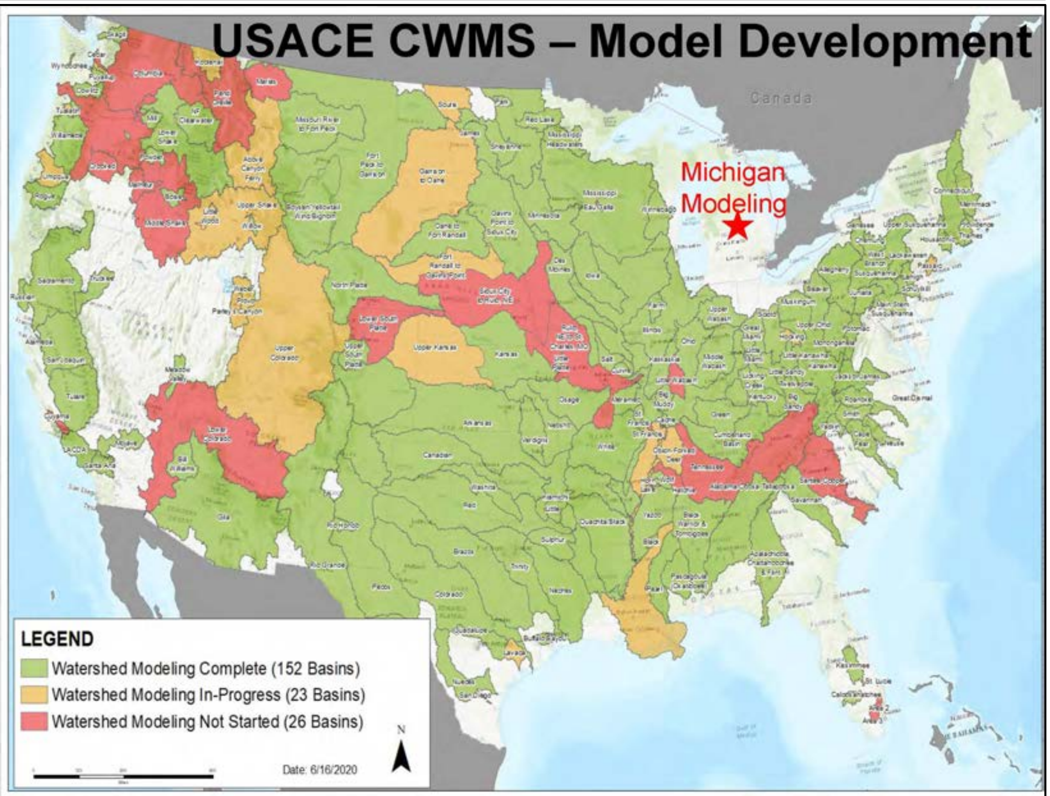
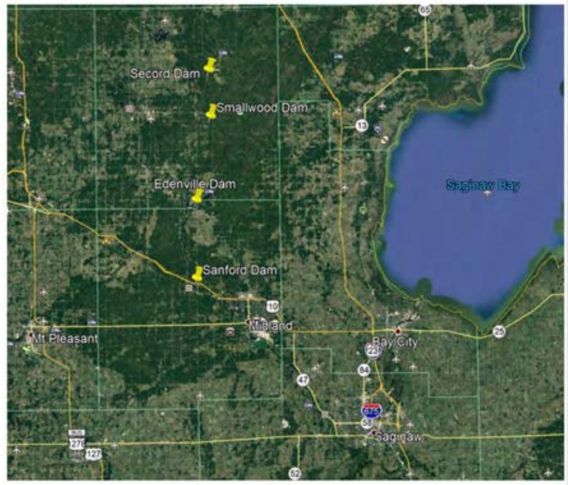
Modeling | Mapping | Consequences



BACKGROUND – MAY 2020 EVENT

- Not federally owned dams
  - Privately owned structures
  - FERC oversight for hydro power structures
  - State oversight
- MMC Modeling was conducted within 24hrs to establish cursory model.



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PROJECT OVERVIEW AND BACKGROUND

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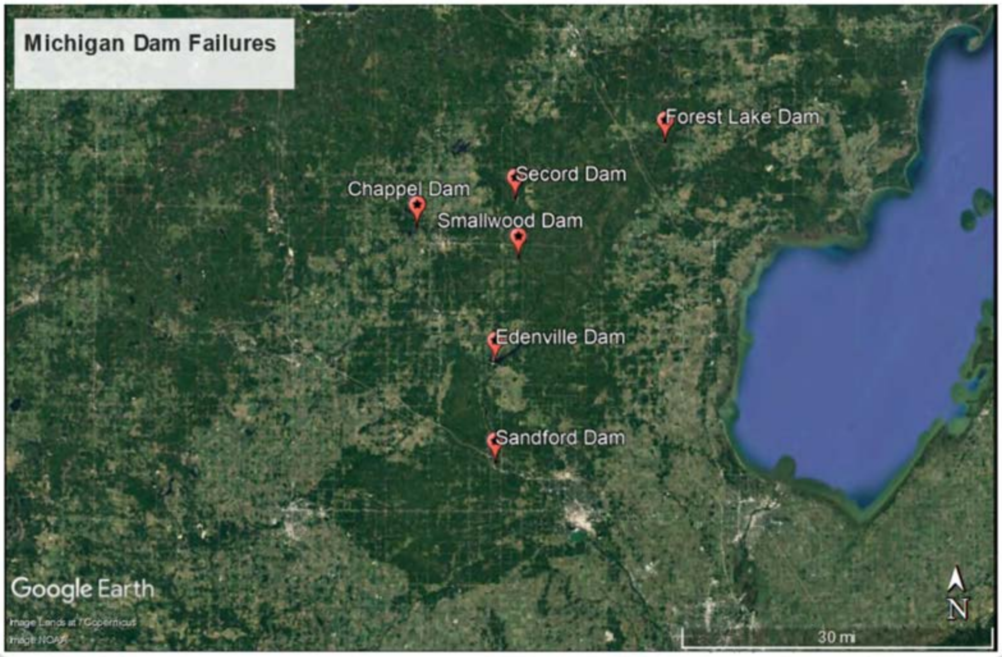
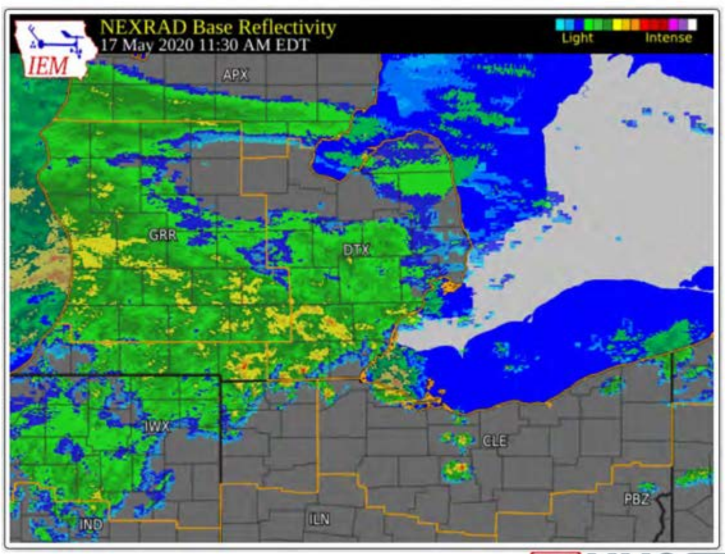
PROJECT OVERVIEW AND BACKGROUND



PROJECT OVERVIEW AND BACKGROUND



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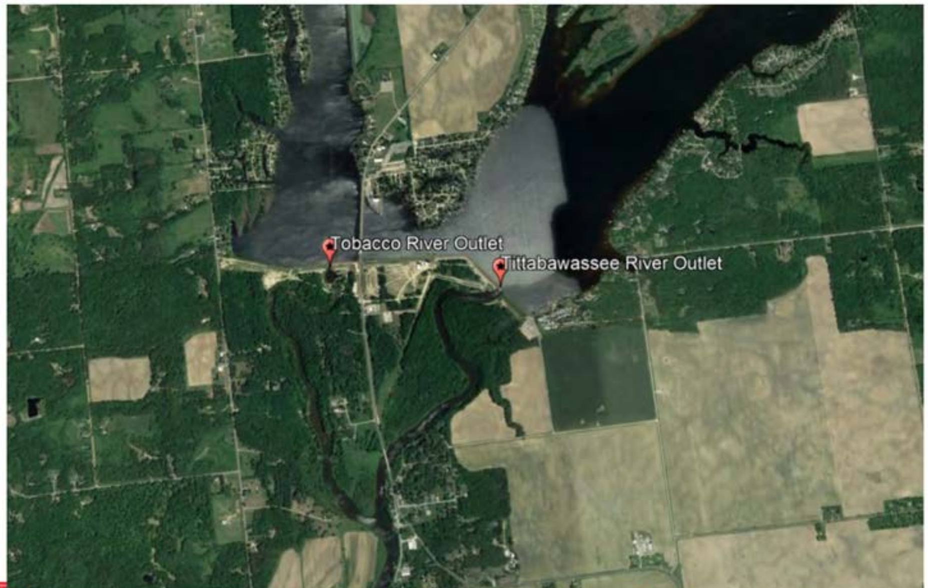
EDENVILLE DAM FAILURE



Aerial photo of site

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EDENVILLE DAM FAILURE

2 Hours before collapse

US Army Corps of Engineers

MMC PRODUCTION CENTER
Modeling | Mapping | Consequences

EDENVILLE DAM FAILURE

US Army Corps of Engineers

Immediately after collapse

SANDFORD DAM FAILURE

US Army Corps of Engineers

Prior to overtopping

SANDFORD DAM FAILURE

After overtopping

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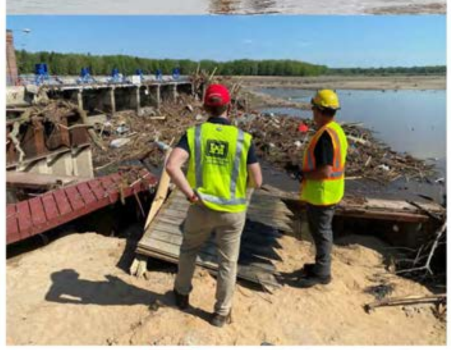
MMC

USACE INVOLVEMENT

- USACE Authority
  - Public Law 84-99, authorizing technical assistance to impacted counties requested by the state of Michigan
- Flood Inundation Mapping
  - Surveying of highwater marks and failure geometry of the dams
  - Flow measurements from failure sites
  - Data acquisition
- Dam Observations
  - 5 Dams that had been impacted by inundation were identified as requiring immediate observation
  - Prior to site visits several had documented damage and attempted stabilization



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MMC

INUNDATION MODELING – BACKGROUND

- HEC-RAS model
  - Simulated the conditions leading to the May 19 failures
  - Model was used to create inundation maps and consequences data to simulate additional dam failures (Secord, Smallwood, & Edenville – West) or rainfall (1" to 3" range) over the basin during the emergency response
- Event specific tool
- 10 different scenarios were assessed
  - Provided risk evaluation of a storm forecasted for May 28th, 2020

Photos and cutlines of Lake Sanford and Dam, Michigan – 26 May 2020

Sanford Lake was inundated by floodwaters May 19, 2020, breaching Sanford Dam, emptying most of the lake downstream. The U.S. Army Corps of Engineers is providing dam assessment and inundation modeling to the state of Michigan.

US Army Corps of Engineers

MMC PRODUCTION CENTER Modeling | Mapping | Consequences

INUNDATION MODELING – DATA COLLECTION & ASSUMPTIONS

- Rainfall and flow data
  - Observed Gage Data for inflows to Dam Failures
  - NWS Forecasted Inflows and HEC-RAS 2D Precip Grids to bound the inflows for event after Dam Failures
- Reservoir Information
  - Storage Area-Capacity (NID & Google Searches)
- Topographic and Terrain Data
  - 1m LiDAR Data
  - Trapezoidal breach approximations
- Calibration Data
  - Surveyed high water marks at Edenville and Sanford Dam pools
  - Aerial imagery from May 20th from time of peak flood stage at the Tittabawassee River gage at Midland
  - Observed high water mark data collected by USACE field staff and flood damage assessors

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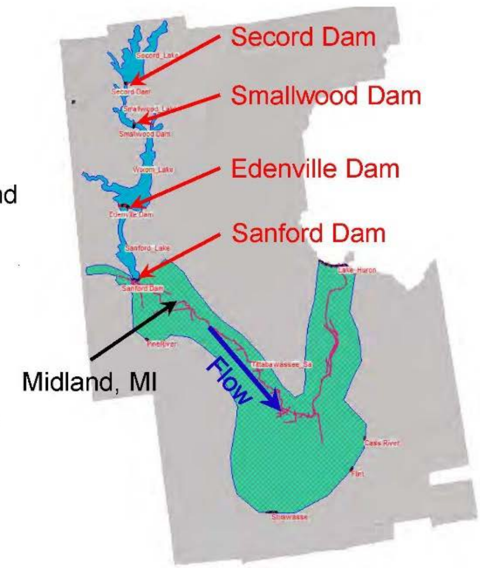
MMC MODELING SUPPORT – MICHIGAN

May 19, 2020

On May 19, 2020, 5:46 p.m., due to massive inflow from heavy rains in the area, the eastern side of the Edenville Dam collapsed, prompting immediate evacuations in the towns of Edenville and Sanford.

Sanford Dam in Midland County, downstream of the Edenville Dam, also failed after Edenville's Dam failure causing heavy flooding on the Tittabawassee River. Sanford Dam was overwhelmed by flood waters rushing from the failed Edenville Dam and resulted in an overtopping failure.



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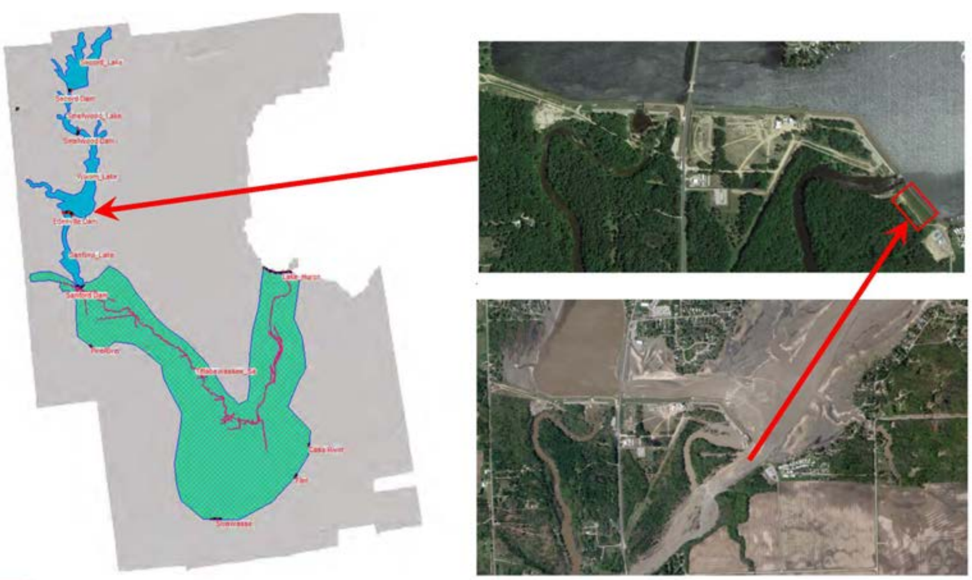
Edenville Dam Failure



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Sanford Dam Failure

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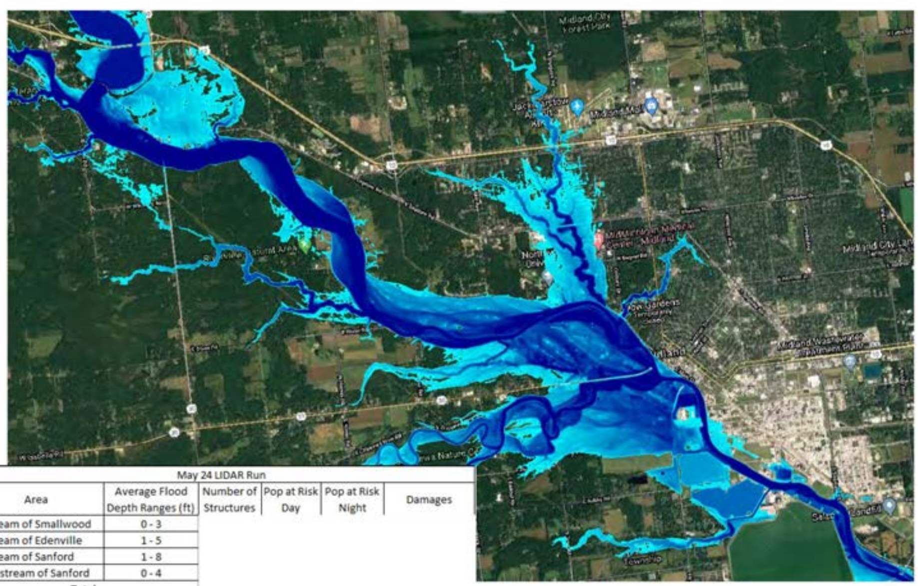
Edenville / Sanford Dam Failures – Max Depth Inundation



May 24 LIDAR Run					
Area	Average Flood Depth Ranges (ft)	Number of Structures	Pop at Risk Day	Pop at Risk Night	Damages
Upstream of Smallwood	0 - 3				
Upstream of Edenville	1 - 5				
Upstream of Sanford	1 - 8				
Downstream of Sanford	0 - 4				
Total					

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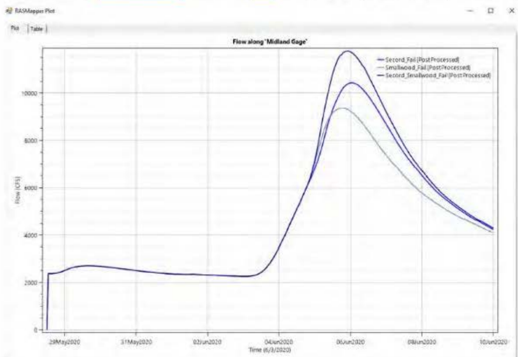
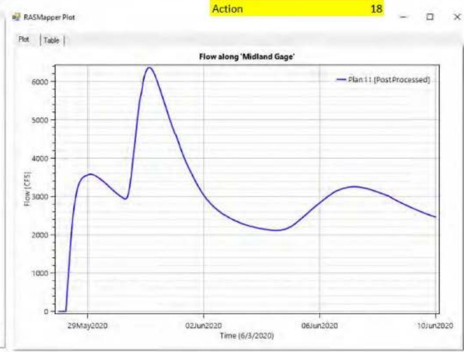
What If Scenarios – Secord / Smallwood Dams

Midland, MI Gage

		Stage	Conversion	NWS Gage Zero	Peak Elevation	Peak Flow	Peak Time	Approximate Arrival Time of Peak	Flow Assumption from Rainfall	Rainfall Model
Breach Events	Event	ft	29 to 88	ft - NGVD29	ft-NAVD88	cfs	MM/DD/YYYY HH:MM	hrs		
	Secord Fail	[illegible]	-0.58	580.28	606.5	10,450	6/6/2020 0:00	36	3"	NWS
	Smallwood Fail	[illegible]	-0.58	580.28	606.0	9,375	6/5/2020 18:00	30	3"	NWS
	Both Fail	[illegible]	-0.58	580.28	607.1	11,775	6/5/2020 22:00	34	3"	NWS
	Edenville (West) Fail	24.7	-0.58	580.28	604.4	6,372	5/31/2020 2:00	26	1.3"	RAS

Flood Stages	
Major	28
Moderate	25
Flood	24
Action	18





Secord Dam and Smallwood Dam Failure					
Area	Average Flood Depth Ranges (ft)	Number of Structures	Pop at Risk Day	Pop at Risk Night	Damages
Upstream of Smallwood	0 - 3				
Upstream of Edenville	0 - 0				
Upstream of Sanford	0 - 0				
Downstream of Sanford	0 - 2				
Total					

Edenville West Dam Failure					
Area	Average Flood Depth Ranges (ft)	Number of Structures	Pop at Risk Day	Pop at Risk Night	Damages
Upstream of Smallwood	0 - 0				
Upstream of Edenville	0 - 0				
Upstream of Sanford	0 - 0				
Downstream of Sanford	0 - 2				
Total					

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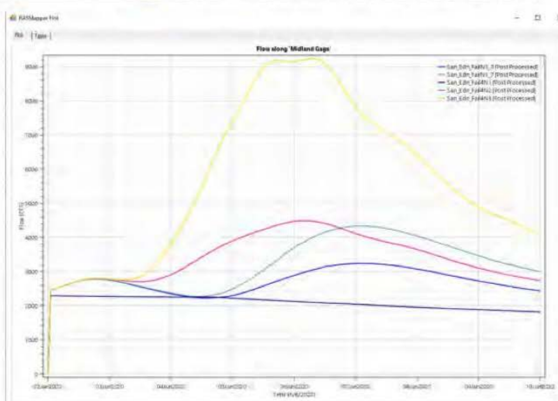
What If Scenarios – NWS Forecasted Precip 1-3"

Midland, MI Gage

	Precipitation	Stage	Conversion	NWS Gage Zero	Peak Elevation	Peak Flow	Peak Time
NWS Inflow Hydrographs		ft	29 to 88	ft - NGVD29	ft-NAVD88	cfs	MM/DD/YYYY HH:MM
	1"	21.3	-0.58	580.28	601.0	2,300	6/6/2020 0:00
	2"	23.5	-0.58	580.28	603.2	4,500	6/6/2020 4:00
	3"	[illegible]	-0.58	580.28	606.0	9,240	6/5/2020 18:00
	1.3"	22.3	-0.58	580.28	602.0	3,250	6/7/2020 2:00
	1.7"	23.3	-0.58	580.28	603.0	4,350	6/7/2020 3:00

Flood Stages	
Major	28
Moderate	25
Flood	24
Action	18



NWS 3in Rainfall					
Area	Average Flood Depth Ranges (ft)	Number of Structures	Pop at Risk Day	Pop at Risk Night	Damages
Upstream of Smallwood	0 - 0				
Upstream of Edenville	0 - 0				
Upstream of Sanford	0 - 0				
Downstream of Sanford	0 - 4				
Total					

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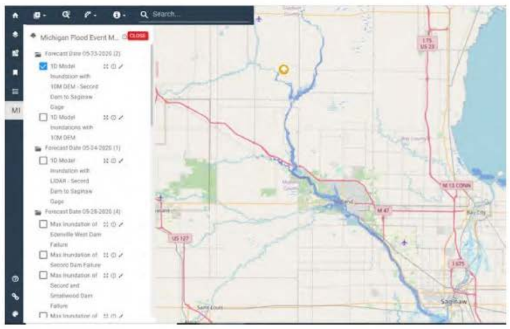
INUNDATION MODELING – OUTCOME

- Final report produced from the modeling
- Immediate answers for use by the state
  - None of the scenarios indicate a return to major flood stage conditions
- Inundation data and estimated consequences also provided to the state
  - The down stream impact to potential additional failures and inundation scenarios were provided



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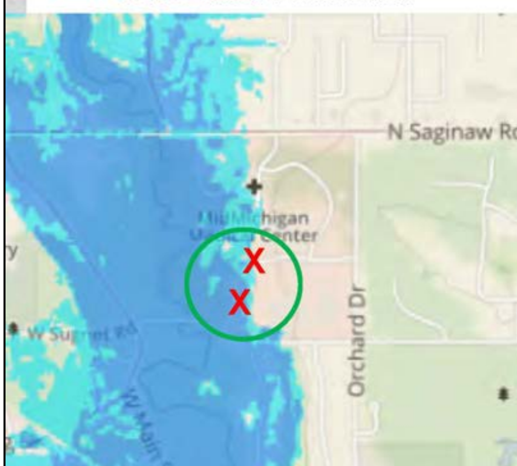
USACE model simulation



Observed Closures

5/20/2020
Rising flood waters have closed Harlow and Wellness Drive entrances to the campus of MidMichigan Medical Center – Midland. Those coming to the Medical Center campus are asked to enter through Orchard Drive west of Eastman Avenue off North Saginaw Road. The Emergency Department and Hospital Entrances remain open.

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Observed Inundation Extents

Source: CNN.com

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Modeled Extents

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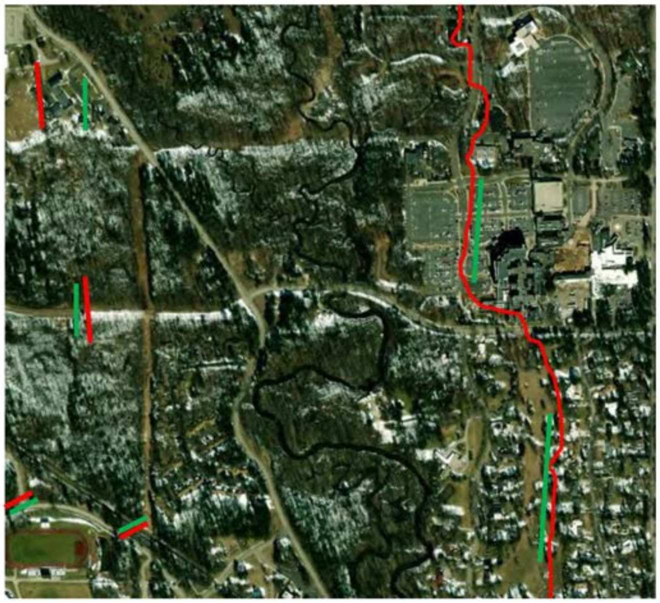

Actual
Modeled

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QUESTIONS?

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U.S. Army Corps of Engineers
Huntington District (LRH)
502 8th Street
Huntington, WV 25701

Ed Stowasser
(304) 399-5106 TEL
Edward.L.Stowasser@usace.army.mil

Special Thanks to Wesley Crosby (MVK) & Chris Warren (LRE)

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3.7.1.3 Questions and Answers

Question:
Has MMC looked at simulation-based dynamic approaches to model the responses to flooding events?

Ed Stowasser:
If this flood event would have fallen within an area where we have what we call SWIMS forecast modeling, then we would have been able to run our HMS models and produce live type flow feeds and then we could have used our local flow hydrographs and things like that to feed into a reservoir simulation model. That would produce something more dynamic than what we were doing. It would be more of a dynamic response, but in this case, we didn't have any mapping available, so we were kind of coming in after the fact and we had to create things from scratch. So, the approach we took was to develop a 2D RAS model for the areas where we want to see the flood routing go through and then we looked at 1D storage areas to make sure we were capturing volumes that were coming out of the reservoirs that failed. It was kind of backing into the answer at first. The goal of the tasks were to establish that base condition, because if the other dams failed, then we didn't have accurate inundation maps that replicated two of the dams downstream that had already failed. And then on top of that we also looked at precipitation events that were supposed to be forecasted and rolling into that area.

Question:

What is the current status of the Edenville dam and Sanford dam?

Ed Stowasser:
I do not know. I got pulled into the effort just for the modeling part.

Question:
Was the development of the Edenville breach investigated for time to fail, width, depth?

Ed Stowasser:
I do know that Chris Warren and some of the Detroit District folks were deployed immediately as soon as the breach happened. I was kind of flying blind, creating breach parameters for the model development that first day. But two or three days in, Chris Warren and his team had survey boats out there and they talked to field personnel to establish the timing of the breaches. So, they were able to give us a better estimate of how long it took things to fail and develop. And they also provided the final breach bathymetry which ultimately helped us put a cap on what those breach parameters looked like. It gave us the width and the depth and all that.

Question:
From a risk perspective, were the chemical plants downstream incorporated into the overall risk assessment?

Ed Stowasser:
I am sure they would have been. Our objective here was just to provide inundation mapping. Chemical plants would have been identified in the consequences part. The RMC study would probably include such studies of the chemical plants and activities downstream.

3.7.2 Presentation 3B-2: Developing a Framework for Flood Barrier Testing Strategies

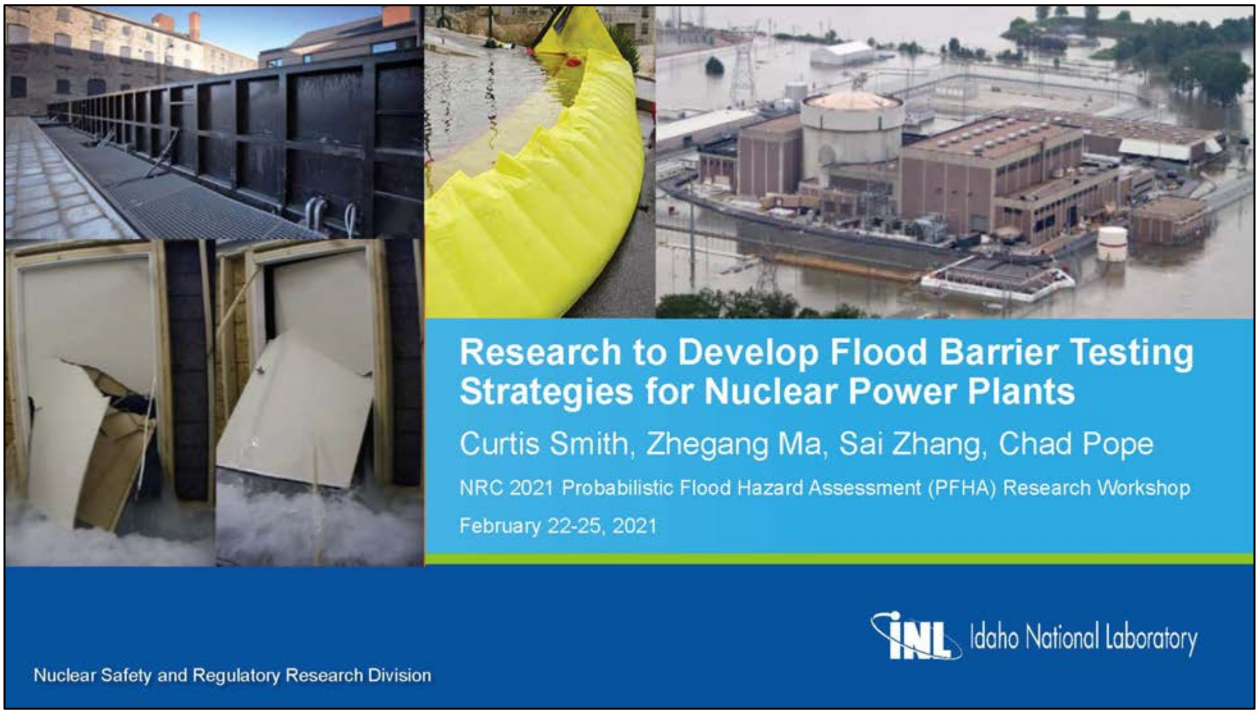
Authors: Zhegang Ma[1], Sai Zhang[1], Chad L. Pope[2], Curtis L. Smith[1], [1]Idaho National Laboratory, [2]Idaho State University

Speaker: Zhegang Ma

3.7.2.1 Abstract

The U.S. Nuclear Regulatory Commission (NRC) has developed regulations regarding the siting and design of nuclear power plants (NPPs) aimed at providing safety from various natural hazards, including flooding. Flood barriers are designed to prevent water from entering NPP areas containing safety important systems and components. They are used at NPPs along with drains, sumps, pumps, valves, plugs, and site grading as part of the plant flood protection features that prevent SSCs from experiencing external or internal flooding and mitigate the effects of flooding on NPP operations. However, performance of flood protection features, including flood barriers at NPPs, has long been an ongoing safety concern. Domestic and international operational experience (OE) provides clear indications that flood barrier performance has significant safety implications, especially as a reactor fleet ages. These OEs show that, to provide reasonable assurance that flood barriers will perform their intended functions in the event of flooding, not only should they be designed and installed properly, but also adequately tested, inspected, and maintained. The objective of this research is to identify and assess options and develop strategies for testing NPP flood barriers. It reviewed available information related to flood barriers employed at U.S. NPPs and provided an overview of on-site permanent flood barriers (e.g., penetration seals, water-tight doors) and temporary flood barriers incorporated into the plants. The research identified potential domestic and international flood barrier testing facilities, including operating and decommissioning U.S. NPPs. Finally, the research presented a list of questions and considerations related to flood barrier testing such as the selection of flood barriers, the test location, mediums, acceptance criteria, and parameters that can be used in developing specific testing strategies and protocols for flood barriers.

