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United States Nuclear Regulatory Commission
Protecting People and the Environment

RIL2021-01

PROCEEDINGS OF THE FIFTH ANNUAL PROBABILISTIC FLOOD HAZARD ASSESSMENT WORKSHOP

February 19-21, 2020
NRC Headquarters, Rockville, MD

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Research Information Letter
Office of Nuclear Regulatory Research

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ABSTRACT

The U.S. Nuclear Regulatory Commission (NRC) Office of Nuclear Regulatory Research (RES) is conducting the multiyear, multiproject 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, and presentation slides for the Fifth Annual NRC Probabilistic Flood Hazard Assessment Research Workshops held at NRC Headquarters in Rockville, MD. The workshop took place February 19–21, 2020, and 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 introductory session that included perspectives and research program highlights from RES and from the NRC Office of Nuclear Reactor Regulation, the U.S. Army Corps of Engineers, industry representatives, and academia. NRC and Electric Power Research Institute contractors and staff, as well as invited Federal and public speakers, gave technical presentations (including 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) external flooding operational experience

(8) external flooding probabilistic risk assessment

TABLE OF CONTENTS

1 INTRODUCTION

This research information letter (RIL) details the Fifth Annual U.S. Nuclear Regulatory Commission (NRC) Probabilistic Flood Hazard Assessment (PFHA) Research Workshop held at NRC Headquarters in Rockville, MD, February 19–21, 2020. 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, the U.S. Army Corps of Engineers (USACE), and the Institut de radioprotection et de sûreté nucléaire (IRSN) 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.

1.1 Background

The NRC is conducting the multiyear, multiproject 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 flooding 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. ML20080M171.

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. ML20080M170. The complete workshop presentation package is available at ADAMS Accession No. ML20080M135.

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 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 $2x10^{-3}$ 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

5th Annual Probabilistic Flood Hazard
Assessment Research Workshop
Headquarters, Rockville, MD, February 19-21, 2020

AGENDA

Welcome to the Nuclear Regulatory Commission's Office of Nuclear Regulatory Research (NRC/RES) 5th Annual NRC Probabilistic Flood Hazard Assessment (PFHA) Research Workshop. Participants include staff and contractors from NRC, Electric Power Research Institute (EPRI), federal agencies, industry, and other organizations involved in flood hazard assessment, flood risk assessment, and flood protection and mitigation research who will provide information on recent results, current activities, and perspectives on future research directions. This 3-day workshop is open to the public at no charge, but registration is required.

WEDNESDAY, FEBRUARY 19, 2020

09:00 – 09:10 **Welcome & Logistics**

Session 1A: Introduction

Session Chair: *Joseph Kanney, NRC/RES/DRA*

09:00 – 09:10 Logistics 1A-0
***Kenneth Hamburger**, NRC/RES/DRA/FXHAB*

09:10 – 09:20 Introduction 1A-1
Raymond Furstenau*, *Director, NRC Office of Nuclear Regulatory Research*

09:20 – 09:35 NRC Flooding Research Program Overview 1A-2
*Joseph Kanney, **Meredith Carr***, Tom Aird, Elena Yegorova, Mark Fuhrmann and Jacob Philip, NRC/RES*

09:35 -09:50 *Overview of recent activities at USACE-RMC* 1A-3
Haden Smith*, *Risk Management Center, U.S. Army Corps of Engineers (USACE)*

09:50 – 10:05 IRSN External Flooding Research Program Overview 1A-4
Vincent Rebour*, *Institut de radioprotection et de sûreté nucléaire (IRSN) Radioprotection and Nuclear Safety Institute*

10:05 – 10:20 Nuclear Energy Agency: Committee on the Safety of Nuclear Installations (CSNI): Working Group on External Events (WGEV) Flooding Overview 1A-5
John Nakoski*, *NRC/RES*

10:20 – 10:40 **BREAK**

**** denotes presenter, ^ denotes remote presenter***

continued... WEDNESDAY, FEBRUARY 19, 2020

Session 1B: Climate

Session Chair: *Elena Yegorova, NRC/RES/DRA*

10:40 – 11:10	Regional Climate Change Projections: Potential Impacts to Nuclear Facilities ***L. Ruby Leung**** *and Rajiv Prasad, Pacific Northwest National Laboratory (PNNL)*	1B-1
11:10 – 11:35	Modeling of climate change induced flood risk in the Conasauga River Basin *Tigstu T. Dullo, Tennessee Technical University (TTU), Sudershan Gangrade, Oak Ridge National Laboratory (ORNL), Md Bulbul Sharif, TTU, Mario Morales-Hernandez, ORNL, Alfred J. Kalyanapu, Sheikh K. Ghafoor, TTU,* ***Shih-Chieh Kao**** *and Katherine J. Evans, ORNL*	1B-2
11:35 – 12:00	KEYNOTE - Causality and extreme event attribution. Or was my house flooded because of climate change? ***Michael F. Wehner^****, Lawrence Berkeley National Laboratory*	1B-3
12:00 – 12:25	Attribution of Flood Nonstationarity across the United States—Climate-Related Analyses ***Karen Ryberg****, Stacey A. Archfield, William H. Asquith, Nancy A. Barth, Katherine J. Chase, Jesse E. Dickinson, Robert W. Dudley, Angela E. Gregory, Tessa M. Harden, Glenn A. Hodgkins, David Holtschlag, Delbert Humberson, Christopher P. Konrad, Sara B. Levin, Daniel E. Restivo, Roy Sando, Steven K. Sando, Eric D. Swain, Anne C. Tillery, Benjamin C. York, Julie E. Kiang; U.S. Geological Survey (USGS)*	1B-4
12:25 – 13:30	**LUNCH**	

Session 1C: Precipitation

Session Chair: *Elena Yegorova, NRC/RES/DRA*

13:30 – 14:00	KEYNOTE: Planned Improvements for NOAA Atlas 14 Process and Products ***Sanja Perica****, Hydrometeorological Design Studies Center, Office of Water Prediction, National Weather Service, National Oceanic and Atmospheric Administration (NOAA/NWS/OWP/HDSC), Sandra Pavlovic, Michael St. Laurent, Carl Trypaluk, Dale Unruh, NOAA/NWS/OWP/HDSC and University Corporation for Atmospheric Research*	1C-1
14:00 – 14:25	Application of Point Precipitation Frequency Estimates to Watersheds ***Shih-Chieh Kao****, Scott T. DeNeale, ORNL*	1C-2
14:25 – 14:50	How well can Kilometer-Scale Models Capture Recent Intense Precipitation Events? ***Andreas F. Prein****, David Ahijevych, Jordan Powers, Ryan Sobash, Craig Schwartz, National Center for Atmospheric Research (NCAR)*	1C-3
14:50 – 15:05	**BREAK**	

* indicates speaker, ^ indicates remote speaker

Session 1C: Precipitation, *continued…*

Session Chair: *Elena Yegorova, NRC/RES/DRA*

15:05 – 15:30 Probabilistic Flood Hazard Assessment of NPP Site considering Extreme Precipitation in Korea **(Tentative due to emergent travel issue)** 1C-4

*__Kun-Yeun Han*__, Beom-Jin Kim, Kyungpook National University, Korea; Minkyu Kim, Korea Atomic Energy Research Institute, Korea*

15:30 – 15:55 Analysis of Heavy Multi-day Precipitation Events in CMIP6 Model Simulations in Support of the Fifth National Climate Assessment 1C-5

*__Kenneth Kunkel*__, North Carolina Institute for Climate Studies, North Carolina State University and David Easterling, NOAA National Centers for Environmental Information*

15:55 – 16:10 **Daily Wrap-up**

THURSDAY, FEBRUARY 20, 2020

08:55 – 09:00 **Day 2 Welcome**

Session 2A: Riverine Flooding

Session Chairs: *Meredith Carr and Mark Fuhrmann, NRC/RES/DRA*

09:00 – 9:30 KEYNOTE: An Overview NOAA's National Water Model 2A-1

__Brian Cosgrove,__ NOAA/NWS/OWP, David Gochis, Research Applications Laboratory, NCAR, Thomas Graziano, Ed Clark, and Trey Flowers, NOAA/NWS/OWP*

09:30 – 09:55 Moving Beyond Streamflow: Quantifying Flood Risk and Impacts through Detailed Physical Process and Geospatial Representation using the WRF-Hydro Modeling System 2A-2

*__David Gochis*__, Aubrey Dugger Laura Read, NCAR*

09:55 – 10:20 Extreme Flood Hazard Assessment – Overview of a probabilistic methodology and its implementation for a Swiss river system 2A-3

V.N. Dang, C.A. Whealton, Paul Scherrer Institute

10:20 – 10:45 Practical Approaches to Probabilistic Flood Estimates: an Australian perspective 2A-4

*__Rory Nathan*__, University of Melbourne*

10:45 – 11:05 **BREAK**

Session 2A: Riverine Flooding, *continued...*

Session Chairs: *Meredith Carr and Mark Fuhrmann, NRC/RES/DRA*

11:05 – 11:30	Columbia River Basin Regional Hydrology Studies: Regional Statistical Analyses for Flood Risk Assessment ***Angela M. Duren****, *Northwest Division, USACE Portland*	2A-5
11:30 – 11:55	Reducing uncertainty in estimating rare flood events using paleoflood analyses: Insights from an investigation near Stillhouse Hollow Dam, TX ***Justin Pearce^***, *USACE, Risk Management Center; Brian Hall, USACE, Alessandro Parola, USACE Fort Worth; Brendan Comport, USACE Seattle; Christina Leonard, Utah State University*	2A-6
11:55 – 12:20	Improving Flood Frequency Analysis with a Multi-Millennial Record of Extreme Floods on the Tennessee River near Chattanooga, TN ***Tess Harden****, *Jim O'Connor, USGS*	2A-7
12:20 – 13:30	**LUNCH**	
13:30 – 13:55	Estimating Design Floods with Specified Annual Exceedance Probabilities Using the Bayesian Estimation and Fitting Software (RMC-BestFit) ***Haden Smith****, *Risk Management Center, U.S. Army Corps of Engineers (USACE/RMC)*	2A-8

Session 2B: Coastal Flooding

Session Chair: *Joseph Kanney, NRC/RES/DRA*

13:55 – 14:20	Coastal KEYNOTE: South Atlantic Coast Study: Coastal Hazards System ***Norberto C. Nadal-Caraballo****, *Chris Massey, Victor M. Gonzalez, USACE Engineer R&D Center, Coastal and Hydraulics Laboratory (USACE/ERDC/CHL), Kelly Legault, USACE Jacksonville District*	2B-1
14:20– 14:45	Data, Models, Methods, and Uncertainty Quantification in Probabilistic Storm Surge Models ***Norberto C. Nadal-Caraballo****, *Victor M. Gonzalez, Efrain Ramos-Santiago, Madison O. Campbell, USACE/ERDC/CHL*	2B-2
14:45 – 15:10	Using Physical Insights in Spatial Decomposition Approaches to Surge Hazard Assessment ***Jennifer Irish*,*** *Virginia Tech, Donald T. Resio, University of North Florida, Michelle Bensi, University of Maryland, Taylor G. Asher, University of North Carolina, Yi Liu, Virginia Tech, Environmental Science Associates, Jun-Whan Lee, Virginia Tech*	2B-3
15:10 – 15:35	Investigation of Surrogate Modeling Application in Storm Surge Assessment ***Azin Al Kajbaf****, *Michelle (Shelby) Bensi, University of Maryland*	2B-4

continued... THURSDAY, FEBRUARY 20, 2020

15:35 – 15:45 **Daily Wrap-up**

15:45 – 17:00 **Session 2C: Poster Session**
Session Chair: *Thomas Aird, NRC/RES/DRA*

18:00 – 20:00 **Group Dinner: TBD**

FRIDAY, FEBRUARY 21, 2019

08:55 – 09:00 **Day 3 Welcome**

Session 3A: Modeling Frameworks

Session Chair: *Thomas Nicholson, NRC/RES/DRA*

09:00 – 09:25	Structured Hazard Assessment Committee Process for Flooding (SHAC-F) for Probabilistic Flood Hazard Assessment (PFHA) ***Rajiv Prasad**** *and Phillip Meyer, PNNL; Kevin Coppersmith, Coppersmith Consulting, Norberto C. Nadal-Caraballo, Victor M. Gonzalez, USACE/ERDC/CHL*	3A-1
09:25 – 09:50	Using HEC-WAT to Conduct a PFHA on a Medium Watershed ***Will Lehman****, *Brennan Beam, Matthew Fleming, and Leila Ostadrahimi, USACE, Institute for Water Resources, Hydrologic Engineering Center (IWR/HEC), Joseph Kanney, Meredith Carr, NRC*	3A-2
09:50 – 10:15	Paleoflood Analyses for Probabilistic Flood Hazard Assessments—Approaches and Review Guidelines ***Tessa Harden*, Karen Ryberg****, *Jim E. O'Connor, Jonathan M. Friedman, and Julie E. Kiang, USGS*	3A-3
10:15 – 10:40	Probabilistic Assessment of Flood Hazards Due to Combinations of Flooding Mechanisms: Study Progress and Next Steps ***Michelle (Shelby) Bensi**** *and Somayeh Mohammadi, University of Maryland, Shih-Chieh Kao and Scott DeNeale, ORNL*	3A-4

10:40 – 10:55 **BREAK**

continued… FRIDAY, FEBRUARY 21, 2019

Session 3B: External Flooding Operating Experience

Session Chair: *Thomas Aird, NRC/RES/DRA*

10:55 – 11:20	Risk and Operational Insights of the St. Lucie Flooding Event ***John David Hanna****, *NRC Region III, Chicago, IL*	3B-1
11:20 – 11:45	Reflections on Fort Calhoun Flooding Yellow Finding and 2011 Flooding Event Response ***Gerond George****, *NRC Region IV, Arlington, TX*	3B-2
11:45 – 12:10	2019 Cooper and Fort Calhoun Flooding Event Response ***Patricia Vossmar**** *and* ***Mike Stafford****, *NRC Region IV, Arlington, TX*	3B-3
12:10 – 12:25	Panel Discussion	3B-4
12:25 – 13:30	**LUNCH**	

Session 3C: Overview of NRC PFHA Pilot Studies

Session Chair: ***TBD***

13:30 – 13:40	Local Intense Precipitation Flooding PFHA Pilot ***Joseph Kanney****, *NRC/RES, Rajiv Prasad, PNNL*	3C-1
13:40 – 13:50	Riverine Flooding PFHA Pilot ***Meredith Carr****, *NRC/RES, William Lehman, USACE/HEC*	3C-2
13:50 – 14:00	Coastal Flooding PFHA Pilot ***Joseph Kanney****, *NRC/RES, Norberto Nadal-Caraballo and Victor Gonzalez, USACE/ERDC/CHL*	3C-3
14:00 – 14:10	Panel Discussion	3C-3

Session 3D: Towards External Flooding PRA

Session Chair: *Mehdi Reisi-Fard, NRC/NRR/DRA*

14:10 – 14:35	EPRI External Flooding PRA Activities ***Marko Randelovic****, *Electric Power Research Institute*	3D-1
14:35 – 15:05	KEYNOTE: Computational Methods for External Flooding PRA ***Curtis L. Smith****, *Idaho National Laboratory*	3D-2
15:05 – 15:30	External Flooding PSA in IRSN – developments and insights ***Maud Kervalla****, *Gabriel Georgescu, Claire-Marie Duluc Institute for Radiological Protection and Nuclear Safety (France)*	3D-3
15:30 – 16:00	Final Wrap-up Discussion	

3 PROCEEDINGS

3.1 Day 1: Session 1A – Introduction

Session Chair: Joseph Kanney, NRC/RES/DRA

There are no abstracts for this introductory session.

3.1.1 Presentation 1A-1: Welcoming Remarks

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

3.1.1.1 Presentation (ADAMS Accession No. ML20080M175)

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Welcome

Ray Furstenau

Director, Office of Nuclear Regulatory Research

5th Annual NRC PFHA Research Workshop
NRC HQ, Rockville, MD
February 19-21, 2020

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

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
    - Flooding OpE session in this year's workshop
  - 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
- Readiness for licensing new and advanced reactor designs

THE FUTURE IS NOW

Progress

- Phased Approach
  - Technical basis
  - Pilot Studies
  - Guidance
- Bulk of technical basis research completed
  - Climate
  - Precipitation
  - Riverine flooding
  - Storm surge
  - Reliability of flood protection and mitigation
  - Modeling frameworks

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Current PFHA Research Focus

- In FY20 NRC/RES turned focus towards PFHA Pilot Studies
  - 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

3.1.2 Presentation 1A-2: NRC Flooding Research Program Overview

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

Speaker: Thomas Aird

3.1.2.1 Presentation (ADAMS Accession No. ML20080M178)

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Overview of NRC's Probabilistic Flood Hazard Assessment Research Program

Thomas Aird*, *Meredith Carr, Mark Fuhrmann, Joseph Kanney, Elena Yegorova*

Fire and External Hazards Analysis Branch
Division of Risk Analysis
Office of Nuclear Regulatory Research

5th Annual PFHA Research Workshop
NRC HQ, Rockville, MD
February 19 – 21, 2020

Outline

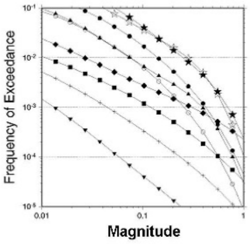
- Objectives
- Key Challenges
- Research Approach
- Selected Projects
- Future Directions

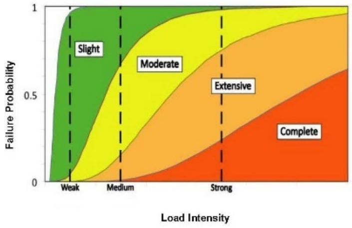
PFHA Research Objectives

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

Key Challenges

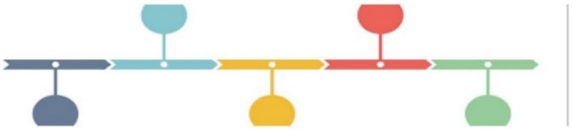
- Hazard Curve Development
  - Range of annual exceedance probabilities (AEPs)
    - Moderately rare to extreme floods
  - Multiple flooding mechanisms
    - Coincident and correlated mechanisms
  - Uncertainty characterization and estimation
    - Aleatory (e.g. storm recurrence rates)
    - Epistemic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





Phased Approach

- Phase 1 (FY15-FY19)
  - Technical basis research
- Phase 2 & 3 (FY20-FY22)
  - Selected draft guidance documents
  - Perform pilot studies
  - Finalize guidance



Phase 1 Technical Basis Projects

- Leverage Available Flood Information
- PFHA Modeling Frameworks
- Improved Modeling
- Reliability of Flood Protection
- Dynamic and Nonstationary Processes

Phase 1 Technical Basis Projects

- **Leverage Available Flood Information**
- PFHA Modeling Frameworks
- Improved Modeling
- Reliability of Flood Protection
- Dynamic and Nonstationary Processes

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Leverage Available Flooding Information

- **Development of Natural Hazard Information Digests for Operating NPP Sites (INL)**
  - ***Completed*** *(continue with updates/maintenance)*
- **Application of State-of-Practice Flood Frequency Analysis Methods and Tools (USGS)**
  - ***Completed – USGS Scientific Investigation Report***
  - *https://pubs.er.usgs.gov/publication/sir20175038*
  - *2nd USGS SIR in publication*
- **Extreme Precipitation Estimates in Orographic Regions (USBR)**
  - ***Completed - NUREG/CR report in publication***
- **Technical Basis for Extending Frequency Analysis Beyond Current Consensus Limits (USBR)**
  - *In progress (completion expected in FY20)*

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Leverage Available Flooding Information

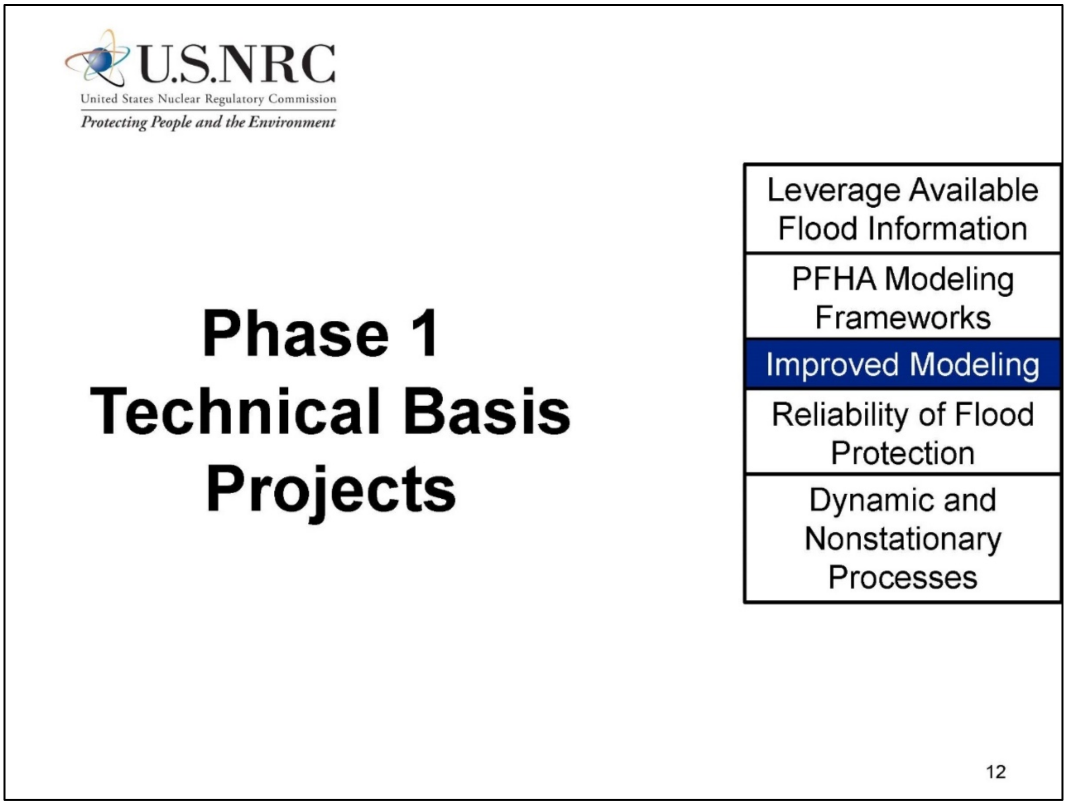
- **Eastern US Riverine Flood Geomorphology Feasibility Study (USGS)**
  - ***Completed – USGS Scientific Investigations Report***
    - *(https://doi.org/10.3133/sir20175052)*
- **Eastern US Riverine Flood Geomorphology Comprehensive Study (USGS)**
  - *In progress (completion expected FY20)*
- **Framework for Technical Review of Paleoflood Information (USGS)**
  - *In progress (completion expected FY20)*
    - *Workshop summary:* ML19200A281
- **Application of Point Precipitation Estimates to Watersheds (ORNL)**
  - ***Completed (NUREG/CR report in publication)***

Phase 1
Technical Basis Projects

- Leverage Available Flood Information
- **PFHA Modeling Frameworks**
- Improved Modeling
- Reliability of Flood Protection
- Dynamic and Nonstationary Processes

PFHA Modeling Frameworks

- **Probabilistic Flood Hazard Assessment Framework Development (USACE)**
  - *In progress (completion expected FY20)*
- **Structured Hazard Assessment Committee Process for Flooding (SHAC-F) for LIP & Riverine Flooding (PNNL)**
  - *In progress (completion expected FY20)*
- **Development of SHAC-F for Coastal Flooding (PNNL & USACE)**
  - *In progress (completion expected FY20)*
- **Methods for Estimating Joint Probabilities of Coincident and Correlated Flooding Mechanisms for Nuclear Power Plant Flood Hazard Assessments (ORNL)**
  - *In progress (completion expected FY20)*
    - *Task 1 (Literature review) completed*
    - *Task 2 (Critical Assessment of Selected Methods and Approaches) Completed.*