3.7.2.2 Presentation (ADAMS Accession No. ML21064A441)



Outline

- Introduction
- Literature Review
- Flood Barrier Categorization/Overview
- Potential Flood Barrier Testing Facilities
- Developing Flood Barrier Testing Strategies

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Introduction

- **Flood barriers are part of the nuclear power plant (NPP) flood protection features**
  - Designed to protect structures, systems, and components (SSCs) important to safety against flood hazard
- **Flood barriers should be qualified, inspected, and maintained to perform intended functions**
- **Performance of flood protection features, including flood barriers at NPPs, has been an ongoing focus**
- **Probabilistic risk assessment (PRA) can be used to evaluate the risk from internal and external flood hazard**
  - The lack of fragility data for flood protection features (including flood barriers) presents a challenge and uncertainty

Introduction (cont.)

- **Idaho National Laboratory (INL) conducted research to support the NRC**
  - Investigate flood barrier testing strategies
  - Explore potential harvesting for flood barrier tests
- **Project Team**
  - NRC
  - INL
  - Idaho State University (ISU)

Introduction (cont.)

- Reviewed available information on flood barrier testing
- Engaged industry stakeholders and technical experts to provide inputs and insights
- Visited decommissioning plant for potential harvesting
- Presented preliminary results from the project in the Flood Barrier Testing Workshop and a NRC seminar
- Final project report will be published as a NUREG/CR report

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Introduction (cont.)

NUREG/CR-XXXXX

U.S.NRC

United States Nuclear Regulatory Commission

Protecting People and the Environment

INL/EXT-19-56427, REV. 1

RESEARCH TO DEVELOP FLOOD BARRIER TESTING STRATEGIES FOR NUCLEAR POWER PLANTS

Office of Nuclear Regulatory Research

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Literature Review

- **Reviewed Materials from a Variety of Sources**
  - Domestic Agencies
    - NRC
    - United States Army Corps of Engineers (USACE)
  - International Agency
    - Organisation for Economic Co-operation and Development Nuclear Energy Agency (OECD NEA)
  - Industry and Academia
    - Nuclear Energy Institute (NEI)
    - Electric Power Research Institute (EPRI)
    - FM Approvals
    - Licensee flooding walkdown reports
    - Others

Literature Review (cont.)

- **List of Reviewed Materials**
  - NRC
    - Materials Related to Flood Barriers
      - Regulatory Guide 1.102, Rev. 1, "Flood Protection for Nuclear Power Plants," 1976
      - Japan Lessons-learned Project Directorate, Interim Staff Guidance, JLD-ISG-2012-05, Rev.0, "Guidance for Performing the Integrated Assessment for External Flooding," 2012
      - NUREG-2240, "Development of an Ex Situ Performance Testing Protocol for Nuclear Power Plant Flood Penetration Seals," 2020
      - Reports prepared by NRC contractors, including Fire Risk Management, Inc. and Center for Nuclear Waste Regulatory Analyses

Literature Review (cont.)

- **List of Reviewed Materials (cont.)**
  - NRC
    - Materials Related to Fire Barriers or Fire Tests
      - NUREG/CR-0152, "Development and Verification of Fire Tests for Cable Systems and System Components," 1978
      - NUREG/CR-2377, "Tests and Criteria for Fire Protection of Cable Penetrations," 1981
      - NUREG-1552, "Fire Barrier Penetration Seals in Nuclear Power Plants," 1996
  - USACE Engineering Research and Development Center (ERDC)
    - ERDC TR-07-3, "Flood-Fighting Structures Demonstration and Evaluation Program: Laboratory and Field Testing in Vicksburg, Mississippi," 2007
    - ERDC/CHL TR-15-3, "Technical Basis for Flood Protection at Nuclear Power Plants," 2015

Literature Review (cont.)

- **List of Reviewed Materials (cont.)**
  - OECD NEA
    - NEA draft report, "Concepts and Terminology for Protecting Nuclear Installations from Flood Hazards," in progress
  - NEI
    - NEI 12-07, Rev. 0-A, "Guidelines for Performing Verification Walkdowns of Plant Flood Protection Features," 2012
  - EPRI
    - Product 3002005423, "Flood Protection Systems Guide," 2015
    - Presentation, "External Flood Seal Risk-Ranking Process," 2019
  - FM Approvals
    - ANSI FM 2510, "American National Standard for Flood Mitigation Equipment," 2020

Literature Review (cont.)

- **List of Reviewed Materials (cont.)**
  - Licensee Walkdown Reports
    - Flooding walkdown reports of reference NPPs
  - INL & ISU
    - Pope et al., "Light Water Reactor Sustainability Program, Nuclear Power Plant Mechanical Component Flooding Fragility Experiments Status (INL/EXT-17-42728)," 2017
    - Wells et al., "Non-watertight door performance experiments and analysis under flooding scenarios," Results in Engineering, 2019
  - Others
    - NPP decommissioning info, vendor info, and scientific publications

Literature Review (cont.)

- **Outputs of Literature Review**
  - Generic categorization of flood barriers in NPPs
  - Plant-specific flood barrier types and performances
  - Existing and potential flood barrier testing facilities
  - Examples of previous flood barrier tests
  - Insights for future flood barrier testing strategy development

Sump	No	n/a	0.70%
Monitor Well	No	n/a	0.23%
Percentage of Barrier Type Flood Protection Features			87.79%
Percentage of Non-Barrier Type Flood Protection Features			12.21%

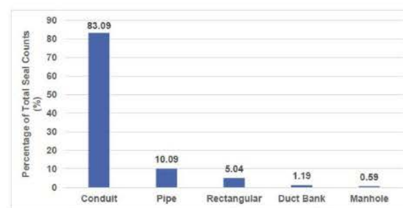


Figure B-1. Statistics of Seal Type Flood Barriers in the Reference Plant.

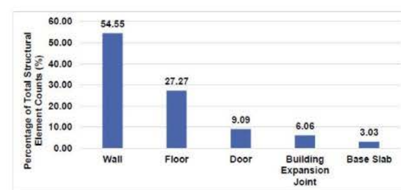
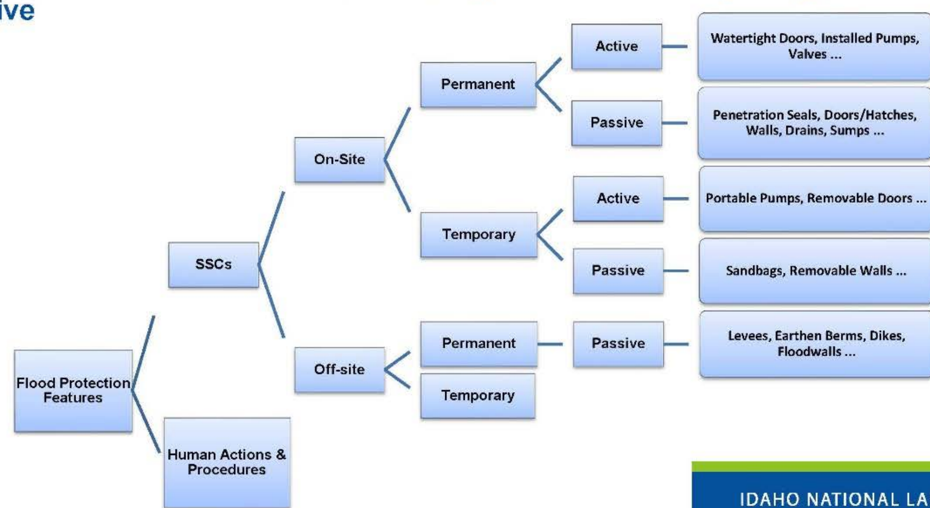


Figure B-2. Statistics of Structural Element Type Flood Barriers in the Reference Plant.

Flood Barrier Categorization/Overview

- Flood barriers can be on-site or off-site, permanent or temporary, active or passive



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Flood Barrier Categorization/Overview (cont.)

- Categorization
  - On-site vs. Off-site
  - Permanent vs. Temporary
  - Active vs. Passive
- On-site Permanent
  - Penetration Seals
  - Watertight Doors
- On-site Temporary
  - Disposable – absorbent pad, etc.
  - Reusable – floodgates, hydrostatic tarp, etc.







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Potential Flood Barrier Testing Facilities

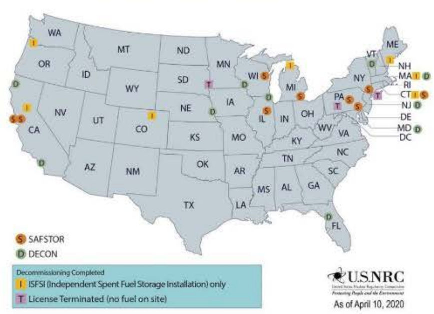
- **Operating Nuclear Power Plants**
  - Currently 94 licensed nuclear power reactors in the United States
  - Potential facilities for in-situ non-destructive testing or enhanced inspection
  - Testing must be carefully incorporated into plant's schedule to avoid inadvertently impacting the safety and reliability of plant operations

Information Digest, 2020–2021 (NUREG-1350, Volume 32)

Potential Flood Barrier Testing Facilities (cont.)

- **Decommissioning Nuclear Power Plants**
  - About 20 power reactors undergoing decommissioning
  - Major Decommissioning Companies
    - Holtec Decommissioning International (HDI)
      - Oyster Creek, Pilgrim
      - Purchase agreements for
        - Palisades
        - Indian Point
    - NorthStar
      - Vermont Yankee
    - EnergySolutions
      - Zion and La Crosse

Power Reactors Decommissioning Status



https://www.nrc.gov/images/reading-rm/doc-collections/maps/power-reactors-decommissioning-sites.png

Potential Flood Barrier Testing Facilities (cont.)

- **Decommissioning Plants (cont.)**
  - A team of NRC and INL staff visited the Oyster Creek NPP in November 2019
  - Conducted a walkdown on flood barriers harvestable for testing
    - Emergency diesel generator (EDG) building
    - Turbine building
    - Reactor containment building
    - And the surrounding areas of key buildings
  - Penetrations into the EDG building were considered for harvesting

17 Courtesy of Oyster Creek NPP

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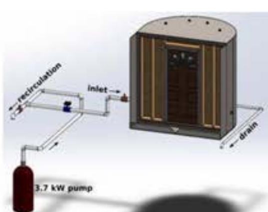
Potential Flood Barrier Testing Facilities (cont.)

- **U.S. Flood Testing Facilities - Idaho State University (ISU)**
  - Portal Evaluation Tank
  - A steel, semi-cylindrical tank with a height and diameter of 8 ft, can hold up to 2,000-gal of water
  - 5 HP submersible pump inside an 8,000-gal water reservoir
  - Inlet electromagnetic flow meter, ultrasonic depth sensor, and pressure transducer, pressure and air relief valves, and a digital pressure gauge



18 A. Wells, et. al., "Non-watertight door performance experiments and analysis under flooding scenarios," Results in Engineering, 2019

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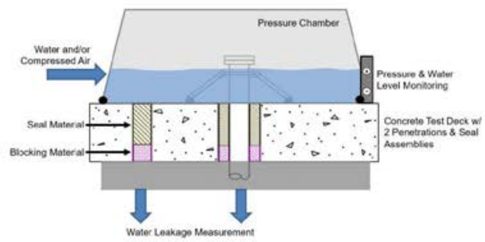
Potential Flood Barrier Testing Facilities (cont.)

- **U.S. Flood Testing Facilities - Framatome Laboratory in Lynchburg, Virginia**
  - Test apparatus for research on penetration seal testing protocol
  - Three main components
    - Pressure chamber
    - Concrete test deck
    - Water leakage measurement system



NUREG-2240, "Development of an Ex Situ Performance Testing Protocol for Nuclear Power Plant Flood Penetration Seals," 2020

Potential Flood Barrier Testing Facilities (cont.)

- **U.S. Testing Facilities - Oregon State University (OSU)**
  - OSU O.H. Hinsdale Wave Research Laboratory (HWRL)
  - Large-scale dynamic wave generators
  - Two separate wave-generating apparatuses
    - Directional wave basin
      - 62,640-ft^3, Tsunami-type inundations and impacts
    - Large wave flume
      - Largest of its kind in North America
      - 342-ft long, 12-ft wide, and a depth of 15 ft

https://wave.oregonstate.edu

Potential Flood Barrier Testing Facilities (cont.)

- **U.S. Testing Facilities - USACE Coastal and Hydraulics Laboratory**
  - 1.5 million ft^2 with six physical research facilities
  - Provide analysis of flood mitigation and damage prevention
    - Wave Flume Facility
    - Field Research Facility
    - Sediment Flume Facility
    - Full-Scale Levee Breach and Hydraulic Test Facility

https://www.erdc.usace.army.mil/Locations/CHL/Facilities.aspx

Potential Flood Barrier Testing Facilities (cont.)

- **International Flood Testing Facilities**
  - China Institute of Water Resources and Hydropower Research
    - 32 different laboratories and over 1,300 staff members
    - Hydraulics modeling experiments on hydraulic structures
    - Hydrodynamics modeling experiments involving sedimentation, tide, outfall, lake environments, and cooling tower
    - Hydraulic cavitation research
  - Electricité De France
    - National Laboratory of Hydraulics and Environment (LNHE) in Chatou, France
    - Numerically and physically model hydraulic systems
    - Test loops to test the reliability of hydraulic conditions under single- or multiphase flows of water, air, or freon

Potential Flood Barrier Testing Facilities (cont.)

- **International Flood Testing Facilities (cont.)**
  - Japan Central Research Institute of Electric Power Industry (CRIEPI)
    - Fluid Dynamics Sector
      - How wind, rain, snow, and tsunami conditions affect power plants
      - Fluid dynamic technology optimization in NPPs
      - Large-Scale Tsunami Physical Simulator
        - 1/3-scale simulation of the tsunami observed in Kesennuma City
        - Fragility experiments - tsunami hydrodynamic loads, debris impact loads, and damage to structures under tsunami-like conditions
        - 20 m in length, 4 m in width, and 2.5 m in height

https://criepi.denken.or.jp/en/publications/annual/2014/041.pdf

Developing Flood Barrier Testing Strategies

- **What to be tested?**
  - Many flood barriers
  - Risk/Safety ranking
  - Location (i.e., Accessibility)
- **Type of Flood Barriers for Testing**
  - Seals, Doors, Walls, Floors, Temporary Barriers
- **Codes and Standards**
  - Penetration Seals
    - Underwriters Laboratories (UL) 1479 and UL 2079 for pressure testing of fire barriers
  - Doors
    - Door testing standards, e.g., American Society for Testing and Materials (ASTM) E331
    - Analytical methods

Developing Flood Barrier Testing Strategies (cont.)

- **Protocols and Plans**
  - Testing Locations
    - In-situ (in plant, in place)
    - Ex-situ but on-site (not in place, but on-site)
    - Ex-situ and off-site (off-site testing facilities)
  - Flood Effect and Failure Modes
    - Hydrostatic pressure, hydrodynamic pressure, debris impact
    - Excessive leakage, loss of integrity, displacement, overtopping
  - Mediums
    - Water, air, steam
    - Standing (without pressure) - static pressure testing
    - Under pressure (via pump or air) - dynamic pressure testing

Developing Flood Barrier Testing Strategies (cont.)

- **Protocols and Plans (cont.)**
  - Test Parameters to Consider
    - Input Parameters: test pressure, water levels, flow rate, duration of applied pressure, rate of pressure change, debris size
    - Output Parameters: leakage rate, maximum pressure before loss of integrity
    - Miscellaneous Parameters: water temperature, test duration, time history
  - Are Acceptance Criteria needed?
    - In accordance with the functional requirements
    - No/negligible leakage, maintained integrity under static and/or dynamic pressure
  - Other aspects
    - Destructive vs non-destructive, sample vs actual flood barriers
    - Other considerations based on material type, barrier age, changes in material strength over years

3.7.2.3 Questions and Answers

Question:
You mentioned the Idaho State facility and it looked like it was testing watertight doors. Do you think it could be used to test other flood barriers like stop logs or penetration seals?

Zhegang Ma:
Yes.

Question:
Could you speak about some of the challenges that you would encounter with harvesting flood barriers from existing sites, aged barriers?

Zhegang Ma:
Some of the challenges would be coordinating with operating or decommissioning plant staff regarding these barriers. Another challenge would be getting the barriers out of the plants intact if you want to do ex situ testing in a lab setting. And also making sure the ex situ testing would be reflective of plant conditions.

Question:
Has there been any testing on the time of installation of different types of temporary barriers during the warning time of an incoming storm?

Zhegang Ma:
I am not aware of any. But for some for the temporary barriers, they are mostly commercial products and may come with manufacturer specifications. These specifications could provide an answer to this question.

3.7.3 Presentation 3B-3: Qualitative Risk Ranking Process of External Flood Penetration Seals

Author: Marko Randelovic, Electric Power Research Institute (EPRI)

Speaker: Marko Randelovic

3.7.3.1 Abstract

Preventing water from entering into areas of NPPs that contain significant safety components is the function that various flood-protection components serve across the industry. Several types of flood barriers, both permanent and temporary, are used at NPPs. These barriers include external walls, flood doors, and flood barrier penetration seals (FBPSs) that allow cables, conduits, cable trays, pipes, ducts, and other items to pass between different areas in the plant. A comprehensive guidance on the design, inspection and maintenance of flood-protection components has been assembled in EPRI's technical report "Flood Protection System Guide". This document includes information related to these topics for a variety of flood-protection components, while focusing specifically on FBPSs. The NRC-RES has initiated a project to develop testing standards and protocols to evaluate the effectiveness and performance of seals for penetrations in flood rated barriers at nuclear power plants. EPRI is currently developing a qualitative risk ranking process for the plants to categorize, or "risk-rank" installed penetration seals according to the likelihood and consequence of seal failure(s) considering the various metrics regarding seal condition, design, and location. In addition to identifying potentially risk significant FBPS for prioritization of surveillance and/or replacement, plants performing an external flood probabilistic risk assessment (PRA) may use this process to identify which penetrations may need to be explicitly modeled in the PRA. The intent of this guidance is to provide a process to categorize and rank penetration seals with regard to likelihood of failure and the significance of a loss of the penetration sealing capability.

3.7.3.2 Presentation (ADAMS Accession No. ML21064A422)

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External Flood Seal Risk Ranking Process

Marko Randelovic - Principal Technical Leader, EPRI

6th Annual Probabilistic Flood hazard Assessment Workshop
February 22-25, 2021

www.epri.com

Risk Ranking of External Flood Penetration Seals (FPSs) Background

- Plants include several hundred penetration seals which provide in-leakage protection from external floods
- Project prioritizes which of the many flood seals are potentially important to plant flooding risk
  - Proactive means to provide a plant-specific assessment of the importance of flood seals
  - Structured classification provides a reasonable basis for graded treatment of seals.
  - Prioritizes actions important to surveilling and maintaining seals
  - Focuses on those seal penetrations as well as internal flood barriers that may be significant to plant risk
  - Provides basis for identifying risk important seals for treatment in an external flood PRA

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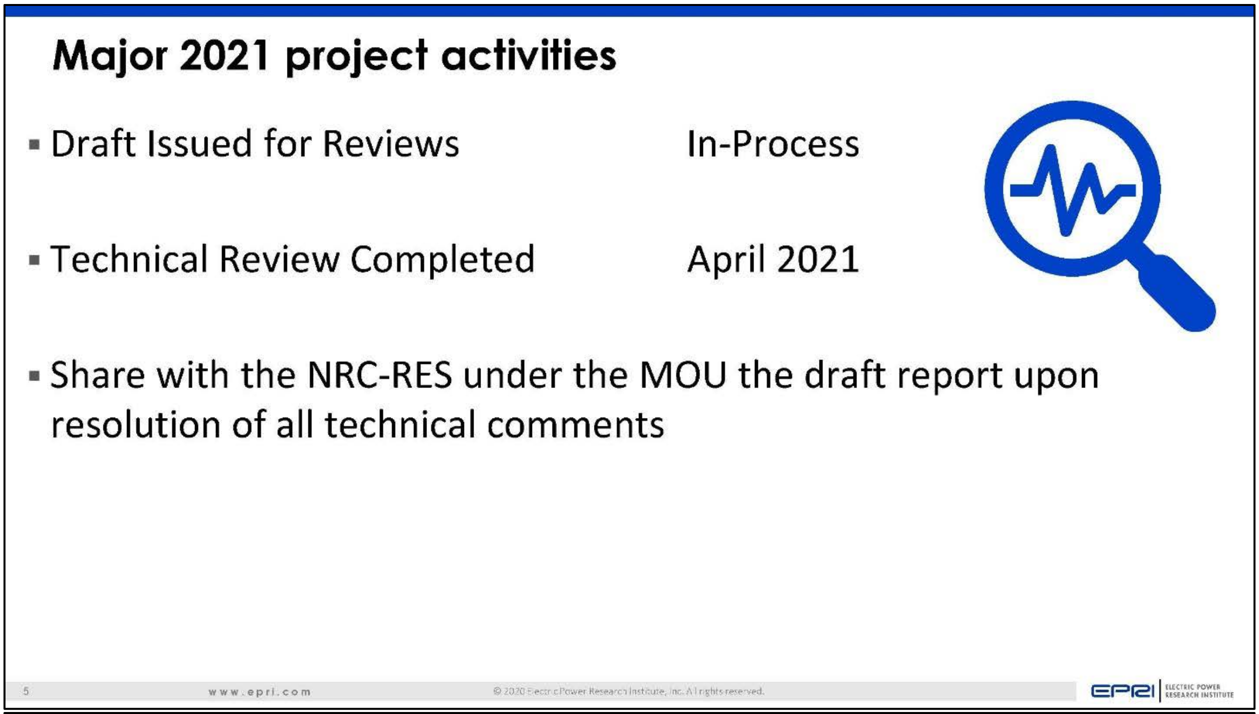
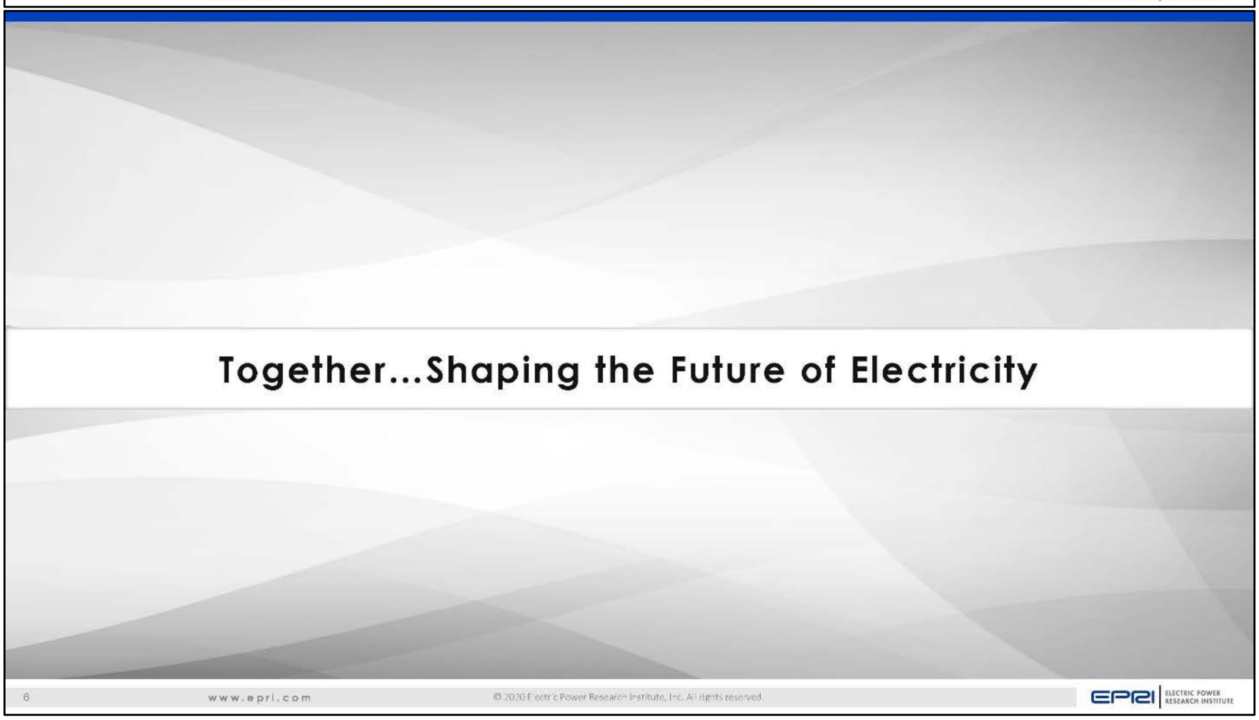
Project Objective

- Develop a practical graded strategy to rank/bin flood penetration seals (FPSs), based on their leakage potential and significance to the plant's limiting flood event(s), and indirectly, to plant safety. Objectives of this effort were to:
  - Integrate lessons learned from EPRI Flood Seal Task Force, Industry experimental experience with penetration seal performance, seal expert judgement and available test data
  - Provide utilities with a practical prioritization process which includes a two-tiered approach for categorizing/ranking penetration seals.
  - FPS Ranking Process:
    - Screens low flood significant seals
    - Identifies seals with high and medium flood significance
- Prioritization process may be used to support plant seal maintenance and surveillance, design and implementation of flood mitigation strategies

Penetration Seals Binning Process

- Phase 1 is primarily based on seal dislodgement potential. At this stage, only the FPS located at the exterior boundaries are considered. Ranking process includes:
  - High level seal screening based on seal design and its location
  - Assessment of FPS dislodgement potential based on seal bounding hydrostatic loads and seal type
  - Assessment also considers contribution due to leakage of non-dislodged seals
- Phase 2 offers a more refined ranking based on the consideration of consequences of seal failures.
  - Process focuses on potential for flood induced failures of flood significant components (FSC)
  - Can be established deterministically or build upon IFPRA.
  - Ultimate ranking based on number of trains of FSC affected by the FPS
- Process is sufficiently flexible to be implemented whole or in part based on the needs of the user.





3.7.3.3 Questions and Answers

Question:
Are there plans to make the work from this project publicly available?

Marko Randelovic:
I believe so. The report is currently undergoing internal review. Then the report is going to be published this year or early next year.

Question:
In the presentation you mentioned that it was particularly focused on exterior boundaries, so does that basically mean anything but internal walls and ceilings and floors?

Marko Randelovic:
So, it does start with the external boundaries, because some users might only be interested in the external boundaries to see what seals would leak and what seals would fail. But in the Step 2 in the report, we are going to room-to-room flooding. So, we're considering the internal effects on the seals, the loads on the seals, and we're looking at the external seals as well.

Question:
Have any plants/utilities tried to apply the draft procedure? If so, any feedback to share?

Marko Randelovic:
No, the plants have not tried yet. We're still addressing comments and then we will be having some potential reviews with volunteers from the industry.

Question:
So, does the process include things like the number of drains, pumps, sump pumps on the one side of the barrier?

Marko Randelovic:
Yes, it does include it.

Question:
Was age of the penetration seal included in the risk-ranking?

Marko Randelovic:
That is a good question. It's very challenging to include the impact of aging. We have discussed with very various experts in the industry and we're kind of providing some bounding leakage and bounding dislodgement pressure to account for the potential aging of the seal.

Question:
When you did your inventory of the penetration seals, was it a combination of walk-downs or did you rely more on internal documentation? What did you find provided the most information?

Marko Randelovic:
We relied on any earlier report done by an EPRI/industry task force.

3.7.4 Flood Protection and Flooding Experience Panel Discussion

Moderator: Thomas Aird, NRC/RES/DRA
Panelists:
John Edward Stowasser, U.S. Army Corps of Engineers (USACE)
Zhegang Ma, Idaho National Laboratory (INL)
Marko Randelovic, Electric Power Research Institute (EPRI)

Question (to William Lehman):
There’s a lot of interest in the scale of the applications of HEC-WAT. You showed us one example in the southwestern part United States. Have you tried it in other areas of the United States under different climatic conditions and different scales?

William Lehman:
One particularly large study has been performed to support the Columbia River Treaty. That study was conducted by the USACE Northwestern Division. It spans three states and includes the Columbia and Snake rivers. And of course, it has different climatic conditions. It's looking at snow melt, for instance. It's looking at long-term simulations on a large system. Another example is the Missouri River. There is a HEC-WAT model that spans the length of the Missouri River. That's a pretty big watershed. It’s similar to the Columbia River in terms of its forcings, though that does change as it gets into the Midwest. They have a different strategy for their stochastic hydrology. We also did a really small one, less than 16 square miles, in Hawaii. A very different type of system altogether. So, I would say we span the gambit of large scale to small scale with WAT applications.

Question (to Rajiv Prasad):
One of the issues you brought up was the ability to characterize and get distributions for the center, body, and range for the flood hazards. How do you determine how much confidence you have that you've adequately characterized the center, body, and range? What steps to take to check to see if you have that confidence?

Rajiv Prasad:
That you have completely captured the distribution of the hazards in a particular study is a very difficult thing to prove; that you have the correct and complete distribution. Now, that said, the process that SHAC-F goes through gives you confidence that there have been multiple interactions, that the data models and methods have been adequately evaluated not only by the project team, but their interactions with both the PPRP and the larger technical community. You bring in resource experts (custodians of data) and you bring in proponent experts that tell you about the strengths and weaknesses of models. The SHAC-F documentation process gives confidence that this whole process has been performed transparently. So that's the only way to say that we did our best, we arrived at the CBR of TDI. If there is evidence later that these need to be updated, you can go back, look at all the justifications that were initially used, and then update them as necessary.

Question (to Miles Yaw):
Are you able to use the TVA's risk-informed decision-making approach to look at environmental aspects in addition to dam safety? For example, using it during a drought period to regulate operation of nuclear and coal-fired power plants in the Tennessee Valley (in addition to the dams/reservoirs). What are your thoughts?

Miles Yaw:
We can, although I have not been involved in that yet. Risk-informed decision making at TVA is relatively young, so it may just be a case of the opportunity hasn't arisen yet. We don't want to get in the box where we are only thinking about extreme floods because TVA’s operations are at risk from severe and prolonged droughts. That's one of the reasons that we went through the dendrochronology analysis, trying to use long-term tree ring studies to look at how dry or wet can these periods get? It doesn't fit neatly in the PFHA system, at least in terms of the stochastic event sampling. But it does fit in the long-term synthetic hydrology. I showed that plot in my presentation, just as an example. There is a very clear correlation between how dry it gets and what the maximum ambient temperature is in the river, and that can threaten operations. You can also look at water supply reliability, in terms of economics and its impact on navigability. It also comes into play when we're looking at risk reduction alternatives at various projects. In Tennessee Valley, TVA operates 10 head-water reservoirs, and they have this equitable balancing scheme where waters are released late in the summer equitably between the reservoirs to meet minimum flow requirements on the lower mainstem of the river. If you

were to have a risk reduction activity at one dam that takes storage out of the cumulative reservoir storage, you may have jeopardized your ability to meet minimum flow requirements downstream. So, the modeling system really allows us to balance all the objectives across the entire system to meet environmental or navigation, or any one of TVA's operations.

Question (to William Lehman):
I'm interested in the use of HEC-WAT by other agencies. For instance, yesterday we heard about the USGS doing a study in the Delaware River basin. Are you using any of your models to help the USGS do their study of that watershed?

William Lehman:
I'm not sure I know exactly which Delaware River study you're referencing (it gets studied a lot). I'm not aware of USGS using HEC-WAT on the Delaware. However, FEMA is considering a project to model the entire state of Delaware with HEC-WAT, which will include part of the Delaware River basin. We do work with other agencies when it's appropriate and would support that as far as it is fit for purpose.

Question (to William Lehman):
I'm interested in how to integrate external hydrologic events in HEC-WAT. How adaptable and how flexible is your modeling framework to bring those external events in?

William Lehman:
In general, that's why we developed the stochastic data import tool, to allow for any kind of externally developed hydrology to be imported into HEC-WAT. Our hydrologic sampler and other event-generator-type plugins also allow for the user to specify boundary conditions however they see fit. The hydrologic sampler is robust for precipitation and flow under a couple of different sampling schemes. We see it as a generic tool that could be applied pretty much anywhere, even internationally. It just depends upon the particular use case. Also, we are interested in supporting non-agency tools. For instance, there's a RiverWare plugin. If you don't want to use HEC-ResSim you can use RiverWare instead within our system.

Question (to Rajiv Prasad):
Has anyone attempted to use SHAC-F for a variety of situations? For instance, have you applied it or are other organizations trying to apply SHAC-F? What is your experience in applying it?

Rajiv Prasad:
The short answer to that is we have not yet. This study was funded by NRC and was looking particularly at NRC applications. We haven't done a study yet that uses SHAC-F in its entirety. There are certain aspects of SHAC-F that you could adopt in any probabilistic flood hazard assessment. But, for now we can't point to one study that was performed using the whole SHAC-F process.