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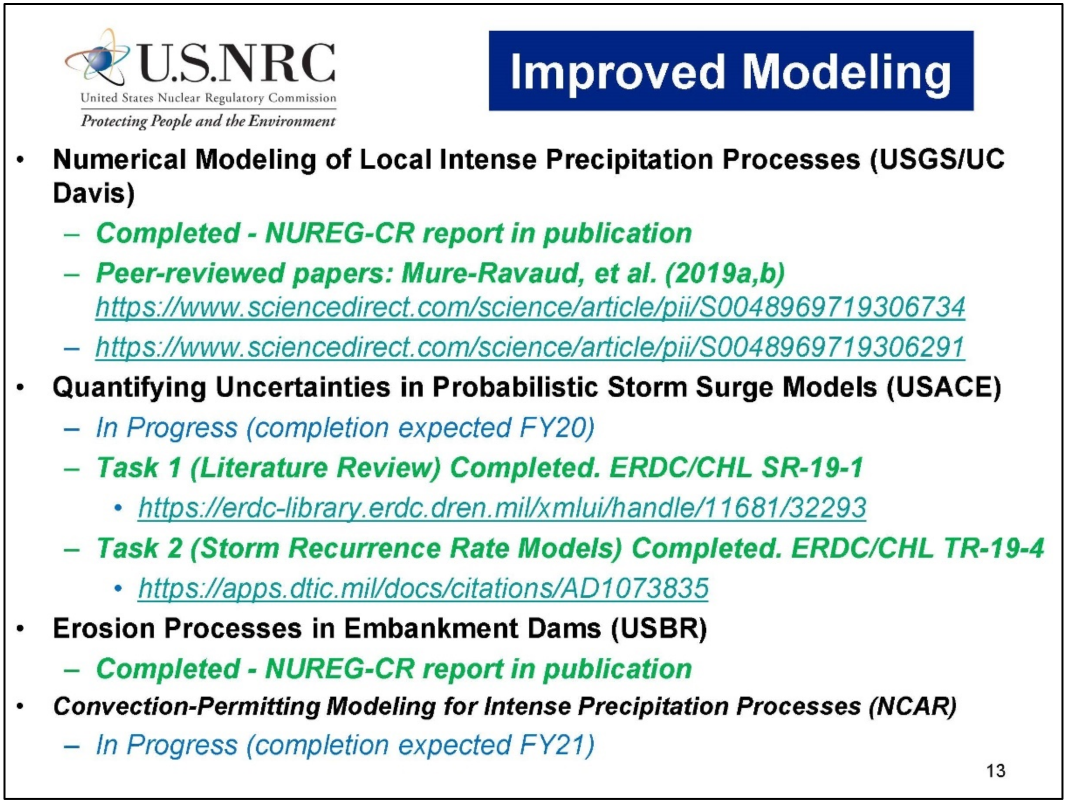
Phase 1 Technical Basis Projects

- Leverage Available Flood Information
- PFHA Modeling Frameworks
- **Improved Modeling**
- Reliability of Flood Protection
- Dynamic and Nonstationary Processes



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Improved Modeling

- **Numerical Modeling of Local Intense Precipitation Processes (USGS/UC Davis)**
  - ***Completed - NUREG-CR report in publication***
  - ***Peer-reviewed papers: Mure-Ravaud, et al. (2019a,b)*** *https://www.sciencedirect.com/science/article/pii/S0048969719306734*
  - *https://www.sciencedirect.com/science/article/pii/S0048969719306291*
- **Quantifying Uncertainties in Probabilistic Storm Surge Models (USACE)**
  - *In Progress (completion expected FY20)*
  - ***Task 1 (Literature Review) Completed. ERDC/CHL SR-19-1***
    - *https://erdc-library.erdc.dren.mil/xmlui/handle/11681/32293*
  - ***Task 2 (Storm Recurrence Rate Models) Completed. ERDC/CHL TR-19-4***
    - *https://apps.dtic.mil/docs/citations/AD1073835*
- **Erosion Processes in Embankment Dams (USBR)**
  - ***Completed - NUREG-CR report in publication***
- ***Convection-Permitting Modeling for Intense Precipitation Processes (NCAR)***
  - *In Progress (completion expected FY21)*

Phase 1 Technical Basis Projects

- Leverage Available Flood Information
- PFHA Modeling Frameworks
- Improved Modeling
- **Reliability of Flood Protection**
- Dynamic and Nonstationary Processes

Reliability of Flood Protection

- **Modeling Plant Response to Flooding Events (INL)**
  - ***Completed. NUREG/CR report in publishing***
- **Effects of Environmental Factors on Manual Actions for Flood Protection and Mitigation at Nuclear Power Plants (PNNL)**
  - ***Completed. NUREG/CR report in publication process***
- **Critical Review of the State of Practice in Probabilistic Risk Assessment for Dams (ORNL, UMD)**
  - ***Completed. ORNL report available at*** https://www.osti.gov/biblio/1592163-current-state-practice-dam-safety-risk-assessment
- **Performance of Flood Penetration Seals at NPPs (Fire Risk Management, Inc.)**
  - ***Completed. NUREG report in publication process***
- **Flood Barrier Testing Strategies (INL/ISU)**
  - *In Progress. Public workshop to be held March 12 - 13*

Phase 1 Technical Basis Projects

Leverage Available Flood Information

PFHA Modeling Frameworks

Improved Modeling

Reliability of Flood Protection

Dynamic and Nonstationary Processes

Dynamic and Nonstationary Processes

- **Regional Climate Change Projections: Potential Impacts to Nuclear Facilities (PNNL)**
  - ***Year 1 (CONUS) – Complete***
    - ***published as a PNNL report (PNNL-24868)***
  - ***Year 2 (Southeast US) - Complete***
    - ***published as a PNNL report (PNNL-26226)***
  - ***Year 3 (Midwest US) – Complete***
    - ***published as a PNNL report (PNNL-27452 Rev1)***
  - ***Year 4 (Northeast US) – Complete***
    - ***published as a PNNL report (PNNL-29079)***

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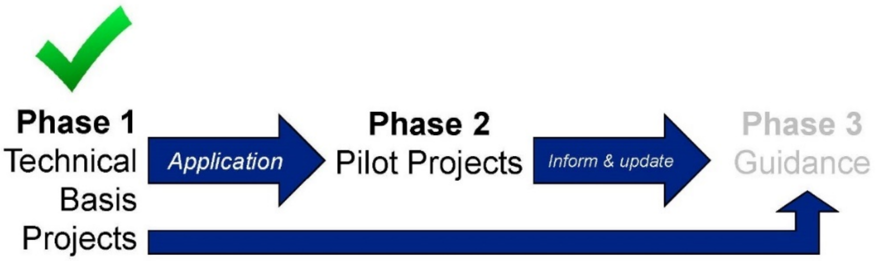
Future Directions for PFHA



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Phase 1
Technical Basis Projects

Application

Phase 2
Pilot Projects

Inform & update

Phase 3
Guidance

U.S.NRC
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Future Directions for PFHA

✓

Phase 1
Technical Basis Projects

Application

Phase 2
Pilot Projects

Inform & update

Phase 3
Guidance

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**

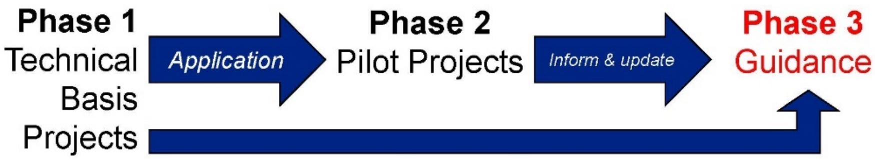
LIP Flooding PFHA Pilot (PNNL)

- Pilot study to inform development of guidance for probabilistic assessment of flooding hazards at NPPs due to local intense precipitation events

Riverine PFHA Pilot (USACE/HEC)

Coastal Flooding Pilot PFHA Pilot (USACE/ERDC)

Phase 3 (FY22-?)



- Revise guidance documents based on pilots
- Stakeholder & Public Interactions
- Finalize guidance

Questions?
Contact: joseph.kanney@nrc.gov

3.1.3 Presentation 1A-3: Overview of recent activities at USACE-RMC

Speaker: Haden Smith, U.S. Army Corps of Engineers, Risk Management Center (USACE/RMC)

3.1.3.1 Presentation (ADAMS Accession No. ML20080M180)

Overview of recent activities at USACE-RMC

Haden Smith, P.E.

Outline

- New Software, Tools, & Methods
- Updates to Policy/Guidance
- Upcoming Training

New Software, Tools, & Methods

- Web-based Rainfall-Runoff Frequency Tool (RRFT)
- Bayesian Estimation & Fitting software (RMC-BestFit)
- Reservoir Frequency Analysis Software (RMC-RFA)
- Consequent estimation with HEC-LifeSim 2.0
- Comprehensive risk analysis software (RMC-TotalRisk)

Web-based Rainfall-Runoff Frequency Tool (RRFT)

General

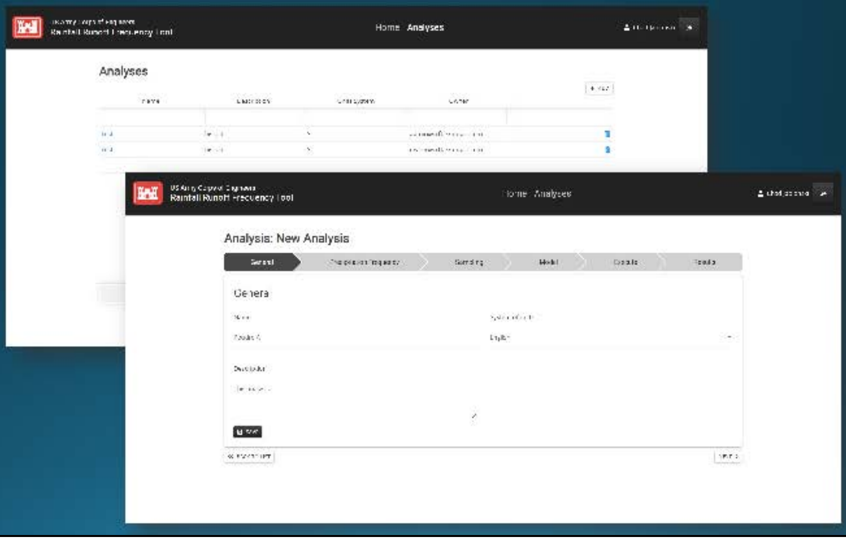
Precipitation Frequency

Sampling

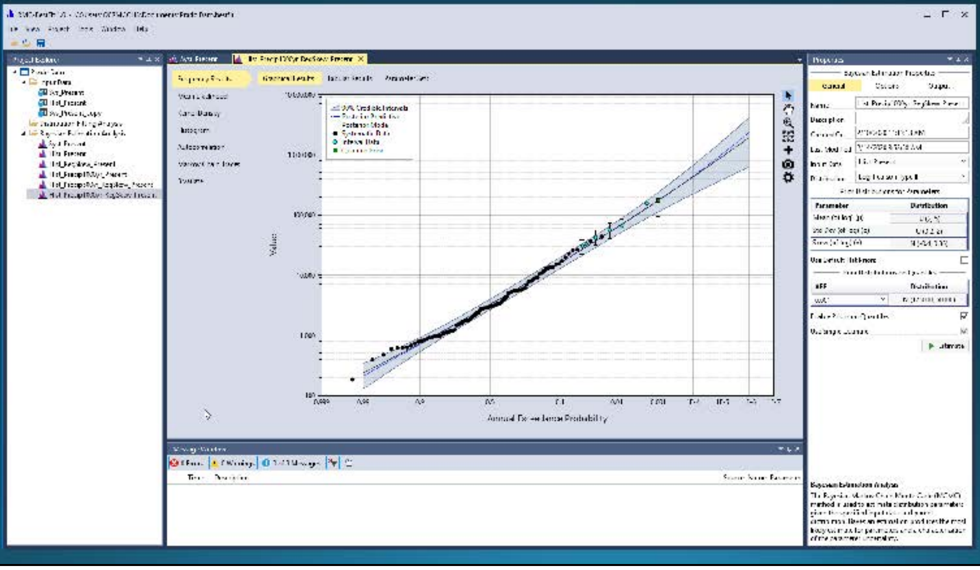
Model

Execute

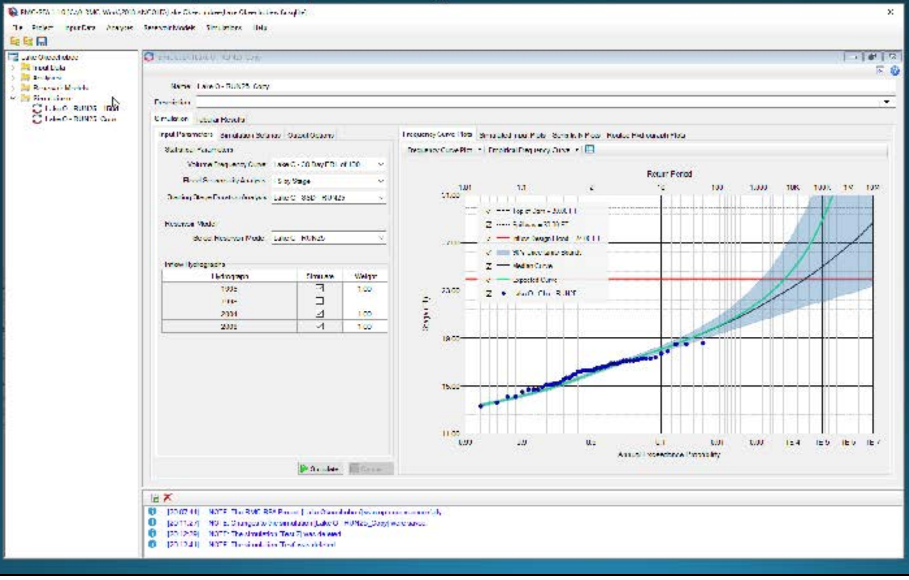
Results

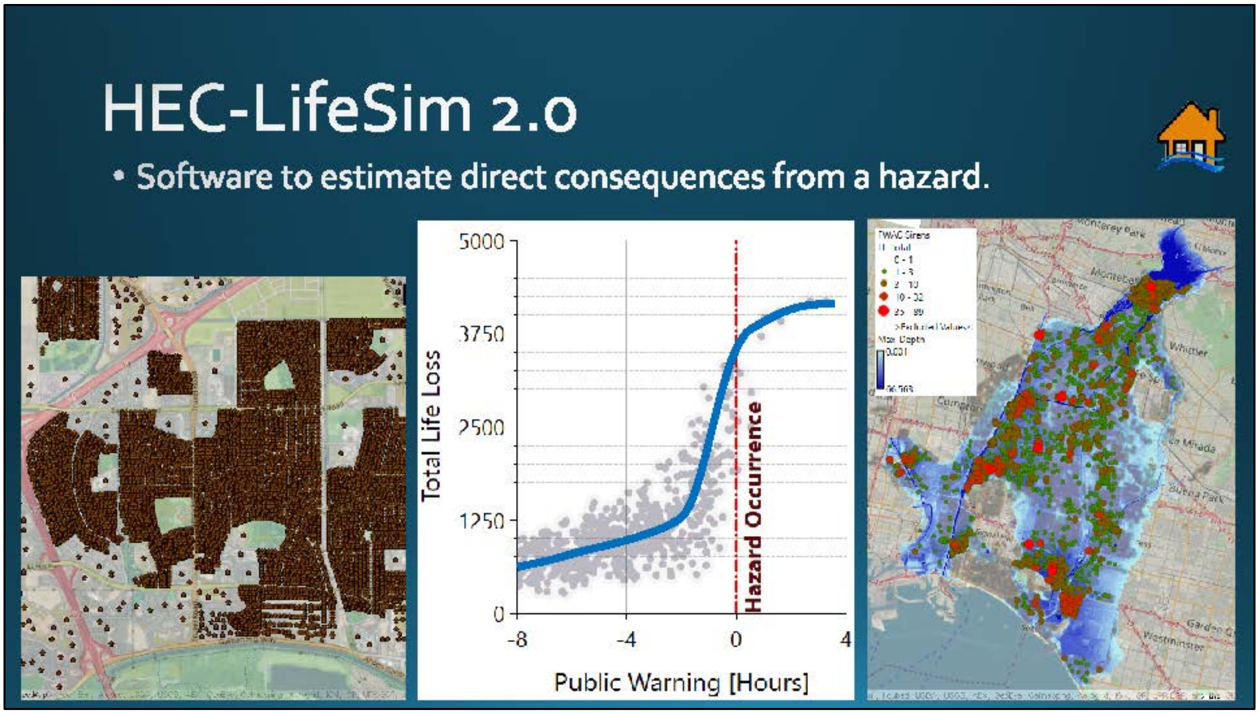


Bayesian Estimation & Fitting software (RMC-BestFit)



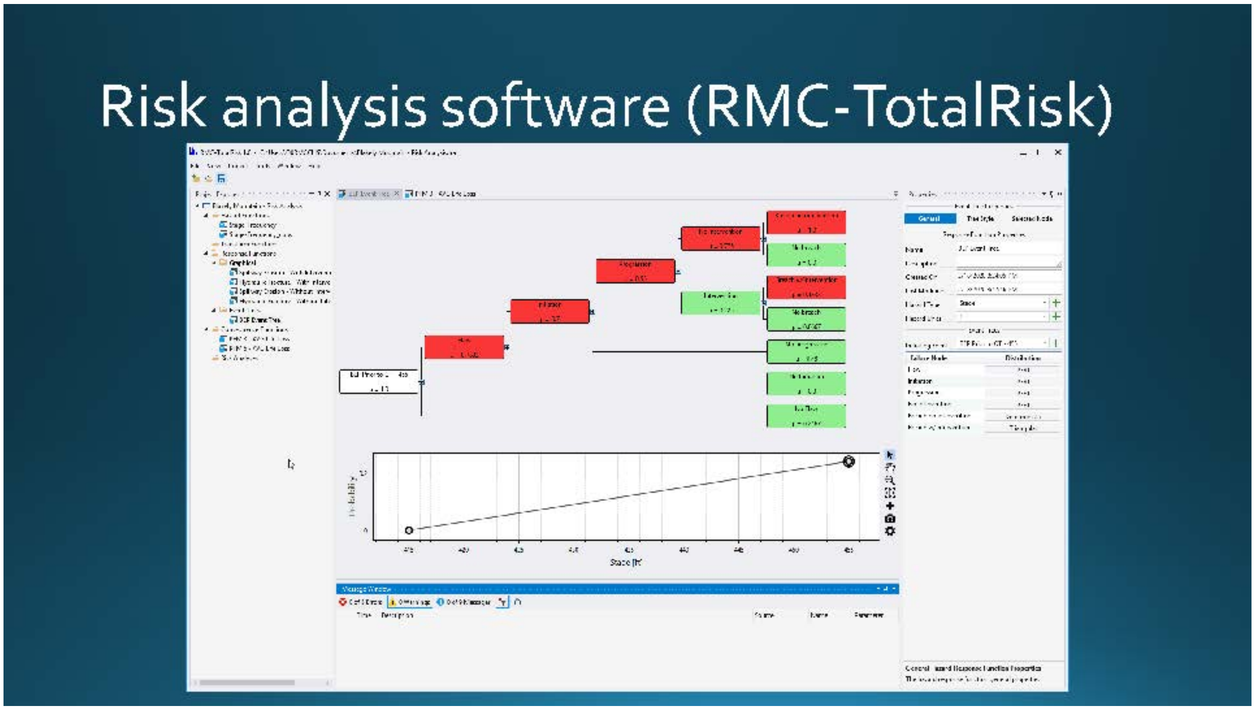
Reservoir Frequency Analysis Software (RMC-RFA)





HEC-LifeSim 2.0

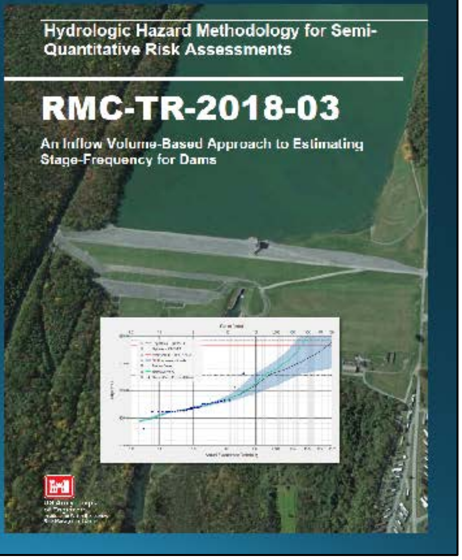
- Software to estimate direct consequences from a hazard.



Risk analysis software (RMC-TotalRisk)

Updates to Policy/Guidance

- Revision to ER 1110-8-2(FR) Inflow Design Floods for Dams and Reservoirs
- Methodology document for performing regional precipitation frequency analysis with examples (extrapolation beyond NOAA 14 and regional studies)
- Updates to our SQRA methodology



Hydrologic Hazard Methodology for Semi-Quantitative Risk Assessments

RMC-TR-2018-03

An Inflow Volume-Based Approach to Estimating Stage-Frequency for Dams

Upcoming Training

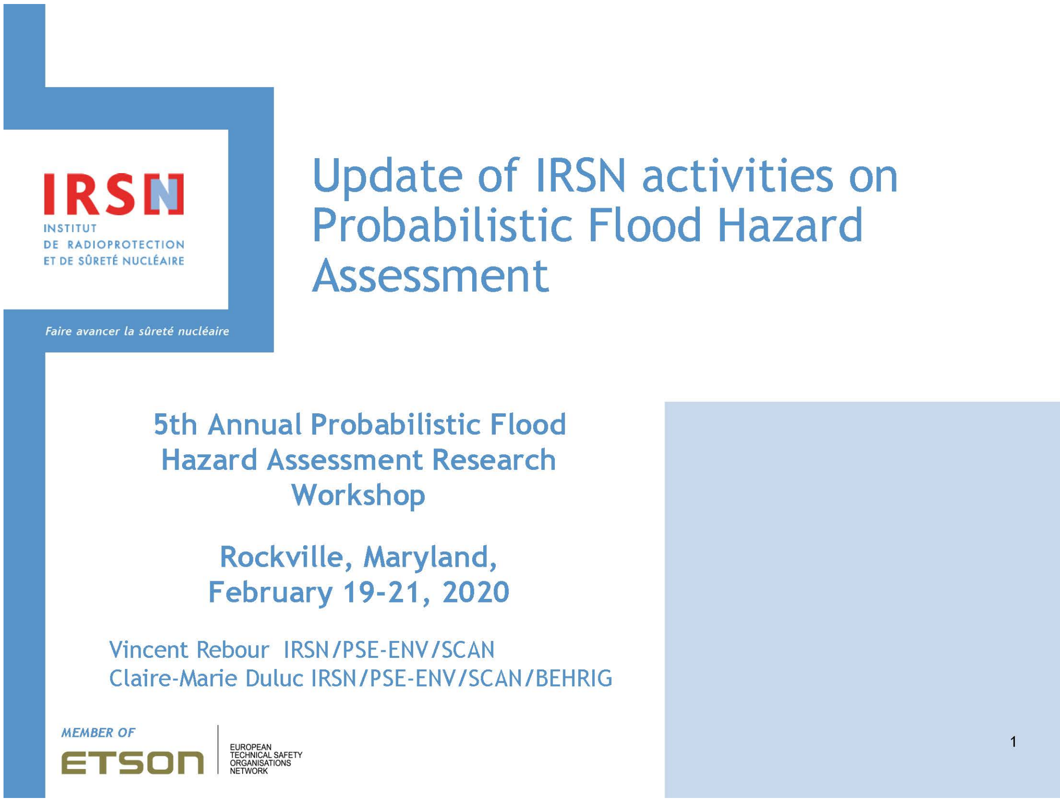
- RMC-RFA short course at USSD - March 2020
- Seminal Papers In Extreme Flood Hydrology (12 papers)
- Paleoflood assessment short course at Harpers Ferry in August 2020.
- RMC-RFA online videos
- Bulletin 17C online videos

https://www.iwrlibrary.us/#/series/RMC-RFA%20Training

3.1.4 Presentation 1A-4: IRSN External Flooding Research Program Overview

Speaker: Vincent Rebour, Institut de radioprotection et de sûreté nucléaire (France Radioprotection and Nuclear Safety Institute, IRSN)

3.1.4.1 Presentation (ADAMS Accession No. ML20080M181)



IRSN
INSTITUT
DE RADIOPROTECTION
ET DE SÛRETÉ NUCLÉAIRE

Faire avancer la sûreté nucléaire

Update of IRSN activities on Probabilistic Flood Hazard Assessment

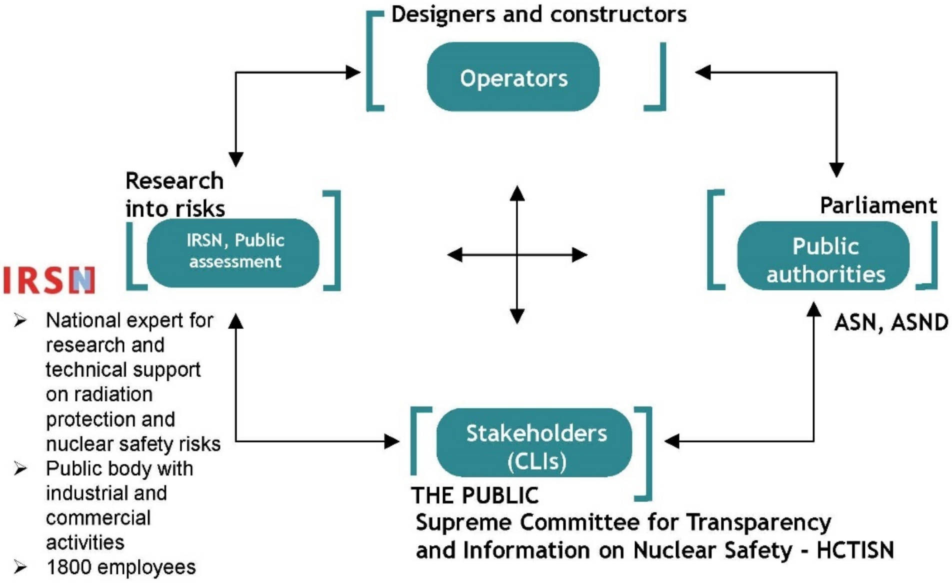
5th Annual Probabilistic Flood Hazard Assessment Research Workshop