Question (to Rajiv Prasad):
Because you are with a Department of Energy (DOE) National Laboratory, I'm curious if you have thought about applying SHAC-F at the Savannah River Site or at Idaho National Laboratory. Have you talked to anyone at DOE looking at their requirements for flood assessment and moving towards a risk informed approach? What are your thoughts?

Rajiv Prasad:
Not yet. There are some modifications to DOE standards that have happened over the last few years. There is an appendix to a DOE Handbook that addresses performing probabilistic flood hazard analysis that reads very similar to the way SHAC-F might come across. But I'm not

aware of anybody doing that. That handbook is not a requirement for DOE sites. DOE Standard 1020 is a requirement, but it doesn't really specify how you should go about doing a PFHA. That said, INL is currently performing an extreme precipitation analysis and they are moving ahead this year to an extreme flood analysis for their Advanced Test Reactor site. I am helping them a little bit on the review side of it. They may adopt some of the PFHA techniques, but I don't think they're doing SHAC-F yet.

Question (to Miles Yaw):
You seem to have a very complex modeling framework for the Tennessee Valley. You have many sub basins. The question I'm thinking about is forecasting. Do you do a weekly forecast? A monthly forecast? What do you do about being prepared? One of the issues the NRC is faced with is that industry says that they have what's called a FLEX approach, in which if something were to happen, they could respond quickly with regard to flood protection measures. How much lead time would TVA have given an approaching storm?

Miles Yaw:
That gets brought up a lot, but I'm going to caveat my answer because I am not a forecaster. TVA has a river forecast center that is manned 24/7. They look at rainfall of course. My impression is that forecasts are very uncertain. If you look at a 72- hour forecast in various basins, it will typically have a long-term bias, either under prediction or over prediction. TVA's general rule of normal daily operations is that we respond to rain on the ground. You don't want to lower the reservoir by a couple feet in the middle of your summer pool because you think that you're going to get a big storm event and then not get that storm event. That doesn't make people very happy. The reservoirs are, by and large, able to withstand and operate well for reasonably common storms or even relatively rare storms. It's when you get very extreme events that things really start to become a problem and you really need to hit the capacity of reservoirs. The other thing is that many of the tributary reservoirs have big pools with very little spigots at the bottom. If you can only get a few thousand cubic feet per second (CFS) out of your turbines and you have a million acre feet behind your damn, a two-day lead time on the forecast isn't going to be a large impact on reservoir storage. But as you work downstream that becomes less and less true. We have bigger main-stem dams that have less storage and very large capacities and so you can start to buy yourself something there. For those reservoirs also, the storm hydrographs take a little bit more time to develop so that maybe is a roundabout way to tell you “It depends”.

3.8 Day 3: Session 3D – Poster Session

3.8.1 Poster 3D-1: Investigating Current and Future Precipitation Frequency Estimates for the State of Maryland: Challenges of Applying Machine Learning for Temporal Downscaling of Climate Model Projections

Authors: Azin Al Kajbaf, Michelle T. Bensi, Kaye L. Brubaker, University of Maryland, Civil & Environmental Engineering

Presenter: Azin Al Kajbaf

Abstract:

Climate change has altered the meteorological and hydrological characteristics of precipitation events in recent decades; extreme rainfall events appear to be occurring more frequently. The contiguous United States has experienced an increase in mean average precipitation in each decade (1951-2013). Increasing trends in extreme precipitation events are more pronounced in the Northeast of the United States. Associated with this trend, Maryland communities have experienced multiple flash flood events (e.g., Ellicott City flash floods in 2016 and 2018); these impacts are expected to worsen due to climate change. This study analyzes current and future climate Intensity/Depth Duration Frequency (IDF/DDF) for the state of Maryland using the North American Regional Climate Change Assessment Program (NARCCAP) model output at 50-km spacing. The high-resolution projections of precipitation generated by NARCCAP, provided in 3-hour intervals, must be temporally disaggregated to obtain IDF/DDF curves for shorter duration rainfall events. This study implements multiple Machine Learning (ML) algorithms, including Artificial Neural Network, Boosted Trees, and Support Vector Regression, to map 3-hour precipitation to durations of 2 hours, 1 hour, 30 minutes, and 15 minutes. The ML models are trained using observational data, then applied to NARCCAP output. Challenges are discussed, including missing data in observations used for training the ML models, selecting the best ML model, and selecting appropriate performance metrics. Response functions are presented for further investigation of the behavior of the ML models under varying inputs (e.g. daily precipitation, maximum daily temperature).

3.8.1.1 Poster Material (ML21064A443):

UNIVERSITY OF MARYLAND

Investigating Current and Future Precipitation Frequency Estimates for the State of Maryland: Challenges of Applying Machine Learning for Temporal Downscaling of Climate Model Projections

AZIN AL KAJBAF, MICHELLE BENSI, KAYE BRUBAKER

UNIVERSITY OF MARYLAND
DEPARTMENT OF CIVIL AND ENVIRONMENTAL ENGINEERING

Ellicott City, Maryland, after flash flooding in late May 2018. Photo by Howard County government

Introduction

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- Climate change has altered the meteorological and hydrological characteristics of precipitation events in recent decades.
- Extreme rainfall events appear to be occurring more frequently.
- The contiguous United States has experienced an increase in mean average precipitation in each decade (1951-2013) [1].
- Increasing trends in extreme precipitation events are more pronounced in the Northeast of the United States [2-4].
- Associated with this trend, Maryland communities have experienced multiple flash flood events (e.g., Ellicott City flash floods in 2016 and 2018).
- These impacts are expected to worsen due to climate change.

Figure 1. Cars overturned by flash flooding in Ellicott City, Maryland. Photo: Howard County government.

Figure 2. Ellicott Mills Drive at Main Street in Ellicott City on May 28. Photo: Howard County government.

2

Objective

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- This study evaluates multiple Machine Learning (ML) algorithms that are used for preparing precipitation data for analyzing current and future climate Intensity/Depth Duration Frequency (IDF/DDF) for the state of Maryland using the North American Regional Climate Change Assessment Program (NARCCAP) model output at 50-km spacing [5].
- The high-resolution projections of precipitation generated by NARCCAP, provided in 3-hour intervals, must be temporally disaggregated to obtain IDF/DDF curves for shorter duration rainfall events.
- This study implements multiple ML algorithms, including Artificial Neural Network (ANN), Boosted Trees (BT), and Support Vector Regression (SVR), to disaggregate 3-hour precipitation to durations of 2 hours, 1 hour, 30 minutes, and 15 minutes.
- The ML models are trained using observational data, then applied to NARCCAP output.
- Response functions are presented for further investigation of the behavior of the ML models under varying inputs.

3

Literature Review

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- A brief literature review is provided on studies that have used ML methods for temporal downscaling in **Table 1**.
- Information regarding location, ML method, predictors and temporal conversion and summary of the study is presented.

Table 1. Literature review

Authors	Location	Data Type	ML Method	Predictors	Temporal Conversion
Burian et al. (2001) [6]	Alabama, USA	3 Rain gauge stations	ANN	Three sequential hours of rainfall amounts in a long-term hourly rainfall record.	Downscaling hourly precipitation to 15 minutes
Mirhosseini et al. (2014) [7]	Alabama, USA	1- Historical rainfall data of NOAA (34 15-mins rain gauges station) 2- Simulated historical precipitation from NARCCAP	ANN, Stochastic method	3-hour precipitation (P3), daily precipitation, monthly precipitation, and daily maximum and minimum temperatures	Downscaling 3h precipitation to 15, 30, 45, 60, 120 minutes
Alam and Elshorbagy (2015) [8]	Saskatoon, Canada	1- Daily, hourly and 5-minutes observations 2- Daily precipitation of climate models of CanESM2, HadGEM2-ES, IPSL, CNRM, CSIRO, BCC, MRI and MIROC	K-nearest neighbors (K-NN)	An optimal window size was chosen on both sides of a disaggregation period	Downscaling from daily to hourly and from hourly to sub-hourly
Sachindra et al. (2018) [9]	Victoria, Australia	1- Monthly observations of precipitation (48 stations) 2- NCEP-NCAR Reanalysis Data	Genetic Programming, ANN, SVR, Relevance Vector Machine	Air temperature at surface and geopotential heights relative and specific humidity at surface, zonal and meridional wind speeds, sea level pressure, pressure at surface and precipitable water content	Downscaling reanalysis data to monthly precipitation

4

Study Area and Data

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- The rectangular area in **Figure 3** indicates the study area.
- Hourly and 15-minute stations in the states of MD, VA, WV, PA, DE and NJ are used as observations for training the ML models and are illustrated in **Figure 3**.
- The observations are collected from Climate Data Online database of the NOAA National Center for Environmental Information (NCEI).
- Hourly and 15-minute stations are used when daily summaries information is available at the same station.

Table 2. Length of record in each type of station

Type of station	Duration of data
Hourly	**Hourly: 1950-2014** **Daily summaries: 1950-2014**
15-Minute	**Hourly: 1970-2014** **Daily summaries: 1970-2014**

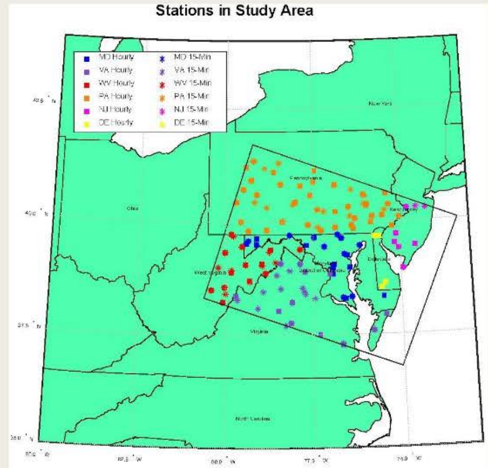

Figure 3. Location of hourly and 15-minute stations in the study area.

5

Challenges Associated with Preparing the Datasets

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- Since daily summaries information (e.g., temperature, daily precipitation) are used in conjunction with hourly and 15-minute precipitation data for training the ML models, stations where daily summaries information are not available, cannot be used in training.
- 3-hour precipitation is mapped to durations of 2 hours, 1 hour, 30 minute, and 15 minute. Since hourly durations of 2 hours and 30 minutes are not available, they are generated from aggregation of 1 hour and 15-minute duration datasets for consecutive events.
- In hourly and 15-minute stations, no observation is recorded when precipitation is zero. To efficiently use the available data for generating longer durations, 45-minute and hourly stations are zero padded for an extra 45 minute and 2 hours, respectively.
- At some locations, reported hourly or 15-minute precipitation exceeds associated reported daily precipitation. Since the exact time of recording for daily precipitation is not clear, observations where daily precipitation is smaller than hourly or n-minute precipitation, are eliminated from the datasets for training.

6

Input Parameters for Each Duration

A. James Clark School of Engineering

- The higher duration precipitation that is used as predictor has the highest importance and a significant difference with other parameters in predicting target durations and hence is not shown in the plots.

- Other parameters including latitude, longitude and elevation of stations were used for prediction. Using geographic information improved the performance of the ML models, however, when applied to NARCCAP dataset, the results were inconsistent. Therefore, they are eliminated from the final set of input parameters.

Table 3. Input parameters for training ML models in each duration

Input parameter	Target precipitation
3h pr, Daily pr, Max daily temp, Min daily temp, Max monthly pr, Max yearly pr	2 hour
2h pr, Daily pr, Max daily temp, Min daily temp, Max monthly pr, Max yearly pr	1 hour
1h pr, Daily pr, Max daily temp, Min daily temp, Max monthly pr, Max yearly pr	30 minutes
30 min pr, Daily pr, Max daily temp, Min daily temp, Max monthly pr, Max yearly pr	15 minutes

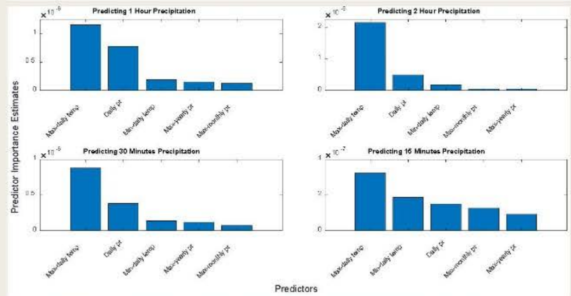

Figure 4. Estimates of predictor importance in predicting different durations.

7

ML Models' Performances

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- ML models of ANN, BT and SVR are developed, and their performance is evaluated before applying to NARCCAP points.

- Models are trained using 70% of randomly selected data (k-fold=10) and tested on remaining 30% percent. The results are shown as vertical bars where top and bottom bars show maximum and minimum, and the center symbol shows the average value of the performance measures in 10 folds.

- ANN and BT constantly outperform SVR. The variation in results of BT is lower than that in ANN and SVR.

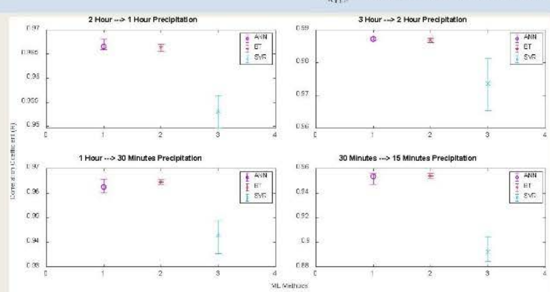

Figure 5. Correlation coefficient of ML models in predicting different durations.

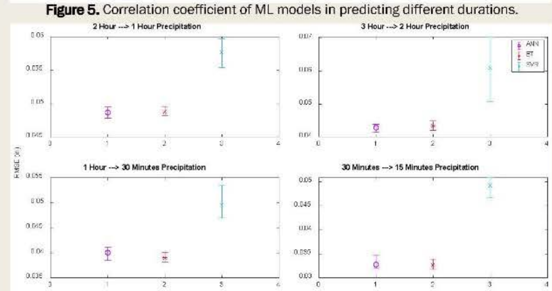

Figure 6. RMSE of ML models in predicting different durations.

8

Response Functions

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- For developing response functions, all variables are locked at a specific value (average of the range considered for each variable) except for two variables which are shown on x and y axes. The colors on the plot show the response of the models with respect to each set of variables.

- For both models the first three figures from the left shows the response function when one of the parameters is a higher duration precipitation which is the leading contributor to the precipitation value.

- Response functions also depict the different mechanisms of the ML models in predicting target precipitation.

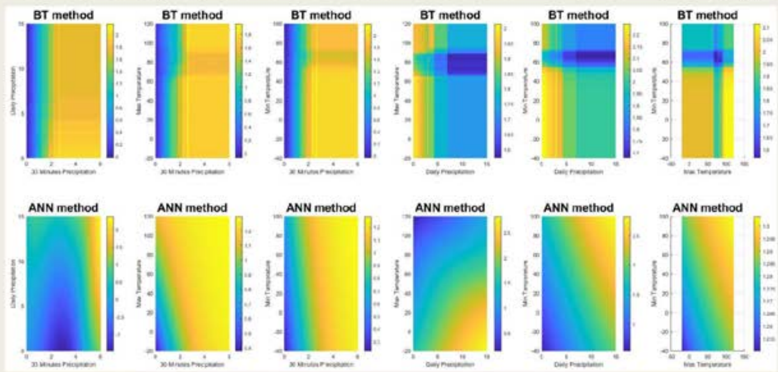

Figure 7. Estimates of predictor importance in predicting 15-minute precipitation.

9

NARCCAP Points in EPC2-gfdl Climate Scenario

A. JAMES CLARK SCHOOL OF ENGINEERING

- The NARCCAP regional model points (centers of the grid cells) that are located in Maryland are extracted. The unit of precipitation in the regional models is $kg\ m^{-2}s^{-1}$ and is converted to inches.

- The values of precipitation in regional models are provided over grid cells at 50-km spacing, or 2500 km^2 in area. They are converted to point values using point/area adjustment following LeClerk and Schaake [10].

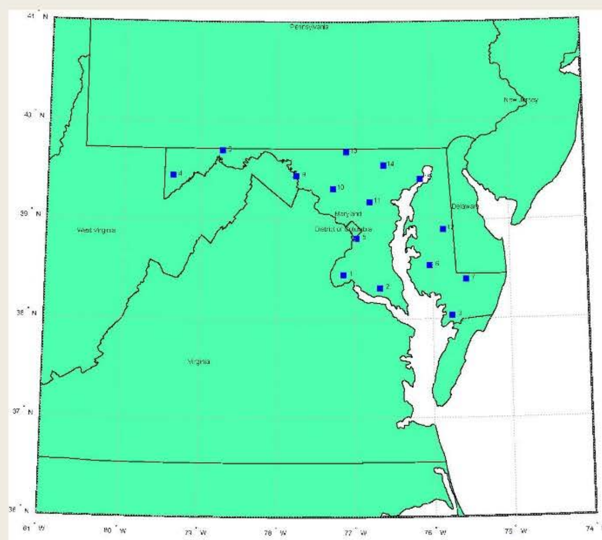

Figure 8. The location of NARCCAP points in state of MD in EPC2-gfdl scenario

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Applying the ML models to NARCCAP Points

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- The trained ML models of ANN and BT are applied to 3-hour precipitation information of NARCCAP points in Maryland.
- Although the results of both models seems to be close, the BT model shows a better performance in predicting smaller values of precipitation.

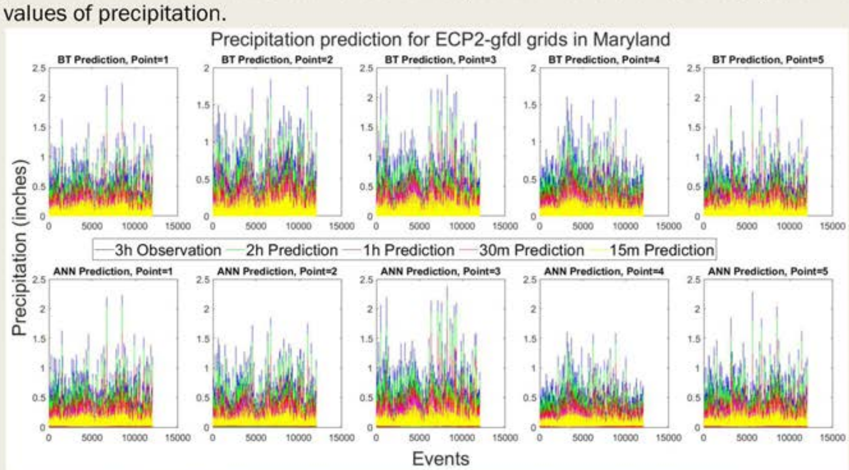

Figure 9. Results of applying BT and ANN models to NARCCAP points for different durations.

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Conclusions

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- Multiple ML methods (e.g., ANN, BT, SVR) are implemented for temporal disaggregation of high-resolution projections of precipitation generated by NARCCAP, provided in 3-hour intervals to durations of 2 hours, 1 hour, 30 minutes, and 15 minutes.
- Challenges that are associated with preparing the datasets for training the ML methods include:
  - unavailability of daily summaries information at some hourly and 15-minute stations (these stations are not considered in the analysis).
  - Inconsistency of precipitation data recorded by daily summaries sets and hourly and 15-minute stations (the observations with this inconsistency are eliminated from dataset).
  - Hourly and 15-minute stations does not record data when precipitation is zero which can be mistaken with periods of missing data (zero padding is applied).
- In selection of set of appropriate input parameters for training ML models, aspects beyond performance metrics (e.g., R, RMSE) that are used for evaluation of such models must be considered.
- Even though comparison of R and RMSE shows that ANN has similar performance (sometimes ANN is slightly better) to BT, when applied to NARCCAP points, BT shows to be better in predicting precipitation values close to zero.
- Response function provide valuable insight regarding behavior of ML models in predicting target response in wide range of input variables.

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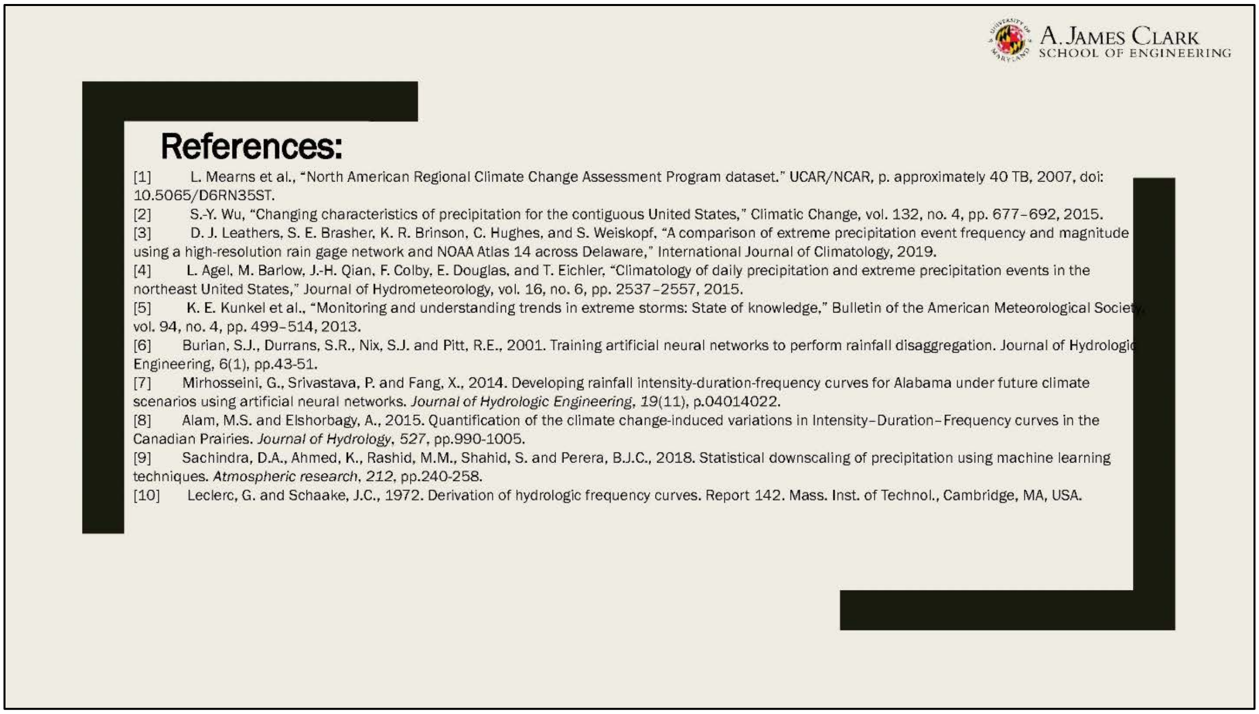


3.8.2 Poster 3D-2: Riverine Flooding HEC-WAT Pilot Project Dam Break Modeling

Authors: Brennan Beam, William Lehman, Sara O’Connell, David Ho, U.S. Army Corps of Engineers, Hydrologic Engineering Center

Presenter: Brennan Beam

Abstract:

This poster describes how the Hydrologic Engineering Center's Watershed Analysis Tool (HEC-WAT) is being used to include dam failure in their probabilistic flood hazard assessment (PFHA) process. The technical details associated with viewing a system wide dam failure for a single event and how that integrates into a broader Probabilistic Flood Hazard Assessment within HEC-WAT is the primary focus of the poster.

3.8.2.1 Poster Material (ML21064A444):

HEC-WAT Hydraulics for PFHA

Brennan B. Beam PE, CFM
USACE Hydrologic Engineering Center

Background

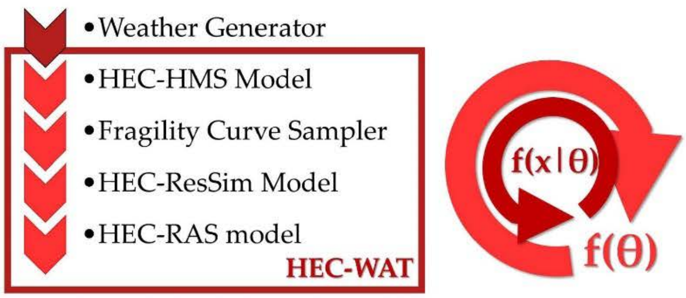
- The Nuclear Regulatory Commission (NRC) requested HEC assistance with methods to include dam failure in their probabilistic flood hazard assessment (PFHA) process.

- The analysis includes evaluation of stochastic precipitation events and random dam failures to drive the hydrologic loading, which were routed through HEC RAS to create the hydraulic hazard frequency curves.

2

The Bigger Picture

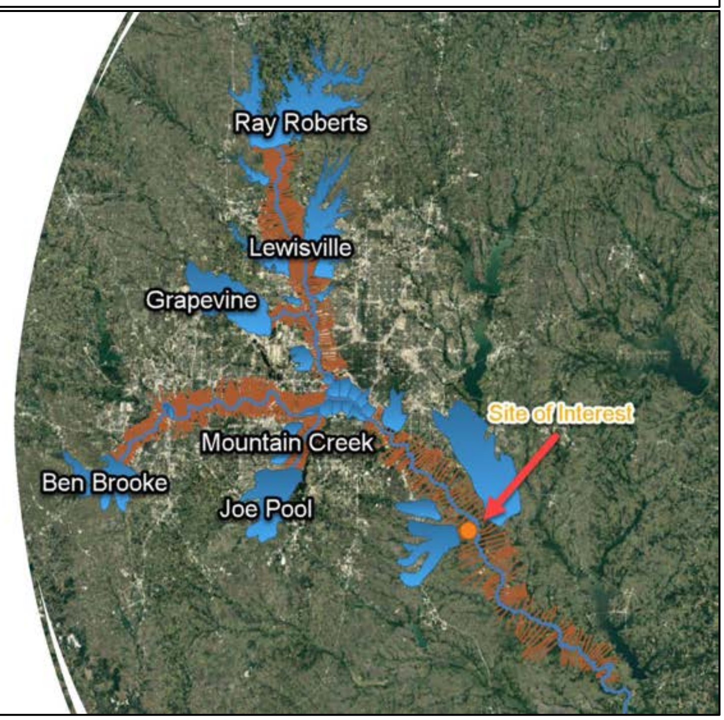
- For each event, HEC-RAS will use lateral inflows provided by HEC-HMS, and reservoir elevations and flows provided by HEC-ResSim, and dam breach thresholds from the fragility curve sampler to calculate maximum stages at a point of interest. The result of many thousands of iterations will be used to calculate stage frequency curves.

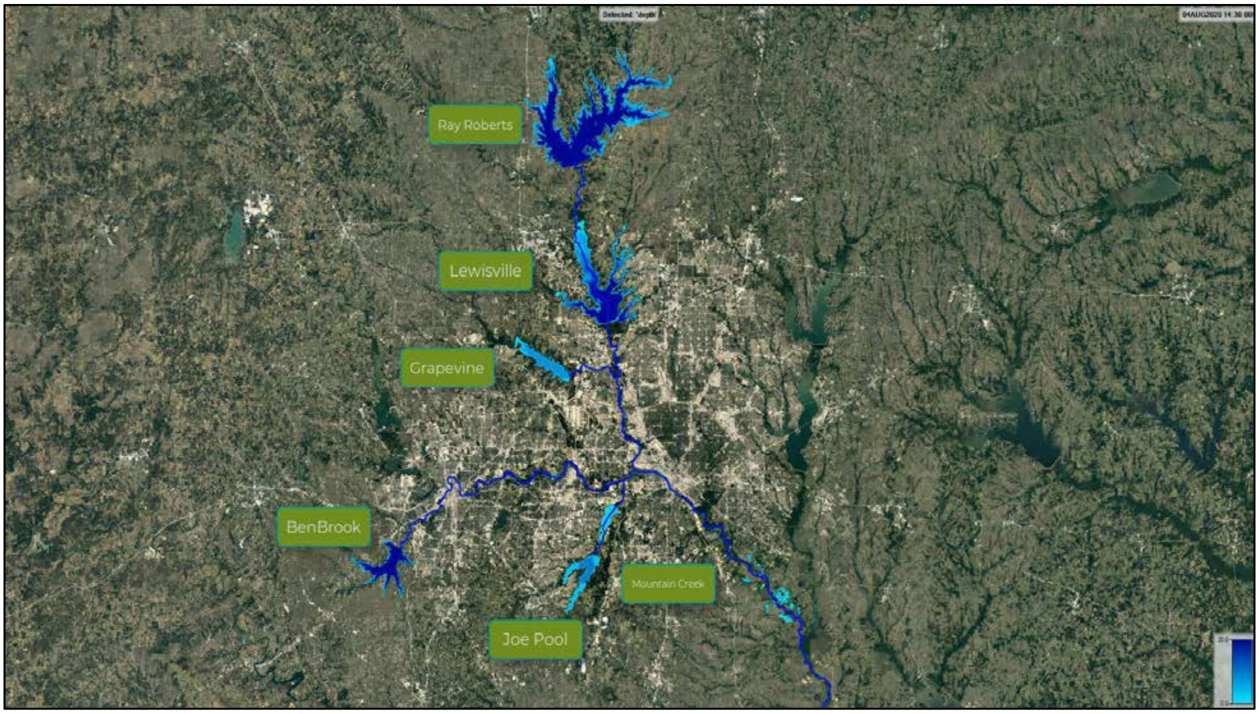


3

Hydraulic Model

- Trinity River Watershed
- Dallas, TX
- Six Breaching Dams
- Two Sets in Series

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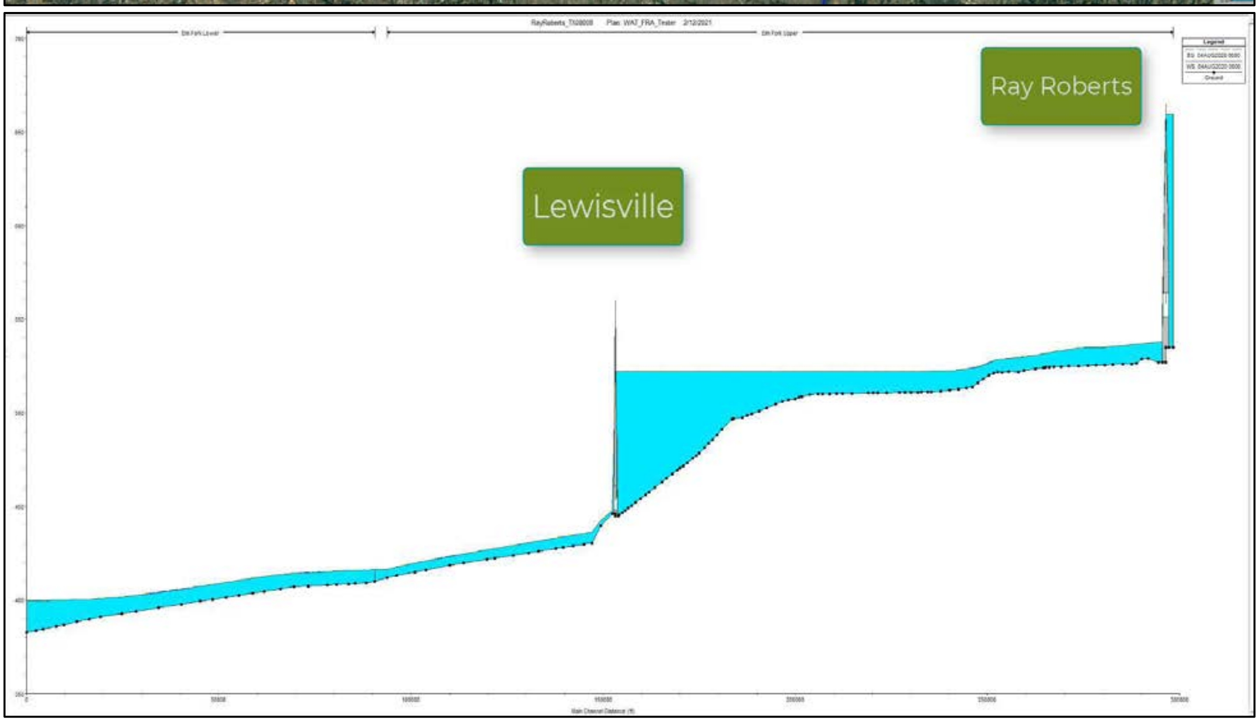
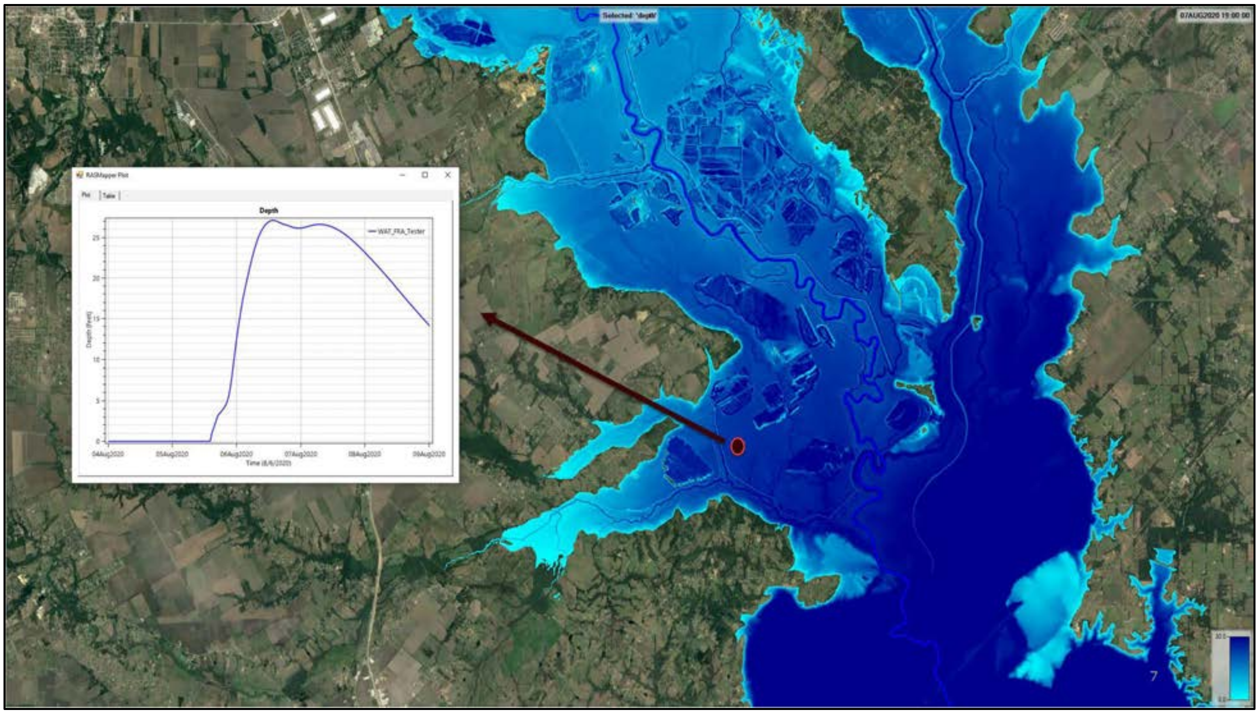
Lewisville
Grapevine
BenBrook
Mountain Creek
Joe Pool


Lewisville
Ray Roberts



3.8.3 Poster 3D-3: Nationwide (USA) Pluvial Flood Modeling via Telemac2D

Author: Max Kipp, Leo Kreymborg, Mike DePue, Atkins North America

Presenter: Max Kipp

Abstract:

FEMA has estimated that approximately 40% of flood damages are due to pluvial flooding, which occurs when locations with small drainage area experience excessive accumulation of direct rainfall runoff. These floods are typically shallow and low-velocity, but can cause significant damage and disruption. In 2018, Atkins developed an automated workflow to run pluvial models en masse, using Telemac2D as the model engine. Telemac2D is FOSS maintained by a consortium of EU and UK organizations. Atkins first piloted the workflow in South Carolina before applying it to vast areas of the United States (anywhere that high resolution ground DEMs were available). The total modeled area to-date is about 1.7 million square miles, covering about 82% of the population of the USA, including portions of 50 states, DC, and major territories. Each state was broken into small independent basins and covered by a triangulated mesh, with node spacing between 11 and 15 meters. A 6-hour nested hyetograph was generated at each node using NOAA data, for four events: 2yr, 10yr, 100yr, and 1000yr. Basins were processed in parallel via cloud computing (Google Compute Engine), with concurrent CPUs as high as 5,000 physical cores' equivalence, allowing speeds of about one USA state per day. Final depth rasters have 3-meter pixels and are approximately 8 terabytes, compressed. FEMA has begun using the data in comprehensive risk calculations. In addition, the results are being leveraged by Atkins' City Simulator, which has allowed Boulder, CO to receive a grant from FEMA to proactively design transportation improvements to mitigate flood impacts. The 2yr results are also being used for enhanced identification of wetlands. In 2020, this project was selected as one of three finalists in the UK Environment Agency's Flood & Coast Excellence Awards, in the Digital Excellence category, and received a Highly Commended Certificate.