Rockville, Maryland,
February 19-21, 2020

Vincent Rebour IRSN/PSE-ENV/SCAN
Claire-Marie Duluc IRSN/PSE-ENV/SCAN/BEHRIG

MEMBER OF
ETSON
EUROPEAN TECHNICAL SAFETY ORGANISATIONS NETWORK

Institutional environment



Designers and constructors

Operators

Research into risks

IRSN, Public assessment

Parliament

Public authorities

ASN, ASND

IRSN

- National expert for research and technical support on radiation protection and nuclear safety risks
- Public body with industrial and commercial activities
- 1800 employees

Stakeholders (CLIs)

THE PUBLIC

Supreme Committee for Transparency and Information on Nuclear Safety - HCTISN

Main recent activities

- Completion of the **reviews** of EdF first implementation of the new guidelines on flooding risk assessment and EDF first PSA studies (4th Periodic Safety Review of 900 MWe NPP)

- **Research**
  - Extension of usable data (historical data from archives)
  - Comparison of USACE and IRSN statistical approaches on extreme sea levels (to be completed)
  - Improvement of modeling capacities (IMC): implementation of meta-models to cope with time consuming calculations
  - IMC: uncertainty propagation in flood routing, methods to address dependency between input parameters (tbc)
  - IMC: aggregation of contributions of flooding phenomena to define a hazard curve at a point of interest (coincidences)

Main recent activities

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  - **IMC: aggregation of contributions of flooding phenomena to define a hazard curve at a point of interest (coincidences)**

Extend usable data (1)

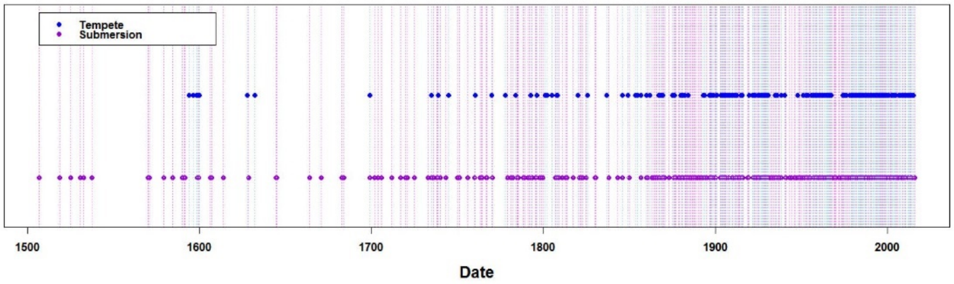
- **Working Group** (WG) « **Historic Storms and Marine Floodings** » created in 2016
  - Mutualize information on historic storms and marine floodings on the french Atlantic coast
  - Perform a multidisciplinary expertise of historical archives (engineers, researchers, statisticians, historians …)
  - Developp a DataBase on Historic Storms and Marine Flooding
  - Current members

IRSN INSTITUT DE RADIOPROTECTION ET DE SÛRETÉ NUCLÉAIRE
Université Populaire du Littoral Charentais 17
SHOM L'océan en référence
ARTELIA
brgm Géosciences pour une Terre durable
Cerema
EDF R&D

Extend usable data (2)

Content of the DB (January 2020): 813 identified events, from 16th century to today.
- 565 Marine Flooding: events where flooding is mentioned
- 248 Storms: events where no indication of flooding is given

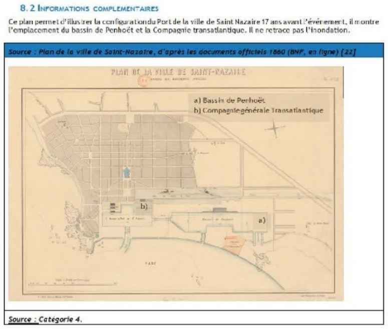
Timeline of storm and flooding events



Extend usable data (3)

Content of the DB (January 2020) : 3 storm sheets
1. Meteorological Synthesis - Retranscription without any interpretation
2. Flooding description for each locality – idem
3. Reconstructed water levels for each locality using flooding description + complementary documents
   Including hypotheses taken during the reconstruction process (interpretation hypothesis, temporal hypothesis, spatial hypothesis, verification of chart datum)

Le petit journal 7th Jan 1877: *" In Saint-Nazaire […] the whole rue Neuve was flooded. The bassin has overflowed on the docks and hangar of the transatlantic company"*



8. 2 INFORMATIONS COMPLEMENTAIRES

Ce plan permet d'illustrer la configuration du Port de la ville de Saint Nazaire 17 ans avant l'événement, il montre l'emplacement du bassin de Penhoët et la Compagnie transatlantique. Il ne retrace pas l'inondation.

Source : Plan de la ville de Saint-Nazaire, d'après les documents officiels 1860 (BNF, en ligne) [22]

Source : Catégorie 4.

Extend usable data (4)

Storm sheet

4. **Synthesis** (1st January 1877 event)

Locality	Tide Gauge Data	Type	Total Water Level [m Fr. Chart Datum]	Surge [m]	
				Instant. surge	Skew surge
Le Havre		○	-nc-	-nc-	-nc-
Cherbourg	yes	△	7.16 M	0.95	0.75
Saint Servan	yes	△	12.97 M	-nc-	0.94
Brest	yes	△	8.02	0.75	0.75
Lorient		■	6.20 Δ	-nc-	0.87
Gavres		●	-nc-	-nc-	-nc-
Vannes		●	-nc-	-nc-	-nc-
Saint-Nazaire	yes	▲	7.23	1.19	1.19
Fort-Boyard	yes	△	6.97	0.85	0.94
Rochefort	yes	△	8.19 M	-nc-	-nc-
Socoa	yes	△	4.45 M	-nc-	0.20

○ Affected locality
No reconstructed water level

△ Affected locality
Water level reconstructed using quantitative data

□ Affected locality
Water level reconstructed using qualitative data

● Affected locality – Flooding confirmed
No reconstructed water level

▲ Affected locality – Flooding confirmed
Water level reconstructed using quantitative data

■ Affected locality – Flooding confirmed
Water level reconstructed using qualitative data

Perspectives

- **Regular analysis of new events**
- **Numerical modeling of historical events**

Improvement of modeling capacities (1)

Aggregation of flooding phenomena

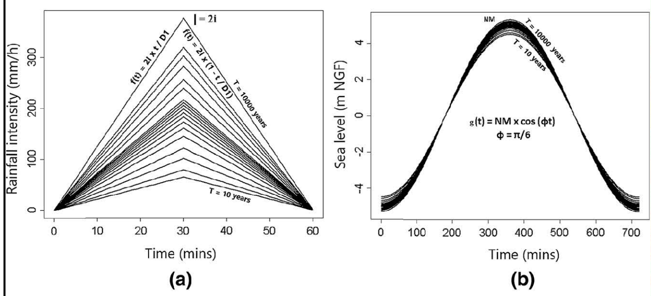
Ben Daoued PhD *"Modeling coincidence and dependence of flood hazard phenomena in a Probabilistic Flood Hazard Assessment (PFHA)* ". Development of a method to deal with coincidence of two phenomena.

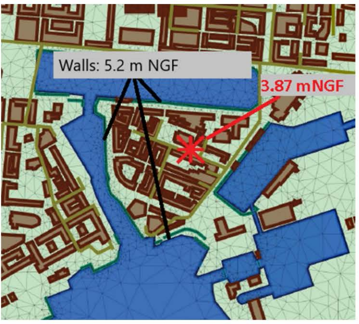
- Coincidence: the chance of occurrence of two phenomena (A and B) at the same time or with an offset time (coincidence does not imply any dependence between A and B)

- The non-coincidence (separate occurrences) case serves as a benchmark background

Improvement of modeling capacities (2)

- Aggregation to get a hazard curve at a point of interest (water levels exceedence frenquencies)
- *Le Havre Case study Local precipitation (LP) and Marine Flooding (MF) in an urban area (with sewerage network)*





Intensity f(duration) for LP (a) and MF (b) for 10 to 10 000 y return periods

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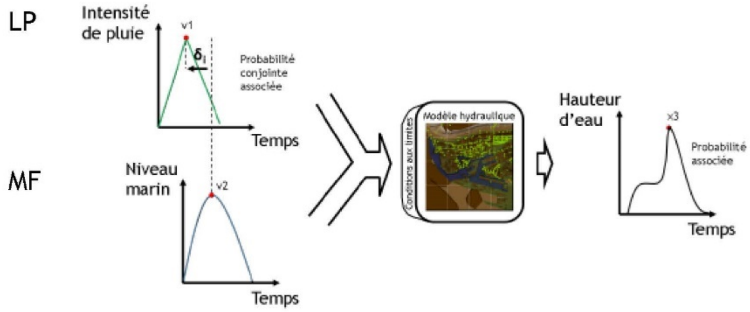
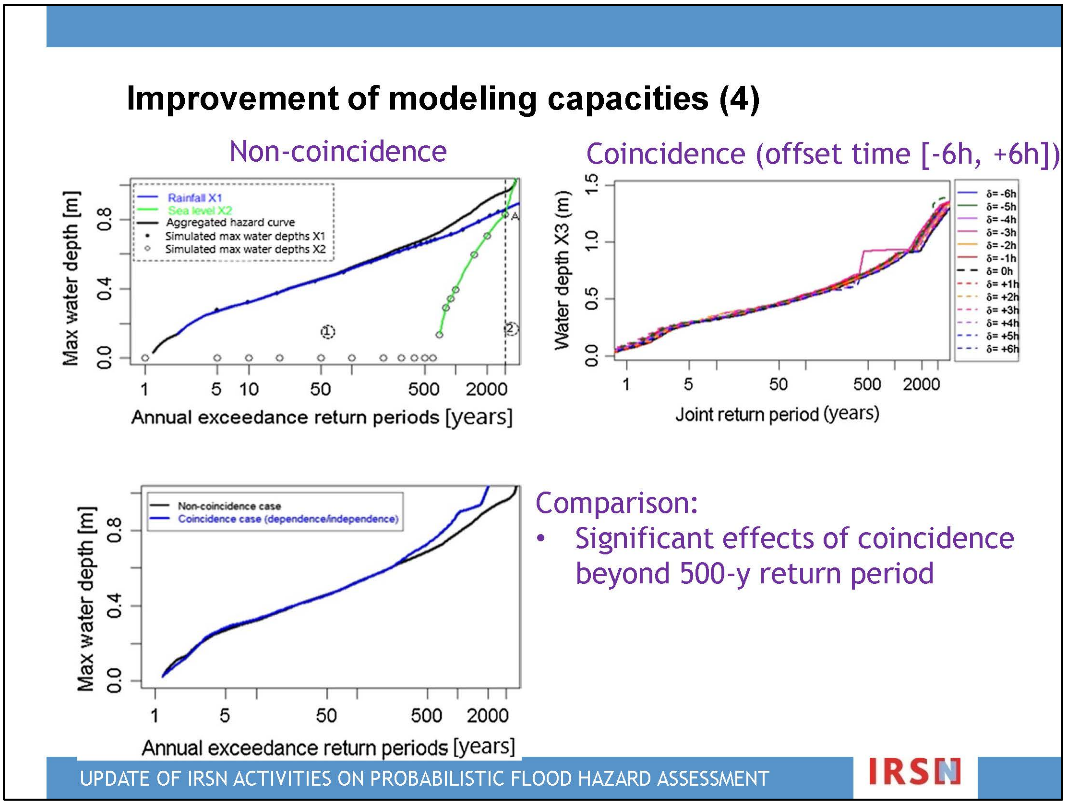
Improvement of modeling capacities (3)

- Aggregation throught hydraulic modelling



Provide a large set of max water level associated with input parameters probabilities (LP, MF and delta)



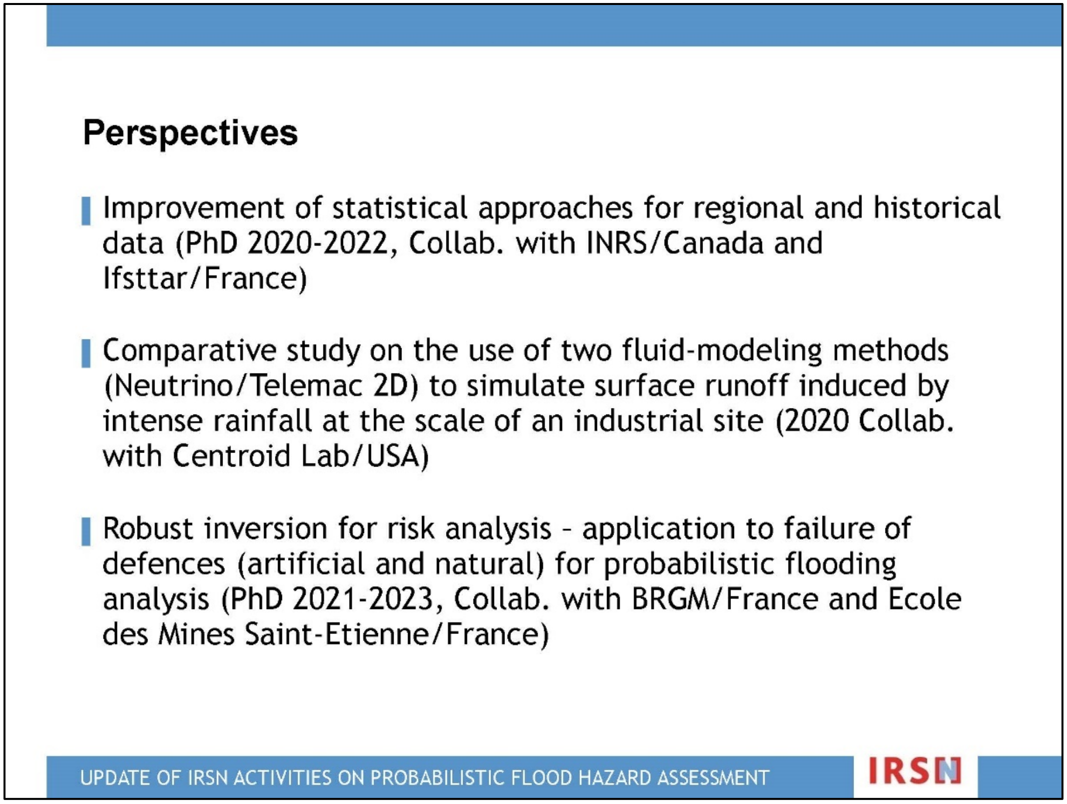
Improvement of modeling capacities (4)

Non-coincidence

Coincidence (offset time [-6h, +6h])

Comparison:

- Significant effects of coincidence beyond 500-y return period



Perspectives

- Improvement of statistical approaches for regional and historical data (PhD 2020-2022, Collab. with INRS/Canada and Ifsttar/France)

- Comparative study on the use of two fluid-modeling methods (Neutrino/Telemac 2D) to simulate surface runoff induced by intense rainfall at the scale of an industrial site (2020 Collab. with Centroid Lab/USA)

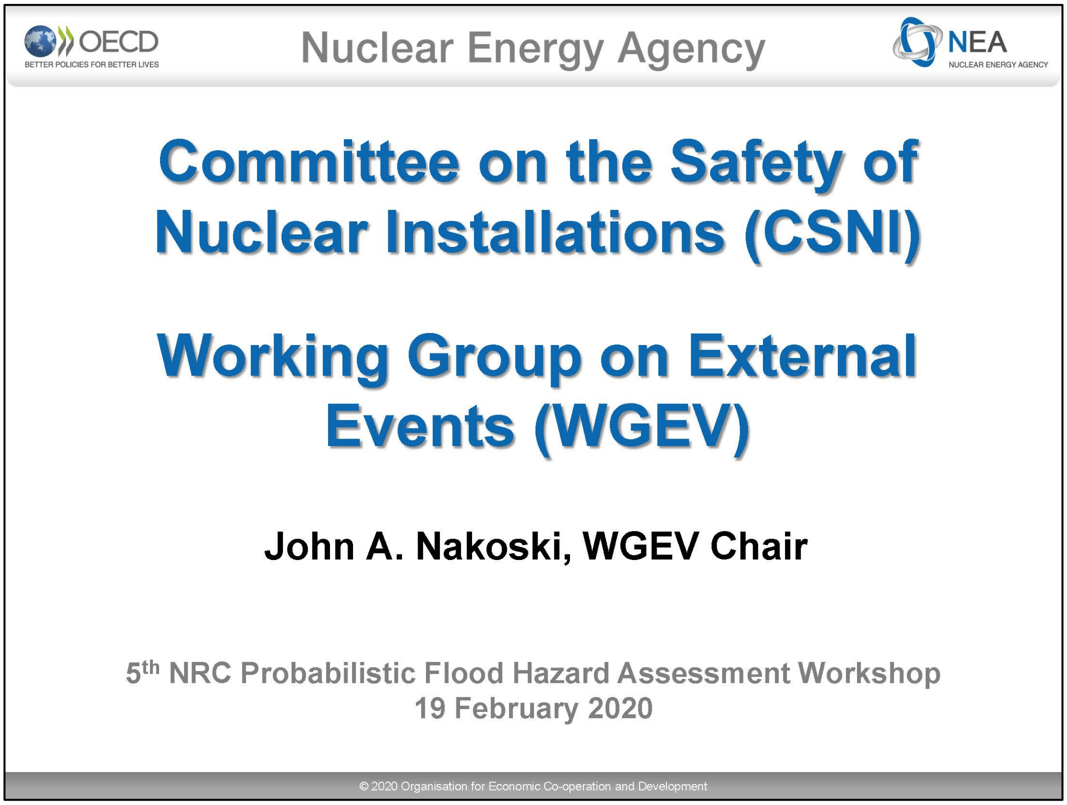
- Robust inversion for risk analysis – application to failure of defences (artificial and natural) for probabilistic flooding analysis (PhD 2021-2023, Collab. with BRGM/France and Ecole des Mines Saint-Etienne/France)

Thanks for your attention

3.1.5 Presentation 1A-4: Nuclear Energy Agency: Committee on the Safety of Nuclear Installations (CSNI): Working Group on External Events (WGEV) Flooding Overview

Speaker: John Nakoski (WGEV Chair), NRC Office of Nuclear Regulatory Research

3.1.5.1 Presentation (ADAMS Accession No. ML20080M183)



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Committee on the Safety of Nuclear Installations (CSNI)

Working Group on External Events (WGEV)

John A. Nakoski, WGEV Chair

5th NRC Probabilistic Flood Hazard Assessment Workshop
19 February 2020

WGEV Administration

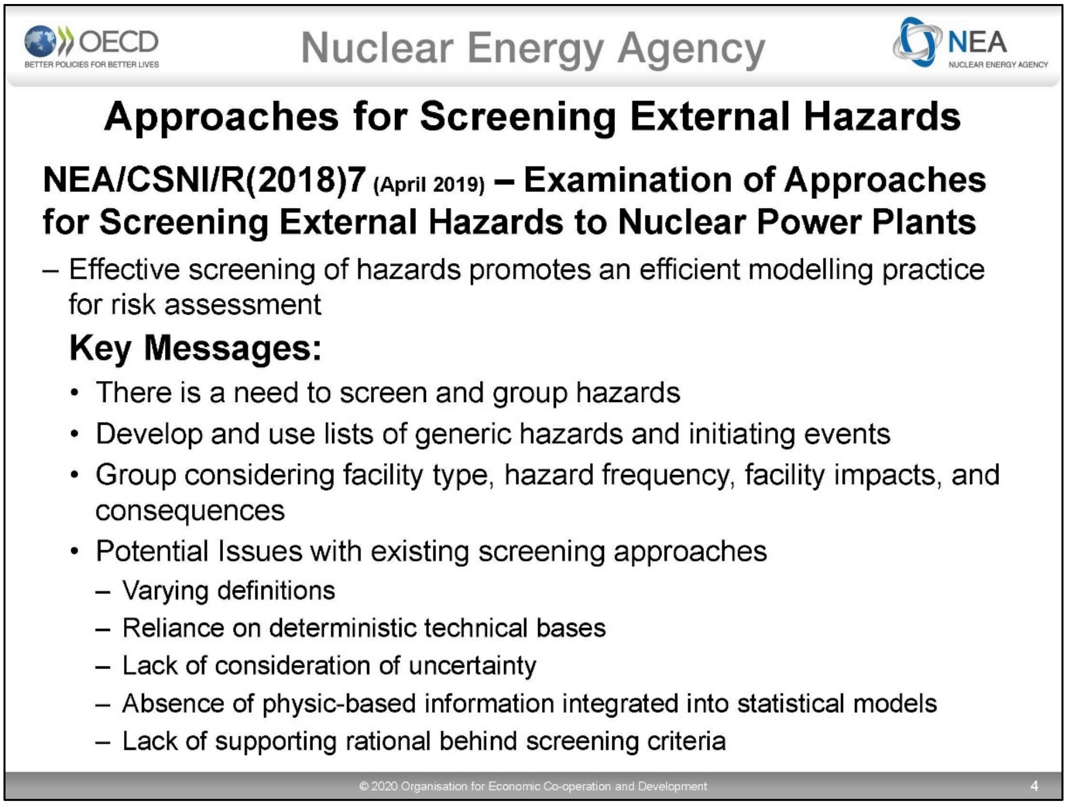
- **WGEV Chair:** John A. Nakoski (NRC, USA)
- **WGEV Bureau:** Vincent Rebour (IRSN, France), Gernot Thuma (GRS, Germany), ShiZhong Lei (CNSC, Canada), Min Kyu Kim (KAERI, South Korea)
- **WGEV Participants from:**
  - Belgium (BelV), Canada (CNSC), Czech Republic (SUJB), Finland (STUK), France (IRSN, 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**

Severe Weather and Storm Surge

Proceedings published – NEA/CSNI/R(2017)13 (16 April 2018)

Key Messages:

- There is a need to improve reliability of information and understanding of boundary conditions for hazard analysis
- Data is sparse
  - Use simulation (needs to be validated)
  - Other data sources to extend available data
- Paleodata and historical data is important, but challenging to use
- Uncertainties need to be better understood and quantified
  - Be aware of the uncertainties and take them into account
- Fragility information for infrastructure is a key knowledge gap
  - Interface between insights gained from hazards assessment and application of those insights in a PRA
- Climate change is introducing new challenges that require new approaches and models



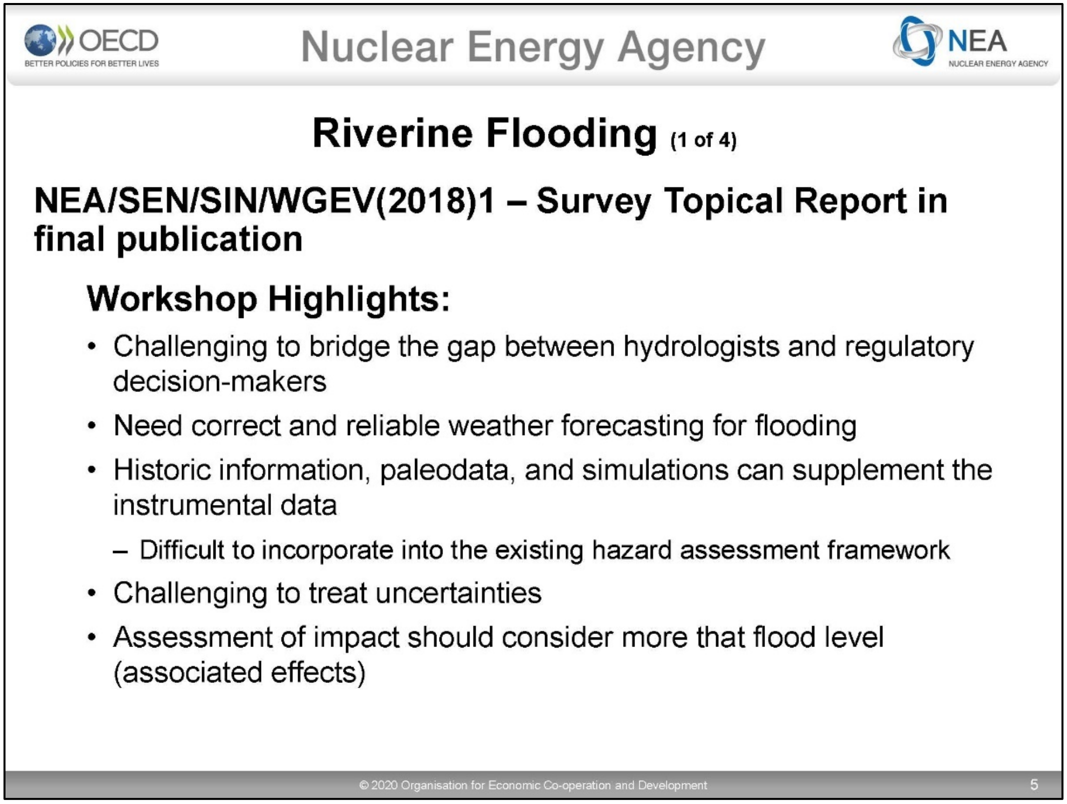
Approaches for Screening External Hazards

NEA/CSNI/R(2018)7 (April 2019) – Examination of Approaches for Screening External Hazards to Nuclear Power Plants

– Effective screening of hazards promotes an efficient modelling practice for risk assessment

Key Messages:

- There is a need to screen and group hazards
- Develop and use lists of generic hazards and initiating events
- Group considering facility type, hazard frequency, facility impacts, and consequences
- Potential Issues with existing screening approaches
  - Varying definitions
  - Reliance on deterministic technical bases
  - Lack of consideration of uncertainty
  - Absence of physic-based information integrated into statistical models
  - Lack of supporting rational behind screening criteria



Riverine Flooding (1 of 4)

NEA/SEN/SIN/WGEV(2018)1 – Survey Topical Report in final publication

Workshop Highlights:

- Challenging to bridge the gap between hydrologists and regulatory decision-makers
- Need correct and reliable weather forecasting for flooding
- Historic information, paleodata, and simulations can supplement the instrumental data
  - Difficult to incorporate into the existing hazard assessment framework
- Challenging to treat uncertainties
- Assessment of impact should consider more that flood level (associated effects)

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Riverine Flooding (2 of 4)

Proceedings in publication – NEA/SEN/SIN/WGEV(2018)13

Workshop Highlights:

- Need rigorous understanding for fragility of facilities to strengthen protective measures technical bases
- Nature of flooding hazards and associated plant impacts challenge PSA methods
- Time consuming calculations, characterization of probability distributions, and dependent input parameters challenge PFHA methodology
- Need to balance consideration of the spectrum of associated effects from flooding and the information necessary to support decision-making
- The concept of a “dry site” needs to be reconsidered

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Riverine Flooding (3 of 4)

Proceedings in publication – NEA/SEN/SIN/WGEV(2018)13

Workshop Conclusions and Recommendations:

- Share information between nuclear and non-nuclear organizations as well as with neighboring countries
- Augment temporally and spatially sparse historical data with simulations and other information
- Further work is needed to understand how metrics, such as a selected value for annual exceedance frequency, can be used in regulatory decision making

Riverine Flooding (4 of 4)

Proceedings in publication – NEA/SEN/SIN/WGEV(2018)13

Workshop Conclusions and Recommendations:

- Uncertainties with data and modelling need to be better understood and quantified
  - Decision makers should be aware of the uncertainties and take them appropriately into account
- Develop new approaches and models to identify and address the challenges introduced by climate change
- The workshop demonstrated that:
  - It is important for the nuclear and meteorological communities to work together
  - Subject matter expert co-operation, including non-nuclear experts, is important as well as regional co-operation to share experience and data

---

Ongoing Activities (1 of 2)

- **Concepts and Definitions for Protective Measures in Response to External Flooding Hazards**
  - Survey responses provided to WGEV writing group (January 2019)
  - Guidance for writing group and assessment of survey responses (March 2019)
  - Preparation of initial draft report - June 2019
  - Final report – June 2020
- **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 – December 2020
  - For more information contact Curtis Smith (Curtis.Smith@inl.gov) or Vincent Rebour (Vincent.Rebour@irsn.fr)

Ongoing Activities (2 of 2)

- **High winds and tornadoes**
  - Survey responses – February 2020
  - Preparation of initial draft report – June 2020
  - Final report – December 2020
  - Workshop – September 2021
- **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

Potential Future Activities

- **Improving understanding and application of uncertainty in hazards assessment and decision-making –** under development
- **Topical discussions – next WGEV meeting topics**
  - Space weather
  - Improving data sources for hazards assessment


Nuclear Energy Agency

Thank you for your attention!