3.8.3.1 *Poster Material (ML21064A445):*

SNC·LAVALIN

ATKINS
Member of the SNC-Lavalin Group

Nationwide (USA) Pluvial Flood Modeling via Telemac2D

Finalist in Digital Excellence category of UK Environment Agency's Flood & Coast Excellence Awards 2020

Max Kipp, PE
Philadelphia
max.kipp@atkinsglobal.com

Need for Pluvial Models

A key component of comprehensive risk.

Pluvial flooding occurs when small subbasins experience excessive accumulation of direct rainfall runoff.

~40% of flood damages in the USA are due to pluvial sources.

Most flood studies and related mapping activities have focused on riverine and ocean activity.

The map image at right shows results of Atkins' mass pluvial modeling routine, which runs the Telemac2D engine in Linux, leveraging cloud computing to scale nationwide.

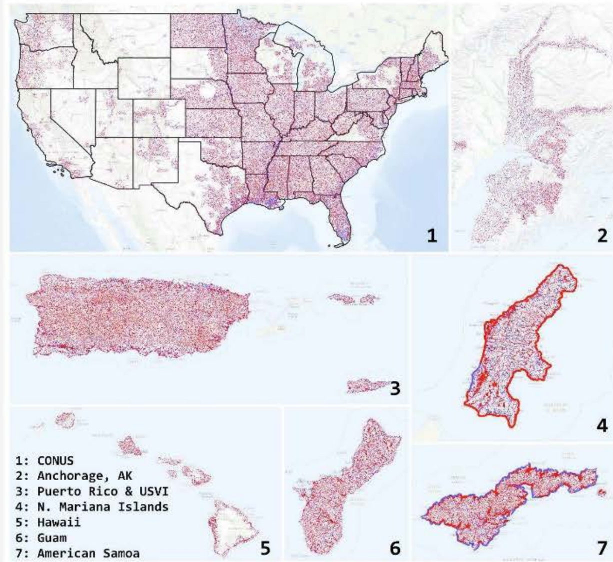
SNC·LAVALIN ATKINS

Modeling Scope

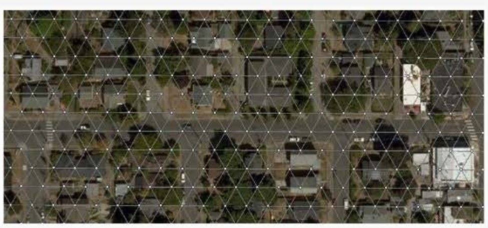
Everywhere in USA (+ territories) where high-resolution DTMs available

As of 2020:

- Over 80% of USA population covered
- Approximately 1.7 million square miles
- Four rain events
  - 2-year
  - 10-year
  - 100-year
  - 1000-year
- Resulting 3-meter depth rasters composed of about 8 terabytes, compressed

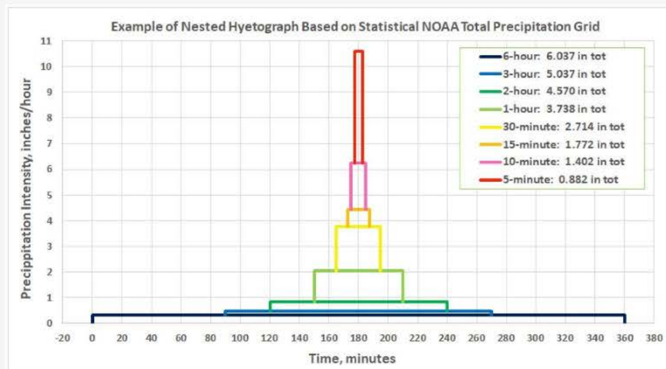


Process Details



Custom triangulated mesh

- Early models at 15-meter node spacing
- Later models improved to 11-meter node spacing
- 3-meter pixels for input DTM and output depth rasters.



Custom Nested Hyetograph Derived For Each Node

- At each node, NOAA Atlas 14 total volume sampled for several storm durations, up to 6-hour duration
- Volumes converted into rates and nested into a 6-hour hyetograph, such that the volume under any time-width (from center) agrees with the corresponding NOAA total volume of that duration.

3.8.4 Poster 3D-4: Combining the Best of Both Worlds, Using Detailed Flood Analyses to Inform Rainfall Accumulation Characteristics for the World-Record July 1942 "Smethport" Storm – Supporting PMP and Flood Frequency Analyses

Authors: Bill Kappel[1], Joe Bellini[2], [1]Applied Weather Associates, [2]Aterra Solutions, LLC

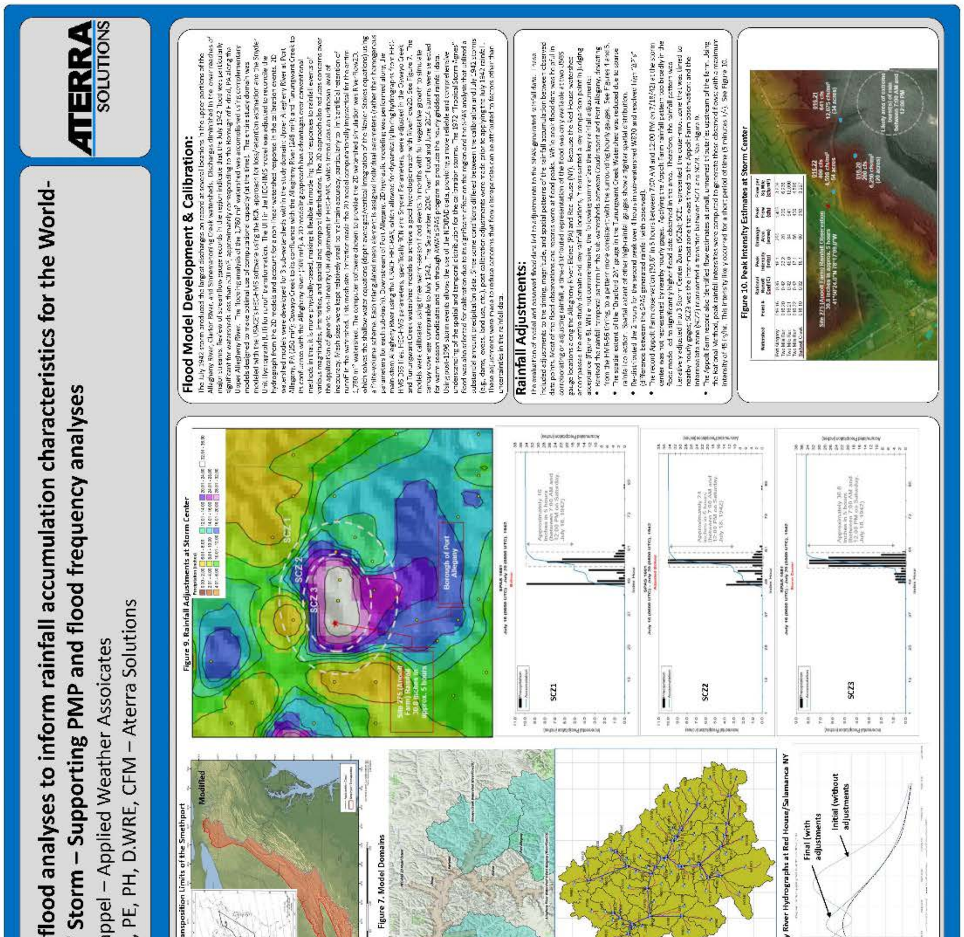
Presenter: Bill Kappel

Abstract:

Applied Weather Associates (AWA) and Aterra Solutions (Aterra) completed a detailed reanalysis of the world record rainfall resulting from the Smethport, PA July 1942 storm using state of the science meteorological and hydrological techniques. The unique combination of work between AWA and Aterra produced updated rainfall accumulation patterns in space, time, and magnitude. These updated results were incredibly important for Probable Maximum Precipitation (PMP) development in the region, and specifically was required as part of the updated statewide PMP study for Pennsylvania. The PMP depths where this storm is transpositionable are controlled by this storm. A significant amount of rainfall and flood data were available, especially from non-conventional observation types. Because of the uncertainties related to the quality of the rainfall data collected, a critical component of the study was a hydrologic and hydraulic (H&H) simulation of the watershed's response. A 2D modeling approach (based on shallow water equation solutions) was used to simulate the H&H processes; coupled with conventional (lumped and semi-distributed) hydrologic models. The 2D modeling approach is physically based, providing greater flexibility in modeling hydrologic and hydraulic responses to rainfall events of various magnitudes, intensities, spatial distributions, and temporal distributions and over irregular terrain. An important consideration in using 2D methods for hydrologic modeling is the mitigation of uncertainties associated with the application of generic non-linearity Unit Hydrograph adjustments, typically used in hydrologic models to transform runoff to flow hydrographs. We will describe the approach used to develop the H&H models, comparisons between modeled and observed flood data, how those H&H

investigations allowed the Smethport rainfall to be updated in a more accurate and realistic manner, and how those results were applied for PMP development.

3.8.4.1 Poster Material (ML21064A446):



3.8.5 Poster 3D-5: A Tale of Two Cores: harmonized paleoflood hydrologic data works best for estimating flood frequency and magnitude

Author: Ray Lombardi, Lisa Davis, University of Alabama

Presenter: Ray Lombardi and Lisa Davis

Abstract:

Sedimentological evidence of past floods (paleofloods) provides long records necessary to examine extreme floods beyond the observed period. This study examines how the spatial variability of flood deposition and preservation over a floodplain affects flood magnitude estimations and flood frequency analyses made using paleoflood hydrologic data. We collected two sediment cores 500 meters apart from a natural levee at equal elevations along the Tennessee River banks near Guntersville, Alabama. We measured grain size from each core at a 1-cm resolution. Optically stimulated luminescence dates revealed approximate age ranges of 50 – 6,500 years calibrated before present (yrs. cal. BP) for the downstream 3.5 m core (BO1) and 120 – 8,500 yrs. cal. BP for the upstream 4.18 m core (EL2). Each sediment cores contained 15 large paleofloods. Most of BO1 paleofloods occurred in the last 2,000 years, while most of the EL2 paleofloods occurred between 2,000 and 5,000 yrs. cal. BP. Four paleoflood events correlate across the two cores. These four floods' timing corresponds with paleofloods identified by prior paleoflood studies on the Tennessee River. The EL2 site contained fewer preserved flood deposits corresponding to the last 2,000 years than the BO1 site. The preserved floods from the last 2,000 years at the EL2 site only preserved the largest floods. The difference in estimated flood magnitude was < 10% for the four paleofloods found in both cores, however. Bayesian flood frequency analyses conducted for each site revealed differences in the shape of flood curves as a function of site paleoflood record. The EL2 site, which predominantly preserved older paleofloods corresponding to a colder and drier past climate, estimated smaller discharges for recurrence intervals crucial to flood risk assessments. Findings suggest that the "completeness" of the paleoflood record is of importance when applying paleoflood hydrologic data to estimates of flood frequency and magnitude.

3.8.5.1 Poster Material (ML21064A447):

A Tale of Two Cores: harmonized paleoflood hydrologic data works best for estimating flood frequency and magnitude

By Ray Lombardi and Dr. Lisa Davis, The University of Alabama Department of Geography

Introduction:

- Particle size offers valuable paleoflood magnitude information for low-lying floodplains.
- The interpretation of the number and size of paleofloods may by locally altered by variation in flood-deposition (Fig 1) and post-deposition disturbances across floodplains.

Fig 1: Flood deposit spatial variability on the Mississippi R. (Gomez et al., 1997).

We reconstructed paleoflood chronologies from two sites that have experienced the same floods over time to address the following research questions:

1. Can two sites on the same alluvial surface represent distinct paleoflood chronologies?
2. Do distinct paleoflood chronologies alter flood frequency models?

Study Area and Research Approach:

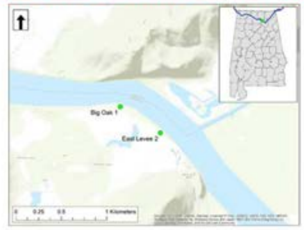


Fig 2: Sample locations for two sediment cores ~ 500 meters apart.

Fig 3: Workflow of methods

Flood Peaks

1. Change point analysis[10]
2. LOESS Smoothing[11]
3. Identify positive residual > 4

Flood Record + Paleostage

4. Extract ages and d90 particle size of flood peaks **
5. Calculate min. flood depth based on d90
6. Cross correlate paleofloods between sites

Paleoflood Magnitude

7. Create HEC-RAS geometry for each paleoflood based on depth
8. Iteratively run discharge until it generates flood stage equals d90 paleostage

Flood Frequency Analysis

9. Independent FFA at each site using Bayesian MCMC estimate in RMC-BestFit
10. FFA of cross-correlated paleofloods only

Address Question 1

Address Question 2

A Tale of Two Cores: harmonized paleoflood hydrologic data works best for estimating flood frequency and magnitude

By Ray Lombardi and Dr. Lisa Davis, The University of Alabama Department of Geography

Can two sites on the same alluvial surface represent distinct paleoflood chronologies? YES

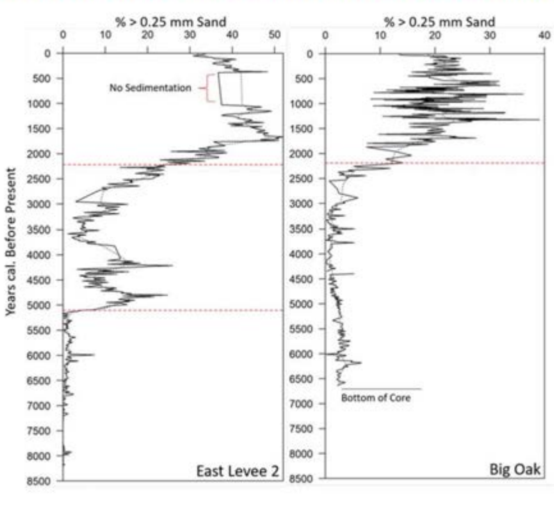


Fig 4: These graphs depict the volume of sediment that is 0.25 mm sand or large at each site over time (black lines). Peaks above the LOESS smoothing line (black dotted lines) are considered flood peaks. Red horizontal dotted lines denote significant change points in average sedimentation of medium to coarse sand.

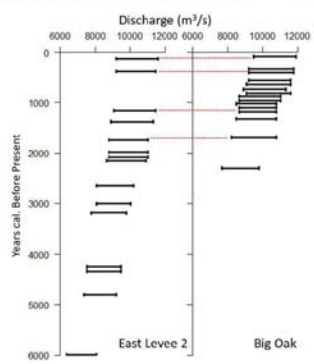
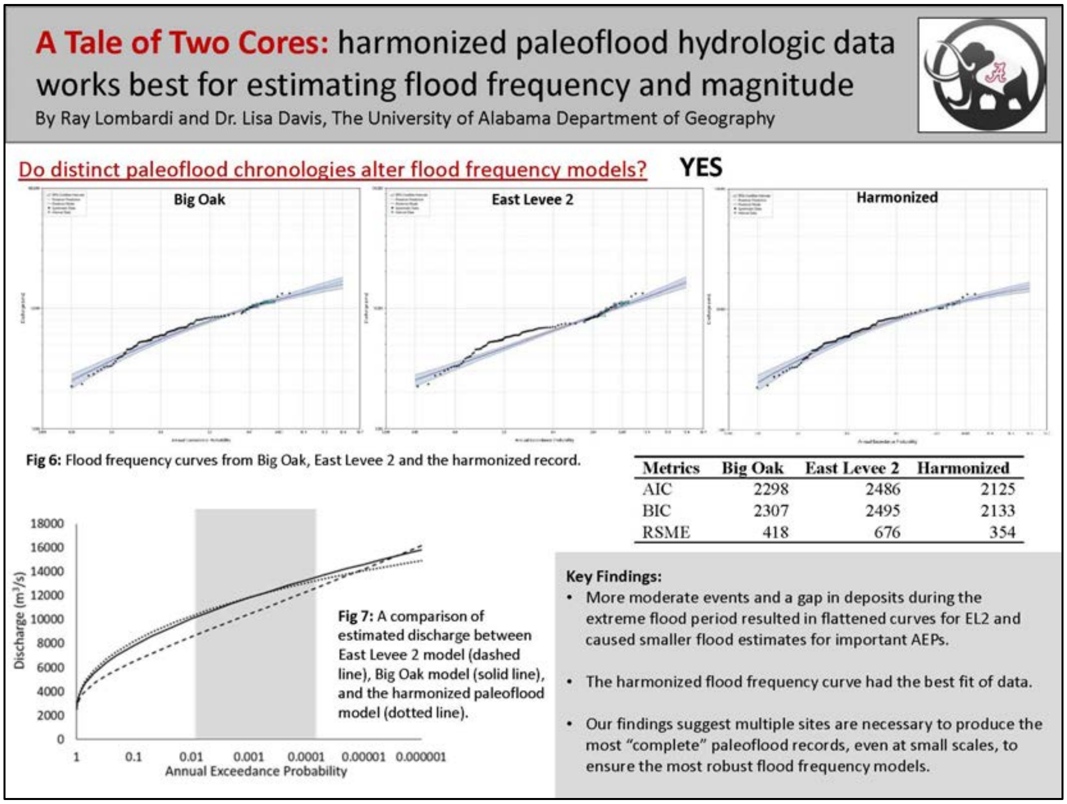


Fig 5: Paleoflood times series for each site. Black bars represent paleofloods, and red dotted lines indicate which floods overlapped between sites.

Key Findings:

- The timing of preserved paleofloods varied between sites but the overall trend in magnitude was consistent.
- EL2 preserved mostly older and smaller magnitude floods and appeared to be missing flood deposits for a high magnitude flood period.



3.9 Day 4: Session 4A – External Flooding PRA

Session Chair: Joseph Kanney, NRC/RES/DRA

3.9.1 Presentation 4A-1: Insights, Limits and Projections for EDF's External Flooding PRAs

Authors: Jeremy Gaudron, Cecile Luzoir, Électricité de France (EDF)

Speaker: Jeremy Gaudron

3.9.1.1 Abstract

Following the Blayais flooding event in 1999, EDF undertook to improve its defenses against external flooding for the full French nuclear fleet. External flooding protections consist of several levels of barriers installed either permanently or temporarily depending on the flood phenomenon that is involved. The 2011 Fukushima event further led to enhancements of protections against extremely rare flooding events. Current protections against external flood at EDF NPPs generally consist in peripheral protection, volumetric protection for underground structures and proximal protections as well as alert systems and preventive procedures. Since 2016 and the 4th decennial safety reassessment of the 900 MWe series, EDF began developing external flooding PRAs for relevant flood phenomena. The first versions of these PRAs have been limited to riverine flooding and surge events (without waves' effect). These studies have enabled EDF to gain various interesting insights, particularly about plant design against external flooding and the numerous benefits of Post-Fukushima enhancements. However, some limits have also been underlined especially concerning hazard characterization of extreme values which lead to substantial uncertainties. Therefore, the external flooding PRAs' calculated risks

(CDF & FDF) should be interpreted cautiously and their insights must not be distorted by the weight of cliff-edge effects. Following these encouraging studies, EDF will continue their development of external flooding PRAs by including relevant correlated external flood phenomena such as surge event + waves and riverine flooding + short fetch waves. An ambitious provisional roadmap has been set for the following years and for the upcoming ten-yearly reassessments which could be readjusted depending on technical issues. Following these new assessments, it could be decided to re-orientate or reduce the scope of relevant external flooding PRAs.

3.9.1.2 Presentation (ADAMS Accession No. ML21064A448)

PFHA 2021 - Insights, limits and projections for EDF's external flooding PRAs

J. Gaudron

EDF/DIPNN/DT

Engagés Ensemble

Engagés Ensemble

Contents

Feedback from Blayais and Fukushima events at EDF

External Flooding protection system

Alert system and specific procedures for external flooding

PRAs context in France – Regulatory issues

First developments for external flooding PRAs

Insight and limits

Projections

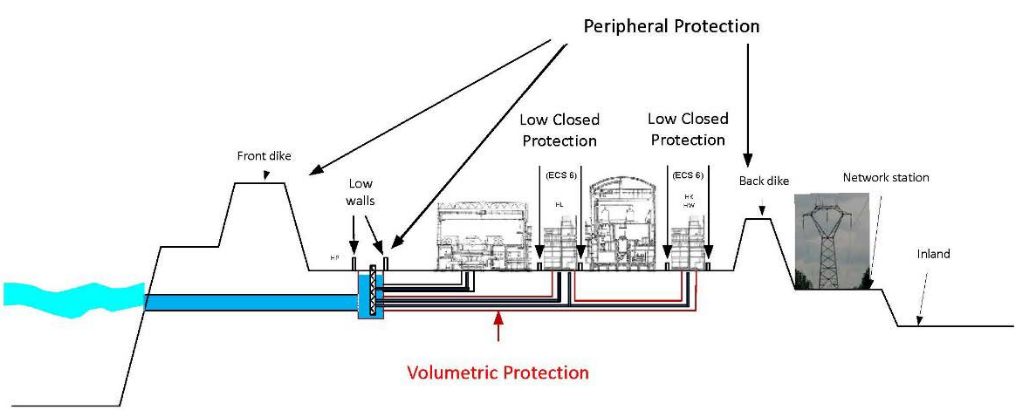
Feedback from Blayais and Fukushima events at EDF

- Blayais – 1999: Update of EDF external flooding deterministic guidance in order to better take into account combinations of hazards that could lead to water ingress on NPPs.
  Additional protections against external flooding installed (volumetric protection, raising of peripheral protection, …).
  Reinforcement of alert systems and of specific external flooding procedures.

- Fukushima – 2011: Stress tests performed on every EDF NPPs. Definition of a beyond design basis water level.
  Additional protections installed related to BDB hazards.
  Creation of off-site emergency teams with portable equipment (French FARN).

PFHA 2021 - INSIGHTS, LIMITS AND PROJECTIONS FOR EDF'S EXTERNAL FLOODING PRAs

External flooding protection system



- Peripheral Protection: protection of the platform
- Volumetric Protection: protection of buildings related to safety from high groundwater level or from flooded buildings non-related to safety.
- Low Closed Protection: protection of buildings related to BDB safety from direct flood of the platform (precipitations, tank break-up)
- High Closed Protection: protection of rooms related to BDB safety from riverine or coastal flooding

External flooding protection system

- Peripheral Protection:

- High / Low Closed Protection:

PFHA 2021 - INSIGHTS, LIMITS AND PROJECTIONS FOR EDF'S EXTERNAL FLOODING PRAs

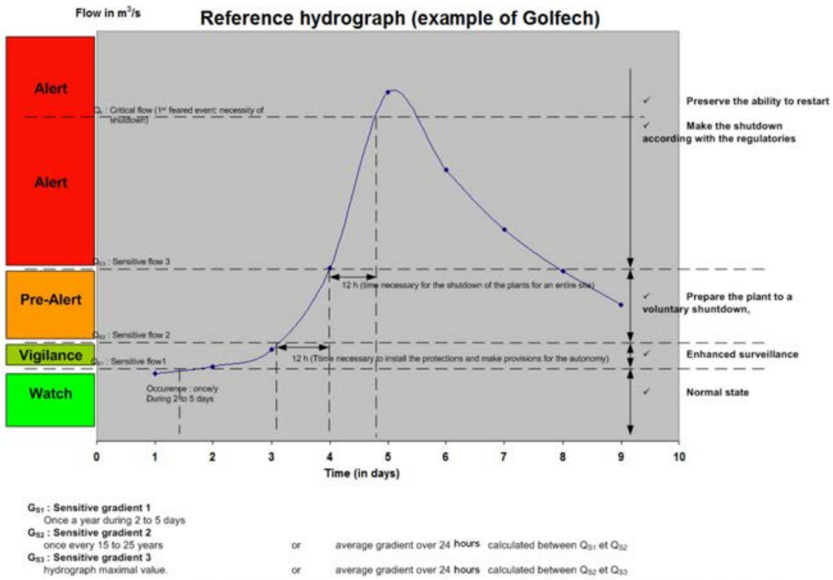
Alert system & specific procedures

It includes 4 levels of surveillance and actions detailed in specific plant procedures:

Surveillance State	Objectives	Actions	Organizations
Watch (Normal Operation)	Establish and maintain operating procedures for all other surveillance states	**Normal operation** No specific actions	Normal ↓S1
Vigilance (Potential risk)	Allow time-efficient handling of any further development	**Strengthened surveillance** Prepare to start protections set-up & specific procedures	Normal ↓S2
Pre-Alert (Confirmed risk)	Ensure durable plant operation in accordance with the regulators. Prepare plant shutdown Protect buildings from water ingress	Safeguard the installation – protections set-up Extended surveillance and checks Ensure durable plant integrity (plant autonomy)	Normal or adapted ↓S3
Alert (Proven risk)	Handle the event while maintaining safety and keeping the ability to re-power later	Anticipated shutdown Management of common commodity storage facilities to enhance autonomy	Adapted

Si = Threshold - Water level, Flowrate or Flow gradient

Alert system & specific procedures



PRAs context in France – Regulatory issues

- In France, the nuclear safety demonstration shall also include probabilistic analyses of accidents and their consequences, unless the licensee demonstrates that this is irrelevant. *(Order of 7 February 2012 setting the general rules relative to basic nuclear installations)*
- Screening process to estimate relevancy of probabilistic analysis for each potential external hazard.

First developments for external flooding PRAs

- 2016: 4th decennial safety reassessment of the 900 MWe series – Beginning of studies
  Riverine flood and surge events are screened in for detailed PRAs developments
- 2016-2018: Developments of EDF first External Flooding PRAs
- 2019: Technical review by the regulator. Approval of results and insights for this specific safety reassessment.