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12

3.2 Day 1: Session 1B – Climate

Session Chair: Elena Yegorova, NRC/RES/DRA

3.2.1 Presentation 1B-1: Regional Climate Change Projections: Potential Impacts to Nuclear Facilities

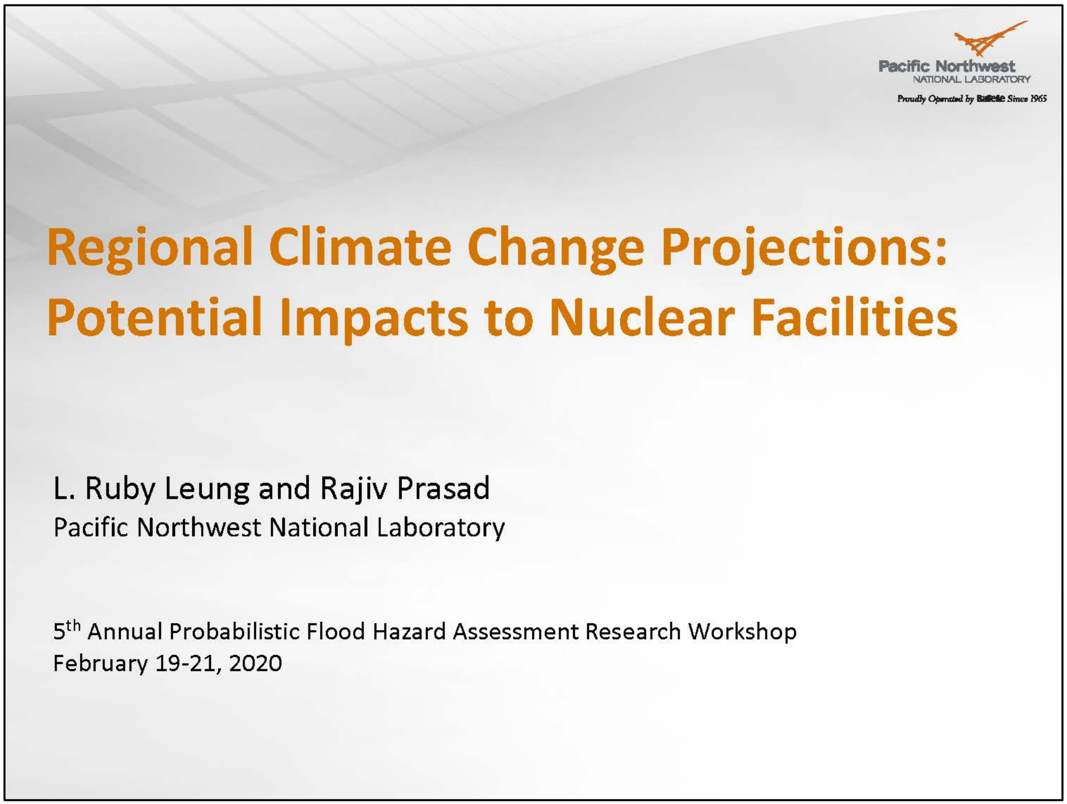
Speakers: L. Ruby Leung and Rajiv Prasad, Pacific Northwest National Laboratory (PNNL)

3.2.1.1 Abstract

As part of the U.S. Nuclear Regulatory Commission’s (NRC) Probabilistic Flood Hazard Assessment (PFHA) research plan to develop regulatory tools and guidance to support and enhance the NRC’s capacity to perform thorough and efficient reviews of license applications and license amendment requests, this study summarizes the current state of climate research and results regarding hydrometeorological phenomena that are of interest in safety assessments and environmental impact assessments for commercial nuclear power plants. This presentation will focus on region-specific scientific findings about climate change for the northeast region. Drawing primarily from the NCA reports and peer-reviewed literature, we will briefly review the observed climate, its past changes, and its projected changes, as well as 21st century hydrologic impacts in the northeast region. The northeast region exhibits long-term warming trends in all seasons in the 20th century. Warming is projected to continue in the future, with greater warming in winter and summer than spring and fall. Annual mean precipitation and extreme precipitation show a long-term increasing trend in the 20th century. Precipitation is projected to increase particularly in winter and spring while changes in summer are not significant. North Atlantic hurricanes are projected to increase in intensity, rainfall, and storm size. Projections of extratropical cyclone activity changes remain uncertain, but theory

suggests that convection associated with extratropical cyclones will become more vigorous even if extratropical cyclone activity may decrease. With warmer temperatures and more moisture, an increase in mesoscale convective system track density and intensity is projected for the mid-Atlantic/northeast region. The northeast region is a hotspot of accelerated sea-level rise in recent decades. Sea-level rise in the region is projected to be highest among cities worldwide due to weakening of the Atlantic Meridional Overturning Circulation. Combining increases in tropical cyclone intensity and sea-level rise, storm surge is projected to increase in the future but a shift of cyclone tracks towards offshore may cancel the effect of increase storm intensity, resulting in little change in storm surge in the future. As warming increases, the ratio of snow to total precipitation is declining and the center-volume date for winter-spring streamflow is shifting earlier in the year. These changes together are affecting seasonality of streamflow in the tributaries of Lake Ontario and show a marked dependence on latitude of the tributary drainage area. Recent efforts point to promising approaches towards using more spatially explicit models over the entire Lake Ontario drainage basin for streamflow simulations.

3.2.1.2 *Presentation (ADAMS Accession No. ML20080M18)*



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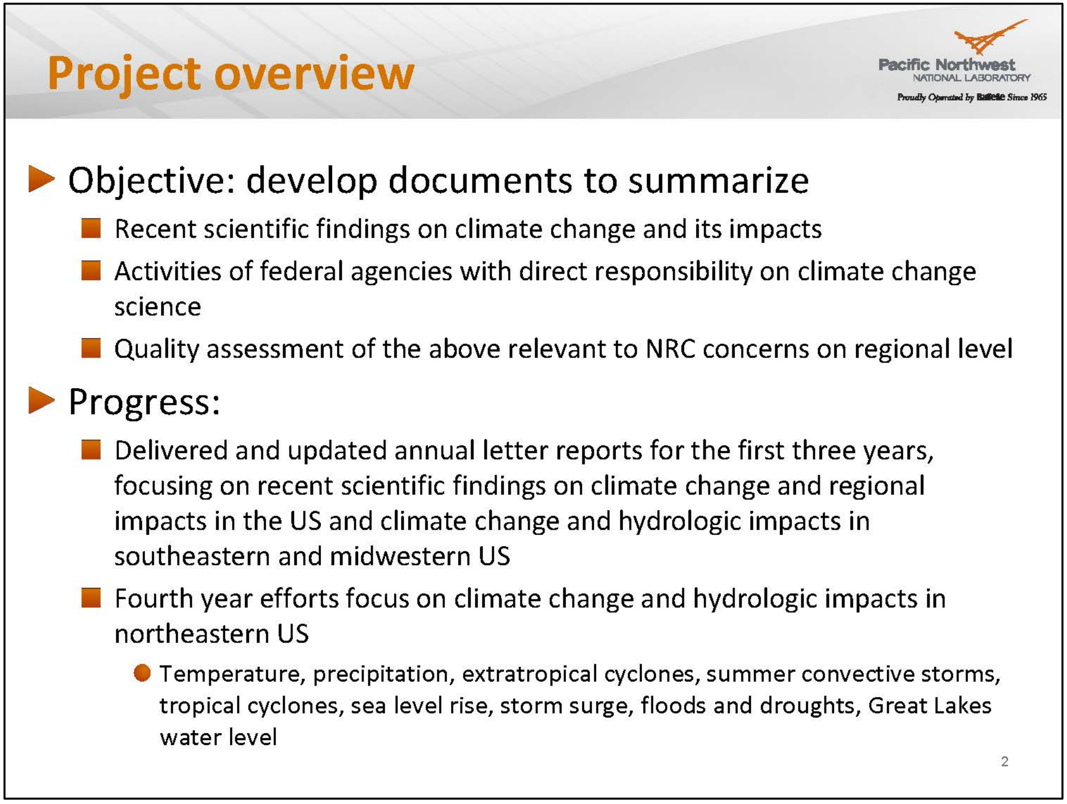
Regional Climate Change Projections: Potential Impacts to Nuclear Facilities

L. Ruby Leung and Rajiv Prasad
Pacific Northwest National Laboratory

5th Annual Probabilistic Flood Hazard Assessment Research Workshop
February 19-21, 2020



Project overview

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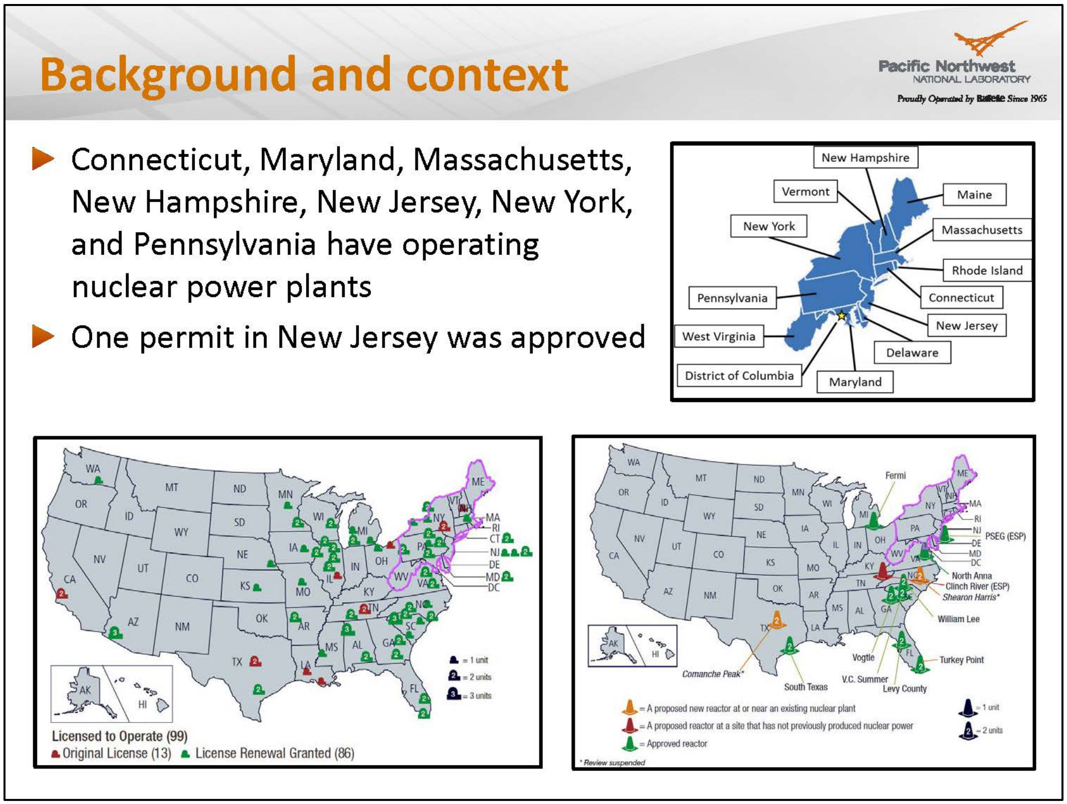
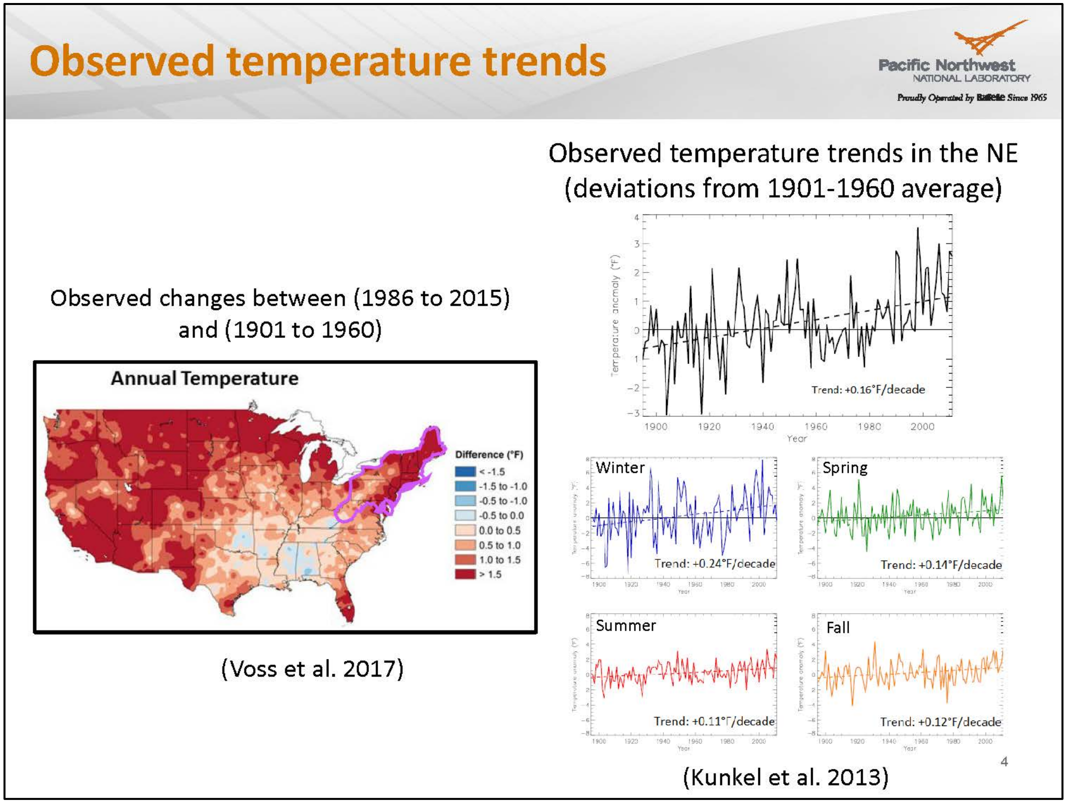
- Objective: develop documents to summarize
  - Recent scientific findings on climate change and its impacts
  - Activities of federal agencies with direct responsibility on climate change science
  - Quality assessment of the above relevant to NRC concerns on regional level
- Progress:
  - Delivered and updated annual letter reports for the first three years, focusing on recent scientific findings on climate change and regional impacts in the US and climate change and hydrologic impacts in southeastern and midwestern US
  - Fourth year efforts focus on climate change and hydrologic impacts in northeastern US
    - Temperature, precipitation, extratropical cyclones, summer convective storms, tropical cyclones, sea level rise, storm surge, floods and droughts, Great Lakes water level



Background and context

- Connecticut, Maryland, Massachusetts, New Hampshire, New Jersey, New York, and Pennsylvania have operating nuclear power plants
- One permit in New Jersey was approved



Observed temperature trends

Observed changes between (1986 to 2015) and (1901 to 1960)

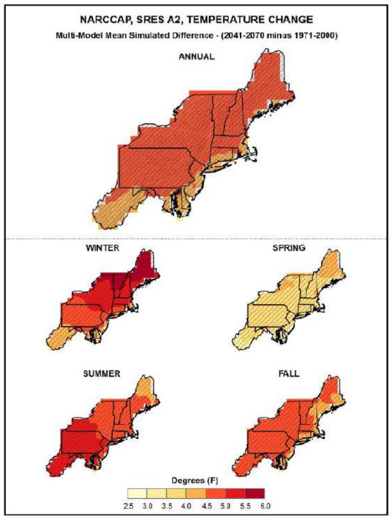
(Voss et al. 2017)

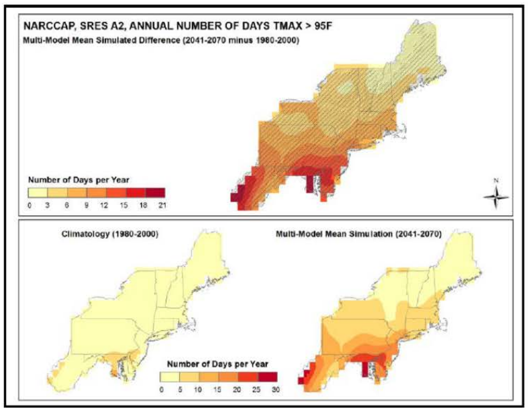
Observed temperature trends in the NE (deviations from 1901-1960 average)

(Kunkel et al. 2013)

Projected temperature trends

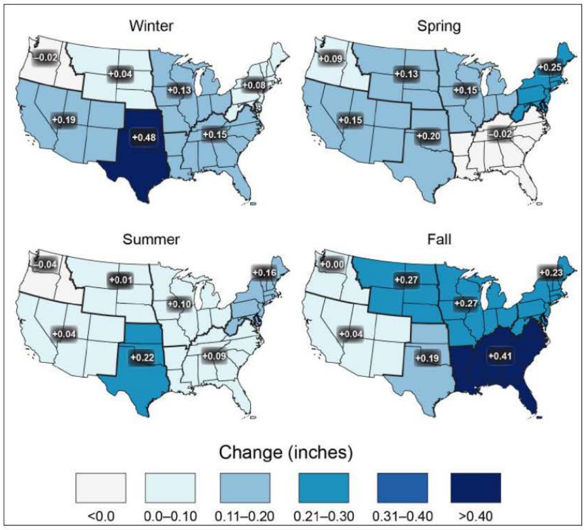
- Projected warming ranges between 3-6°F, with the largest warming in winter





Historical seasonal precipitation changes

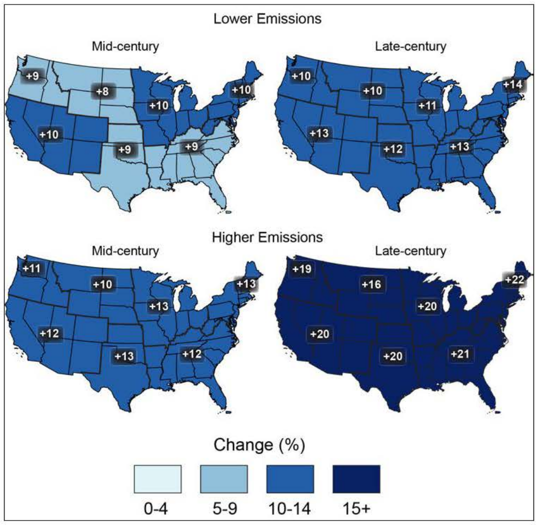
- Annual precipitation in the NE has increased by 0.39 in/decade from 1901-2015, mainly associated with spring and fall seasons
- 0.05 AEP daily precipitation has also increased, mainly in spring and fall (1948-2015)



(Easterling et al. 2017)

Projected changes in extreme precipitation

Projected change in 0.05 AEP daily precipitation using Localized Constructed Analog downscaled data

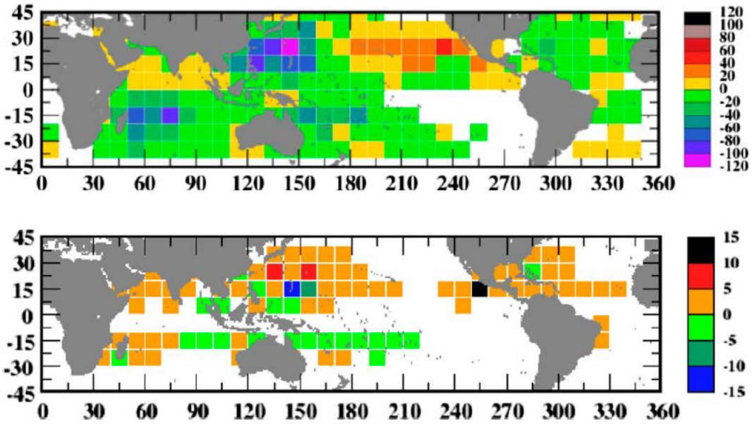


(Easterling et al. 2017)

Projected changes in tropical cyclones

Simulations by GFDL hurricane model (6 km) used to downscale the HiRAM model (50 km)

Change in occurrence (#/decade) of all storms (upper) and cat 4-5 storms between late 21st century and present based on RCP4.5



(Knutson et al. 2015 J. Clim.)

Projected changes in tropical cyclones

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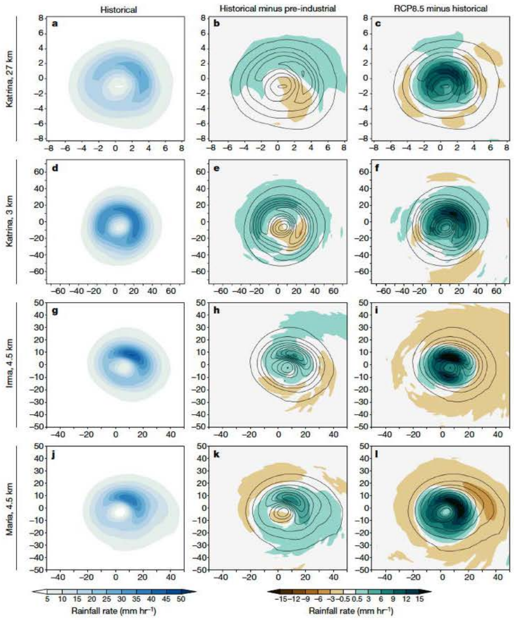
- WRF model used to simulate selected historical TCs
- Perturb boundary conditions to simulate the same storms under pre-industrial and RCP8.5 scenario
- Climate change so far did not change TC intensity, but warming in the future robustly increase TC intensity
- TC rainfall increases from pre-industrial to present and from present to future



(Patricola and Wehner 2018 Nature)

Projected changes in extratropical cyclones

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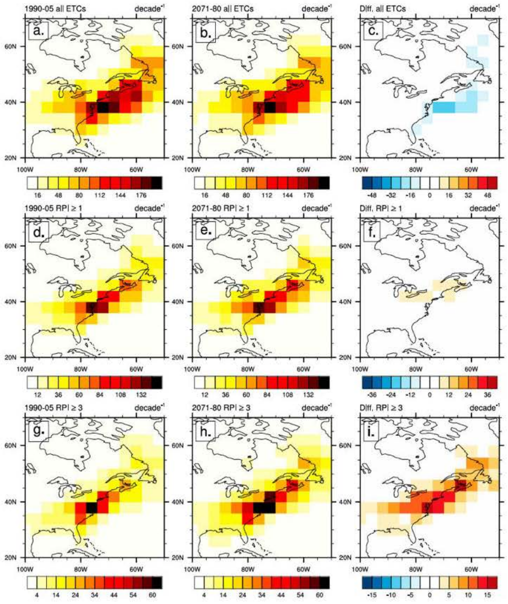
- Analyze CESM LENS simulations for RCP8.5
- Track ETCs in the simulations and define an RPI index that applies area and population weightings to the precipitation
- Track density decreases when all storms are considered
- Track density increases mainly for intense storms

End of century (2071–2080) minus present day (1990–2005)

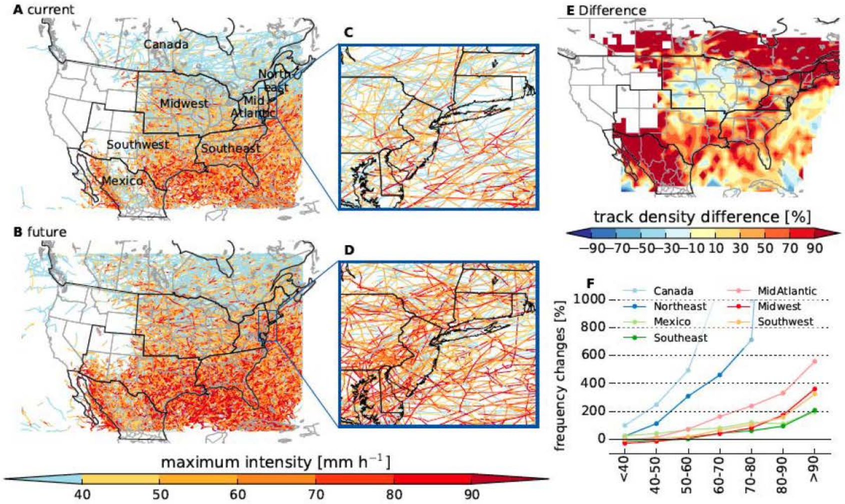


(Zarcycki 2018 GRL)

Projected changes in convective storms

Larger increase in frequency for more intense storms

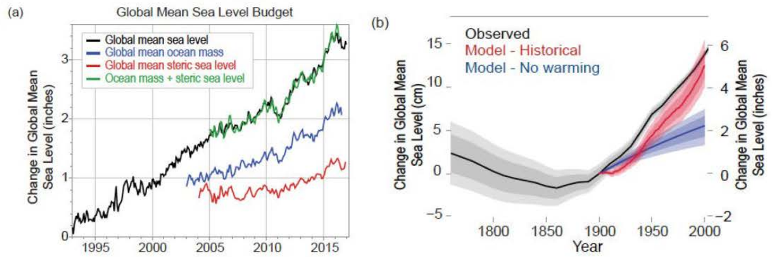
MCS tracks at the end of century (2071-2100) under RCP8.5 and present day (1976–2005)

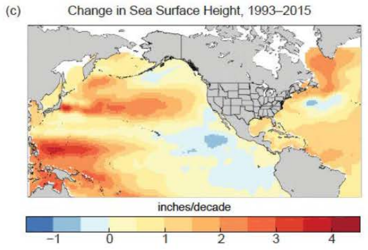


(Prein et al. 2017 Nature Clim. Change)

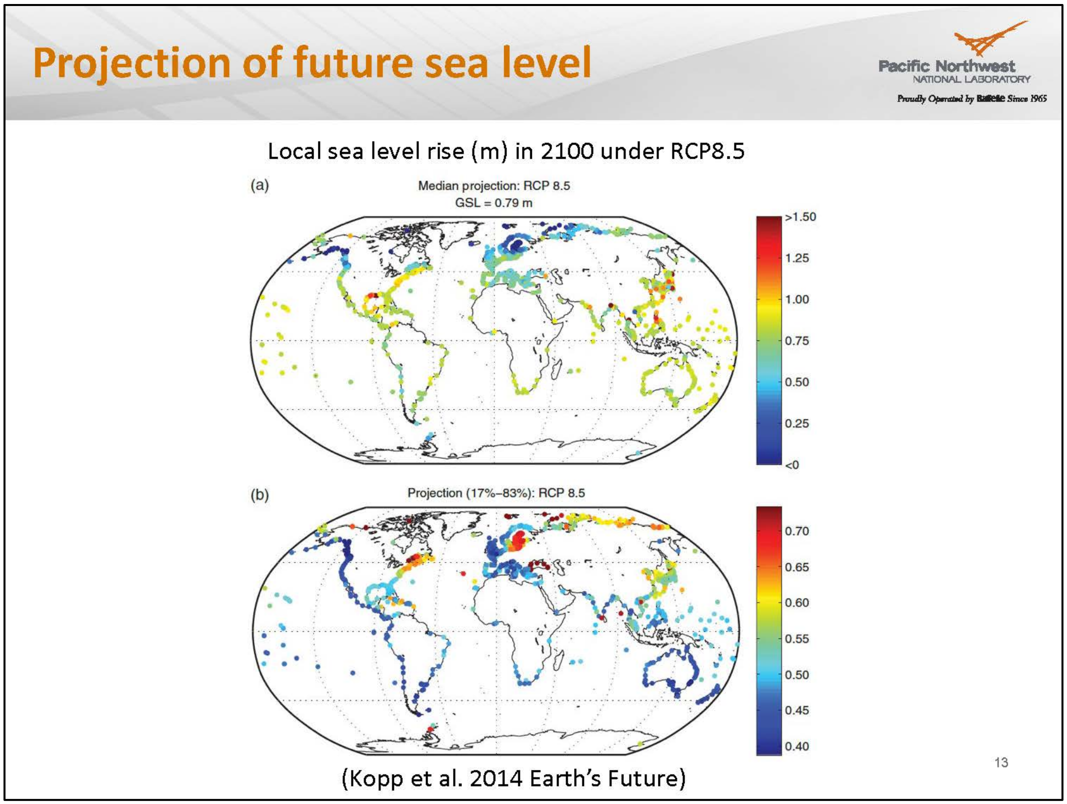
Historical changes in global and regional sea level

The higher LSL rise in northeastern U.S. has been attributed to land subsidence induced by GIA and weakening of the Gulf Stream that may be related to the weakening of the Atlantic meridional overturning circulation (AMOC)





(USGCRP 2017)



Projection of future sea level

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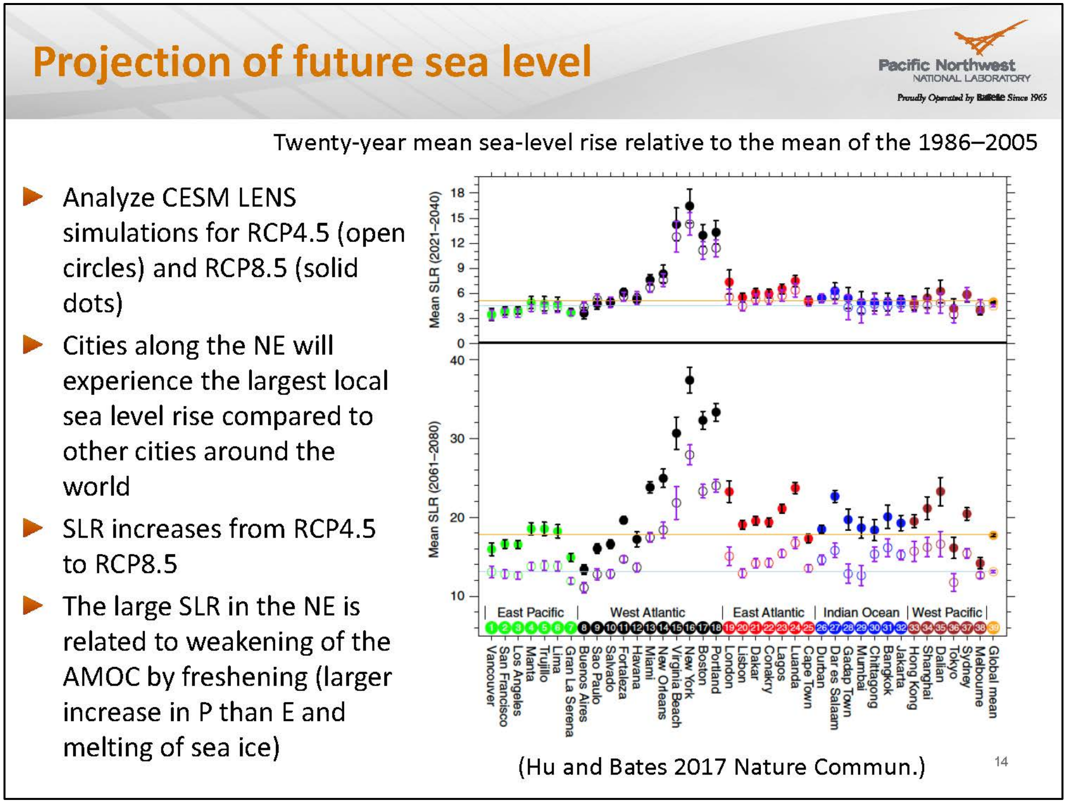
Local sea level rise (m) in 2100 under RCP8.5

(Kopp et al. 2014 Earth's Future)



Projection of future sea level

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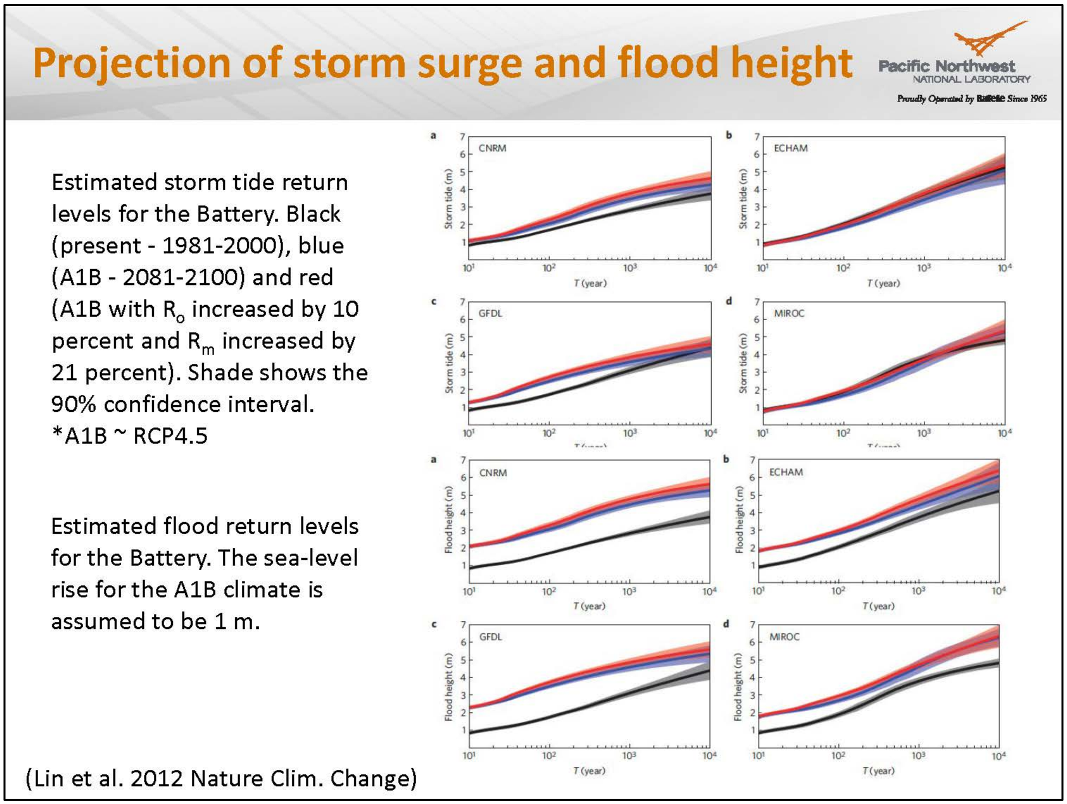
Twenty-year mean sea-level rise relative to the mean of the 1986–2005

- Analyze CESM LENS simulations for RCP4.5 (open circles) and RCP8.5 (solid dots)
- Cities along the NE will experience the largest local sea level rise compared to other cities around the world
- SLR increases from RCP4.5 to RCP8.5
- The large SLR in the NE is related to weakening of the AMOC by freshening (larger increase in P than E and melting of sea ice)

(Hu and Bates 2017 Nature Commun.)



Projection of storm surge and flood height

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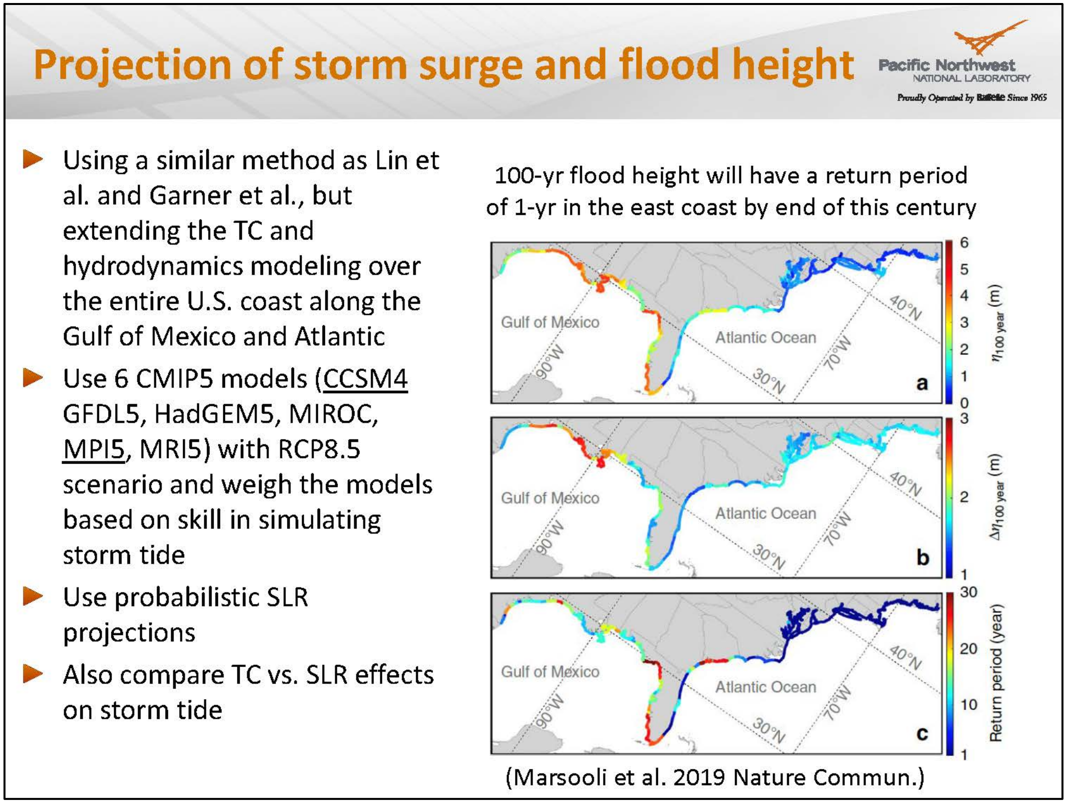
Estimated storm tide return levels for the Battery. Black (present - 1981-2000), blue (A1B - 2081-2100) and red (A1B with R_o increased by 10 percent and R_m increased by 21 percent). Shade shows the 90% confidence interval.
*A1B ~ RCP4.5

Estimated flood return levels for the Battery. The sea-level rise for the A1B climate is assumed to be 1 m.

(Lin et al. 2012 Nature Clim. Change)



Projection of storm surge and flood height

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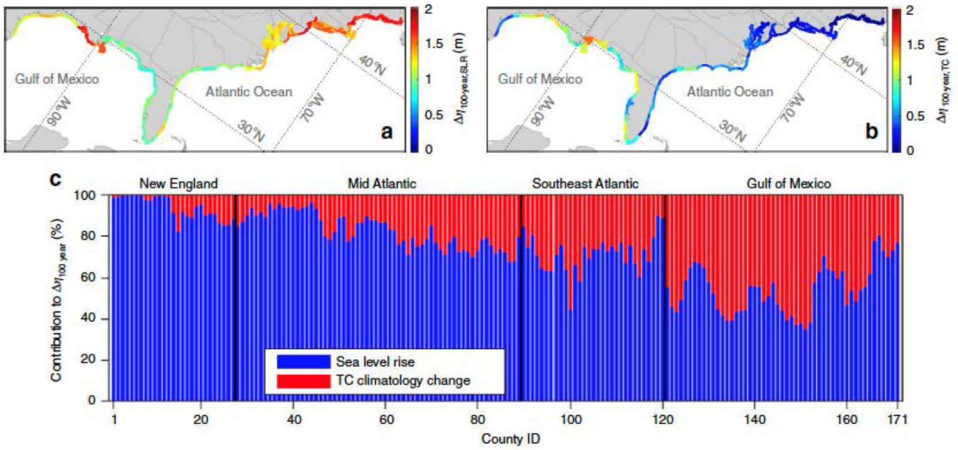
- Using a similar method as Lin et al. and Garner et al., but extending the TC and hydrodynamics modeling over the entire U.S. coast along the Gulf of Mexico and Atlantic
- Use 6 CMIP5 models (CCSM4 GFDL5, HadGEM5, MIROC, MPI5, MRI5) with RCP8.5 scenario and weigh the models based on skill in simulating storm tide
- Use probabilistic SLR projections
- Also compare TC vs. SLR effects on storm tide

100-yr flood height will have a return period of 1-yr in the east coast by end of this century

(Marsooli et al. 2019 Nature Commun.)

Projection of storm surge and flood height

SLR dominates future changes in storm tide in the NE U.S. mainly because LSR is much larger in the NE than in Gulf of Mexico, but also TC changes such as maximum winds and intensity-size are smaller



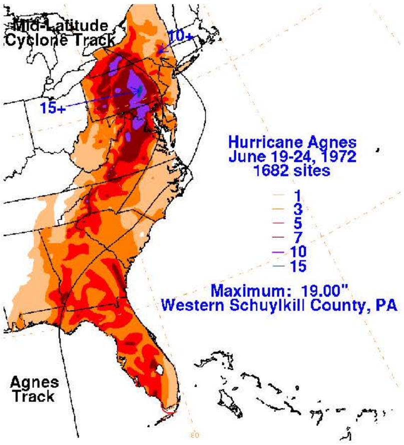
(Marsooli et al. 2019 Nature Commun.)

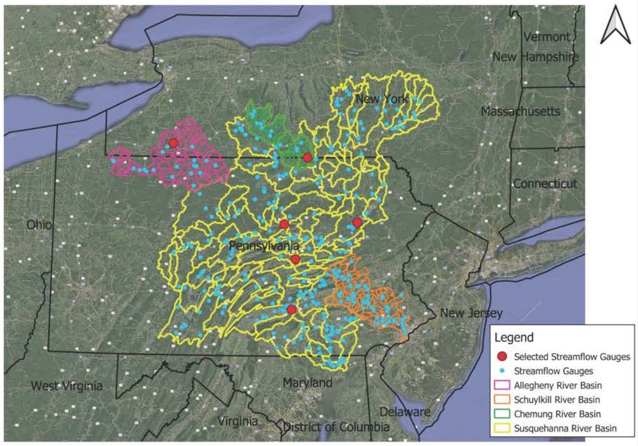
Hydrologic characteristics of the Northeast region

- Floods in the northeast region can be produced by
  - locally heavy precipitation
  - regionally persistent rainfall
  - slow-moving extratropical cyclones
  - remnants of tropical cyclones during summer and fall, and
  - late spring rainfall on snowpack.
- Examples of historical floods
  - June 1972 floods from Hurricane Agnes
  - April 2005 floods
  - April 2007 floods
  - February-March 2010 floods
  - February-September 2011 floods
  - October 2012 floods from Hurricane Sandy

June 1972 floods from Hurricane Agnes

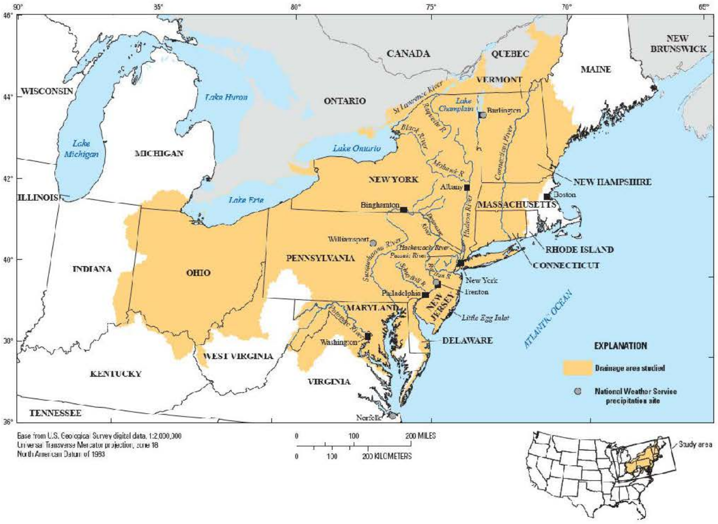
- Precipitation and flooding
  - Extensive flooding in the northeast U.S., particularly in the Susquehanna River Basin
  - Schuylkill River at Philadelphia, PA: 14.65 ft on 6/23 (recorded 14.7 ft on 8/24/1933)
  - Chemung River at Chemung, NY: 31.62 ft, over 7.5 ft higher than pervious record
  - Susquehanna River at Wilkes-Barre, PA: 40.91 ft (previous record 33.1 ft on 3/18/1865)
  - West Branch Susquehanna River at Willamsport, PA: 34.75 ft (previous record 33.57 ft on 3/18/1936)





February-September 2011 floods

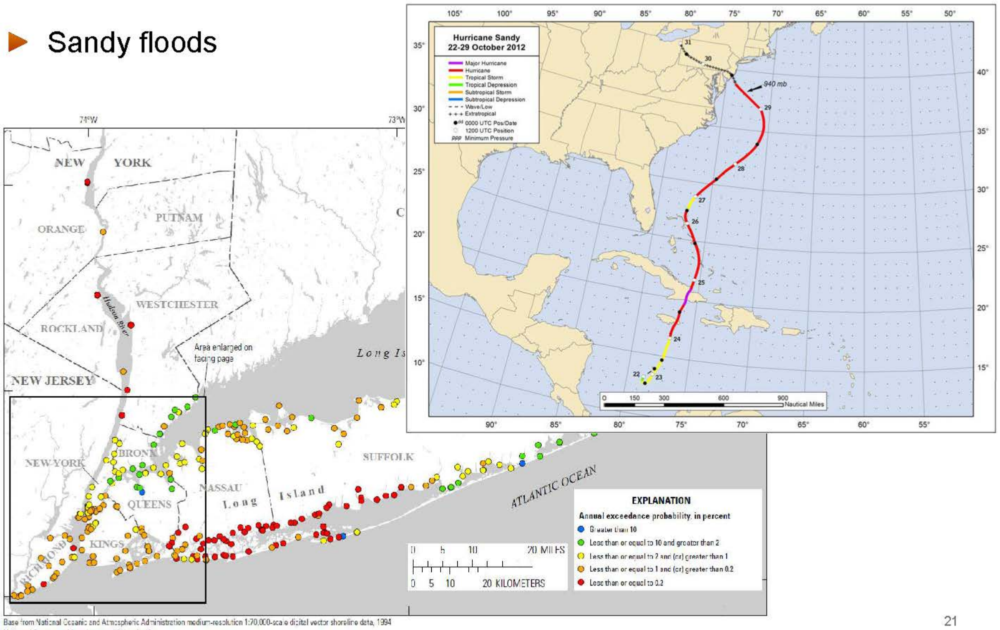
- Precipitation and flooding
  - Widespread flooding in the northeast U.S. during 2011
  - Flooding occurred in the months February through May and July through September



Base from U.S. Geological Survey digital data, 1:2,000,000
Universal Transverse Mercator projection, zone 18
North American Datum of 1983