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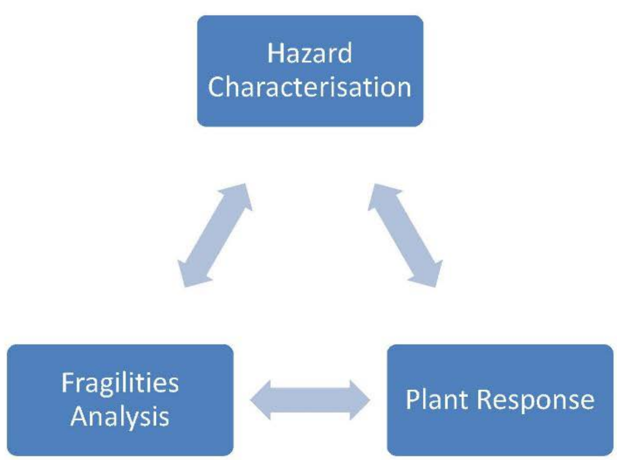
First developments for external flooding PRAs

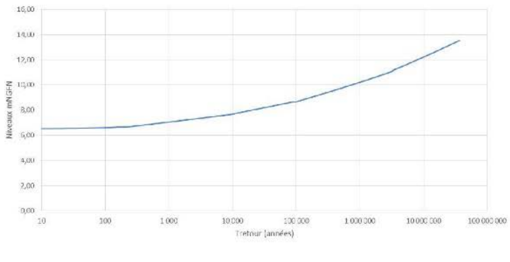
3 main steps methodology



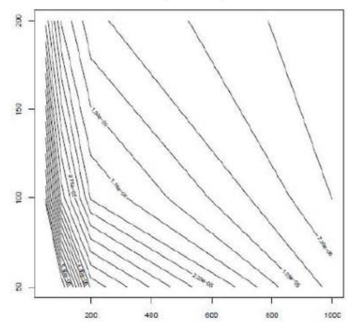
First developments for external flooding PRAs

- Hazard characterization (1/2)

Extreme value analysis (sea surge)



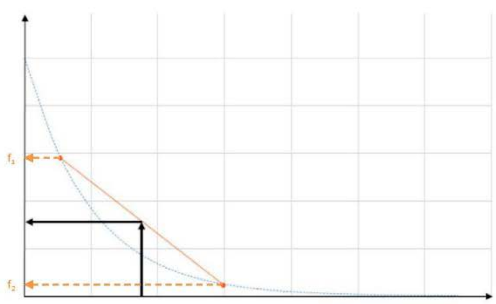
Multivariate analysis (combinations)



First developments for external flooding PRAs

- Hazard characterization (2/2)

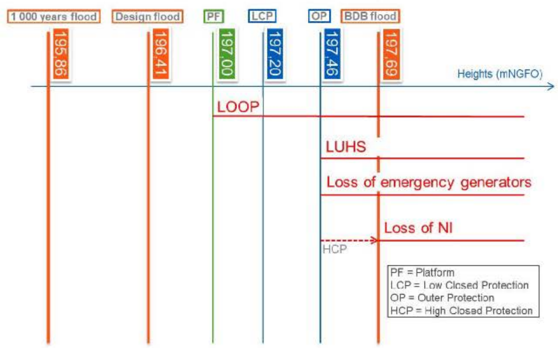
Decoupling frequencies for extreme values (riverine flood)



Phenomenology / physical analysis

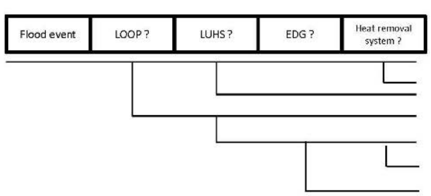
First developments for external flooding PRAs

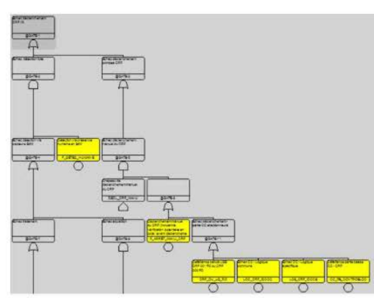
- Plant fragility analysis
  - Protections means
  - Preventive human actions evaluations
  - Preventive plant shutdown evaluation
  - Vulnerabilities analysis (losses of safety functions)



First developments for external flooding PRAs

- Plant response
  - Initiators analysis
  - Mitigation means analysis
  - Post-accidental human actions evaluations
  - Quantifications
  - Sensitivities





Insight and limits

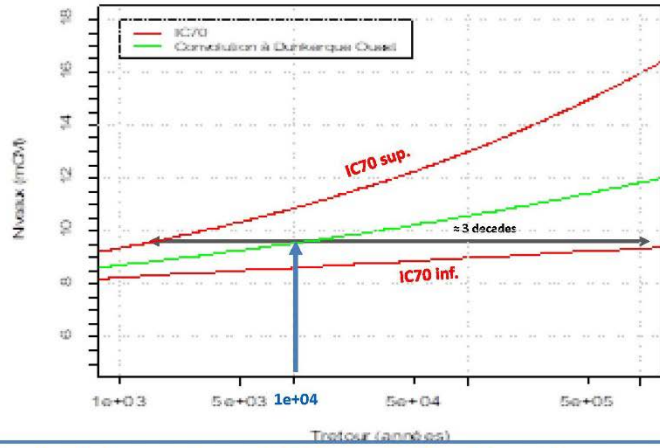
- Simplified approach for external flooding PRAs is used with decoupling assumptions that could limit insights
  - E.g. water propagation inside buildings is not modelled and assumption of unacceptable consequence is made
  - → Very conservative assumption for flood mechanisms leading to low water volumes on-site
- Developments are still ongoing to improve external flooding PRAs depending on what benefits are expected

Insight and limits

- Large difficulties concerning the characterization of flood single mechanisms (e.g. riverine flooding) & flood combined mechanisms (e.g. storm surge + waves + wind) for extreme flood events (10^{-6} to 10^{-8}/y)
  - Limited observed and historical available data (80 to 200 years of data)
  - Definition of correlation degree between mechanisms often unknown for extreme values
  - Use of decoupling and/or conservative arbitrary values instead of curves

Insight and limits

- Large uncertainties above 1 000 year return period not included in results

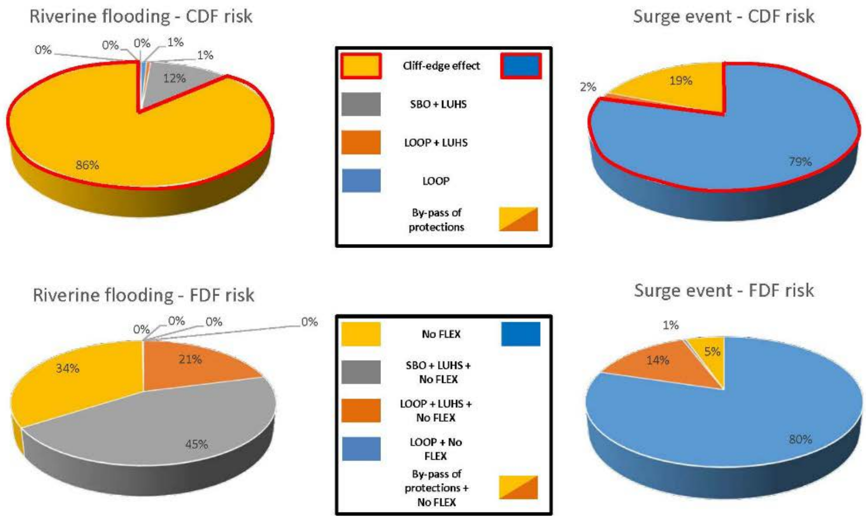


Risk calculations above 10 000 years flood events are considered as hypothetical risk

Insight and limits

- Protection enhancements following Blayais and Fukushima events lead to large reduction of both CDF and FDF risks.
- No flooding risk up to very high water level (> 10 000 years return period) except for some rare by-pass negligible scenarios
- Contribution coming from flood scenario assuming total loss of power supply remains low
- Off-site "FLEX" means (FARN) are helpful to avoid fuel uncover in the spent fuel pool
- Large part of the risk is due to overtopping of highest protections (cliff-edge effect)

Insight and limits



Insight and limits

- Results from external flooding PRAs should therefore be interpreted cautiously
- Verification of effectiveness and sufficiency of NPPs current design is achievable

  But proved to be limited for design modification decision making for extreme flooding events
- **Depending on the relevancy of results and insight of external flood PRAs, EDF could decide to re-orientate or reduce the scope of relevant external flooding PRAs.**

External flooding projections

- 2019: 4th decennial safety reassessment of the 1300MWe series – Beginning of studies
  Adding of following external flooding correlated mechanisms for detailed PRAs developments
  - Storm surge (surge + swell + waves + wind)
  - Short fetch waves (riverine flood + wind)
  - Induced flood on platform (exterior) due to intrinsic failure or seismic event
- 2020-2022: Developments of EDF External Flooding PRAs for 1300MWe series

From expertise to integrated solutions, a highly-regarded standard-bearer in industrial design engineering, supporting existing facilities and new-build projects

Working together for the safety and competitive edge of the nuclear industry

3.9.1.3 Questions and Answers

Question:
Did the French regulator set the regulatory criteria for the PFHA? I think in your presentation you said that they require it. What sort of detailed criteria did they prescribe for how you do it?

Jeremy Gaudron:
A: Good first question. The only requirement we have is to perform dedicated probabilistic studies on relevant external hazards. We don't have any specific criterion. EDF defined its own probabilistic goals for each safety reassessment.

Question:
Please discuss analysis of the groundwater flooding scenario which may occur for long-duration external flooding.

Jeremy Gaudron:
Do you mean how we deal with groundwater level? We have volumetric protection underground, and we assume that it's perfectly efficient. If we do have some groundwater reaching the platform, we have more protection above the platform. So, groundwater is not a big priority for EDF up to now, due to the existing protections we implemented following the Blayais event.

Question:
How did you account for the effects of flood duration or other flooding characteristics in the in the PRA?

Jeremy Gaudron:
When performing external flooding PRAs, we're looking at mitigation means to enable the plant to withstand a flood duration of three days. We don't specifically look at what could happen after three days of flooding. If the flood lasts more than three days, we assume that we will have all the necessary means to protect the plant. In France, we do have potential means to bring in external, offsite teams.

Question:
Where are you getting reliability/fragility data or information to use in your PRAs, especially with respect to flood barriers or flood protection.

Jeremy Gaudron:
We had to make some assumptions depending on the type of protection. For concrete walls and similar structures, we assume that this kind of protection will withstand the flood up to the height of the protection. That also applies to any permanent and potential temporary barriers we can put on the site. All the concrete walls and all the steel sheet piles we could install are assumed to be 100% efficient up to the top level of the protection. It comes from some requirements we have and some testing we have performed on those kinds of protections. We evaluate the preventive human actions before the occurrence of the events. And we perform human reliability analysis (HRA) to assess the probability of failure of some non-permanent protections.

Question:
You mentioned assuming perfect performance of concrete barriers and things like that. Are there any penetrations in those barriers such as seals, and are those accounted for in the PRAs? Is reliability estimated for those?

Jeremy Gaudron:

Concerning penetration seals, we do have them. We have specific maintenance on those penetration seals. When one of these penetration seals should be opened there is a risk analysis performed before any opening. All penetration seals are followed at least once a week, I think, by the plants. The flood procedures require checking all the perimeter volumetric protections and that includes penetration seals that have a flood protection role. So, we assume that they are all reliable when the flood event occurs. We also have some penetration ways that could be closed with valves and equipment. For those, as I already mentioned, we perform human action evaluations under specific actions.

Question:
You mentioned that the cliff-edge effect was an important insight from your PRA results, and I was wondering to what specific protection features that insight applies? Was it with respect to a specific protection feature such as the peripheral protection, the volumetric protection, or something else?

Jeremy Gaudron:
The cliff-edge effect is due to overtopping of the highest protections we have on each site. Those flood protections protect a small number of essential equipment to maintain the plants in a safe state. So, the cliff-edge effect is related to the loss of that safety-related equipment.

Question:
What are the largest uncertainties in your external flooding PRA results?

Jeremy Gaudron:
The largest uncertainties are the ones on the hazard. As mentioned in the presentation, we have several orders of magnitude in uncertainty when considering the very rare flooding events. I mentioned the cliff-edge effect. We put a frequency estimate on the cliff-edge effect, but it's just an expert judgment. We can't clearly say if it's realistic or not. It's quite conservative, in my opinion. But we don't have a tool to fully evaluate the uncertainties on this cliff-edge effect.

Question:
What is FDF?

Jeremy Gaudron:
That is the frequency to uncover fuel in the spent fuel pool. We do calculations both for the reactor and for the spent fuel pool.

3.9.2 Presentation 4A-2: Methodology Developed for the Belgian External Flooding PSA

Authors: Bogdan Golovchuk, Filip Van Opstal, Tractebel ENGIE

Speaker: Bogdan Golovchuk

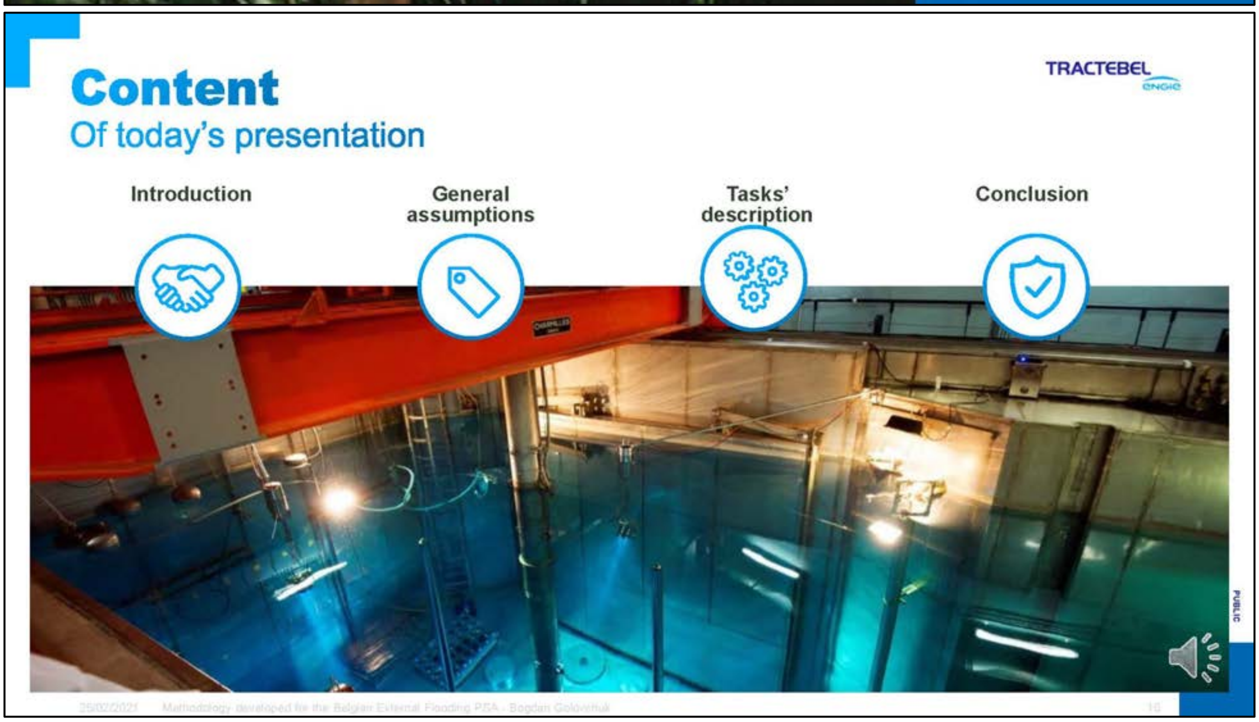
3.9.2.1 Abstract

External hazards are in the scope of the Belgian Level 1 Probabilistic Safety Assessments (PSA). One of the external hazards to be assessed is external flooding for a river site. The methodology described below was used for the external flooding PSA from the Meuse River at Tihange nuclear power plant. It can be applied for both reactor and spent fuel pool PSA. The methodology was organized in 10 tasks and consists of the following elements:

- Task 1 - “Hazard curve characterization” with the primary goal of defining the discrete flood level intervals to analyze and with a secondary goal of assessing and reducing the epistemic uncertainties linked to the flooding hazard curve;
- Task 2 - “Structures, Systems, and Components (SSC) identification” with the goal of identifying SSCs to be considered in the project;
- Task 3 - “Site walkdown and topological characterization of the site” with the goal of on-site data collection;
- Task 4 - “Tihange site peripheral wall reliability model” with the goal of determining the reliability of this wall and of the barriers for preventing water ingress into the buildings;
- Task 5 - “Water level correlations” which map the relationship between the critical water levels and SSC failures;
- Task 6 - “Human Reliability Analysis (HRA)”;
- Task 7 - “Additional system analysis and miscellaneous” which in this case is the Ultimate Means System (CMU);
- Task 8 - “PSA consequence definition”;
- Task 9 - “PSA model integration” which uses the internal events level 1 PSA, and flood sequences and flood fault trees to develop an external flooding model; and
- Task 10 - “Quantification and presentation of the result.

In addition, sensitivity, uncertainty, and importance analyses will be performed within the Task 11. The objective is to reach ASME capability category II.

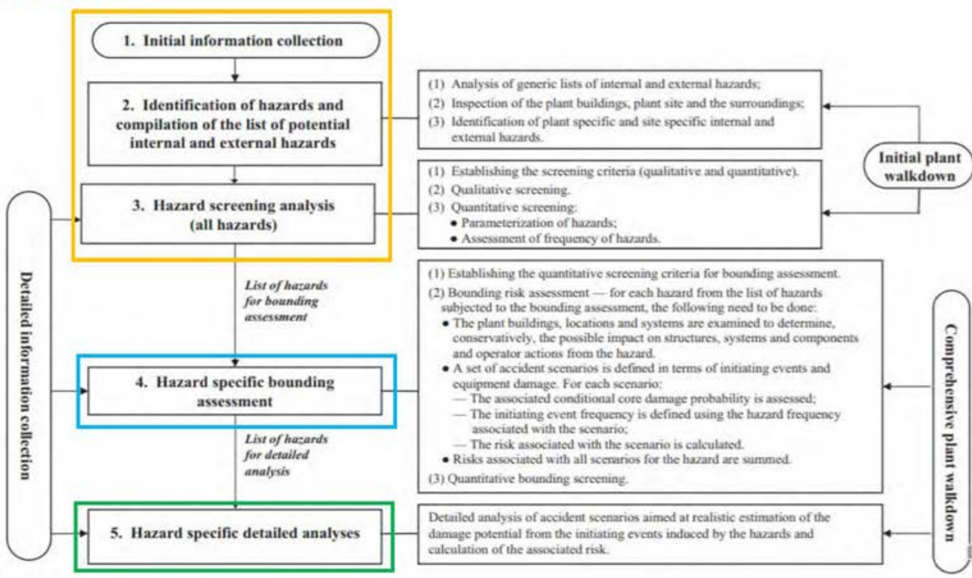
3.9.2.2 Presentation (ADAMS Accession No. ML21064A449)



Introduction

Introduction

TRACTEBEL ENGIE



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Tihange site

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General assumptions

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Scope, assumptions and limitations

- Applicable equally to Reactor or Spent Fuel Pool PSA
- Level 1 PSA methodology
- Based on the available internal events PSA
- Site-level response: isolation of the peripheral wall
- Single unit system modelling (except for the flex/ultimate means, for which cross unit back-up is credited)

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Scope, assumptions and limitations

- Reflection the operator's strategy
- Two optimal safe shutdown states
  - Power operation => Intermediate shutdown
  - Outage => Shutdown for refuelling

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Task descriptions

Task 1 : Hazard curve characterisation

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Instrumental Hydrology:

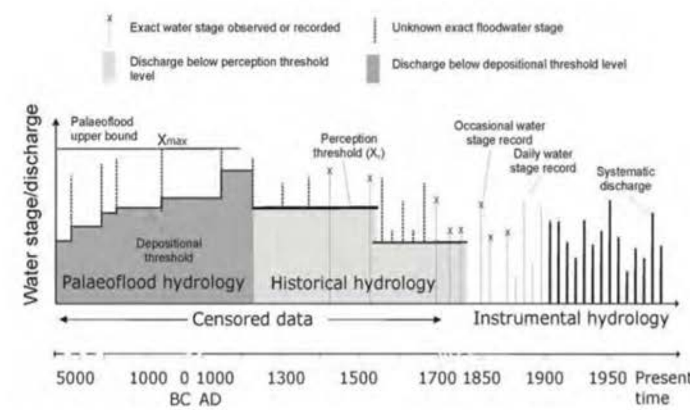
- Some 60-70 years

Historical flood doc sources :

- Newspapers
- Flood mark on a house
- Personal correspondence

Palaeoflood indications :

- Scars on trees
- Flood deposit



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Task 1 : Hazard curve characterisation

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- Converted into PSA compatible form
- Estimation of uncertainty
- Goals:
  - Define the discrete intervals to analyse
  - Assess and reduce the epistemic uncertainty

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Task 2 : SSC Identification

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- Modelling for external flooding
  - Existing reactor PSA model
  - SFP model
  - Input data : functional descriptions, P&IDs, logical diagrams and maintenance records.
- Examination and adaptation of existing internal events PSA fault trees

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Task 3 : Site walkdown data collection

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- Complete topographical models of the site with and without the anti-flooding wall exist
- When additional details are needed :
  - Request from the site – for clarifications
  - Site walkdown to be organized – for significant amount of details
- An interview with the site personnel

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Task 4 : Peripheral wall reliability model

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- Detailed characterisation of the wall :
  - Wall elements
  - Actions to isolate the wall
  - Maintenance procedures
- Sources of data for failure probabilities :
  - Site specific empirical experience
  - Empirical experience from other plants
  - Generic industry data or failure probabilities
  - Engineering judgement

Goal : Determine the reliability of the wall by FT analysis

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Task 5 : Water level correlations (optional)

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- Calculation of onsite water levels and propagation inside buildings
- Task 5 inputs : from Tasks 1, 2, 3, and 4
- Map the relationship between the critical hazard parameters for an external flooding PSA
- Optional:
  - Depends on the extent, to which the methodology will be applied

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Task 6 : Human reliability analysis (HRA)

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- River flooding is a predictable hazard, HRA is focused on :
  - Pre-emptive human actions (close the wall and install barriers, bring plant to safe state)
  - Post initiating event human actions
- Flood monitoring and warning system has an essential role to trigger pre-emptive actions that should be included in the model :
  - Principles of implementation and equipment used for monitoring the Meuse river flow
  - Ability to detect the on-going flooding
  - Ability to ensure sufficient time during warning phase
  - Successive warnings phases

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Task 6 : HRA - Post-initiating event human actions

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- Re-quantification of existing HEPs can be performed by using penalizing factors to account for the additional stress and organizational workload

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Task 7 : Additional system analysis

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- Internal events PSA model will be expanded with the modelling of critical systems required to cope with external flooding events
- Ultimate Means System
  - Make-up to the primary, SG, SFP
  - Diesel generator
- Detailed fault trees will be developed
- Extension of the modelling of other systems

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Task 8 : PSA consequences definition

TRACTEBEL engie

- External flooding event trees development
- Task 8 outputs :
  - Relevant function events
  - Definition of scenario sequences
  - Consequences defined for each sequence
  - Assignment of boundary condition sets
- Same success criteria as internal events PSA
  - Success
  - Induced accident
  - Core damage

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Task 9 : PSA model integration

TRACTEBEL ENGIE

- External flood PSA quantification
  - Sequence/consequence analysis
  - CCDP estimation per interval
  - CDF Quantification
- Risk quantification consider :
  - Flooding induced failures
    e.g. loss of the safety systems when the water reaches a certain height
  - Non flooding failures : random failures, human actions, etc.;
    e.g., a pump fails to start, CCF.

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Task 10 : Sensitivity, uncertainty and importance analysis

TRACTEBEL ENGIE

Parameters for the interpretation of the results :

- Uncertainty : confidence interval
- Importance analysis : evaluate the importance of basic events
- Sensitivity analysis : re-quantification of the analysis using alternative assumptions

→ To assure robustness of further decisions based on PSA and provide important inputs to any recommended design or procedure changes

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Task 11 : Presentation of the results

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Technical note with final result, includes :

- Numerical value of the core damage frequencies
- Split of the results per plant operating state
- Dominant sequences
- List of top minimal cut-sets
- HSS basic events
- Sensitivity results
- External flood vulnerabilities
- Insights and recommendations

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Conclusion

Conclusion

TRACTEBEL engie

- Methodology for the external flooding detailed probabilistic safety analysis was developed
  - High level: describes the overall philosophy
  - Ad hoc adaptations possible
  - Based of literature review, benchmarking
  - Lessons learnt from the bounding analysis
- CDF quantification, Error Factor and identification of the potential vulnerabilities

PUBLIC

25/02/2021 Methodology developed for the Belgian External Flooding PSA - Bogdan Golovchuk 25

3.9.2.3 Questions and Answers

Question:
What is an intermediate shut down?

Bogdan Golovchuk:
It's a situation when you can still cool down with the steam generator. So, it's for PWRs. You can use the shutdown heat removal system, taking water from the primary and putting it through the heat exchangers or the steam generators. The pressure is still high enough for you to have two different heat sinks.

Question:
In your analysis of the peripheral wall reliability, do you assess the possibility of increased groundwater flow beneath the wall, especially during a long-duration external flooding event?

Bogdan Golovchuk:
No, we did not assess anything like this. We looked at foundation design studies and, in principle, with respect to the foundations, groundwater is not a problem. If you mean that water would start seeping through and appear on site, for that we have a dedicated drainage system which can cope with low flow rates. Of course, it wasn't designed for when the world breaks. But if you have some-on site precipitation or wind waves overtopping the wall, we have the drainage system which can deal with it. For very long durations, we should model it with an increased mission time. Then it would boil down to a failure to run during a slightly longer mission time.

Question:
Is there monitoring outside and inside of the power plant site for groundwater levels of which can be influenced by local and external flooding? Is the monitoring part of the hazard alert system?

Bogdan Golovchuk:

Actually, we do monitor the groundwater level very closely because we have wells, which are used as a redundant ultimate heat sink. In case you lose, for example, water intake from the river, you can get water from the aquifer. So, it's very well monitored.

Question:
OK, but for your heat sink you'd have low-level alarms. Do you have high-level alarms as well which can play for the flooding question?

Bogdan Golovchuk:
Yes, I believe so, because there are underground galleries. But then again, it's not really the focus for us because we were able to screen it out a few years ago. We are focused on the high discharge of the river.

Question:
How do you use the results of the uncertainty analysis of flood hazards in the PSA? Do you use a mean flood hazard curve or upper and lower confidence bounds on that mean estimate? How do you incorporate the uncertainty?

Bogdan Golovchuk:
We use the percentile. We use the mean value plus an error factor. We look at the 5th percentile and 95th percentile and we carry that along all the way till the final quantification when we run the Monte Carlo simulation. We sample different values on the curve and then we plot the distribution of the CDF it gives us. You know, the whole distribution of possible CDF values contrary to a point estimate. That’s how we carry it along.

Question:
Do you follow the beyond-design-basis flood (BDBF) concept from the IAEA? If you accept the concept of the BDBF, do you have any protection measures for it?

Bogdan Golovchuk:
The anti-flood wall is a post Fukushima measure. I don't remember the original design-basis return period, but now it is approximately two orders of magnitude beyond that. So, yes, we’ve looked at beyond design-basis.

Question:
Are there openings in the walls that need to be closed before floodwaters arrive at the site? And following on the previous question to Jeremy, are there penetrations that have seals?

Bogdan Golovchuk:
Yes, and yes. I'll start with the seals. There are seals and how we model them is pretty much a function of how frequently they are inspected. We assume that if they are left unattended, they might deteriorate (for example, due to sunlight if they are made of polymers or due to rust). We consider them as a potential flood source. As for openings, there is a canal that leads from the river to the reactors and the reactor discharges for each of the units. All of this must be closed, and properly configured. And then there is a bypass that goes over the wall, to be able to release the water back into the river over the wall. Then you also need to isolate all the sewers. So, many actions must be performed to make sure that there is no water intrusion.

Question:
You have outlined a very detailed methodology, so I’m curious about how completely it has been implemented.

Bogdan Golovchuk:

PSA is an iterative process. We performed the first bounding study which followed the same philosophy. So, I would call it iteration 1, and now we are halfway through iteration 2.

3.9.3 Presentation 4A-3: External Flooding PRA Guidance

Authors: Marko Randelovic[1], Raymond E Schneider[2], [1]Electric Power Research Institute, [2]Westinghouse Electric Company

Speakers: Marko Randelovic and Ray Schneider

3.9.3.1 Abstract

EPRI has developed 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 future requirements of the ASME/ANS PRA Standard. To facilitate understanding simple hypothetical example applications illustrating 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. Specifically, this presentation provides an overview of the content of the guidance with emphasis on the interface with the PFHA.

3.9.3.2 Presentation (ADAMS Accession No. ML21064A450)

ELECTRIC POWER RESEARCH INSTITUTE

External Flooding PRA Guidance

Marko Randelovic - Principal Technical Leader, EPRI
Ray Schneider, Fellow Engineer, Westinghouse

6th Annual Probabilistic Flood Hazard Assessment Workshop
February 22-25, 2021

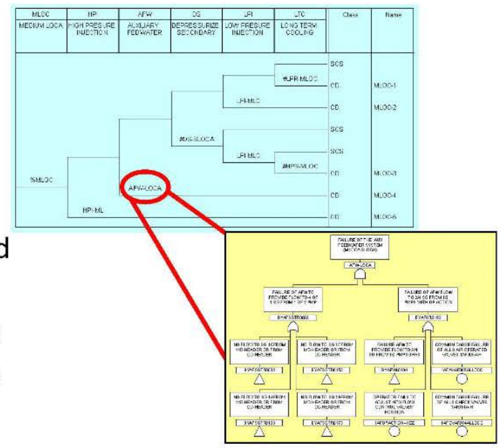
www.epri.com

Background

- Past EPRI projects have provided guidance supporting implementation of the ASME/ANS PRA Standard to assess risks of internal and external hazards. EPRI projects in the internal and external flooding area include:
  - Development of screening methodology for the external hazards
  - Development of external flood walkdown guidance
  - Development of the methodologies for variety of the flood hazard curves
  - Development of the 3D modeling technique for internal flooding
- The current project expands the external flood PRA effort by integrating available information on external flood modeling to develop a practical methodology for the development of the external flooding PRAs

External Flood Guidance for Probabilistic Risk Assessment

- Provides a structured roadmap for performing an External Flood PRA (XFPRA) consistent with meeting requirements of the ASME/ANS PRA Standard.
- Includes guidance for:
  - Defining and characterizing the external flood hazard
    - Including estimation of external flood hazard frequencies, severity and associated uncertainties
  - Identifying flood induced failure modes and develop external flood fragility curves for flood significant Systems, Structures, and Components (SSCs).
  - Preparing and quantifying a PRA external flood event tree.



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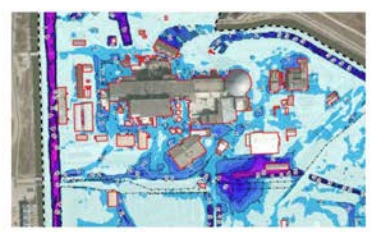
External Flood Guidance for Probabilistic Risk Assessment

- Guidance uses baseline internal events and internal flood PRAs as basis for developing relevant flood-induced failures for inclusion in an External Flood PRA.
- Guidance is structured consistent with the ASME/ANS PRA Standard
- Guidance builds upon prior relevant EPRI references for hazard screening and example PFHA studies for representative NPPs
- Where available and appropriate USACE and NRC documents and methods are identified to support both PFHA and fragility assessments



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External Flood PRA Process

Information flow through an External Flood PRA

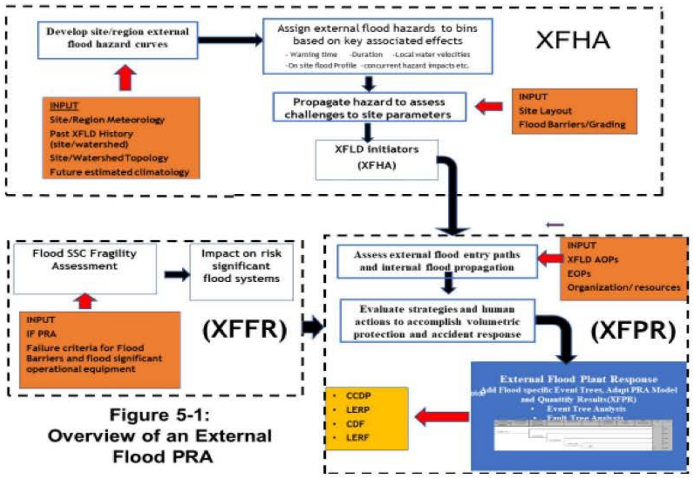


Figure 5-1:
Overview of an External Flood PRA

External Flood PRA Process

Information flow through an External Flood PRA

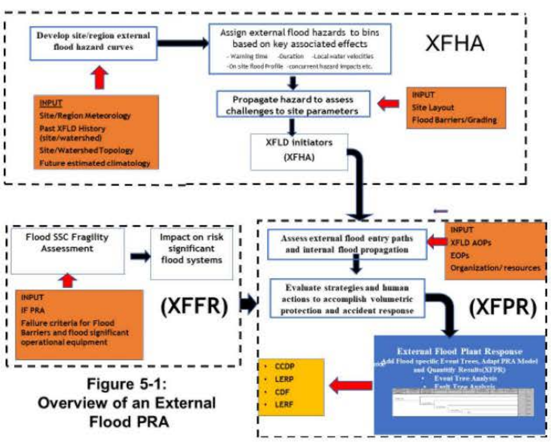


Figure 5-1:
Overview of an External Flood PRA

External Flood Hazard Analysis (XFHA)

– Interface with PFHAs
– PFHA provides event frequencies, uncertainties and may be disaggregated into specific event classes
– PFHA results are parsed into representative scenarios and characterized with features important for risk assessment
  - Event warning time
  - Event duration
  - Site-wide water levels and velocities
  - Any relevant coexistent / concurrent conditions that may affect plant challenge/response

External Flood PRA Process

Information flow through an External Flood PRA

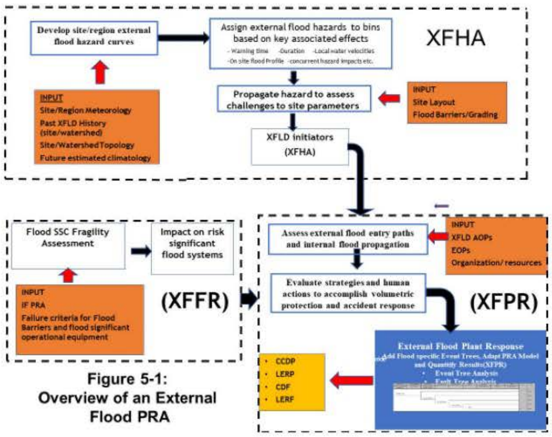


Figure 5-1:
Overview of an External
Flood PRA

External Flood Fragility Response Analysis (XFFR)

- Includes guidance for development of hazard specific loadings for fragility representation for:
  - Integrity / effectiveness of permanent and temporary flood barriers,
  - Flood penetration seals leakage/ dislodgement
  - Equipment wetting/submergence of flood significant components (FSCs)
  - Consideration of potential effects of coexistent/concurrent hazards

External Flood PRA Process

Information flow through an External Flood PRA

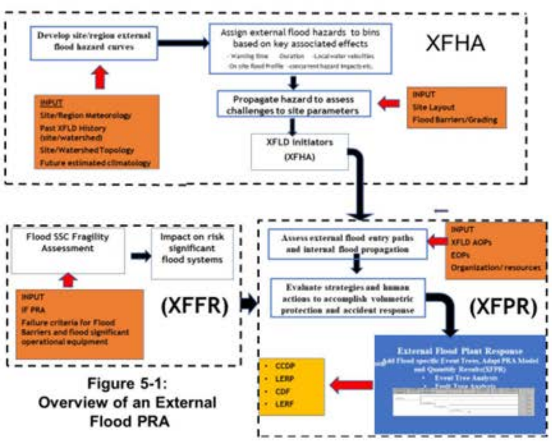


Figure 5-1:
Overview of an External
Flood PRA

External Flood Plant Response Analysis (XFPR)

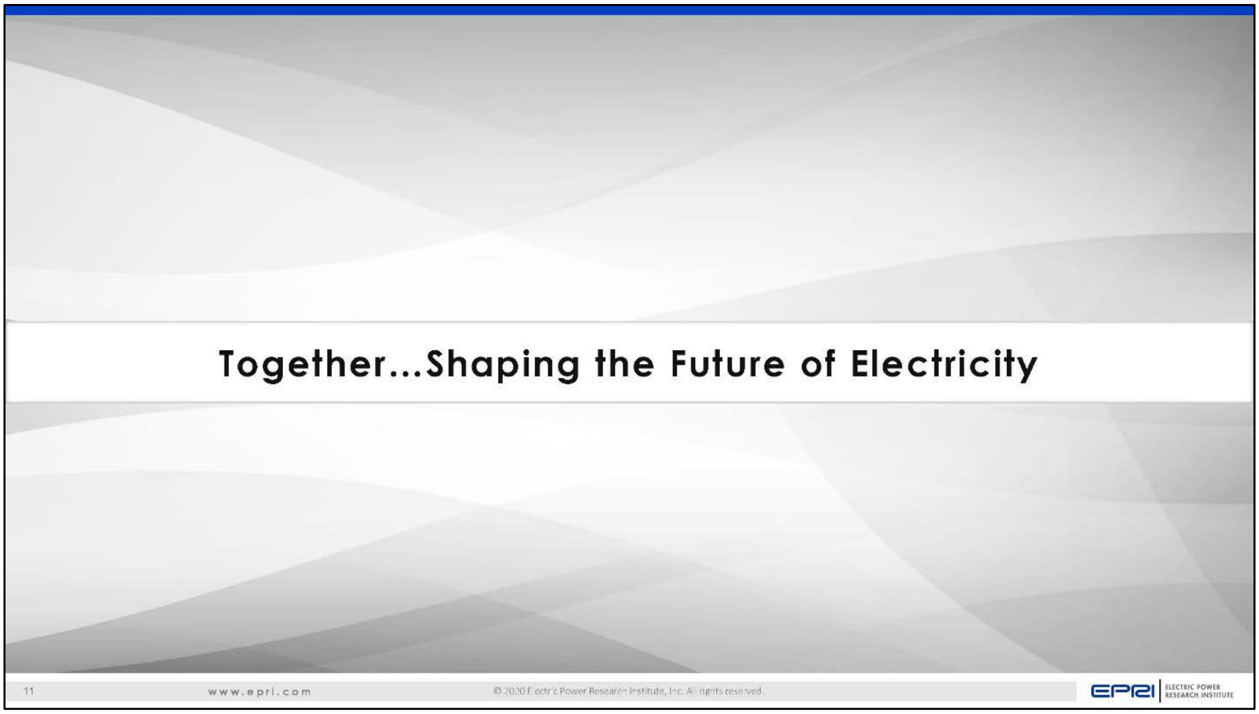
- Guidance is provided to map flood hazard characteristics and flood related SSC fragilities within the External Flood event tree framework to identify the probability of various core damage hazard end states.
- Specific consideration is given to modeling of
  - Pre-flood preparatory actions
    - Based on warning time and pre-flood site and region conditions
  - Post-flood on-site response as it affects outside activities and external site support
  - External Flood challenges on implementation of FLEX/portable equipment response strategies
- Guidance for quantification and calculation of core damage end states

Illustrative Examples

- Examples illustrate External Flood PRA models of hypothetical plants for:
  - Local Intense Precipitation
  - Riverine Flood
  - Storm Surge
- Discussion of PFHA methods with reference to example PFHAs for similar hazards for each example
- Illustrative characterization of hazard constituent events
- Examples are presented to guide the analyst through a structured process from PFHA method selection, disaggregation of the hazard curve(s) and hazard characterization through development and quantification of the external flood event tree.

Illustrative Examples

- Results of example analyses are provided to structure results for presentation of external flood PRA insights.
- Key flood scenarios are identified
- Risk insights are drawn along with discussion of potential for additional mitigation strategies.
- Example hazard illustration concludes with a comparison of the external flood modeling process to the ASME/ANS Supporting Requirements



3.9.3.3 Questions and Answers

Question:
Did you evaluate your flood and structure systems and component response PRA using real-time data from the Fort Calhoun flooding conditions and mitigation over the long-term flood inundation? To paraphrase, did you use the Fort Calhoun flooding experience in developing your PRA guidance?

Ray Schneider:
Absolutely. One reason we got involved in external flood PRAs is that we supported Fort Calhoun with its flood issues well before the actual flood event, post-Fukushima. We developed an external flood PRA using U.S. Army Corps of Engineers dam failure information in advance of the flood event. We helped develop procedures because of insights we learn from that. So, all that information was the impetus for doing this. There were a lot of lessons learned in the process, both in predicting the possible events that could occur, and then living through the events that did occur and determining the various organizational interactions and behaviors. The Fort Calhoun process had FLEX actions before FLEX actions were formalized. We knew we needed to mitigate the event with other portable equipment for serious hazards. In short, all that information was factored into the thinking and structure and the needs and our insights from that was in this process.

Question:
Were there other significant operational experience that you also considered and included?

Ray Schneider:
Blayais was certainly an instructive example of storm surge. Fort Calhoun was the riverine example, with dam failure flooding potential. Site precipitation was an issue there. And then we also looked at the understanding of what happened at Blayais due to the coastal storm. Since then, we've been following other kinds of issues like the SDP at St. Lucie, missed seals impacts. There were a lot of insights that factored into this from both real and hypothetical events.

Question:
Is EPRI guidance subject to any regulatory approval?

Marko Randelovic:
We don't have the specific process to have regulatory approval for EPRI guidance, but there are exchanges with the regulator. For example, we have a research collaboration MOU with the NRC Office of Research. When we work together under the MOU there's usually review by the regulator, and sometimes the endorsement of different EPRI documents. For this effort, we are still in the working phase, and we expect we will be having reviews from NRC Research. Once we are completed, we then will see how we proceed with the guidance.

Joseph Kanney (NRC):
I'll just add to that to say that there's not any specific regulatory approval required but the NRC does from time to time endorse guidance that has been developed externally, for example, by EPRI or by industry (e.g., the Nuclear Energy Institute). There are mechanisms by which the NRC can endorse, in whole or in part, somebody else’s guidance.

Question:
Are you also considering combined effects or compound events in the guidance?

Marko Randelovic:
Yes. For example, for the storm surge we're also considering high winds. The high winds in our example would potentially challenge the offsite power. So, we have the discussion of challenging wind conditions in the storm surge event regarding the loss of offsite power. High winds would also have potentially wind-driven missiles at this site, so that would require other types of analysis. We are not going deep into that, but we are providing guidance on how this could be done if needed.

Question:
How do you treat passive flood seals? Are those treated probabilistically? Is a failure probability is assigned to them with some appropriate distribution or they are they assumed not to fail?

Marko Randelovic:
For those who followed the presentations yesterday, we discussed that EPRI is working on a penetration seal qualitative risk ranking process where we gathered data and expertise from the industry. I would not call this a fragility curve. I would call this a curve that says what seals leak at what pressure and what seal potentially dislodges at what pressure. We are adding this type of discussions in the guidance. There is no distribution. We don't have fragility in those terms. But we have some discussion on, you know, if you have this level, this type of seal may leak a little bit or here is how much it might leak. If you have this level and you're fully submerged and we know that potentially that seal may dislodge completely then we are advising to consider the full dislodgment of the seal.

Question:
What kind of regulatory requirements require this kind of PRA for flooding and with what kind of QA system is applied to your program in developing the PRA for flooding?

Marko Randelovic:
I think Joe that maybe a question for the NRC.

Joseph Kanney (NRC):

I'm not a PRA person, so if there's an NRC PRA person online, please jump in. But as far as I know we do not require PRA. If licensees choose to use a PRA, we do have guidance on the acceptability of PRAs. But as far as I know, we don't require a PRA for flooding.

Ray Schneider:
You're right, it's not required, but it is handled in the ASME standard along with PRAs for high winds and PRAs for seismic as well. So basically, if it's needed to justify a certain condition or for regulatory process. Otherwise, it would follow the ASME standard so and that's normally the guidance for accepting the PRA capability.

Joseph Kanney (NRC):
Jeff Mittman has offered to provide some information on NRC requirements for PRA. Jeff is a PRA analyst in the Office of Nuclear Reactor Regulation. So, again, we are speaking generically. No plant specific information, just general information.

Jeff Mittman (NRC):
I'm a senior reliability and risk analyst with NRC/NRR. There are currently two categories of plants. There's the existing fleet that were that were licensed and are regulated under 10 CFR Part 50, and there's two new reactors that are being built under 10 CFR Part 52. For the old plants, the Part 50 plants, there's no regulatory requirement to have a PRA across the board. However, if the licensees wish to use risk informed applications (which is voluntary), there are requirements to have a PRA. The individual applications will look at the specific hazards and decide which hazards are applicable and which ones aren't for that particular risk application. For the Part 52 plants that are being built, there is a requirement to have a PRA. I don't know specifically what the requirements are as far as external events go for the Part 52 plants. My educated guess is that there are requirements to evaluate flooding hazards and to include in the PRA those hazards which are deemed credible or possible.

Question:
Does EPRI plan to submit this guidance for NRC review and endorsement?

Marko Randelovic:
We are still in the development process, and I haven't thought about that. Potentially we would share the guidance with NRC Research under the NRC-EPRI MOU. We would discuss and resolve the potential comments.

Question:
Can you elaborate on the extent of guidance to be provided in the external flood hazard assessment portion? Will the guidance provide for all the different flooding mechanisms? How will it differ from current guidance in the ASME standard?

Marko Randelovic:
For now, we have included three flooding mechanisms in the guidance. We have riverine flooding, storm surge flooding, and LIP. What we are saying in the guidance is that the owner of the plant is to develop their own site-specific hazard curves. Since we have so many members all over the world, we're not developing the guidance for any particular site. We have the methodologies on how to develop hazards hazard curves. So, in this guidance we're just referencing those different methods. We are saying: if LIP, riverine flooding, or storm surge is one of the conditions that you have to deal with, please refer to those reports and develop your own hazard of curves.

Question:

What are the EPRI recommended guidelines for using the uncertainty in the flood hazard estimates in establishing the hazard scenarios for the PRAs. Do you use the uncertainties to develop different hazard scenarios as input to the PRA?

Ray Schneider:
Yes, you need the uncertainties in the in the hazard. The main challenge is it's more than just a hazard curve. We need to break it into scenarios. Either we could propagate the uncertainties through or break up the hazard, weighting it based on details of the uncertainty. Say, 5% or 10% of these may be very high with this mean value, and then some may be lower and then propagate those in separate scenarios. Both would be reasonable ways of dealing with that, but the hazard uncertainty must be included because that's an important piece of the puzzle.

Question:
Could you describe the QA system that is applied for the PRA of flood hazards?

Ray Schneider:
It shouldn't be any different than the QA for PRA of any other external hazard. We're not requiring SHAC-F if that's what you mean. We believe it's the hazard analysts' role to determine the QA for the hazard. But once the hazard has been defined, we go through the standard quality assurance that you do for PRA and in general, throughout the industry, following the standard, peer reviews, and internal validation.

Marko Randelovic:
We don't have a specific requirement in the guidance. For each of the pieces there are different standards, different requirements, and those may vary from country to country. Each country should use their own regulations and their own requirements to meet their standards. This guidance methodology just provides an approach of how to combine all the pieces together and how to create scenarios, run the scenarios, and what risk insights you're gaining.

Joseph Kanney (NRC):
I would like to add that NRC regulations require that applicants and licensees have a QA program and when they submit information to the NRC for licensing purposes, they need to develop that information or analysis you under that required QA system.

Question:
Has an external flood PRA considering tsunami been developed for NPP sites?

Marko Randelovic:
We currently do not have a guidance that addresses tsunami. I'm not sure about the NRC.

Joseph Kanney (NRC):
NRC Research has published several reports on tsunami hazard analysis, but most of that research has been devoted to deterministic methods. Tsunami has been considered for a few coastal sites in the U.S. but, as far as I'm aware, it has not been addressed probabilistically to this point in submittals that NRC has reviewed.

3.10 Day 4: Session 4B – Special Panel Discussion: Drivers of Uncertainty in External Flood Probabilistic Risk Assessment

Session Chair: Michelle (Shelby) Bensi, University of Maryland

Panelists:

Fernando Ferrante, Electric Power Research Institute (EPRI)
Norberto Nadal-Carraballo, U.S. Army Corps of Engineers (USACE)
Kit Ng, Bechtel Corporation
Jeremy Gaudron, Électricité de France (EDF)
Bogdan Golovchuk, Tractebel ENGIE
Ray Schneider, Westinghouse Electric Company;
Curtis Smith, Idaho National Laboratory (INL)
Jeff Mitman, U.S. Nuclear Regulatory Commission (NRC)

Panel Discussion Overview:

Our fundamental understanding of external flooding hazards, sources of uncertainty, and nuclear power plant (NPP) response strategies has increased in recent years. Nonetheless, significant uncertainties remain associated with external flooding probabilistic risk assessment (XFPRA). These include uncertainties related to: (1) characterization of hazard severity, frequency, and temporal evolution; (2) the impacts of hazard events on NPP structures, systems, and components; (3) event progressions; and (4) the close coupling of the physical aspects of hazards with human performance. In existing XFPRA practice, knowledge gaps have been addressed via conservative assessments, expert judgment, or simplified models and assumptions. There have been overall enhancements in many aspects of NPP probabilistic risk assessment (PRA). However, it remains challenging to represent the spatially and temporally dynamic nature of flood events within existing PRA modeling tools. Further, the current PRA frameworks reflected in existing guidance and standards (initially developed with a focus on internal events) are not inherently able to accommodate some of these unique characteristics. Improvements in model realism (through understanding, assessment, and/or reduction of uncertainties) can yield important safety and operational insights through enhancement of plant response procedures and expand the usefulness of XFPRA to assist in evaluating alternative response strategies. Limited resources are available to support uncertainty reduction efforts, and there is a need for a risk-informed strategy to identify, characterize, and prioritize drivers of hazard uncertainty. This panel session will bring together experts in multiple aspects of external hazard PRA to discuss these drivers of uncertainty as well as opinions regarding the future direction and potential benefits of efforts to improve model realism and reduce uncertainties.

3.10.1 Moderator Introductory Remarks (Shelby Bensi)

Speaker: Shelby Bensi, University of Maryland

3.10.1.1 Presentation (ADAMS Accession No. ML21064A451)

Panel Discussion

This panel session brings together experts in multiple aspects of external flooding probabilistic risk assessment (XFPRA) to discuss:

- Drivers of uncertainty and other challenges in XFPRA
- Opinions regarding future directions
- Potential benefits of efforts to improve model realism and reduce uncertainties

Shelby Bensi
University of Maryland
[*Facilitator*]

Curtis Smith
Idaho National Lab

Norberto Nadal-Caraballo
U.S. Army Corps of Engineers

Fernando Ferrante
EPRI

Ray Schneider
Westinghouse

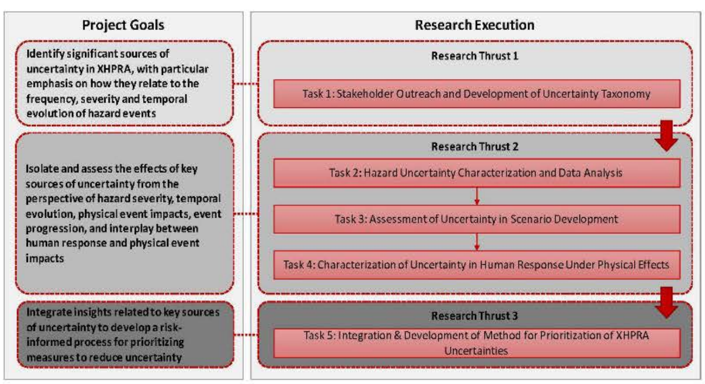
Bogdan Golovchuk
Tractebel Engie

Jeremy Gaudron
EDF

Jeff Mitman
NRC

Kit Ng
Bechtel

Project: Identifying and Prioritizing Sources of Uncertainty in External Hazard Probabilistic Risk Assessment



Project supported by: U.S. Department of Energy, Nuclear Energy University Program

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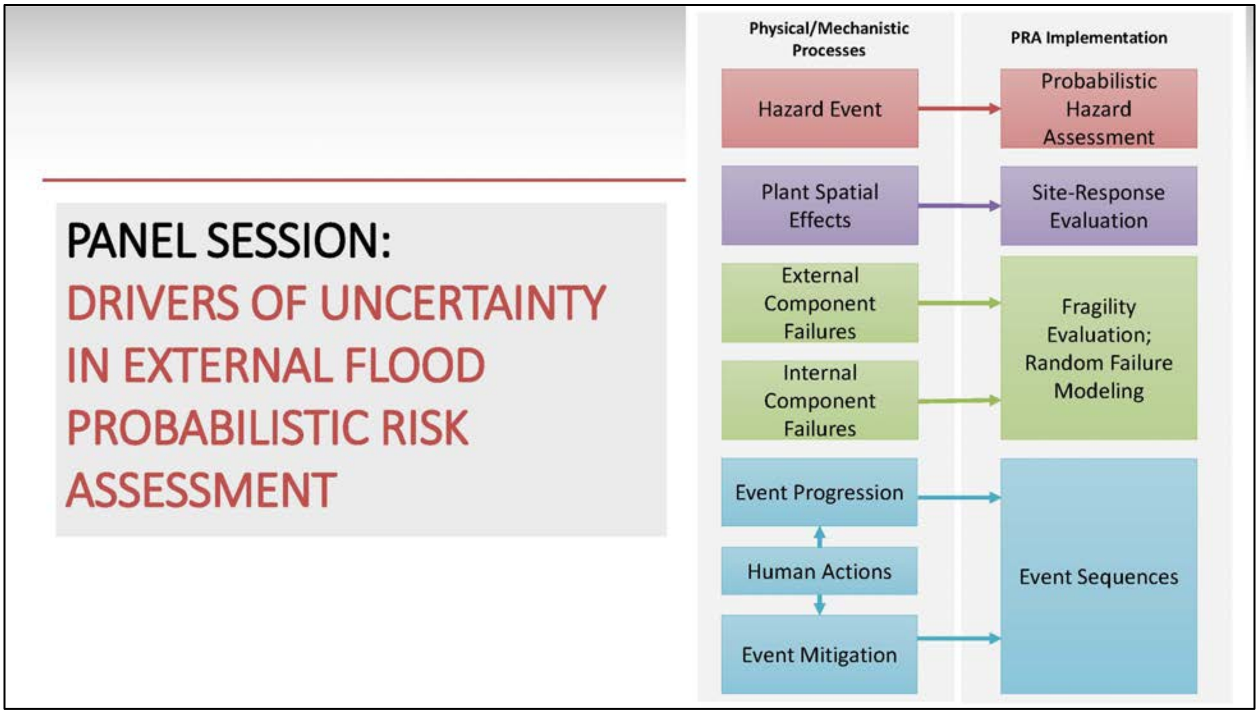
Ray Schneider [Westinghouse]
Zhegang Ma [Idaho National Lab]
Hongbin Zhang [Idaho National Lab]



3.10.1.2 *Transcript*

Slide 1
Hello and welcome to our panel session on drivers of uncertainty in external flood probabilistic risk assessment.

Slide 2
I'm Shelby fancy and I'm an assistant professor in the Department of Civil and Environmental Engineering at the University of Maryland. I'll be serving as facilitator for this panel session and here on the screen you can see the set of experts that will be participating in our panel discussion. Each of these panelists will introduce themselves in just a moment, either via pre-recorded mini presentation or a live introduction. Unfortunately, due to an emergent issue, Kitt Ng from Bechtel will not be able to participate in our live discussion, but she was part of the team that prepped for this.

You've already heard from a number of folks on the panel, so you probably can tell that this panel session brings together experts with experience and knowledge in multiple aspects of external flooding PRA, including topics ranging from hazard assessment to human performance to using existing and innovative PRA tools. Our goal today is to discuss the drivers of uncertainty and other challenges in external flooding PRA. We'll also discuss our panelist opinions and, hopefully, the opinions of audience members on future directions in external flooding PRA, as well as potential benefits of efforts to improve model realism and reduce uncertainties.

While we've prepped a few questions to kick things off, we hope to hear from members of the audience and invite everyone to pose questions, and offer their thoughts, insights, and opinions during our panel discussion. We will be monitoring the chat window throughout the session.

Slide 3

I would like to note that our interest in the thoughts and opinions of everyone here in this workshop doesn't end after this panel session. This panel session is inspired by an ongoing research project supported by the U.S. Department of Energy, Nuclear Energy University Program. This project is a collaboration between the University of Maryland, Virginia Commonwealth University, Westinghouse, and Idaho National Lab here. On the right side of the screen, you can see our project team members as well as their affiliations. This project is focused on development of a strategy for identifying and prioritizing sources of uncertainty in external hazard PRA. This includes hazards beyond flooding, such as earthquakes and high winds. The goals of the project include identifying significant sources of uncertainty in external hazard PRA, isolating and assessing the effects of key sources of uncertainty on multiple aspects of plant response, and then integrating those insights to develop a risk-informed prioritization process.

One of our first project tasks includes stakeholder outreach. This has naturally been challenged a bit by the current restrictions on in-person meetings, but we also had the opportunity to engage with experts via virtual workshops and expert discussions. So, if in addition to weighing in as part of this panel discussion, you're interested in sharing your thoughts and experiences with us in more detail, please reach out to me or any member of our project team.

Slide 4
As we move into our panel discussion, I'd like to take a quick moment, emphasize the broad nature of the discussion we will be having. External hazard PRA includes assessment of hazards, fragility, human performance in plant response. In today's discussion, panelists will be tackling questions related to drivers of uncertainty in external flooding PRA from a range of perspectives. This includes uncertainties from both the physical and mechanistic processes associated with flooding, as well as how these processes are mapped into the PRA. For example, from the perspective of physical and mechanistic processes, we plan to discuss: (1) uncertainties associated with the characteristics of flood events, including flood heights, waves, temporal duration, and other affects; (2) the spatially varying effects of the hazard on the site; and (3) the potential for damage or failure of external components such as flood barriers as well as failures of internal barriers and the effects of floodwaters on internal components. We'll also discuss the ways that events can progress, the types of decisions that organizations may have to make, and how humans may perform during flood events.

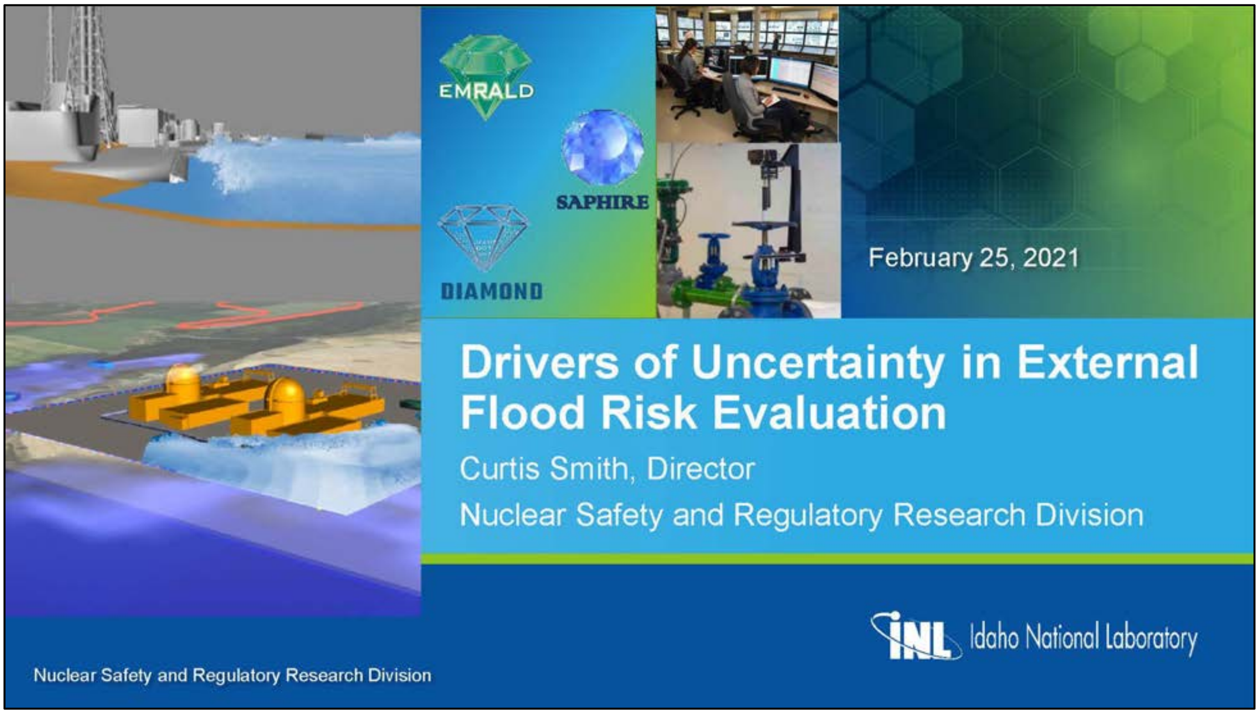
As I mentioned, beyond just the physical event impacts and progression, we'll also tackle uncertainties that arise from the way that we map these physical effects into the PRA. This includes the capabilities and limitations of existing tools. From that perspective, we will consider the ways in which we probabilistically characterize flood hazards, which of course you've heard a lot about this week, as well as the spatially varying effects of the flood. We'll address fragility modeling and the treatment of random failures as well as event sequences in the PRA. This is going to be a pretty broad discussion, so we look forward to hearing from an equally broad range of voices, whether that's from the panel or people speaking up in the chat.

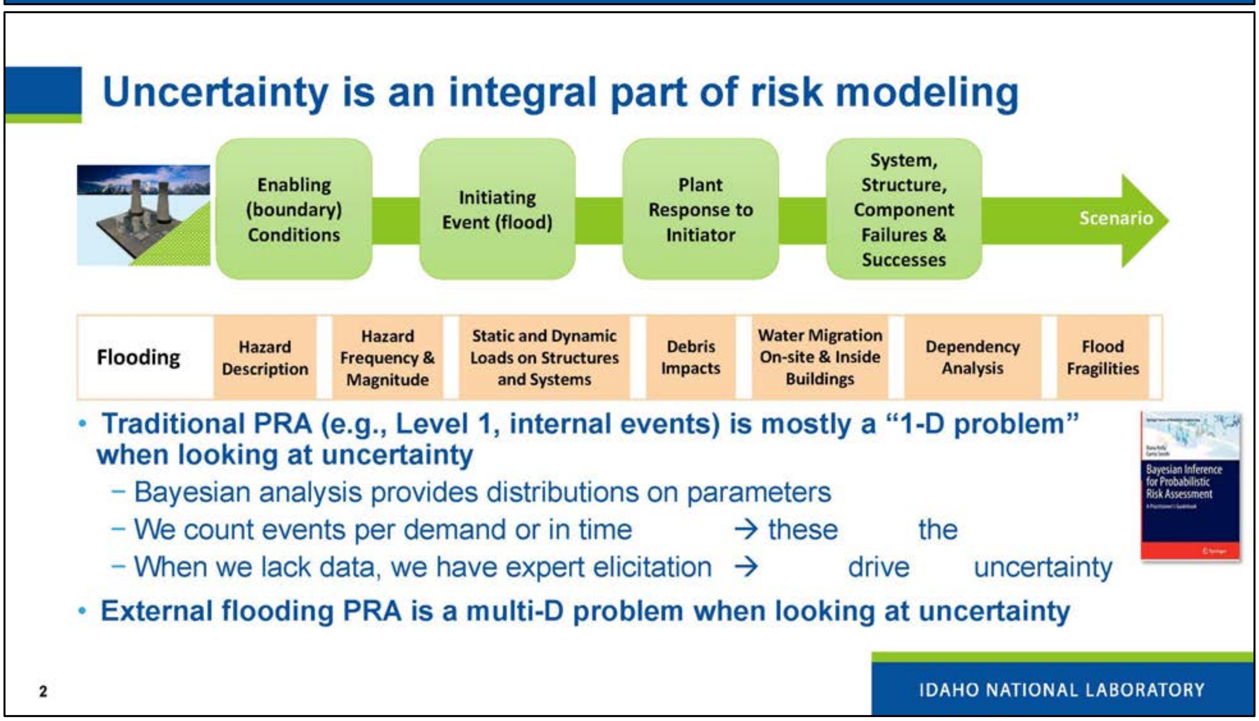
Next up, we'll hear intros from our panelists and then get started with the discussion.

3.10.2 Panelist Introductory Remarks (Curtis Smith)

Speaker: Curtis L. Smith, Idaho National Laboratory (INL)

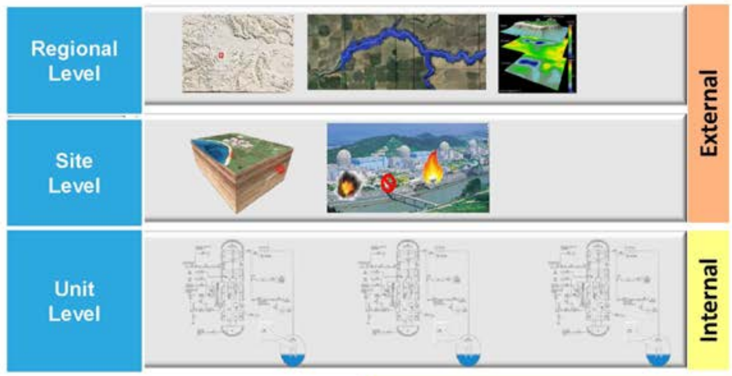
3.10.2.1 Presentation (ADAMS Accession No. ML21064A452)





Uncertainties for external flood modeling

- **Unlike the "counting approach" found in Level 1 internal events PRA, external flood risk models must embrace**
  - Time Space
  - Physics Complexity
- **Computational Risk Assessment integrates risk and physics models**
  - An effective way to capture multi-dimensional uncertainty aspect of external flood scenarios
  - Probabilistic scenario creation
    - Scenarios unfold (in the computer) & are not defined a priori



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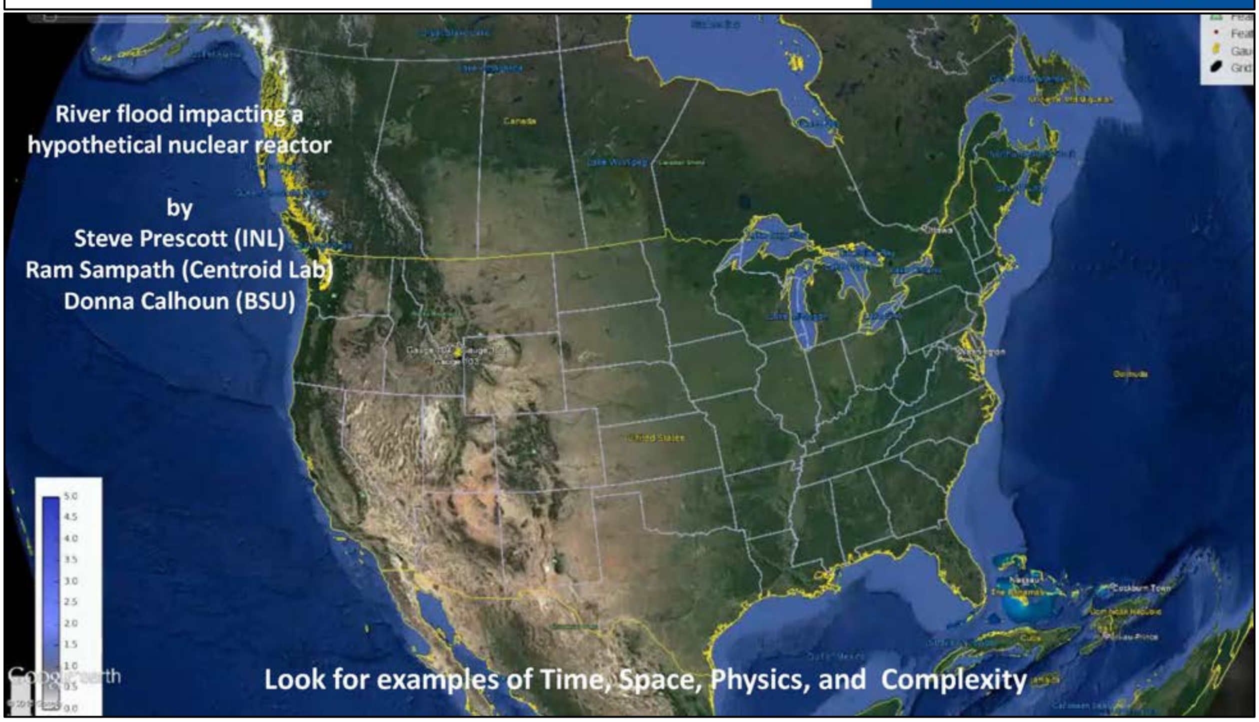
IDAHO NATIONAL LABORATORY



In summary

- **Uncertainties for external flooding risk analysis are more complex than other models**
- **Uncertainty drivers include elements that represent**
  - Time → flood rate, when does water impact components, fragility of barriers, …
  - Space → where does the water go, what does it impact, does water reduce human performance, …
  - Physics → representation of water phenomena, static and dynamic loading conditions on doors and structures, …
  - Complexity → water may have many different paths through a facility, estimating flood frequency may pose challenges, …
- **These uncertainties, however, can be addressed through computational approaches (CRA)**
  - Modern computers and software are available to tackle these issues now

5 IDAHO NATIONAL LABORATORY

3.10.2.2 Transcript

Slide 1

Hello, I'm Curtis Smith, division director for Nuclear Safety and Regulatory Research at Idaho National Laboratory, and I'd like to give some thoughts related to uncertainty and external events, specifically, flood risk and some of the drivers that we see in that space.