October 2012 floods from Hurricane Sandy

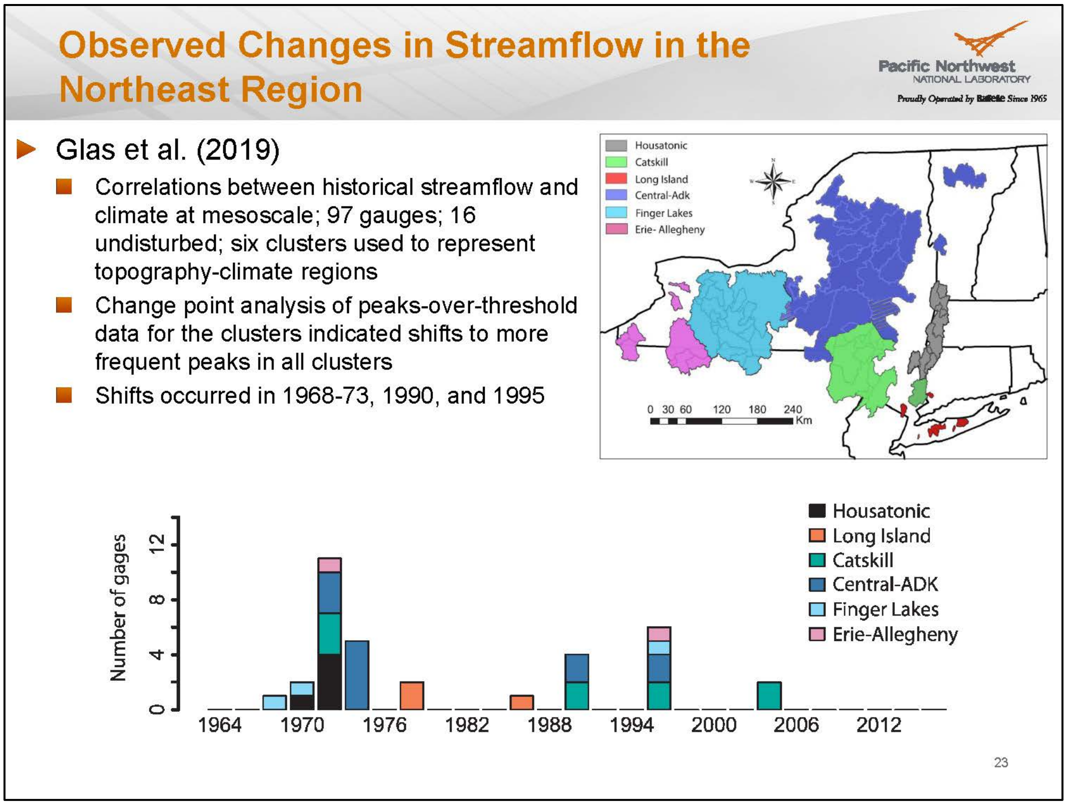
- Sandy floods



Base from National Oceanic and Atmospheric Administration medium-resolution 1:70,000-scale digital vector shoreline data, 1994
Universal Transverse Mercator, zone 18N projection

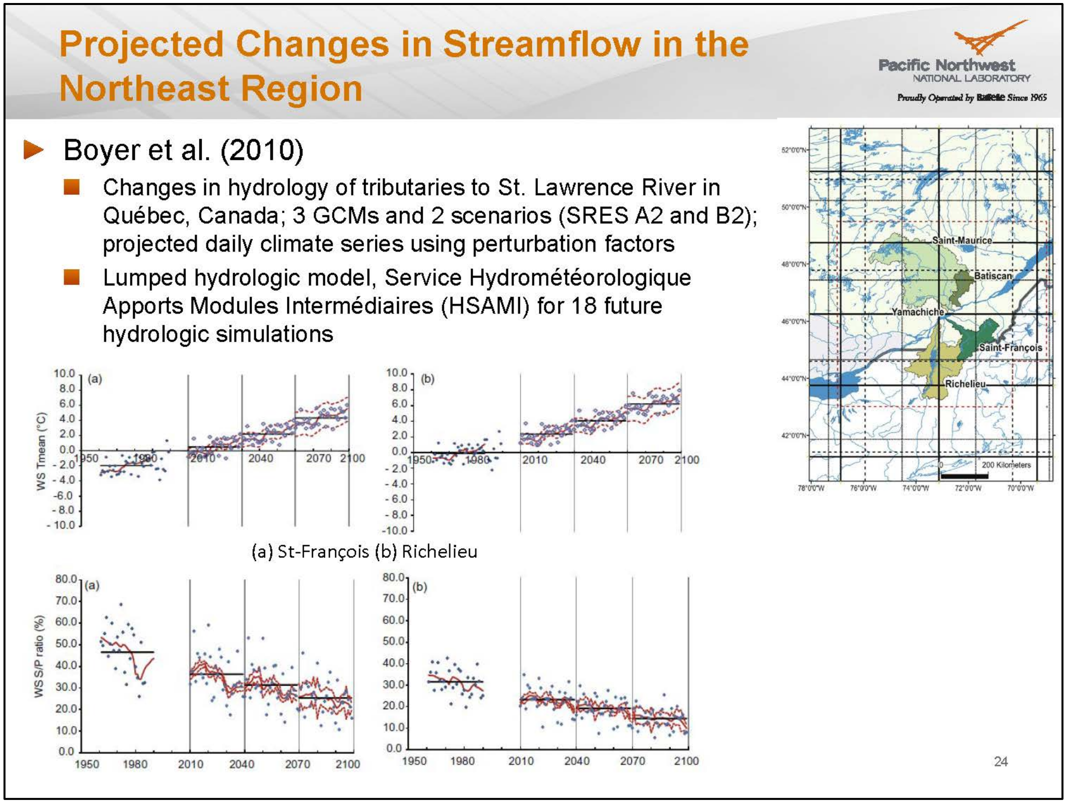
Observed and Predicted Changes in Streamflow in the Northeast Region

- Observed Changes
  - The northeast U.S. experienced a dry period in the 1960 and wet periods in the 1970s and 2000s. The mean annuals cycle of streamflow for three river basins in the northeast U.S. seem to be caused by annual cycles of evapotranspiration and snowmelt, not precipitation. Some, although weak, correlations between NAO, AO, and AMO and the three river basins' hydrology exist, both in undisturbed, small and larger, more regulated drainage areas.
  - The streamflow peak during spring shows a clear shift to earlier in the season, by as much as 10 days in 2014 compared to mid-20th century. There seems to be periods in the historical record when frequency of floods increased-these periods occurred around 1970, 1990, and 1995.
- Projected Changes
  - The winter-spring mean temperature in drainage areas of selected tributaries to the St. Lawrence River, depending on their latitude, will cross the freezing threshold during various decades of the 21st century resulting in projected reduced snow to total precipitation ratio and large shifts of winter-spring center-volume date to earlier in spring.
  - Peak streamflow magnitude is projected to increase and low flow magnitudes is projected to decrease in the northeast region as the 21st century progresses, particularly for RCP 8.5 scenario.



Observed Changes in Streamflow in the Northeast Region

- Glas et al. (2019)
  - Correlations between historical streamflow and climate at mesoscale; 97 gauges; 16 undisturbed; six clusters used to represent topography-climate regions
  - Change point analysis of peaks-over-threshold data for the clusters indicated shifts to more frequent peaks in all clusters
  - Shifts occurred in 1968-73, 1990, and 1995

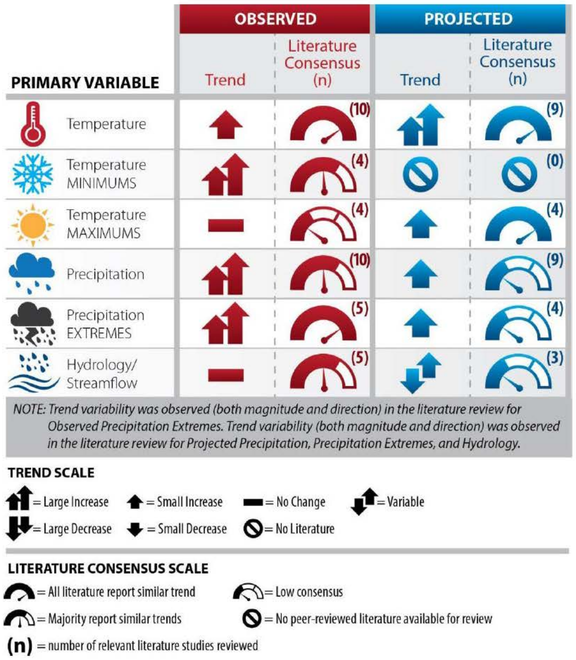


Projected Changes in Streamflow in the Northeast Region

- Boyer et al. (2010)
  - Changes in hydrology of tributaries to St. Lawrence River in Québec, Canada; 3 GCMs and 2 scenarios (SRES A2 and B2); projected daily climate series using perturbation factors
  - Lumped hydrologic model, Service Hydrométéorologique Apports Modules Intermédiaires (HSAMI) for 18 future hydrologic simulations

(a) St-François (b) Richelieu

Summary of observed and projected climate trends in USACE Water Resources Region 01



PRIMARY VARIABLE	OBSERVED Trend	OBSERVED Literature Consensus (n)	PROJECTED Trend	PROJECTED Literature Consensus (n)
Temperature	⬆	(10)	⬆⬆	(9)
Temperature MINIMUMS	⬆⬆	(4)	⊘	⊘ (0)
Temperature MAXIMUMS	▬	(4)	⬆	(4)
Precipitation	⬆⬆	(10)	⬆	(9)
Precipitation EXTREMES	⬆⬆	(5)	⬆	(4)
Hydrology/ Streamflow	▬	(5)	⬇⬆	(3)

NOTE: Trend variability was observed (both magnitude and direction) in the literature review for Observed Precipitation Extremes. Trend variability (both magnitude and direction) was observed in the literature review for Projected Precipitation, Precipitation Extremes, and Hydrology.

TREND SCALE

⬆⬆ = Large Increase
⬆ = Small Increase
▬ = No Change
⬇⬆ = Variable
⬇⬇ = Large Decrease
⬇ = Small Decrease
⊘ = No Literature

LITERATURE CONSENSUS SCALE

◠ = All literature report similar trend
◠ = Low consensus
◠ = Majority report similar trends
⊘ = No peer-reviewed literature available for review
(n) = number of relevant literature studies reviewed

Contact Information

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3.2.2 Presentation 1B-2: Modeling of climate change induced flood risk in the Conasauga River Basin

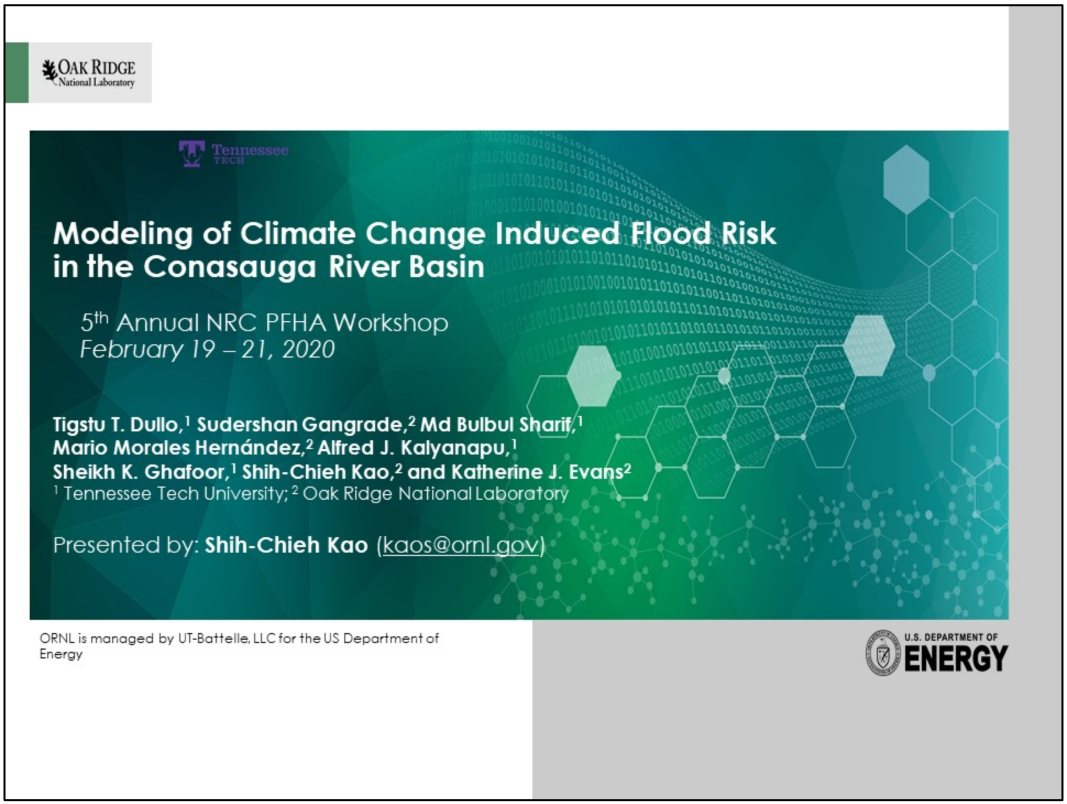
Authors: Tigstu T. Dullo, Tennessee Technical University (TTU), Sudershan Gangrade, Oak Ridge National Laboratory (ORNL), Md Bulbul Sharif, TTU, Mario Morales-Hernandez, ORNL, Alfred J. Kalyanapu, Sheikh K. Ghafoor, TTU, Shih-Chieh Kao and Katherine J. Evans, ORNL

Speaker: Shih-Chieh Kao

3.2.2.1 Abstract

The goal of this study is to evaluate the potential impacts of climate change on flood regimes and infrastructures at a high-spatial resolution through coupled hydrologic-hydraulics models. The hydrologic simulations are conducted using the high resolution Distributed Hydrology Soil Vegetation Model (DHSVM) driven by (1) 1981–2012 Daymet meteorologic observation, and (2) 11 sets of downscaled Coupled Model Intercomparison Project phase 5 (CMIP5) global climate model projections for 40 years in the historical period (1966–2005), and 40 years in the future (2011–2050). Flood simulations are performed using a graphic processing unit (GPU)-accelerated hydraulics model (TRITON) that solves the full 2D-shallow water equations using a new finite-volume numerical scheme. The TRITON model is first evaluated for its sensitivity to several model parameters, namely, the digital elevation model, Manning’s roughness, and initial conditions. Then, the TRITON model performance is assessed by comparing to the existing Federal Emergency Management Authority flood inundation maps. Finally, the verified flood model is used to simulate 912 annual maximum streamflow events at 10 m spatial resolution for an ensemble-based flood risk evaluation. The flood simulation results are used to evaluate changes in flood regimes and to assess the vulnerability of infrastructures in a changing climate.

3.2.2.2 *Presentation (ADAMS Accession No. ML21022A085)*



Oak Ridge National Laboratory

Tennessee Tech

Modeling of Climate Change Induced Flood Risk in the Conasauga River Basin

5th Annual NRC PFHA Workshop
February 19 – 21, 2020

Tigstu T. Dullo,[1] Sudershan Gangrade,[2] Md Bulbul Sharif,[1] Mario Morales Hernández,[2] Alfred J. Kalyanapu,[1] Sheikh K. Ghafoor,[1] Shih-Chieh Kao,[2] and Katherine J. Evans[2]
[1] Tennessee Tech University; [2] Oak Ridge National Laboratory

Presented by: **Shih-Chieh Kao** (kaos@ornl.gov)

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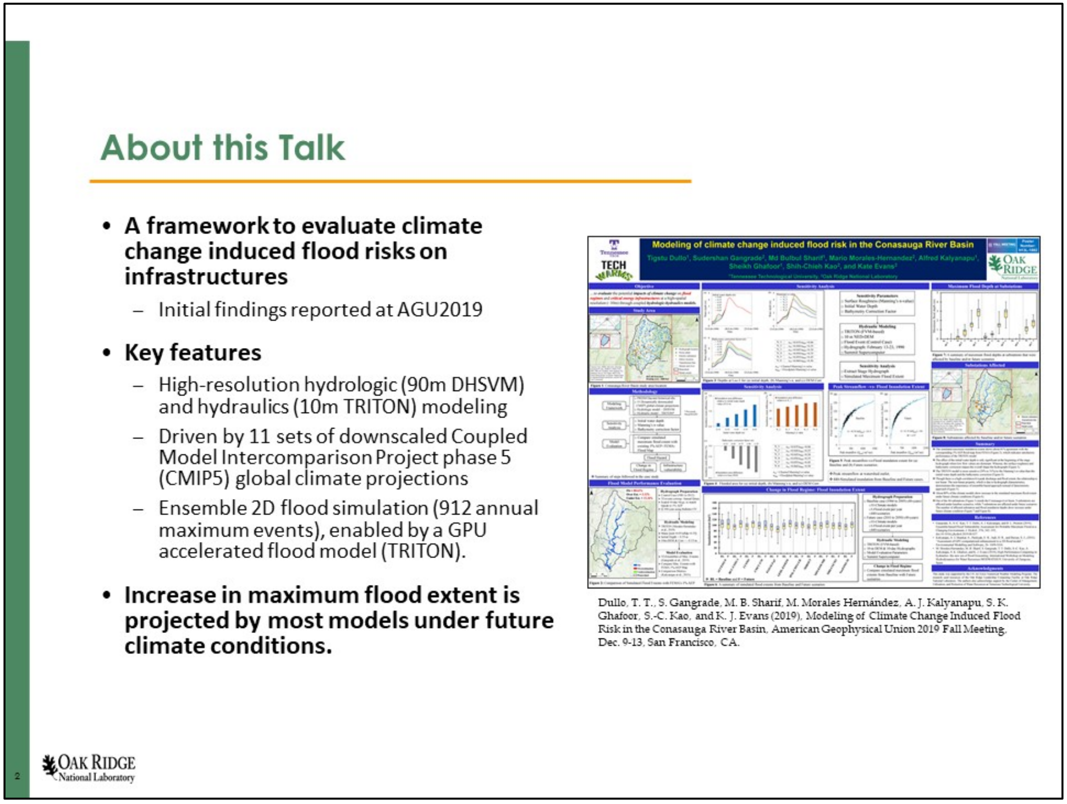


About this Talk

- **A framework to evaluate climate change induced flood risks on infrastructures**
  - Initial findings reported at AGU2019
- **Key features**
  - High-resolution hydrologic (90m DHSVM) and hydraulics (10m TRITON) modeling
  - Driven by 11 sets of downscaled Coupled Model Intercomparison Project phase 5 (CMIP5) global climate projections
  - Ensemble 2D flood simulation (912 annual maximum events), enabled by a GPU accelerated flood model (TRITON).
- **Increase in maximum flood extent is projected by most models under future climate conditions.**

Modeling of climate change induced flood risk in the Conasauga River Basin

Dullo, T. T., S. Gangrade, M. B. Sharif, M. Morales Hernández, A. J. Kalyanapu, S. K. Ghafoor, S.-C. Kao, and K. J. Evans (2019), Modeling of Climate Change Induced Flood Risk in the Conasauga River Basin, American Geophysical Union 2019 Fall Meeting, Dec. 9-13, San Francisco, CA.

Changing Hydrology in a Warming Environment

2009 flood near Atlanta

Increasing Extreme Precipitation

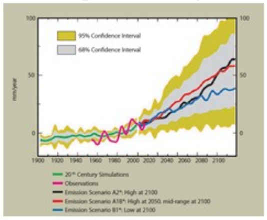
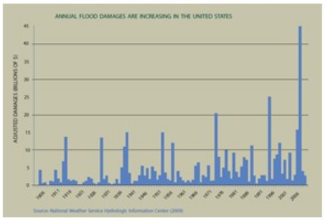


Figure Source : National Wildlife Federation, 2009, Data Sources: U.S. Climate Change Science Program (CCSP),2008

Annual Flood Damages in US



National Weather Service Hydrologic Information Center (2009)

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Main Challenges of Climate-Flooding Risk Assessment

- **Cannot be done through deterministic approach**
  - Ensemble-based approach is needed, but is very expensive.
- **Across a wide range of spatial and temporal scales**
  - global -> regional -> watershed -> site
- **Need a variety of different domain knowledge and models. Interdisciplinary collaboration is needed.**
  - Selection of global climate models and emission scenarios
  - Regional downscaling and bias-correction
  - Watershed-scale hydrologic modeling
  - Site-specific inundation modeling
  - High-performance computing (GPU!)

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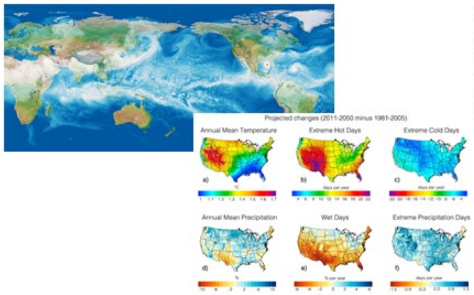
Climate Change Induced Flood Risk Assessment

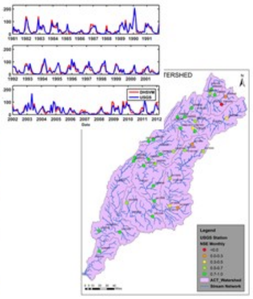
Climate Modeling
- CMIP5 Models (~150km)

Regional Downscaling
- RegCM4 (18km)
- Bias-correction (4km)

Hydrologic Modeling
- DHSVM (90m)

Inundation Simulation
- TRITON (10m)





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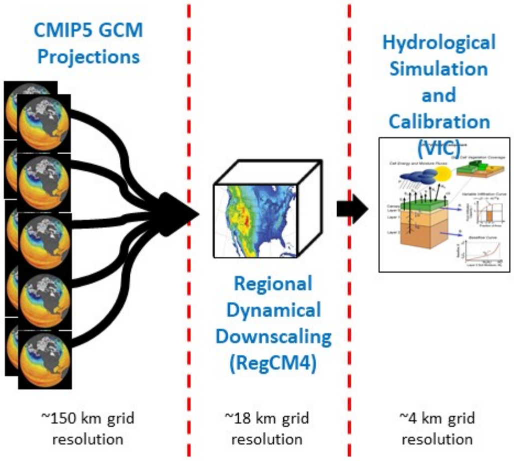
ORNL CMIP5 Hydroclimate Projection Dataset



CMIP5 GCM Projections

Regional Dynamical Downscaling (RegCM4)

Hydrological Simulation and Calibration (VIC)

~150 km grid resolution

~18 km grid resolution

~4 km grid resolution

- **11 sets of hydro-climate projections**
- **RCP8.5 (high) emission scenario**
- **Baseline: 1966–2005**
- **Future: 2011–2050**

- Ashfaq et al. (2016). High-resolution Ensemble Projections of Near-term Regional Climate over the Continental United States, *J. Geophys. Res.-Atmos.*, *121*, 9943-9963, doi:10.1002/2016JD025285.
- Naz et al. (2016). Regional Hydrologic Response to Climate Change in the Conterminous United States Using High-resolution Hydroclimate Simulations, *Global Planet. Change*, *143*, 100-117, doi:10.1016/j.gloplacha.2016.06.003.

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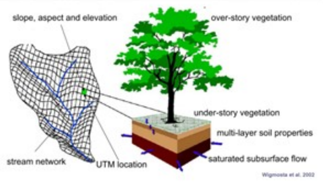
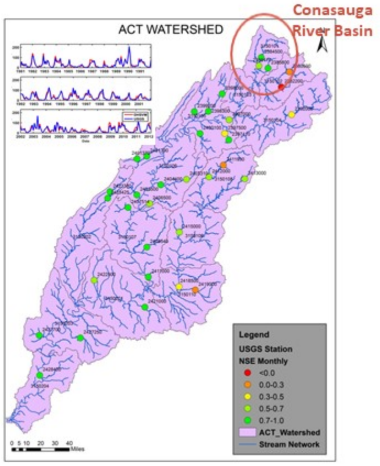
DHSVM Hydrologic Model

- **Distributed Hydrology Soil Vegetation Model (DHSVM)**
  - High-resolution (90m)
  - Process based distributed model
  - Model calibration to reproduce historic obs





Gangrade et al. (2018). Sensitivity of Probable Maximum Flood in a Changing Environment, *Water Resour. Res.*, *54*(6), 3913-3936, doi:10.1029/2017WR021987.

TRITON Hydrodynamic Model

- **Two-dimensional Runoff and Inundation Toolkit for Operational Needs (TRITON)**
  - Previously Flood2D-GPU (Kalyanapu et al., 2011)
  - Developed by ORNL and TTU, supported by USAF Numerical Weather Modeling Program
- **2D model based on full shallow water equations**
  - Mass and momentum conservation
  - Upwind finite volume explicit scheme
  - Accurate wet/dry fronts tracking
  - Valid for various spatial resolution
- **Support multi-platform and high-performance computing**
  - GPU implementation (CUDA)
  - Multiple CPUs (OpenMP+MPI)
  - Multiple GPUs (CUDA+MPI)

TRITON: Input Data

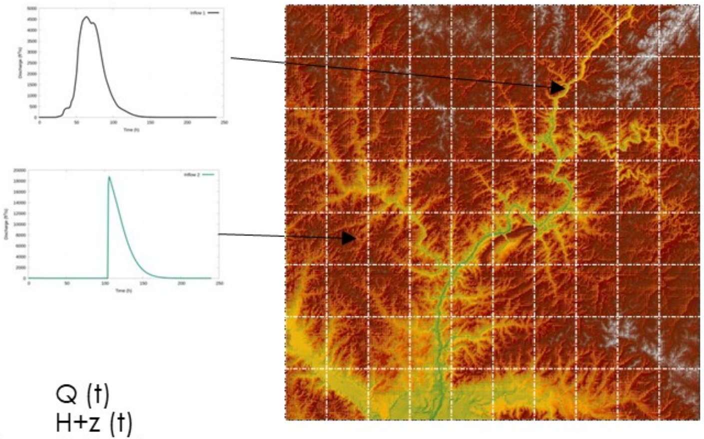
Digital elevation (DEM)

Inflow hydrographs

Local runoff (Excess rainfall)

Land use (roughness)

External boundary conditions



⇨

Q (t)
H+z (t)
Q (h+z)
Normal slope
Froude number

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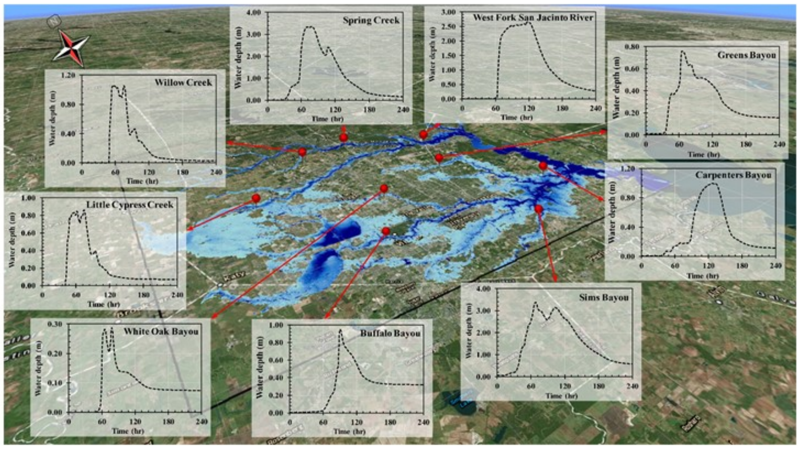
TRITON: Output Data

Flooding maps
- Water depth
- Velocities

Temporal evolution at certain locations
- Water depth
- Velocities



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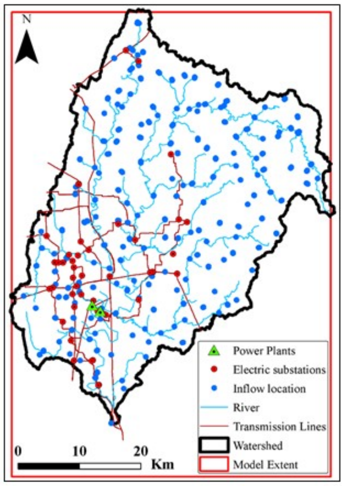
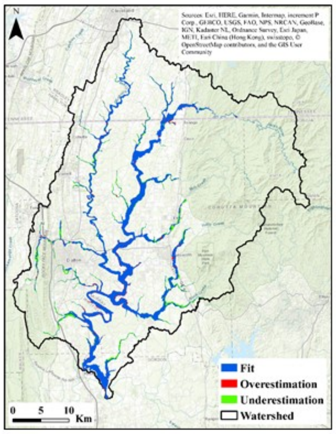
Proof-of-Concept: Conasauga River Basin

- **Evaluate the vulnerability of energy infrastructures due to climate change induced riverine flooding**
  - Conasauga River Basin in GA
  - 2 power plants and 44 substations
- **3 sets of rainfall**
  - Control: 1981–2012 Daymet/PRISM observation
  - Baseline: 1966–2005, 11 CMIP5 models
  - Future: 2011–2050, 11 CMIP5 models
- **Inflow hydrographs simulated by DHSVM**



TRITON Performance Analysis

- **Select 32 annual max. flood events from Control (1981–2012).**
- **Scale peak discharges to 1% annual exceed. probability (AEP) flow calculated from USGS gauge observations.**
- **TRITON simulation**
- **Extract the maximum inundation extent and compare to FEMA 1% AEP map.**



TRITON Evaluation by FEMA Maps

Summary

- ❖ Fit = **80.65 %**
- ❖ Overestimation= **5.52 %**
- ❖ Underestimation= **15.36 %**

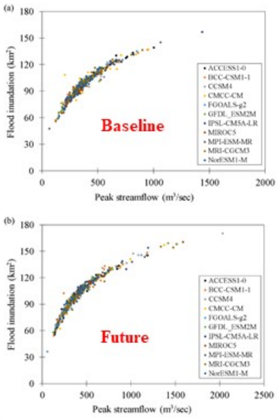
Selected Hydraulic and Geometric Parameters

- ❖ Initial water Depth [**0.35 m**]
- ❖ Manning's n [n_{ch}=**0.05** / n_{fldpl}=**0.35**]
- ❖ Bathymetry correction factor [**-0.15 m**]

Ensemble TRITON Simulation

Select Annual Max. at Each Model Year

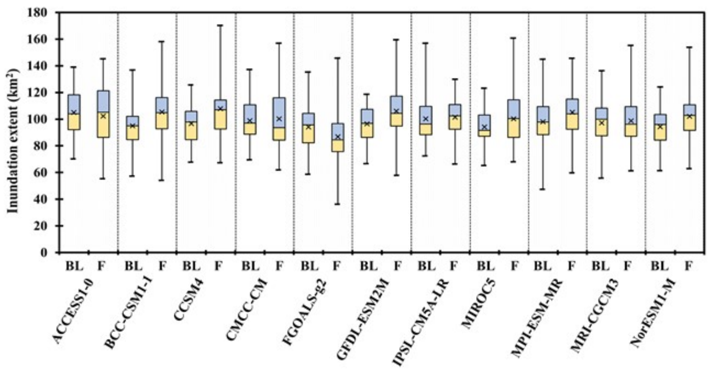
CMIP5 model	Baseline Period (1966–2005)	Future Period (2011–2050)
ACCESS1-0	40	40
BCC-CSM1-1	40	40
CCSM4	40	40
CMCC-CM	40	40
FGOALS	40	40
GFDL_ESM2M	40	40
IPSL-CM5A-LR	40	40
MIROC5	40	40
MPI-ESM-MR	40	40
MRI-CGCM3	40	40
NorESM1-M	40	40
Total	**440**	**440**



Between peak streamflow & max. inundation extents.

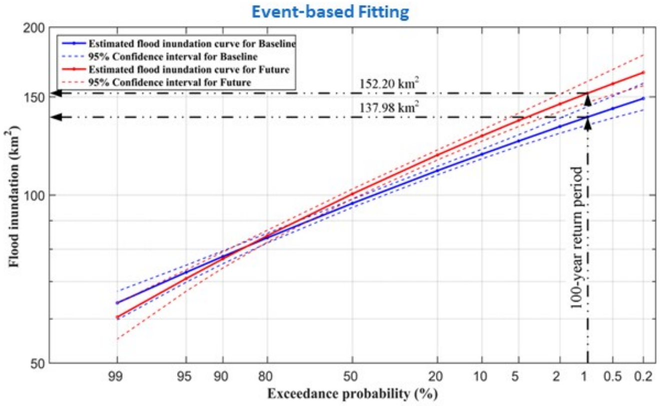
- **High correlation between peak streamflow and inundation**
  - Non-linear relationship
- **Affected by peak discharge, flood volume, and spatiotemporal variability of hydrographs**
- **Importance of using ensemble based approach instead of deterministic approach**

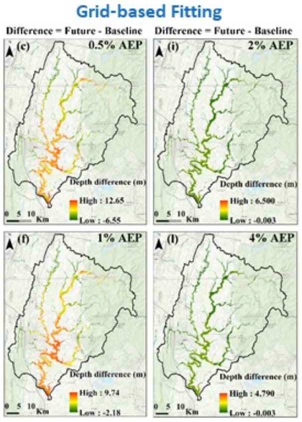
Projection by Each Model



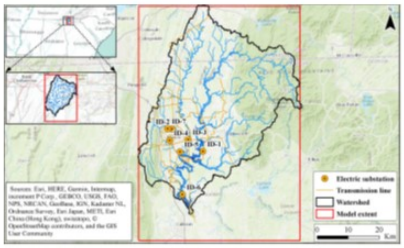
- **Increase in maximum flood extent is projected by most models under future climate conditions.**
- **The spread and uncertainty are also projected to increase by most models.**

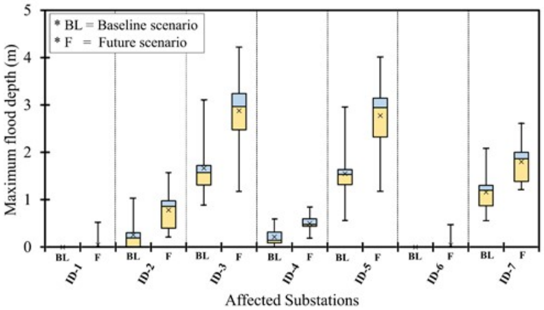
Flood Inundation Frequency





Affected Substations





- Out of 44 substations, 5 substations are affected under baseline scenarios while 7 substations are affected under future scenarios.
- The number of affected substations and flood inundation depths are projected to increase under future climate conditions.

Main Takeaways

- **Increase in maximum flood extent is projected by most models under future climate conditions.**
  - Cannot be evaluated through deterministic analysis. Probabilistic or ensemble-based approach is needed.
- **Enhanced high-performance computing capabilities has enabled process-based ensemble flood simulation.**
  - Provide surface flood regime for more **intuitive** flood vulnerability assessment of energy-water infrastructures.
- **The proposed framework can be adjusted based on other site-specific needs.**
  - Changes of rainfall scenarios (climate or non-climate), hydrologic / hydraulics models, calibration target and procedures, and other land surface conditions.

Thank you!

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

3.2.3 Presentation 1B-3 (KEYNOTE): Causality and extreme event attribution. Or was my house flooded because of climate change?

Michael F. Wehner, Lawrence Berkeley National Laboratory (LBNL)

3.2.3.1 Abstract

Extreme event attribution is an exercise in causality. Rather than some deep philosophical statement, an attribution statement is a probabilistic one. However, it is also a conditional statement and is incomplete if the conditions and uncertainties are not clearly specified. We will review a hierarchy of extreme attribution statements types and their uncertainties ranging from those with very few conditions to those that are highly constrained. Real world examples will include interpretations of recent attributions statements about Hurricanes Harvey, Maria and Irma. In particular, we will explore the confidence in the human induced portion of the Harvey's record rainfall and flooding in the greater Houston area by examining five independent analyses.

3.2.3.2 Presentation (ADAMS Accession No. ML20080M188)

The human influence on recent extreme storms.

Probabilistic Flood Hazard Assessment (PFHA) Research Workshop
US Nuclear Regulatory Commission
February 19, 2020

Michael F. Wehner
Lawrence Berkeley National Laboratory

Houston, Texas after Harvey

The human influence on recent extreme storms.
Or
Did global warming flood my house?

Probabilistic Flood Hazard Assessment (PFHA) Research Workshop
US Nuclear Regulatory Commission
February 16, 2020

Michael F. Wehner
Lawrence Berkeley National Laboratory

Houston, Texas after Harvey

US DOE Policy 411.2A

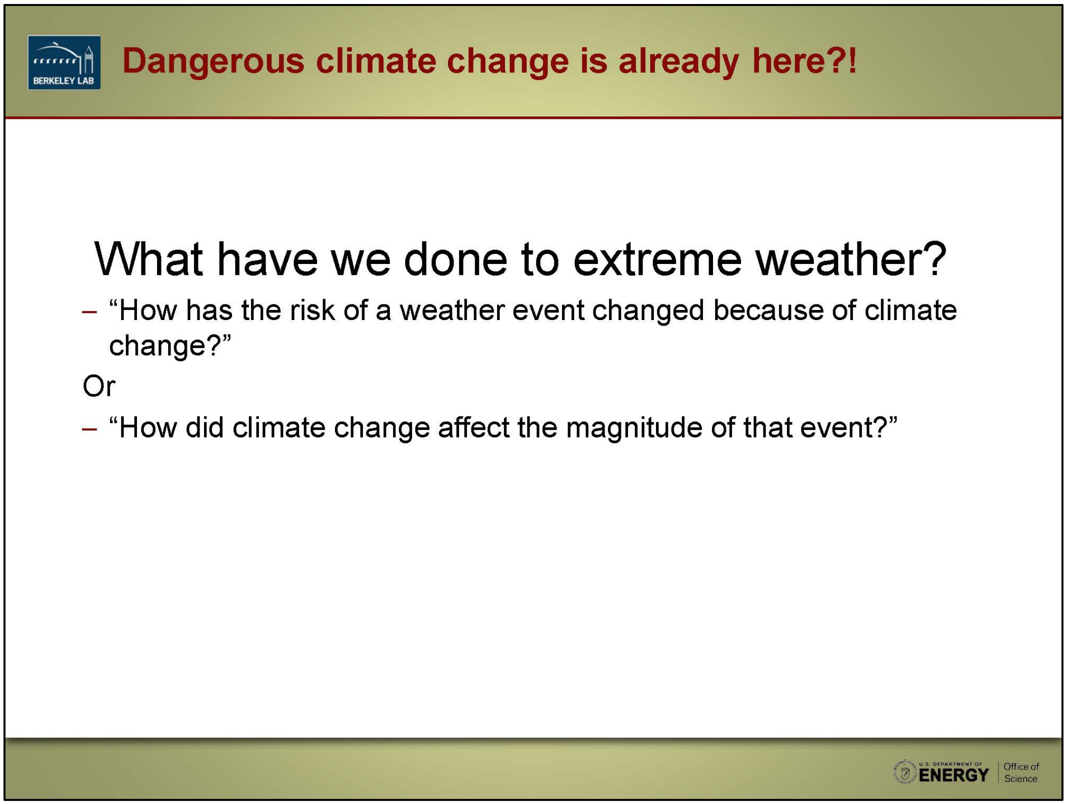
SUBJECT: SCIENTIFIC INTEGRITY

When expressing opinions on policy matters to the public and media, research personnel must make it clear when they are expressing their personal views, rather than those of the Department, the U.S. Government, or their respective institutions. Public representation of Government or DOE positions or policies must be cleared through their program management to include DOE headquarters.

In accordance with this policy, any material in this presentation should be considered the opinion of the speaker and not necessarily that of the US Dept. of Energy, the University of California or the Lawrence Berkeley National Laboratory.

What is the “safe” amount of climate change?

- United Nations Framework Convention on Climate Change”
  - “to achieve stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic [human] interference with the climate system.”
- 2009 Copenhagen Accord:
  - This level is such that the global average temperature should be stabilized at two degrees Celsius (3.6 degrees Fahrenheit) above its preindustrial level.
- 2015 Paris Agreement (COP21):
  - “Invites the Intergovernmental Panel on Climate Change to provide a special report in 2018 on the impacts of global warming of 1.5 °C above pre-industrial levels and related global greenhouse gas emission pathways”
- 2020: We are already over 1^{o}C above pre-industrial levels.
  - I will argue that this is not safe.
  - Dangerous climate change is here now.



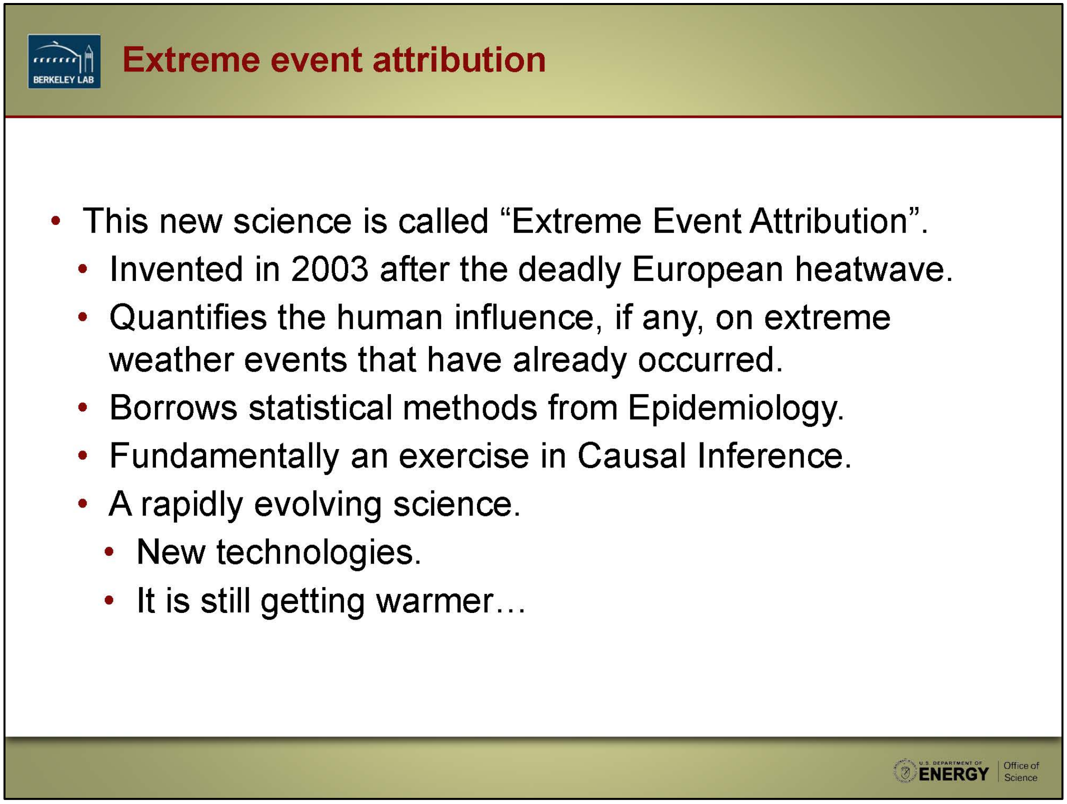
Dangerous climate change is already here?!

What have we done to extreme weather?

- “How has the risk of a weather event changed because of climate change?”

Or

- “How did climate change affect the magnitude of that event?”



Extreme event attribution

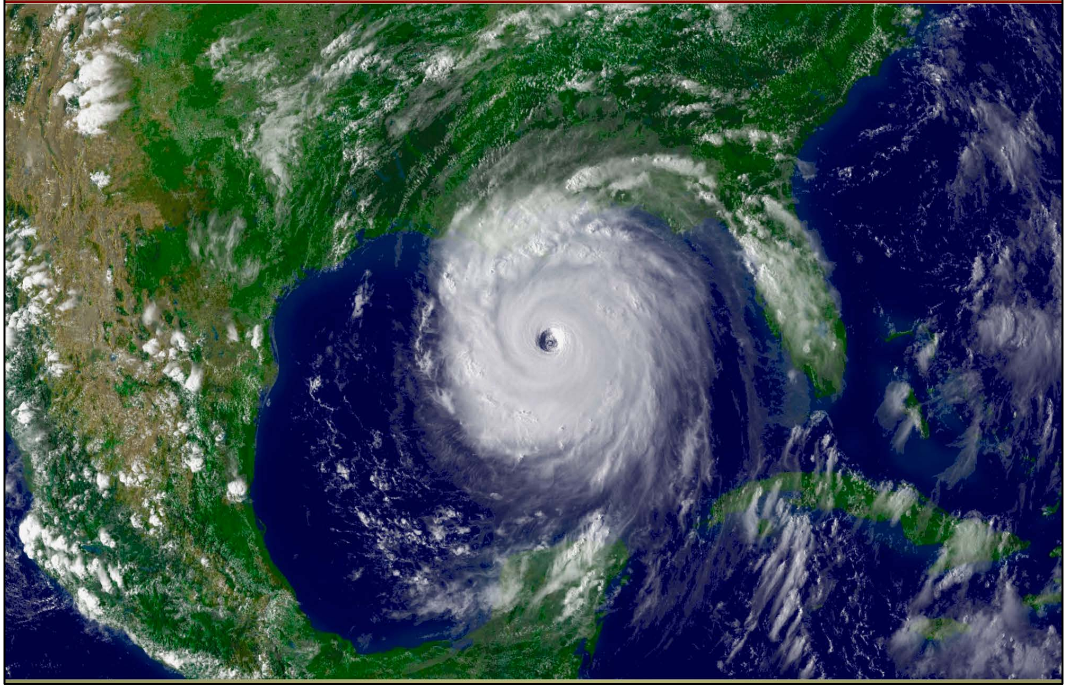
- This new science is called “Extreme Event Attribution”.
  - Invented in 2003 after the deadly European heatwave.
  - Quantifies the human influence, if any, on extreme weather events that have already occurred.
  - Borrows statistical methods from Epidemiology.
  - Fundamentally an exercise in Causal Inference.
  - A rapidly evolving science.
    - New technologies.
    - It is still getting warmer…

Extreme event attribution examples

- The chances of the 2003 European heat wave were found to be doubled.
  - Now, those chances have been increased by 10x.
- Global warming increased the chances of the 2015 hot and humid heat wave in Pakistan by a factor of at least 1000.

- Some seasonal flooding has been made more severe.
  - E.g. Spring 2013 Midwestern US
- As have some droughts.
  - E.g. 2011 East Africa

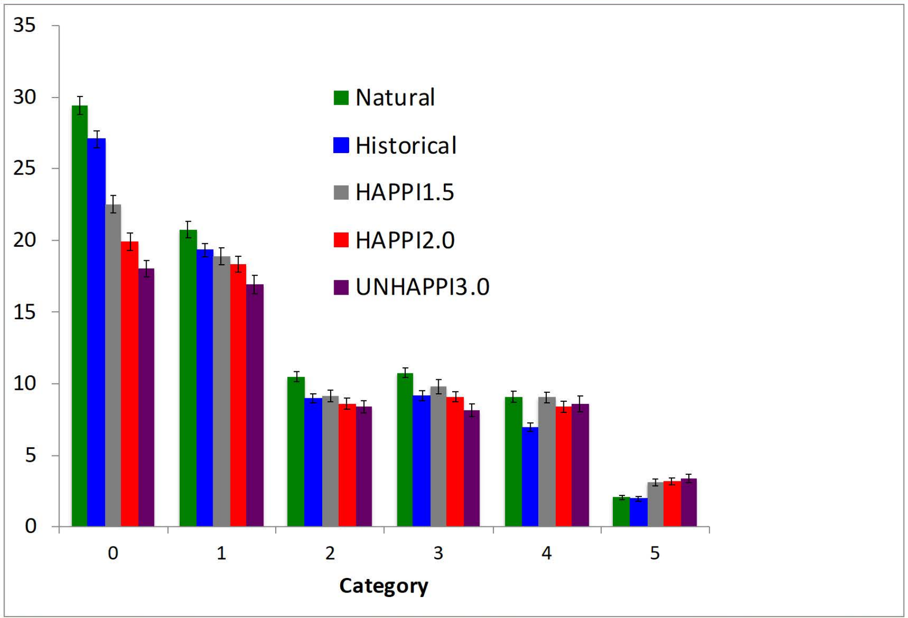
A significant human influence has been found in hundreds of similar large scale events.



Expectations about global warming and hurricanes.

- Tropical cyclones are the most intense storms on the planet.
  - They require warm ocean temperatures, high humidity and low wind shear to get really large.
  - Climate change increases temperature and humidity, but has only small effects on wind shear.
    - The general consensus is that global warming causes the most intense hurricanes to become more intense.
    - No real consensus on changes in the total TC number.
      - Either no change or a decrease.
    - Number of intense (cat 4 or 5) will either increase or decrease depending on the magnitude of this change.
    - Precipitation will increase. Available water increases according to Clausius-Clapeyron relationship
      - ΔQ = ~6% per ^{o}C warming

Global TC # (25km CAM5.1)



Extreme Event Attribution is causal inference.

Two complementary philosophies

1. Design ensembles of climate model simulations tailored to event attribution.
   - Actual world vs counterfactual world without human changes to the atmosphere. A direct interference.
   - Pearl causal inference.

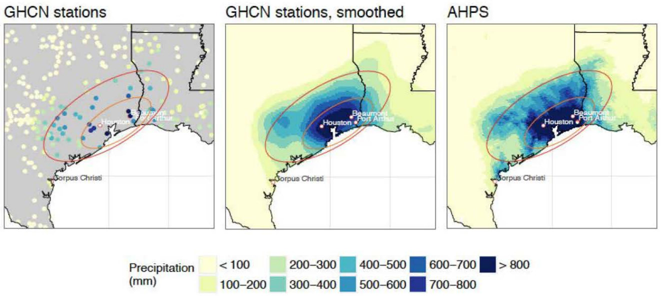
Prof. Judea Pearl, UCLA

2. Analyze observed trends with a statistical model.
   - Postulate a plausible cause but beware of hidden covariates.
   - Granger causal inference.

Sir Clive Granger (1934-2009)

Granger causality statement for Hurricane Harvey

- We constructed a non-stationary generalized extreme value statistical model of observed extreme precipitation (***Y***) in coastal Texas with two "covariates":
  - X_1=Atmospheric carbon dioxide: The human influence
  - X_2=El Nino index: The natural influence
- Two regions
- Three observational datasets
- No climate models.