Slide 2

I think it helps to kind of take a half step back and talk about uncertainty and how we capture that in current risk models. On this slide you see I have a notional representation of what a scenario is. We typically say we understand how the plant is going to operate and there's upset conditions. We want to represent those upset conditions. The boundary conditions we capture in terms of the plant design and operation. But ultimately, we will then pick initiating events, in this flood would be the initiator. And then following that we look at what could happen to the plant in terms of plant response and then systems and structures components. How we represent those parts of the scenario depends on which tool. Largely a lot of these analysis take place as fault tree entries to represent accident scenarios. We could also simulate directly events such as flood. So, it's important to think about what the characteristics of a flood risk model are. The middle part here, in terms of the constituent parts of the analysis, gives you a sense of some of the complexity that you'll see. Obviously, we need to be able to understand the hazard, the flood itself, the frequency of that. But then also what happens to the plant after that. So, things like debris, where does the water migrate? Do we impact multiple components, for example because of the water? And do things fail ultimately because of this specific hazard through things like flood fragilities? So, each of these boxes brings up a different kind of discussion related to uncertainties. It's important, I think, to contrast what we currently do with other kinds of risk models, for example, Level-1 internal events. I call that a sort of 1-dimensional problem, because, if you look at the uncertainties and how we characterize those, it's fairly simple. We come up with parameters and those parameters have distributions. We have analysis to look at those distributions, but essentially, it's accounting process. We count events, number of demands, events per time, whether it be initiating event or failure rates. Where we don't have data, we tend to focus on expert elicitation. Those handful of data and observations or elicitations drive the uncertainty for Level-1 internal events. That's different if we look at external events, specifically flooding. It's a multidimensional problem.

Slide 3
What do I mean by that? Unlike the counting process found in other types of PRAs, in flood analysis, we need to look at the time element, the space element, and physics of the water flow. Where is it going to go? When is it going to impact? What is it going to damage? And then the fact that these scenarios can be complex themselves, just representing those is a type of uncertainty that we would like to capture. Fortunately, we have approaches that can start to tackle these characteristics. Another thing that's unique here, especially for external hazards like floods, we have very large region that we could be talking about. A regional scale watershed, for example, impacting clear down to a plant specific unit. So, this notion of different levels in terms of what the analysis may have to capture is critical because a flood could impact an entire site, but ultimately we still have answers to what can happen within a particular unit on a particular site.

We can sometimes look at fault trees as is traditionally done but moving beyond that to something called computational risk assessment is where we take the risk analysis ideas and scenarios and combine that with the physics, in this case physics of water, to really address the multi-dimensional aspect of the uncertainties. This is really almost a virtual representation of the plant. We don't really know what the scenarios might be a priori, but we let the computer kind of unfold the scenarios through time and space and what's going on with the water to figure out ultimate outcomes.

Slide 4
An example here of time, space, physics and complexity is a calculation where we combine a two-dimensional watershed code with a three-dimensional physics code representing water, and so we're able to look at a specific flood that might impact a hypothetical nuclear power plant. We

simply push the button and kind of let the initiating event go. This is actually a dam failure representation, but, nonetheless, we traced the water until we either get to a state in the plant that's OK or not OK. You can see in this case we have representation of water going through a door which could impact components, but we're able to keep track of these water particles, what's impacted, when they are impacted and how that might affect things like the core and core temperature.

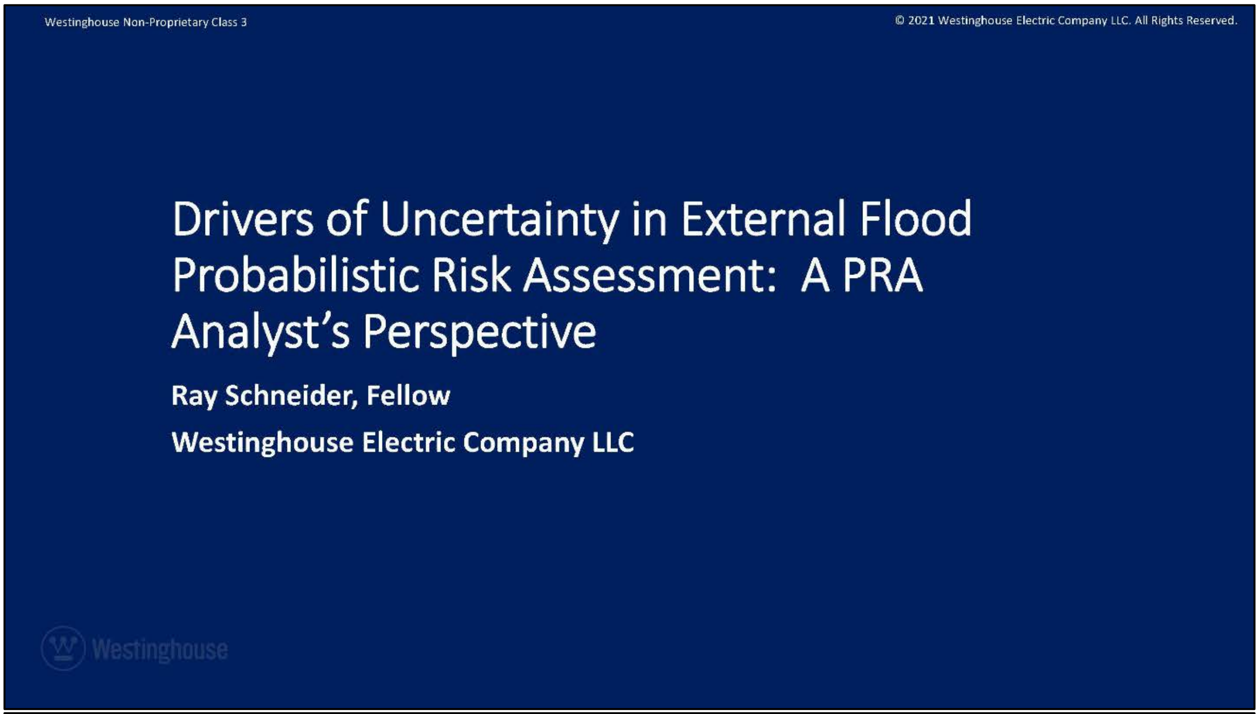
Slide 5

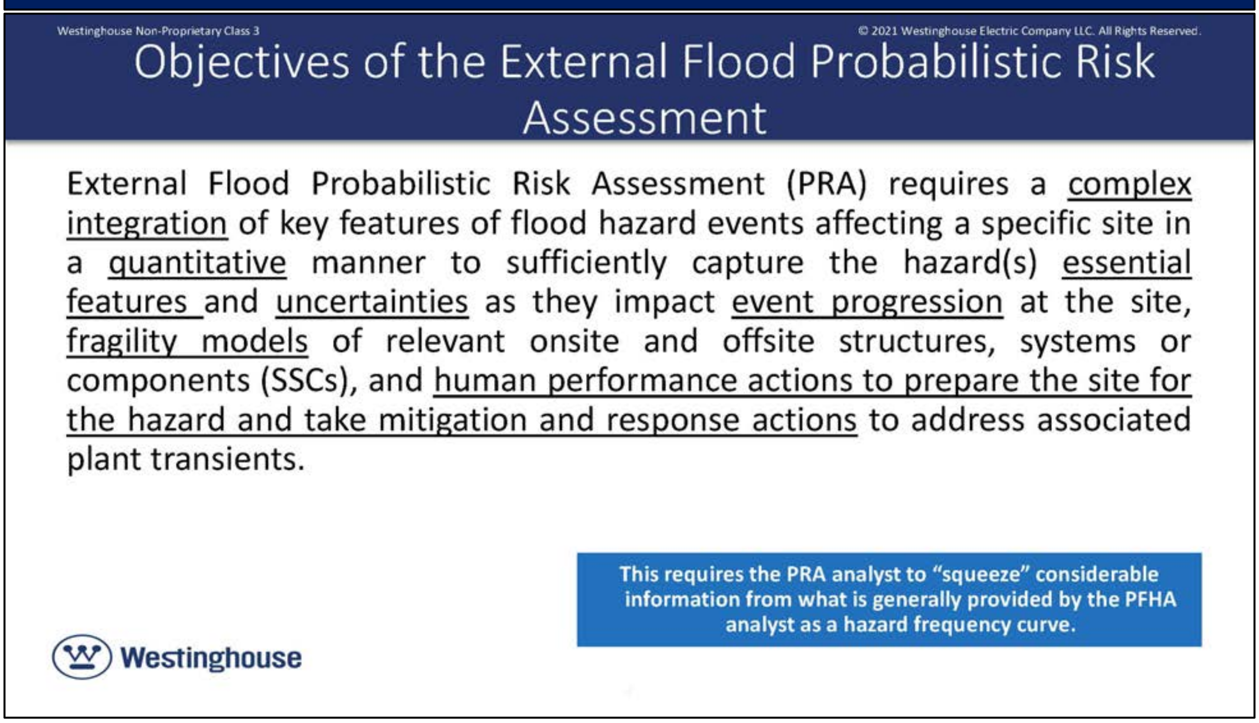
In summary, and back to the uncertainty drivers within external flood risk assessment, the uncertainties are more complex than other types of approaches and other types of models. We must hit the uncertainties related to the time, space, physics, and complexity. And within those, depending on a specific facility, a specific type of flood, and specific vulnerabilities. What will actually drive the uncertainties tend to be plant specific kinds of information. But the kinds of questions listed here address and go back to the time, space, physics, and complexity ideas. The takeaway thought should be that yes, these uncertainties are real. They can be a challenge, but with modern approaches through the computers and the software we have, we can tackle these approaches now.

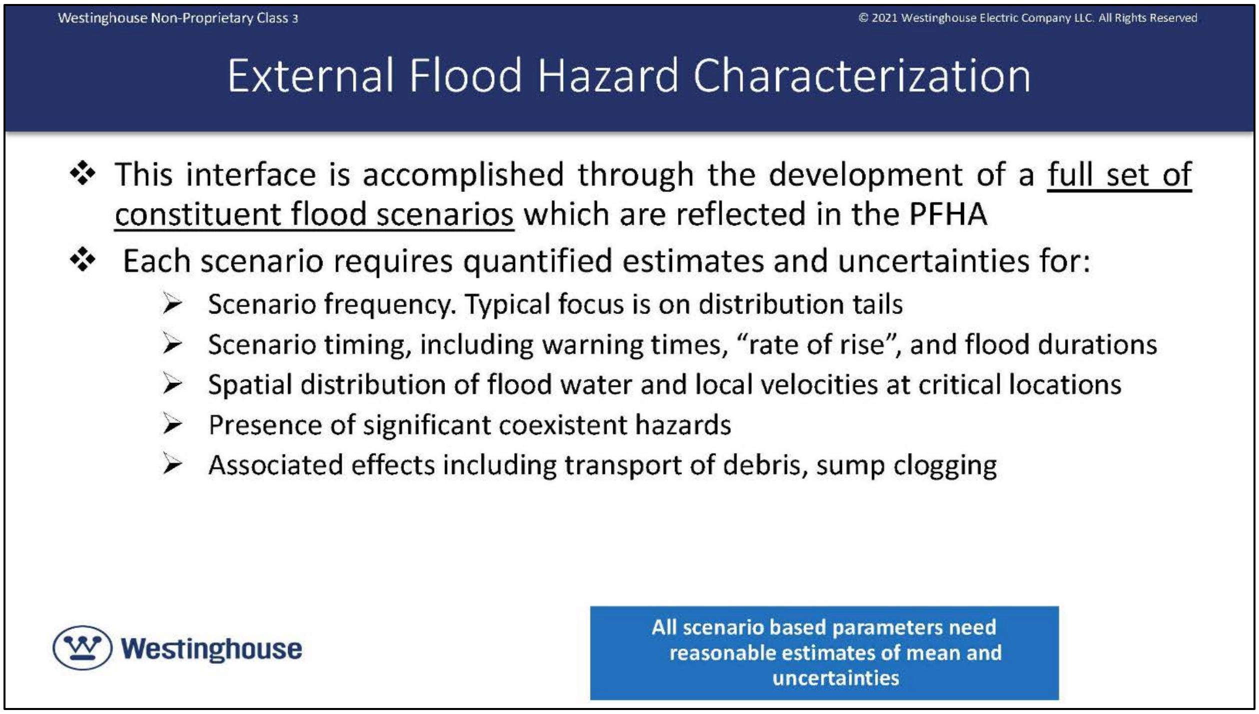
3.10.3 Panelist Introductory Remarks (Ray Schneider)

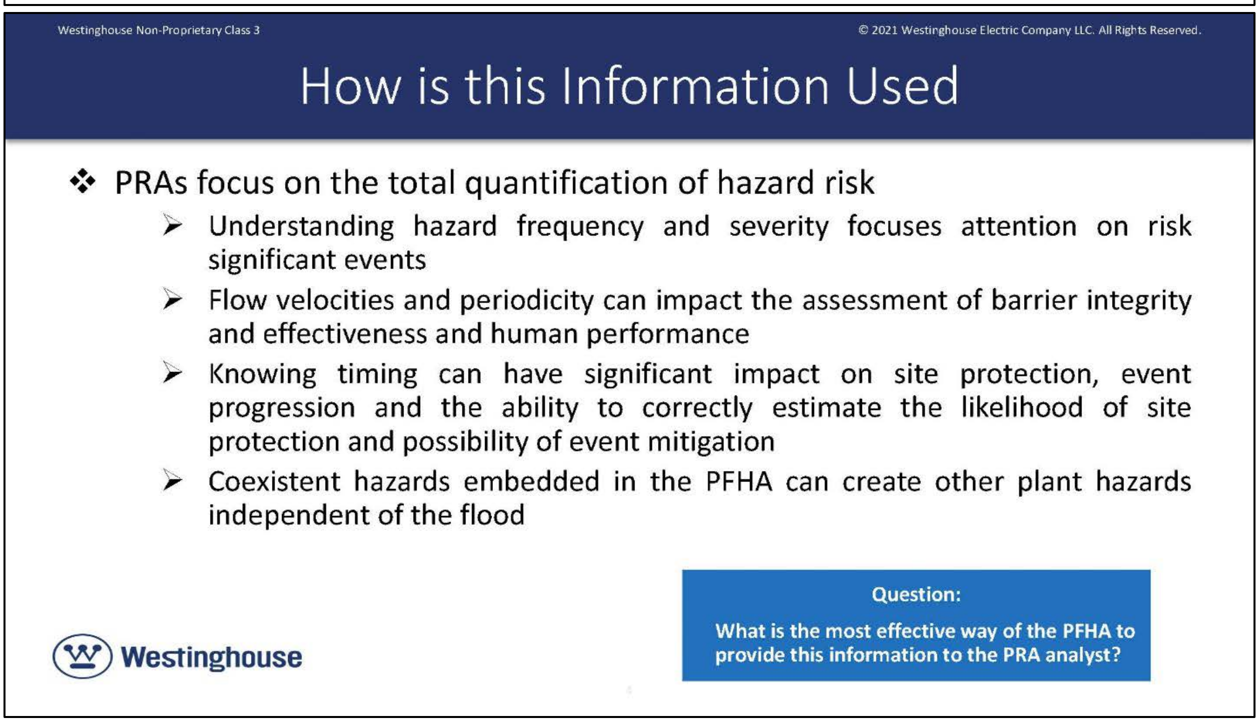
Speaker: Ray Schneider, Westinghouse Electric Company, LLC

3.10.3.1 Presentation (ADAMS Accession No. ML21064A453)









3.10.3.2 Transcript

Slide 1

I'm Ray Schneider, fellow with the Westinghouse Electric Corporation. I work in the area of risk assessment. Today, in this short presentation, I'd like to talk about the drivers of uncertainty in external flood probabilistic risk assessment, and I'd like to talk about that from a PRA analyst perspective.

Slide 2
First, I'd like to take a few moments to talk about the objectives of external flood probabilistic risk assessment. The external flood probabilistic risk assessment requires a complex integration of key features of the flood hazard events affecting a specific site in a quantitative manner to sufficiently capture the hazard(s) essential features and uncertainties as they impact the event progression at the site, fragility models of relevant onsite and offsite structures, systems or components, and human performance actions to prepare the site for the hazard and to take mitigation and response actions to address associated plant transients. To do this requires the PRA analyst to "squeeze" considerable information from what is generally provided by the PFHA analyst in the form of a hazard frequency curve.

Slide 3
It is the job of the PRA analyst to take the PFHA information and create an external flood hazard characterization. This interface is accomplished through the development of a full set of constituent flood hazard scenarios which are reflected in the PFHA. Each scenario requires quantified estimates and uncertainties for scenario frequency (typically, focusing on the distribution tails), scenario timing (including warning times, rate of rise and flood durations) necessary to perform human performance assessments, spatial distribution of floodwaters and local velocities at critical locations on the site, and the presence of significant coexistent hazards, along with associated defects that may occur, along with the flood (including transport of debris and sump clogging). All the scenario-based parameters need reasonable estimates of the mean and uncertainties associated with these parameters and events.

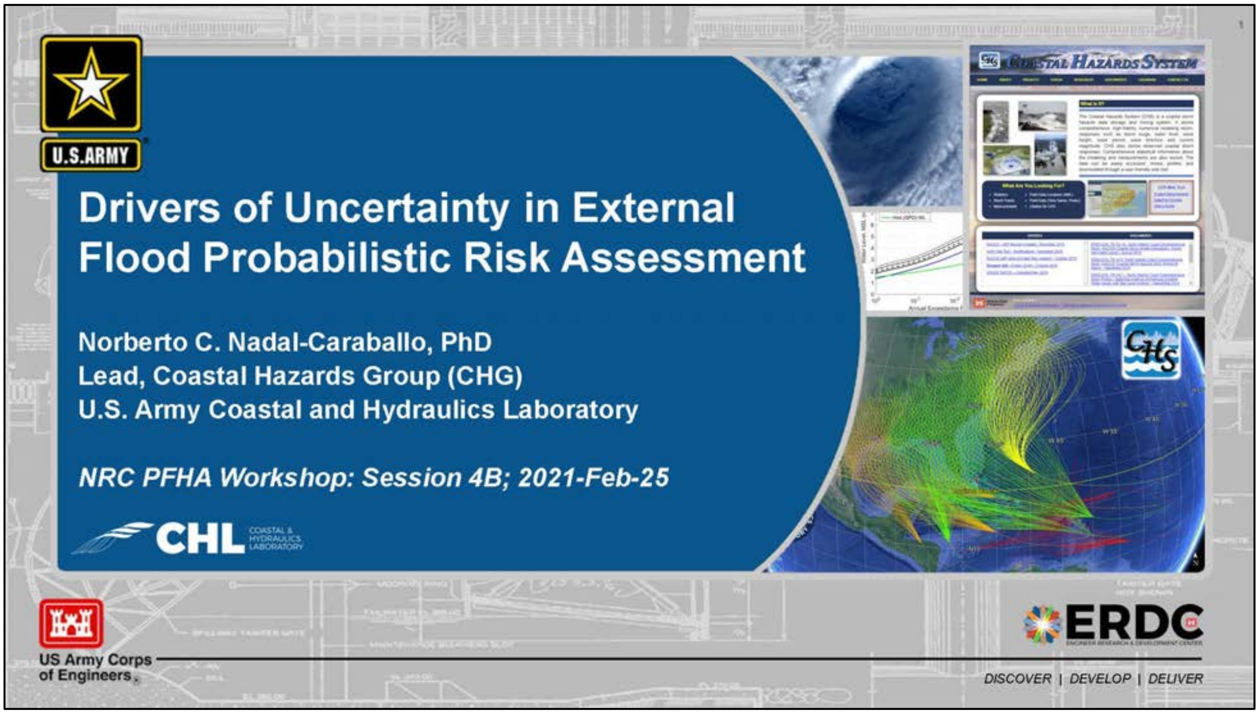
Slide 4
The final slide in this short presentation addresses how this information is used. PRAs focus on the total quantification of hazard risk. Understanding hazard frequency and severity focuses attention on risk-significant events. Flow velocities and periodicity of these flows can impact the assessment of barrier integrity and effectiveness and human performance. Knowing timing can have significant impact on site protection, event progression, and the ability to correctly estimate the likelihood of site protection and the possibility of event mitigation.

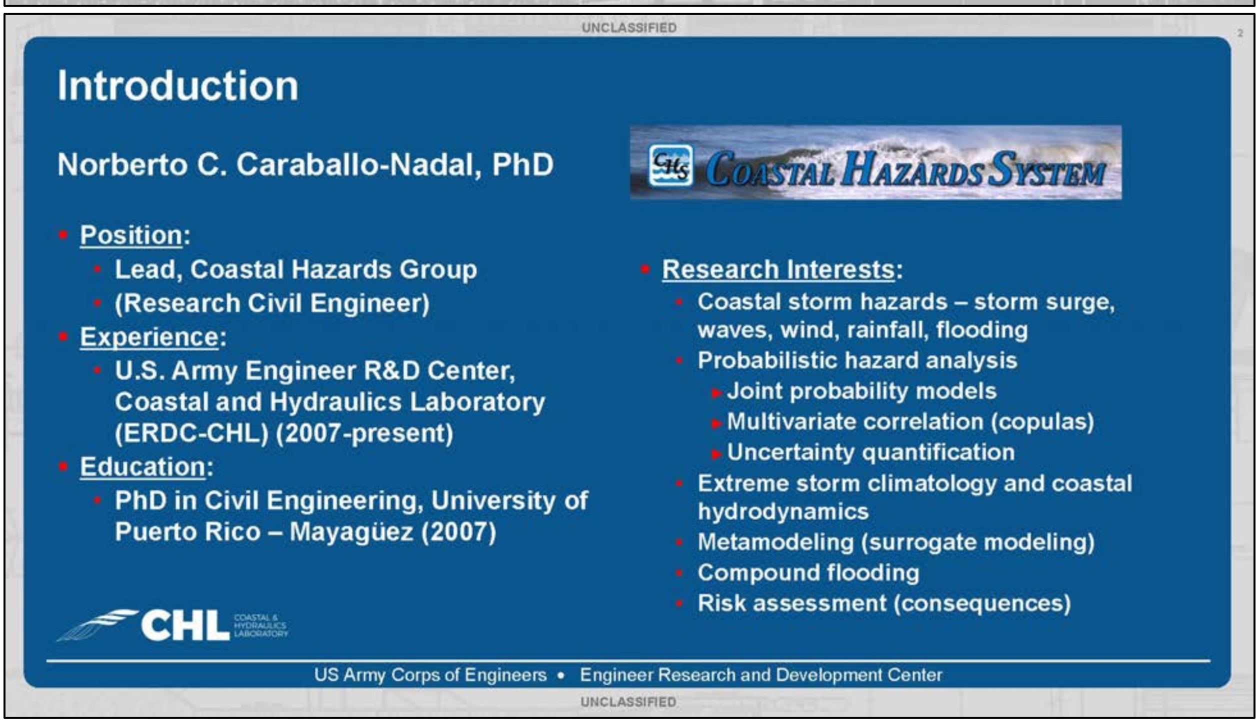
Finally, coexistent hazards embedded in the PFHA can create other plant hazards independent of the flood that can also affect estimating fragilities of components and human performance. So as a parting question, the idea I'd like to leave the audience with is: What's the most effective way of the PFHA and the PFHA analyst to provide this information to the PRA analyst.

3.10.4 Panelist Introductory Remarks (Norberto Nadal-Caraballo)

Speaker: Norberto C. Nadal-Caraballo, U.S. Army Coastal and Hydraulics Laboratory

3.10.4.1 Presentation (ADAMS Accession No. ML21064A454)





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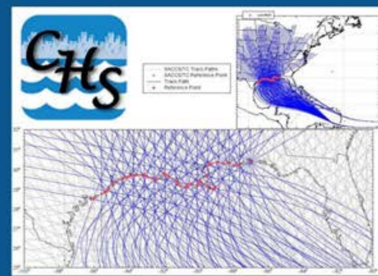
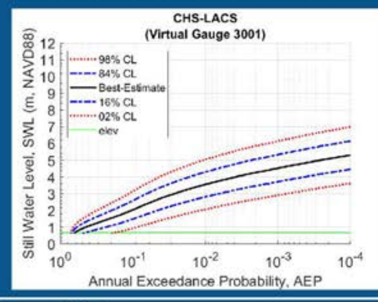
Coastal Hazards System (CHS)

<u>A Probabilistic Coastal Hazard Analysis (PCHA) framework</u>

- Products: storm hazard and uncertainty
- Applications: planning, economics, engineering design
- Regional studies:
  - North Atlantic Coast Comprehensive Study (NACCS)
  - Coastal Texas Protection and Restoration Study
  - South Atlantic Coast Study (SACS)
    - Phase I: Puerto Rico & U.S. Virgin Islands
    - Phase II: North Carolina to South Florida
    - Phase III: South Florida to Mississippi
  - Louisiana Coastal Protection and Restoration (LACPR 2020)
- Use of CHS data in Coastal Storm Risk Management (CSRM) projects:
  - CSRM systems currently under construction or in review are expected to return +$280B in prevented damages.





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Thoughts on Uncertainty

- Different definitions:
  - Epistemic Uncertainty vs. Aleatory Uncertainty/Variability
- Major contributors to uncertainty:
  - Atmospheric and hydrodynamic modeling – per storm and localized uncertainty
  - Storm climatology – unreliable data prior to 1940s; storm size (Rmax)
  - Probabilistic analysis – relatively small storm suites; parameter correlations
- Most critical source of uncertainty:
  - Numerical modeling – lack of validation data; unreliable measurements
- Overcoming challenges associated with uncertainty:
  - Metamodeling (surrogate) of atmospheric and hydrodynamic responses
  - Spatially-varying estimation of bias and uncertainty

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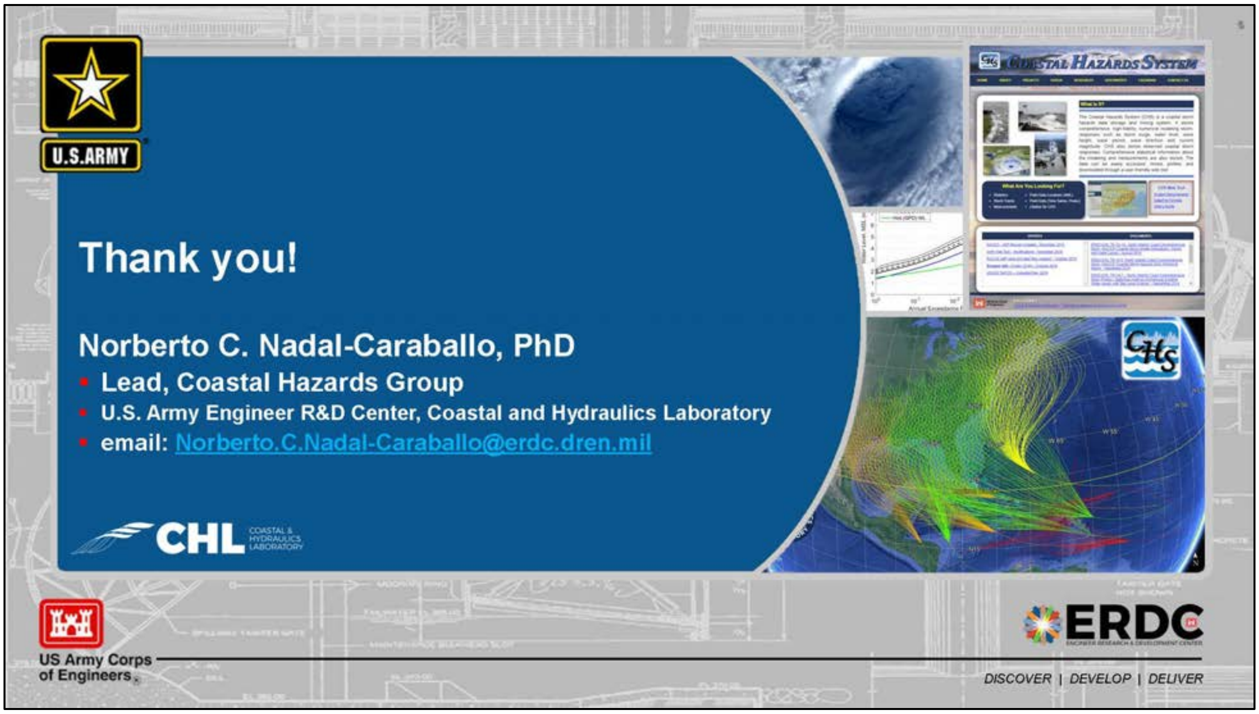

3.10.4.2 Transcript

Slide 1
Hello everyone. My name is Norberto Nadal-Caraballo. I am the Coastal Hazards Group Lead at the U.S. Army Corps of Engineers Coastal and Hydraulics Laboratory. Today I am participating as a panelist in Session 4B: Drivers of Uncertainty in External Flood Probabilistic Risk Assessment.

Slide 2
Continuing with my introduction, I have been working as a research civil engineer at the Coastal and Hydraulics Laboratory (CHL) since 2007. CHL is one of the laboratories of the U.S. Army Research and Development Center (ERDC) located in Vicksburg, MS. In terms of my education, I have Bachelors, Masters and PhD degrees in Civil Engineering from the University of Puerto Rico at Mayaguez. My research interests include the quantification of coastal storm hazards, the development of probabilistic hazard analysis frameworks, including joint probability models, multivariate correlation models and bias and uncertainty quantification. The characterization of extreme storm climatology and numerical hydrodynamic modeling are also critical components of our work. In recent years we have been advancing the development of metamodels or surrogate modeling of coastal hazards. Other areas of interest are compound coastal and inland flooding and coastal storm risk assessment.

Slide 3
Our main development at CHL is the Coastal Hazard System (CHS), and it's Probabilistic Coastal Hazard Analysis (PCHA) framework resolved from the CHS including hazard and uncertainty, quantification of storm responses such as storm surge, waves, wind and rainfall. CHS results have been widely used in planning studies, economic analysis, and engineering design by federal and state agencies, private industry, and academia.

CHS now covers all the U.S. hurricane-exposed coastlines through different regional studies including: the North Atlantic and South Atlantic Comprehensive Studies, the Coastal Texas

Study and the Louisiana Coastal Protection and Restoration Study of 2020. In all, coastal storm risk-management projects based on CHS data and CHS probabilistic analysis results that are currently under construction or in review are expected to return more than $280 billion in prevented damage and economic losses.

Slide 4
Moving on to the topic of this session, quantification of uncertainty is clearly a critical component of any hazard analysis or risk assessment effort. How uncertainty is classified as either epistemic uncertainty or aleatory uncertainty or variability is too often the focus of debate, but ultimately it is a question of practical significance in probabilistic coastal hazard analysis. For example, how the U.S. Army Corps of Engineers (USACE) and the Federal Emergency Management Agency (FEMA) define epistemic and aleatory uncertainties is quite different from the NRC’s classification. As part of our collaboration with NRC, we have been developing a probabilistic framework based on logic trees where epistemic uncertainties are estimated through the evaluation of multiple datasets, models, and methods. In this logic tree approach, it is acknowledged that there is random variability in the physical world that cannot be exactly replicated, regardless of how much data we collect or how much our knowledge of the system improves. So, model skill error, for example, is considered an aleatory uncertainty. In terms of major contributors to uncertainty, in my experience these are the atmospheric and hydrodynamic modeling and storm climatology, specifically short record lengths and lack of reliable estimates of parameters like storm size. Also, in the probabilistic analysis we typically rely on relatively small storm suites due to the high computational burdens of high-resolution numerical models, potentially leading to sampling errors and coarse probability estimates. The most critical source of uncertainty, in my view, is the numerical modeling and the lack of reliable validation data. Things we have done to overcome some of these challenges include the development of metamodels to generate tens of thousands or even millions of storms for more accurate definition of the parameter and probability spaces and the estimation of spatially varying bias and uncertainty. Thank you so much for your attention.

3.10.5 Panelist Introductory Remarks (Fernando Ferrante)

Speaker: Fernando Ferrante, Electric Power Research Institute

I'm Fernando Ferrante. I'm in the Risk and Safety Management Group with the Electrical Power Research Institute (EPRI). Thank you for the invitation by the NRC and Dr. Bensi. I want to highlight a couple of things in the same theme of the presentations we just heard. EPRI has produced about a dozen reports in the last seven years or so, ranging from paleoflood studies in rivers to storm surge. These have included stochastic modeling, data analysis, as well as general guidance in terms of walkdowns. They deal with both probabilistic, and, in tandem with our Nuclear Maintenance Center here at EPRI, deterministic aspects since they are intertwined. So, I’ll share some of my thoughts, although I think Curtis and others have covered is very well. PRA is a very integrated framework as it is applied to the large commercial nuclear reactors. There are several issues, and one is certainly the hazard, where I think the majority of the uncertainty resides. It is important to understand any combination of uncertainty with other areas, particularly plant response at a higher level. And, from our perspective of working with our members utilities, trying to figure out how to leverage advanced methods. We investigated stochastic flood modeling for specific hazards. We did work on smooth particle hydrodynamics (SPH) as Curtis alluded to earlier. The essential idea we're looking for is how to make the insights and advances in this area as practical as possible in terms of the risk insights we can obtain. So, advanced tools are very important. We do have a framework and the framework is not just to do probabilistic modeling in the sense of systems analysis integrated with hazard assessment, but also in terms of the use that some of these tools have today in the industry. PRA in the nuclear industry is used for risk ranking of important components. It's used for online maintenance, so the plants don't have to shut down to fix a particular component. It's used in a wide variety of activities and applications, including by the NRC. One thing that is of particular importance to me in terms of this panel is the impact of uncertainty and how to use it in decision making. So not just characterizing it (trying to understand the aleatory and epistemic divide), but what does it mean in terms of what do you do for these plants? Where is it important and then what can you do about it? Not necessarily just quantification but understanding where knowledge needs to be expanded and how it needs to be used. So again, thank you for the invitation, and I'm looking forward to the discussion.

3.10.6 Panelist Introductory Remarks (Jeff Mitman)

Speaker: Jeff Mittman, U.S. Nuclear Regulatory Commission

I will give a short introduction about myself and one comment about the topic at hand. My name is Jeff Mittman. I'm a Senior Reliability and Risk Analyst with the NRC. I started my career with General Electric, spending about 10 years working in startup testing and outage support. I was a shift technical advisor, and I did some construction, so that's where my grounding in plants comes from. In the middle of my career, I spent about 12 years working with EPRI, mostly in the outage risk assessment area, but some work in the PRA area also. For the last 16 years I've been with the NRC and here I've been doing mostly risk analysis, in the area of event analysis. Something happens at the plant, a plant trip, a flood, something like that, or a condition analysis where equipment is unavailable because of unplanned, unforeseen circumstances. And as such, I'm a consumer of a hazard curve and so all the work that's been done over the last decade to understand probabilistic flood hazards helps me tremendously to understand what the hazard is. Then I attempt to input that into PRA models and understand what the significance of that is. I've been involved with several flooding situations, in what we call a significance determination, where we're looking at consequences of, typically, conditions. Typically, things are not set up as the plant was initially designed, and we want to know what the risk impact is of that.

I'd like to put a little bit of perspective on uncertainty and how that's used from a regulatory standpoint. Uncertainty is a very important input into the PRA as everybody knows. It supplies a lot of insights. It changes the risk results. But the Commission policy is clear on how we're supposed to use this information. The NRC PRA Policy Statement says: “PRA evaluations and supportive regulatory decisions should be as realistic as practicable”. So, at the end of the day, the risk decision, the decision with risk input should be based on the most realistic case, which is not conservative and not non-conservative. And of course, that kind of focuses in on the mean. But we know that the mean is influenced by the uncertainty, so the uncertainty is important. But at the end of the day, we're looking at the mean value to help us make a regulatory decision. And with that I'll stop.

3.10.7 Panelist Introductory Remarks (Bogdan Golovchuk)

Speaker: Bogdan Golovchuk, Tractebel Engie

Thanks first of all for this opportunity to speak up. And as a PSA practitioner, when we look at how our plant responds to a flood, it's fairly straightforward to understand if a component survives or not. On the other hand, it's really not obvious what would be the behavior of the personnel and it's something that I'm interested in. I would like to hear if someone has thoughts about the human side of the whole event because some of our bounding studies showed that it can be quite a significant contributor to overall risk. I mean the performance of the personnel and how to quantify the additional stress? How to put a value on deteriorated conditions? So that's something that I am particularly interested in.

3.10.8 Panel Discussion

Shelby Bensi (Question to Panel):
What are the most pressing sources of uncertainties? If you were sort of ordained with the ability to reduce one, or maybe just a couple sources of uncertainty, what would that be and why?

Curtis Smith:
I think a lot of the discussion that I've heard over last couple days is focused on the hazard. But if I were king for a day and could reduce the uncertainty to zero, I would attack the fragility, specifically, SSCs and component fragilities. If you look at all of the extensive work going on in terms of hazard modeling, both deterministically, and probabilistically, it's pretty impressive if you think about it. A lot of people are weighing in on that part of the scenario. We can do a fairly decent job of modeling where the water goes. We have one- two- or three-dimensional models for that. Maybe a weakness in some of our PRA models is the human element, so that might have some considerations. But a lot of uncertainty exists in terms of the component failures. What is going to fail as a function of water inundation? For example, if you look at the seismic community, we've been shake testing components for decades. We don't have a similar program in place for components related to water hazards. So, I see that as a fairly large driver of uncertainty.

Shelby Bensi:
If I can follow up on that real quick Curtis, do you think that there's an emphasis on the hazard just because we're starting to understand what those uncertainties are? Sort of the known unknowns versus the unknown unknowns, or appreciated uncertainties versus not appreciated because we haven't spent the resources on fragility?

Curtis Smith:
I think understanding the hazards better is very important and the work that's going into that is sort of multi-application. Understanding that better is just something we must do as a society, independently of doing PRAs. I don't know if there's been a conscious decision early on regarding knowing more or less on the fragilities, so I don't know if I have a really good answer to what you're asking.

Shelby Bensi:
Does anyone else want to weigh in on this question?

Norberto Nadal-Caraballo:
In terms of uncertainty, we know that if we consider the center body and range of all the data, models, and methods, we can end up with thousands of branches and hazard curves. If I had the ability to reduce one uncertainty it would be in the atmospheric and hydrodynamic modeling. That's where more of our headaches are; our bias beginning with the storm wind and pressure field (both historical and synthetics). We always try to correct that bias and to estimate uncertainty, but one of the main problems associated with that is our lack of validation data. Many times, we know that there is bias and uncertainty localized in a given region, but we don't have the necessary data to make the necessary corrections and adjustments. That applies to waves as well as the surge. When we are doing a risk assessment we have to rely on the

computational models for overtopping, and the uncertainty associated with the waves is really high. Sometimes we have just one measurement for one storm. So, what do we do with that information? Do we correct for the uncertainty based only one measurement at that one point? Or are we making things worse by doing that correction. So yeah, there is a fear of uncertainty associated with uncertainties! So, my wish list is to improve the numerical models and have more, and more reliable, validation data.

Fernando Ferrante:
Very good discussion. I think it's important for the audience to consider this. Sometimes we talk about uncertainty as a uniform thing. We're talking about an integrated risk assessment, so how, where and to what extent uncertainty impacts the analysis is very important to understand upfront. Sometimes we say the hazard has a lot of uncertainty and I agree with Curtis, that doesn't mean there aren't important uncertainties in other parts, for example the human aspect and facilities. My perspective, having seen some of these issues in risk assessment, is of course you have to deal with uncertainty in the hazard. For a lot of plants, you're dealing with very extreme scenarios. In some cases, it could be combinations of less extreme hazards with other scenarios. So, I don't think you can get away the uncertainty in the hazard. That must be quantified. It's very important for the analysis and that doesn't mean it's more or less important than others. If a plant has a major structure and they're depending on that structure to survive, say, a tsunami challenge, then the uncertainty of the hazard coupled with the uncertainty in the response of the barrier is extremely important. For a scenario where flooding overwhelms a barrier, human impacts will not be unimportant, but there is less focus on the credit you can give operators given that the plant is overwhelmed. For lower floods you can have uncertainty in the seals within penetrations from the outside to the inside and internally. So, if that's what's driving your uncertainty, as opposed to a barrier, then that uncertainty is very important. There is also site response level, how organizations that are set up to respond to an event. A lot of the industry, since Fukushima, has worked on adding capabilities to respond to scenarios involving extreme natural hazards and there are uncertainties to that because you can't truly practice for an event that know you will not see, maybe, ever or you'll see it for the first time when it happens. So, there are compounding uncertainties. We tend to talk about uncertainty within distributions and equations but, ultimately, we're talking about confidence in our analysis and how it impacts our decision making. So, uncertainty at different levels reflects the confidence in the information we have in different parts of the model. And of course, the drivers can change and therefore what's important from an uncertainty perspective can change.

Jeff Mitman:
I want to extend a little bit of what Curtis and Fernando said about the fragility side. You know, one of the things we've seen at the NRC, and I asked a question about this in a previous session, is about flood seals. Our plants are 30 to 40 to 50 years old. Those seals were installed a long time ago. They're passive components and in a deterministic analysis, they are assumed to always be effective. My opinion is that that's not realistic. Some of the seals probably weren't installed in the way we would install them today, and they've probably aged. So, I think that there's a lot of uncertainty as to the condition of the seals and how that impacts the plant's ability to respond to a flood event. Another thing to keep in mind is something that Curtis touched on, and that's the human aspect of this. Many of these flooding scenarios are quite lengthy and most of them require human actions. How do we analyze the probability of failure or probability of success of the operations with humans involved? And how to incorporate that into the probabilistic analysis? It's always a challenge. It's often controversial and there's always room for getting to more consensus and lowering the uncertainty there. The final thing I'll say on the hazard side is, as everybody knows, oftentimes there's a cliff-edge effect with many of these things. A small change in elevation can have a rather dramatic impact on the risk analysis, as

well as an impact on the plant response (what survives and what doesn't), and therefore on the risk analysis quantification. So that's another place where the uncertainty becomes very critical.

Ray Schneider:
I think Jeff was getting at the idea that we are integrating all these pieces together. That's what happens in the analysis. For example, if you have a flood event with pre-warning, the issue then is putting in a lot of temporary pieces of equipment for operating sites that may not have everything permanently installed. So, if you have the pre-warning then the question is how effectively you in are taking the pre-actions, putting barriers in place at that particular time. So, the human factor gets to be much more of an issue. Plus, may be doing it with competing actions. You may have multiple teams doing different kinds of work, so it's more like a project management issue if you have enough advance warning for some of these things. So, the question you come up with is, when you do the PRA, you're actually ending up with multiple end states at the beginning of the transient. What does your plant actually look like? What are you actually protecting? What is actually vulnerable? So, this is where human factors, I think, become a big deal because it makes the complications harder. And then when you recognize that there are all these cliff-edge effects. At what point are my actions being interfered with by the flood? For example, if I start the actions and I think I have plenty of additional time, but the flood rises too quickly, and I have to suddenly slow things down. How does that that play into it? So, it makes it a more complicated analysis. So, planning operations, doing things in advance becomes important. The human factors are, in my mind, probably the bigger aspects, at least for the older plants that may have advance warning of the hazard. If you don't have advanced warning then, then it is the cliff-edge effects.

Shelby Bensi (Question to Panel):
I think we could probably keep going back and forth on this question for a little while, but just in the interest of expanding our discussion, I am going to turn to the chat questions. This is a bit on the hazard side and the notion of mapping the hazards into the PRA and the fidelity of that mapping. So, the question: Is 1D or 2D flood hazards analysis more reasonable for the PRA?

Curtis Smith:
I think the general answer is you want to try to make it as simple as possible for whatever is appropriate. So, if you can get a one-dimensional flood analysis that answers the hazard part, you know that kicks off the scenario, the question would then be, are you capturing the right elements of the scenario? Is that one-dimensional answer getting you to where you can talk about the impacts to the plant, impacts to specific components, in tracing the scenario to core damage or not. If that works, great! There really is no one universal answer to a lot of these questions, as you're starting to see. It's very specific to the hazard.

Shelby Bensi:
Yeah, I think having better appreciation for the diversity of strategies that are used. We saw some of the presentations this morning where you have walls and barriers, but some of the other strategies rely on portable equipment in dewatering. I think in that case it sort of changes the importance of the spatial resolution. Does anyone else want to add in?

Curtis Smith:
Let me also answer that in a different way. I think it's important to look at and think about what we currently do for other parts of the PRA. We're talking about uncertainty in PRA, so I think a good surrogate for the discussion is to look at what we do for the loss of coolant accident (LOCA). It has a frequency and magnitude just like flooding. We have small LOCAs, medium LOCAs and large LOCAs. For example, the frequency of large LOCA is a one-in-a-million kind of event. We haven't run our power plants for a million years, so how do we represent that? There are of course, statistical ways. We typically don't have a really complex finite element

model for all piping in the plant to come up with that LOCA frequency. We go to a simpler approach for the hazard and we’re completely fine with that. We've been using LOCA frequencies for 50 years now. So, if you think about that and look at the uncertainty on, say, a large LOCA, essentially a one-in-a-million-year event. In current practice that's plus or minus an order of magnitude. So, I can have a simple hazard curve that's plus or minus an order magnitude. I should be fine with that in theory. And thinking about some of the plots I saw this week, yeah, there's uncertainties in the estimates of the frequencies. But a lot of those frequency estimates were less than an order of magnitude. So, in that respect, you can probably argue that the uncertainties on flood hazards might be less than the uncertainties in some of the other comparable initiating events that we have in the model.

Shelby Bensi (Question to Panel):
Any comments regarding the propagation or amplification of uncertainties along the calculation train. So, propagation of uncertainty. Does anyone want to weigh in there?

Curtis Smith:
I'm not exactly sure on the question, but I think each element that we've mentioned of course has their own respective uncertainties and you could treat those independently. But I think the big question comes up: Are there dependencies along the calculation chain? If you don't handle those dependencies correctly, that's going to cause some issues. But for the other, simpler things, that would just be kind of what we normally do for the numerical analysis of uncertainties.

Shelby Bensi (Question to Panel):
We have another question here. Are there any ideas on how to tackle “*black swan*” events; to tackle the unknown uncertainties? An example is given: Some events are outside the experience horizon because they have never occurred in human historic period, or they were not recognized as being exceptional but were nevertheless markedly distinct from considered events.

Fernando Ferrante:
This issue of the *black swan* or unknown unknowns kind of circulates around the nuclear industry, strongly. At a high level you know the issue is much deeper than we can cover here, but this ties to the concepts of defense in depth. Understanding what we know and what we don't know, and then conditioning how good is our capability if this event were to happen. I think it's one of those issues that comes up and it doesn't have a pretty answer. But I think the issue with external flooding is not always the most extreme event. It's not so much the *black swan*. In a prior discussion I heard somebody say, it’s sometimes unusual combination of common events that can take you there. So, there's a couple of things that, at least in this business, we’ve tried to deal with. One is trying to prevent over-reliance on any single barrier. Plants shouldn't get rid of a flood protection just because there's the idea that certain events will never happen.

The issue goes both ways is another thing I want to say. We can always assume the plant can be hit by a meteorite full on, or the entire state of Arkansas is flooded. But at some point, we need to balance what we don't know with the amount of requirements that need to be put on top of the plant. We can always add more. Say, you have this defense, but add another defense. The issue is what is reasonable given what we know and what we don't know, and so we try to create zones where maybe the requirement is not quite that everyday thing you should be prepared for, but it's something in between. Of course, the devil is in the details. How exactly to modulate that can become an important debate since there are financial costs associated with protecting plants.

Norberto Nadal-Carballo:
In terms of the *black swan* that can be highly subjective. Thinking about hurricanes for example, Sandy was considered by many to be a *black swan* when it affected the New York area. Other hurricanes have been *black swans* in terms of the of the rainfall that they produced. One approach to be prepared for *black swans* is to try to predict the magnitude of those events and try to estimate what will be the consequences even if we cannot exactly estimate their frequency. That's the approach that we've been following in our study. So, what's the most intense hurricane that the numerical models can handle with some degree of certainty and reliability and then try to estimate their likelihood. For example, we are including hurricanes up to an intensity or central pressure of 865 millibars (which have not yet been observed along most of our coastlines). We are estimating the magnitude of the surge and waves they produce, and we are trying our best to estimate their likelihood, even though we know they're not going to be happening in many of the locations we are studying. Along those lines, we also need to maximize that the use of the historical record. For example, in our analysis we typically go back, in terms of record length, to the 1940s. But we have a lot of data before that that has been recorded by the Natural Hurricane Center and they have been doing hindcast analysis. So, we should be using that data to better estimate the uncertainty associated with the frequency of these *black swans* or very rare events.

Jeff Mitman:
I'd like to argue that we do think about *black swan* events quite a lot. The general public would probably consider a one-in-100-year event as a *black swan*. Certainly, a one-in-1000-year event is considered a *black swan*. But in the nuclear field, we think about one-in-a-million-year events. We try to extend the hazard curves out there. There's a lot of debate and argument about it, but we try to think about them and what they would look like and what the challenges would be. So, I'd say in the area of known unknowns, we think a lot about what many would consider be *black swans*. In the area of unknown unknowns I would fall back on Fernando's perspective of that's why the nuclear industry is required to have defense in depth. It's there explicitly to deal with unknowns. If you read the literature from way back, it talks about we don't know everything, so let's add in defense in depth. So, we try to deal with it. We could always do a better job, but I think that we really do try to think about it and deal with it.

Curtis Smith
I agree with Jeff's comment. I think the one thing we could probably do a little better, specific to external hazards, and this is one of the points of Norberto brought up, the idea of the physical maximum possible. How much precipitation can a cloud or the atmosphere hold at any one time? There's a physical upper bound to that. If we understood those physical limits at least, I think it would give us a sense of what are those *black swans* that might come around very rarely.

Shelby Bensi (Question to Panel):
Can the panelists address the question of how important drivers of uncertainty might change as the focus is shifting from the existing fleet to new large light-water reactors (LWR's) or as we move into thinking more about small modular reactors (SMRs) and advanced reactor designs?

Curtis Smith:
That's definitely an interesting question. I don't think I have a good answer, but I hope that, as an industry, we've learned from the existing fleet to help address the other two parts to that question. But I think there's going to be some unique issues that will have to be addressed. If you go to some of the extremes, for example, microreactors are portable and deployable across the world. What happens if that drives off a bridge over the Snake River, to use an example

locally here. So, the idea of siting becomes an interesting question when your reactor moves. Things like that, I think, will be questions that will have to be addressed.

Jeff Mittman:
So, I'd offer that we have learned a lot already. I mean for the two reactors currently being built at the one site in the U.S., a lot of thought went into where to site them. I won't say it's the only reason, but they were sited someplace where the flood hazard is minimal. Leaving aside the issue of mobile reactors, for the new small modular or microreactors, people are thinking about this explicitly from the get-go, something that wasn't well done back in the 60s and the 70s. It's being thought about from the beginning as part of the design, how to construct them and where to site them. So, I think that some lessons have been learned, probably pretty well, and that's being factored into the design and location of new reactors.

Ray Schneider:
I'd like to follow up on that. Putting on my ANS hat, we've modified the design-basis flood hazard standard (ANS-2.8) which used to be based on the pretty much standard deterministic methods. We built in the requirement to look at the probabilistic aspects of these hazards. So that you're factoring in beyond just the deterministic, what we know now, trying to look at the probabilistic aspects. That's in the new ANS-2.8 which was just issued this year.

Fernando Ferrante:
I think it is an interesting question. There are multiple regulatory and technical aspects of that question. We're getting questions from the SMR and microreactor folks. The most interesting part for this community, I think, kind of alludes to what Ray, Curtis, and Jeff said, which is we have a lot of information, and the probabilistic flood hazard assessment community is gaining momentum and understanding of how to bring those things together. The most interesting to me is the scalability of what needs to be done. We are bringing in risk-informed approaches from the get-go, as Jeff said, to our new designs: large, small, modular and so forth. The key issue, I think, is how to scale it. If a small modular reactor is required to have exactly the same, say security protection or the same level of rigor as a large reactor, that will potentially impact its financial viability. This is not to say the requirements need to be reduced, but if you have a microreactor which is going to be inherently simpler than a large commercial reactor, what is the scalability for the probabilistic methods that is most applicable? Because some vendors may start thinking, well, let's just go deterministic and that way we don't have all these complications. I think the idea of risk-informing is important. I think it adds to safety. The question is how we apply it in a way that is practical and commensurate with the technology we're dealing doing with. So, it's a very good question.

Bogdan Golovchuk:
I would say to really understand where uncertainty lies, which uncertainty propagates till the very end, you need to have at least an idea of your list of minimal cut sets. What are the sequences? I would say that is the way to really answer this question for whatever type reactor we might have in the future. At least in the design stage, once you have some design PRA and you have an idea of what are the dominant sequences. Then you do standard tackling of uncertainty with some sort of Monte Carlo simulation and see what actually contributes, then you can prioritize. So, basically it heavily depends on the type of the reactor and siting.

Shelby Bensi (Question to Panel):
Building off what was just said related to the uncertainty propagation we have a question here regarding the reasonable number of Monte Carlo iterations when dealing with the PRA. I think that this might be something that's interesting to address from the perspective of where we aggregate and de-aggregate in the PRA. We do the hazard analysis and aggregate it down to the hazard curve and then we have to sort of break that out and put it into the into the PRA. And

if we want to deal with uncertainty in that it's a de-aggregation process. So, does anyone want to chime in on that?

Ray Schneider:
There must be at least enough samples to basically cover the spectrum that you're interested in, i.e., in the tails. We're looking at 10^{-4} to 10^{-6} kind of hazards but that's more for the PFHA people to define. That's kind of why, when I ended the presentation before, I said we need all this information, but not just the levels. We also need to know the timing. I need to know enough of these scenarios that you can give me, uncertainties on the on the full spectrum of how these hazards will emerge and that's going to be the determined based on when we de-aggregate these things, how many sub events are actually included in there?

Shelby Bensi (Question to Panel):
I don't know if there was any specific question here, but there's been a couple of comments in the chat related to how paleoflood hydrology might provide insights that can help turn some swans from black to white or push back the limits of what was been missed. Does anyone want to weigh in on the use of paleoflood information?

Ray Schneider:
From what we saw earlier the workshop, paleoflood information is going to be important to basically get better estimates of the tails. I'm not quite sure if it'll turn swans from black to white or to maybe close to gray, but it will certainly provide more information. And the more data points you have out there on the hazard curve, the better you understand the frequency, the better you understand relative elevations and do better estimates of the mean. If the site is capable of providing that information, and if there's really risk at the very low end of the tails and then paleofloods should be part of the investigation and part of the hazard curve development.

Curtis Smith:
I'll go back to my LOCA example because the paleo-data is similar to what we do for LOCA frequency evaluation. For LOCAs we combine operating experience which we do have some of, with expert elicitation and some modeling to get things outside the operating experience. So that operating experience would be sort of the analogous to having flooding data from river gauges for the last, say 100 years, and the paleo-data would get things outside the operating experience. We combine all of those. The goal in PRA uncertainty is to be honest. What do we know? What do we not know? That goes for every part of the PRA model. Some things we know pretty well and some things we don't. But that doesn't stop us. And of course, the more data you have, in terms of actual data points and the variety of the data, generally the better off you are.

Shelby Bensi:
I think we keep coming back to contextualizing the uncertainties relative to what else is dealt with in the PRA relative to what matters and what impacts the plants.

Shelby Bensi (Question to Panel):
I don't see any more questions in the chat right now, so I'll go back to some questions we had on the side. Does anyone want to comment on the approaches you've used to address sources of uncertainty in the external flood PRA? We've heard a lot about the hazard side of things, so maybe in dealing with the fragility or the human response. Or maybe dealing with the characterization of the hazard from spatially and temporally dynamic perspective. So, thoughts?

Bogdan Golovchuk:
I would say it also depends on where you are in your analysis. Start with a more conservative assumption and then once you progress or have a different iteration then you might reduce it to

a best estimate. As I mentioned earlier, after the first iteration you can already have an idea how sensitive your model is to certain parameters. If some parameters matter significantly less than you thought, keep whatever was assumed and focus on what you can improve and what uncertainties you can reduce and where you can refine.

Shelby Bensi:
So, an iterative process. Anyone else want to weigh in on these approaches?

Jeff Mitman:
The thing I'd like to add here is sensitivity analysis. We've touched on it a little bit, but it’s a very useful way to test what's important and what's not. Does a little variation have a big impact, or does it require a big variation to have a significant impact? That’s one way that NRC frequently uses to deal with uncertainty.

Shelby Bensi (Question to Panel):
I’m going to hit another question which is, I think, a hard one for many in practice. What approaches have been used to screen out hazards? Flooding hazards come in all different flavors: LIP, river flooding, dam failure, tsunami, storm surge, etc. Some of these can be screened out pretty obviously based on location. But in some locations, it's not always obvious. So, thoughts on screening of hazards from the PRA such that you wouldn't do a full analysis of it?

Curtis Smith:
I'll mention an OECD/NEA report published in 2019 that talked specifically about screening of external hazards. It included many hazards such as seismic, fire, and flood. That report was an amalgamation of many countries’ practices, mostly on the regulatory side. You know, here's what the regulations say in Germany, the U.S., and so on. Going from memory, I think there's probably less information in terms of external floods than some of the other hazards, like high winds and seismic. But I believe there was some flooding there. That report captured some of the best practices and some of the limitations and gaps found in current screening practices.

Jeremy Gaudron:
From the EDF point of view, we usually use a screening process, based on similar criteria used in the U.S., I think. We do this screening process on each of our sites. We base our screening process on deterministic studies. Deterministic conservative studies are used to screen out some of the mechanisms. We only keep the flood mechanisms that seem to be the most relevant for the site. It's kind of a prioritization process, because we can’t do everything.

Ray Schneider:
The PWR and BWR owners groups also have screening processes that are tied to the ASME PRA standard to screen out the different hazards. When you get to floods, it's difficult because it is a frequency screen. You often must do a lot of analysis to estimate the flooding frequency. Of course, some sites you can easily screen, for example if they are located maybe 300 feet above the water level. In addition, there's guidance in ANS-2.8 that has some screening for floods. Again, the screening ties into frequency. You're left with screening tied to frequency, which requires a decent amount of work. In some cases, screening can be relatively simple for some hazards, for example lightning and some of the wind events in certain areas of the country. But using frequency as a part of the screen for a flood hazard is still a decent amount of analysis.

Shelby Bensi (Question to Panel):
We have about 10 minutes left, so I'll finish with a broader question related to your perspectives and experience with regard to external flooding PRAs. From PRAs, or parts of them, that you have done, what have been the key insights or the key risk contributors?

Ray Schneider:
We competed an external flood PRA for Fort Calhoun Station early on. One of the insights that we came up with, which stuck in my mind because it was a little bit surprising, is that a lot of the risk came from failing to prepare the temporary barriers before the flood arrived. Part of that was due to the surrounding area being inundated, making it difficult to get staff in place. Part of it was due to procedures not being in place. Part of it was due to competing factors. It wasn't clear what to prioritize because they wanted to protect everything because everything was going to get flooded all at once. As time went on after that, the insights were translated into procedures, guidance and strategies and additional equipment that basically made that a little less risky. But, at least as a first cut, you're going to find for sites that have to prepare and rely on temporary protection in some form, that's going to be a major insight. Being able to get your plant into the condition you want it to be in before the flood hits is going to be the biggest challenge.

Fernando Ferrante:
I'll add to that, both risk insights and then thinking about external flooding PRA in general, including uncertainties of course. One of the things that struck me when I was at the NRC was that external flood can be a significant risk. You know the hazard is definitely out there. Part of that might be historically from the way early reactors were licensed. Based on Joe's question, different types of designs might lead to a different approach moving forward. The other thing is, following the theme of our panel, there is significant uncertainty, which by itself is neither a deterrent or necessarily a bad thing. You know, John Stetgar had a comment regarding SHAC-F and the use of expert elicitation and the uncertainty in external flooding that we're struggling with is. I've seen everything from Mel Schaefer's detailed stochastic flooding simulations to folks taking 100 years of data and extrapolating that and thinking there is no uncertainty in that. And so following Stegar's comment, we do need an improvement in how to deal with this as a whole. We also need more practice with some of these models. A lot of the times we're dealing with very narrow ranges of, say, elevation in plant response. The uncertainties driving those cases may be different, which means upfront, we should understand where our models are going, where are the compounding of uncertainties. Tom Nicholson had a question about that. If we can have a better understanding of where those are and how to deal with the uncertainty. Does paleoflood information help? Not always. It depends on what site you are at and how much you have. I think that there's a lot of for this audience to deal with, which is to bring a little bit more on some of the challenges that exist to getting the characterization of the hazards, of plant response and of the overall risk. I stress that practice with a lot of the tools that we are talking about and integration between the different groups of experts is essential for us to move forward and show that external flooding risk can be done, can be applied in a way that is practical that it provides insights, and despite the uncertainties of the challenges, can continue to support safety.

Jeff Mitman:
I want to build on a comment made earlier about this question and give my perspective on the pre-planning and the pre-setup of the site. I think that's a critical issue and there's a lot of uncertainty there. To set up the plant to deal with an extreme event is a very significant thing. It can encompass a lot of preparatory work, a lot of time and money. And there's also the consequences. Do you shut down the plant in anticipation of the event? That has two impacts. One is direct monetary impact on the on the utility and the other is that the community may be relying upon the plant to supply power during extreme events. These are really tough questions. To illustrate how tough it is, look at when Hurricane Sandy to hit the East Coast about five years ago. Everybody knew it was coming. Everybody knew it was a rather large storm. They had fairly good ideas of the path and three nuclear plants shutdown in preparation for Hurricane Sandy. Three plants lost offsite power because of the hurricane, but not any of the three plants that shut down. So, everybody knows it's coming. Everybody knows that it's significant. But how

to make that decision to start the preparatory efforts is a really tough one, both from probabilistic standpoint and a risk standpoint. But also, what's best for the community? What's best for all the entities involved? It's a challenge to plant ownership that I wouldn't want to have to be in the middle of.

3.10.9 Moderator Concluding Remarks (Shelby Bensi)

I will give sort of recap and maybe just a final remark. I thought one theme was placing the uncertainties within context and reminding ourselves that PRA in general has plenty of strategies for dealing with uncertainties. I think Curtis mentioned keeping in mind that there's plenty of orders-of-magnitude uncertainties all over the place in the PRA, and there are strategies for dealing with that. Not getting caught up in that, but more just being transparent about where the uncertainties are so that we can put those forward into the PRA.

The other theme that I think came out of our discussion was really thinking about the need for integrated work. You know, different parts of the PRA team working together, not just thinking about PRA is a linear process. We often think about hazard, fragility, human performance, and plant responses as this linear process. But keeping all the different parts of the PRA in mind at the same time is important. Uncertainty in the hazard may not be as important as something related to how the evolution of the plant response is going to play out in terms of organizational decision making or human factors. So, keeping those drivers of uncertainty in mind as we think about the uncertainties in the hazard.

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5 SUMMARY AND CONCLUSIONS

5.1 Summary

This report includes the agenda and presentations for the Sixth 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.

5.2 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 nearly complete, and the NRC has initiated a 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 third phase (development of selected guidance documents) is an area of active discussion between RES and NRC user offices. 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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