Risser & Wehner (2017) Attributable human-induced changes in the likelihood and magnitude of the observed extreme precipitation in the Houston, Texas region during Hurricane Harvey. *Geophysical Review Letters*. 44, 12,457–12,464. https://doi.org/10.1002/2017GL075888

Hurricane Harvey attribution statement (small region)

- Anthropogenic climate change *likely* increased Hurricane Harvey’s total rain fall by at least 19% with a best estimate of 38%.
  - This is substantially larger than the 6-7% expected from thermodynamical arguments and C-C scaling.
- Anthropogenic climate change *likely* increased the chances of the observed rainfall by a factor of at least 3.5 with a best estimate of 9.6.

$$G_t(x) \equiv \mathbb{P}(Z_t \leq x) = \exp\left\{-\left[1+\xi_t\left(\frac{x-\mu_t}{\sigma_t}\right)\right]^{-1/\xi_t}\right\},$$

→ defined for $\{x : 1+\xi_t(x-\mu_t)/\sigma_t > 0\}$

Attribution statements about Harvey total precipitation

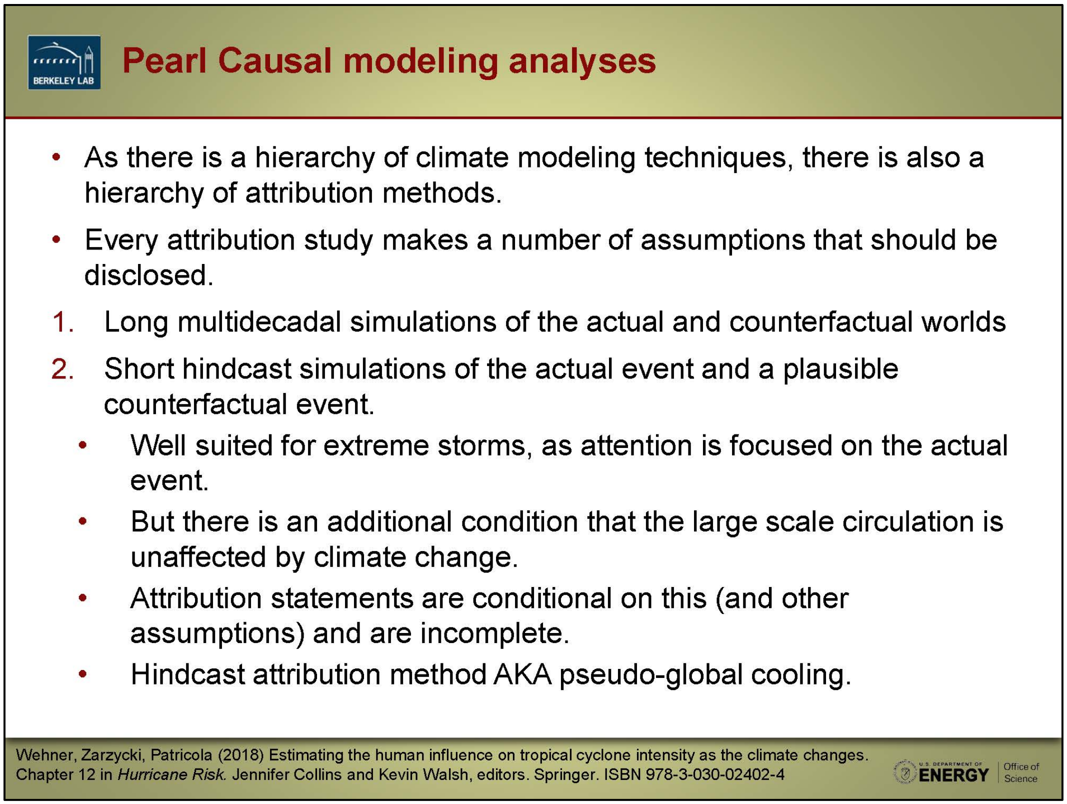
Granger causality

- Risser & Wehner 2017 (small region)
  - Chances increased by 10X (*likely* lower bound of 3.5X)
  - Precipitation increased by 38% (*likely* lower bound of 19%)
- Risser & Wehner 2017 (large region)
  - Chances increased by 5x (*likely* lower bound of 1.4X)
  - Precipitation increased by 24% (*likely* lower bound of 7%)

Pearl causality:

- Van Oldenborgh, van der Wiel et al. 2017
  - Chances increased by 3x (range =1.5 to 5)
  - Precipitation increased by 15% (*very likely* range= 8-19%)
- Wang et al. 2018
  - Precipitation increased by 20% (interquartile range 13-37%)

The statements are all within each other stated uncertainties.

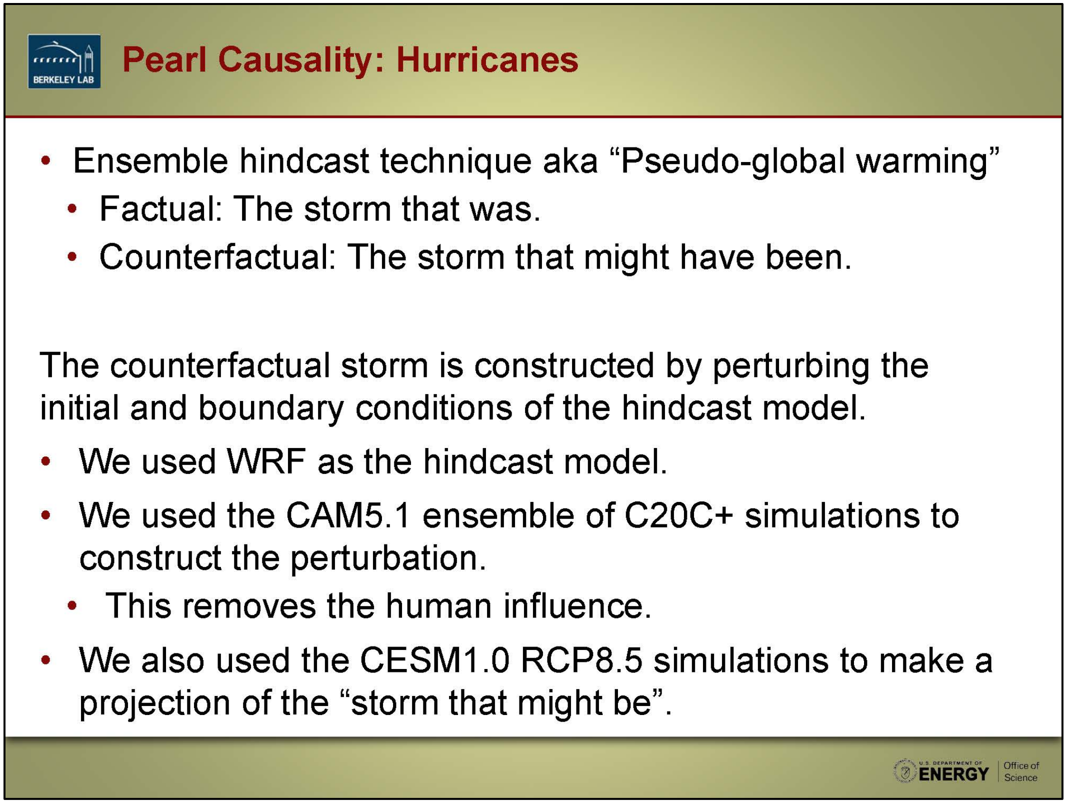


Pearl Causal modeling analyses

- As there is a hierarchy of climate modeling techniques, there is also a hierarchy of attribution methods.
- Every attribution study makes a number of assumptions that should be disclosed.

1. Long multidecadal simulations of the actual and counterfactual worlds
2. Short hindcast simulations of the actual event and a plausible counterfactual event.
   - Well suited for extreme storms, as attention is focused on the actual event.
   - But there is an additional condition that the large scale circulation is unaffected by climate change.
   - Attribution statements are conditional on this (and other assumptions) and are incomplete.
   - Hindcast attribution method AKA pseudo-global cooling.

Wehner, Zarzycki, Patricola (2018) Estimating the human influence on tropical cyclone intensity as the climate changes. Chapter 12 in *Hurricane Risk.* Jennifer Collins and Kevin Walsh, editors. Springer. ISBN 978-3-030-02402-4



Pearl Causality: Hurricanes

- Ensemble hindcast technique aka “Pseudo-global warming”
  - Factual: The storm that was.
  - Counterfactual: The storm that might have been.

The counterfactual storm is constructed by perturbing the initial and boundary conditions of the hindcast model.

- We used WRF as the hindcast model.
- We used the CAM5.1 ensemble of C20C+ simulations to construct the perturbation.
  - This removes the human influence.
- We also used the CESM1.0 RCP8.5 simulations to make a projection of the “storm that might be”.

3 km resolution regional climate model simulation of Hurricane Katrina (2005)

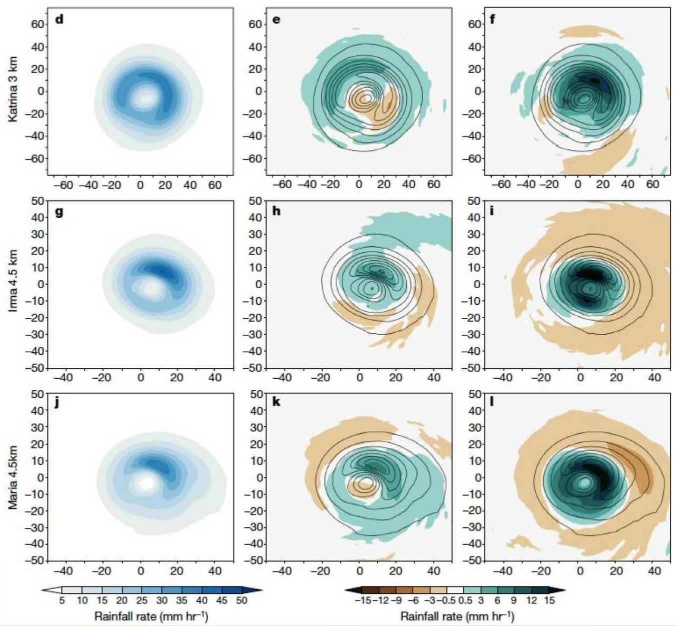
Christina Patricola, Lawrence Berkeley National Laboratory
cmpatricola@lbl.gov

Pearl Causality statements for Katrina, Maria & Irma

Human induced increases in hurricane precipitation totals are already large and can exceed Clausius-Clapeyron scaling.

- Global warming induces a structural change in the storm

Storm composites →



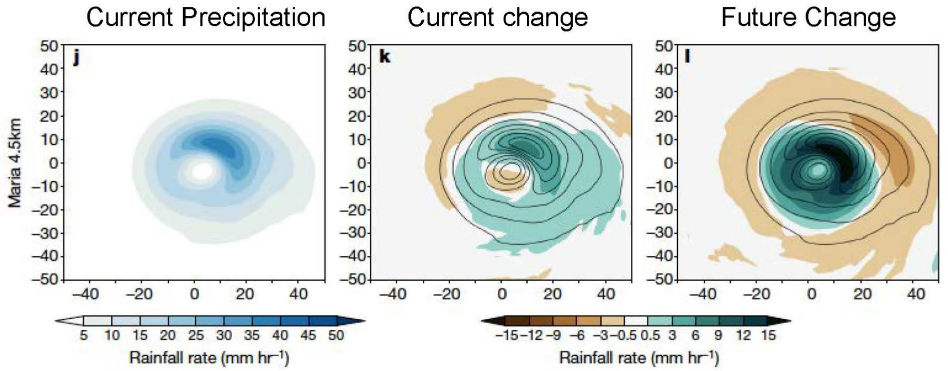
Precipitation

Current change

Future Change

Patricola & Wehner Nature 2018

C-C scaling case Study: A closer look at Maria



- Clausius-Clapeyron constraint on specific humidity= ~7%/°C
- Actual is 0.6C warmer than counterfactual.
  - C-C scaling = ~4%
    - At peak = >6 mm/hour (20%)
- RCP8.5 is 2C warmer than actual.
  - C-C scaling = ~14%
    - At peak = = >12 mm/hour (40%)

Patricola & Wehner Nature 2018

Flooding of Houston

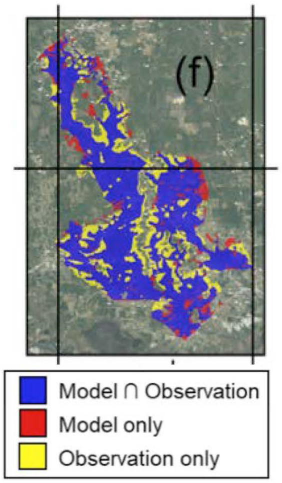
- How did this attributable increase in precipitation affect the Harvey flood?
- Design a storyline attribution analysis of the flood. (Pearl causality)
- Fathom-US, a continental-scale hydraulic model
  - 30 meter resolution
  - Demonstrated to be "fit for purpose"
    - "flood that was"
    - Most of the errors are at the periphery of the flood.

The "flood that was".

- Driven by observed rainfall.

The "flood(s) that might have been".

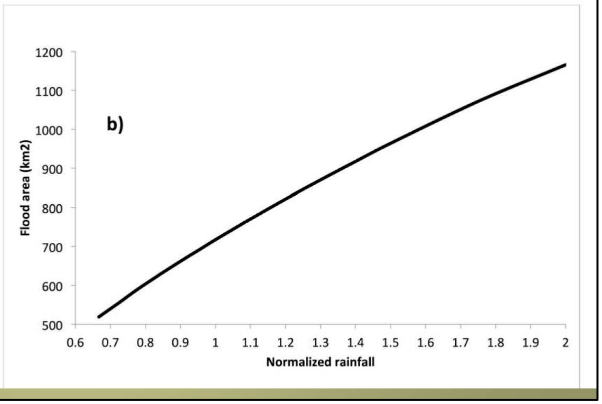
- Alter the rainfall uniformly by the published attribution statements.
- e.g. Risser & Wehner's 24% statement
  - Decrease precipitation by 1/1.24=0.81



Wing, O. E. J., Sampson, C. C., Bates, P. D., Quinn, N., Smith, A. M., & Neal, J. C. (2019). A flood inundation forecast of Hurricane Harvey using a continental-scale 2D hydrodynamic model. *Journal of Hydrology X*, *4*, 100039. https://doi.org/https://doi.org/10.1016/j.hydroa.2019.100039

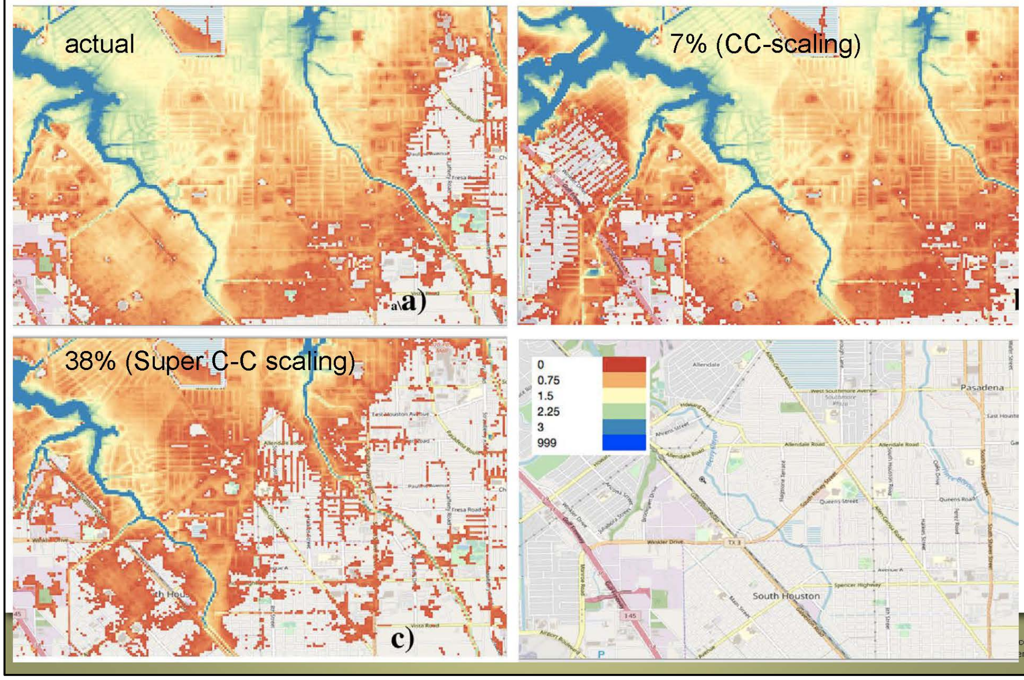
Greater Houston area

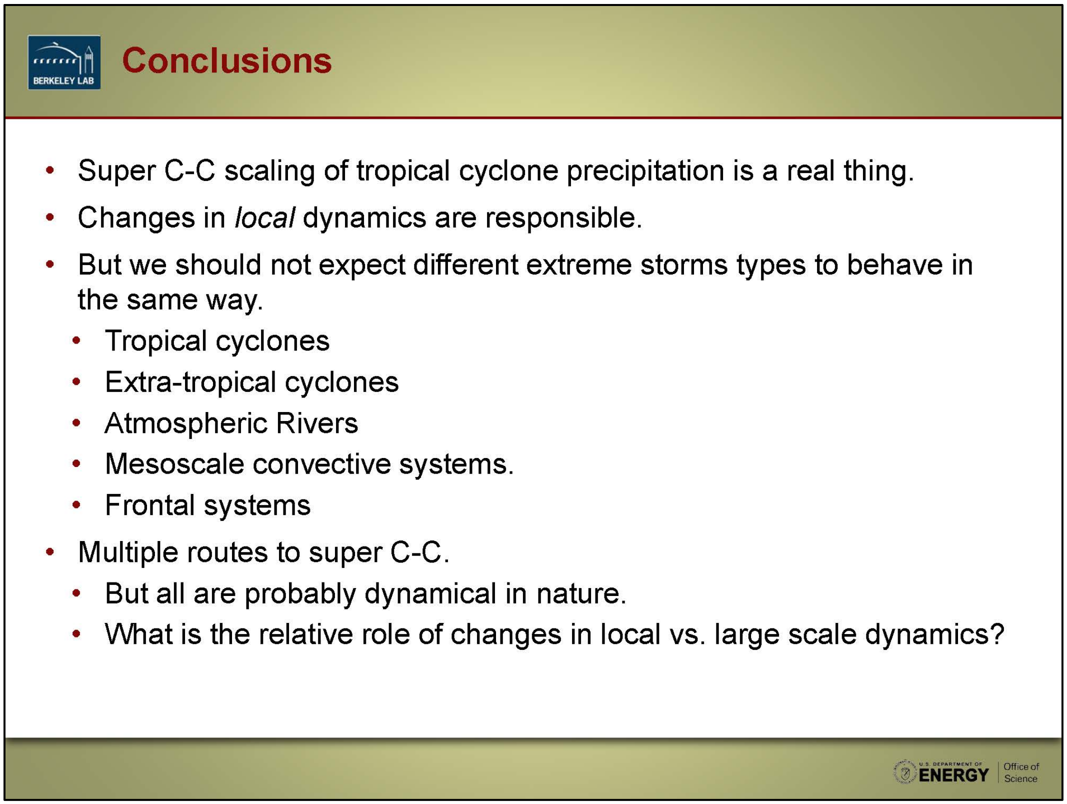
- Attributable flood water volume is essentially the same as the attributable precipitation.
  - Drainage to the Gulf is slow compared to rainfall rates
- Attributable flood water area is less than the attributable precipitation.
  - Weakly sublinear
  - But not small…
  - Highly non-uniform.



Wehner & Sampson, in preparation.

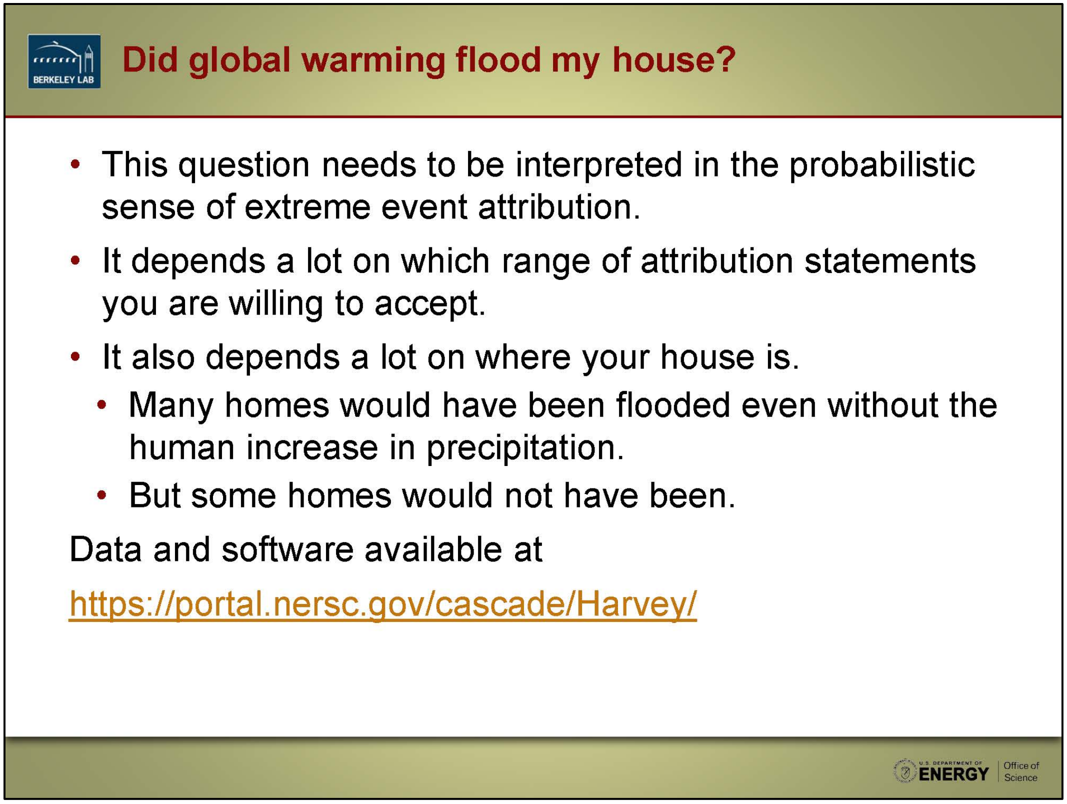
South Houston / Pasadena flooding after 5 days





Conclusions

- Super C-C scaling of tropical cyclone precipitation is a real thing.
- Changes in *local* dynamics are responsible.
- But we should not expect different extreme storms types to behave in the same way.
  - Tropical cyclones
  - Extra-tropical cyclones
  - Atmospheric Rivers
  - Mesoscale convective systems.
  - Frontal systems
- Multiple routes to super C-C.
  - But all are probably dynamical in nature.
  - What is the relative role of changes in local vs. large scale dynamics?



Did global warming flood my house?

- This question needs to be interpreted in the probabilistic sense of extreme event attribution.
- It depends a lot on which range of attribution statements you are willing to accept.
- It also depends a lot on where your house is.
  - Many homes would have been flooded even without the human increase in precipitation.
  - But some homes would not have been.

Data and software available at

https://portal.nersc.gov/cascade/Harvey/

Thank you!

mfwehner@lbl.gov

3.2.4 Present 1B-4: Attribution of Flood Nonstationarity across the United States—Climate-Related Analyses

Authors: Karen Ryberg, Stacey A. Archfield, William H. Asquith, Nancy A. Barth, Katherine J. Chase, Jesse E. Dickinson, Robert W. Dudley, Angela E. Gregory, Tessa M. Harden, Glenn A. Hodgkins, David Holtschlag, Delbert Humberson, Christopher P. Konrad, Sara B. Levin, Daniel E. Restivo, Roy Sando, Steven K. Sando, Eric D. Swain, Anne C. Tillery, Benjamin C. York, Julie E. Kiang; U.S. Geological Survey (USGS)

Speaker: Karen Ryberg

3.2.4.1 Abstract

As a statistical method, flood-frequency analysis has fundamental underlying assumptions, including an assumption that floods are generated by stationary processes (constant mean within a window of variance). Observed changes in precipitation and temperature patterns, along with continued human modification to the natural landscape, such as dams, agricultural drain tiles, and the expansion of irrigation, can impact flood-frequency analysis and make the estimates become increasingly questionable for some sites or time periods. Yet, flood-frequency analysis remains critical for the appropriate sizing and construction of flood-control infrastructure and for informing decisions related to the risk reduction. As part of a multi-year project funded by the U.S. Federal Highway Administration, trends and change points (nonstationarities that are violations of the assumptions of flood-frequency analysis) in annual peak streamflow data across the conterminous United States were identified. Then, a team of regional experts attributed these changes, where possible, to anthropogenic and environmental factors for which there are long-term data. Once the anthropogenic or environmental changes causing these nonstationarities are better understood, analysts can then begin to make choices about the best approaches for adjusting flood-frequency analyses. This presentation focuses on the climate-related analyses undertaken by regional experts.

3.2.4.2 *Presentation (ADAMS Accession No. ML20080M189)*

USGS
science for a changing world

Probabilistic Flood Hazard Assessment Workshop

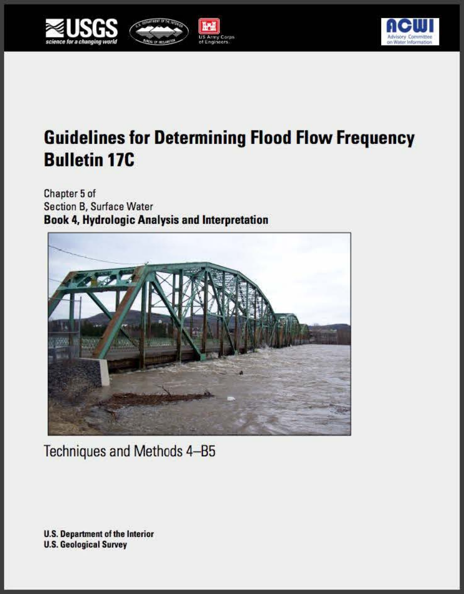
February 19–21, 2020

Attribution of Flood Nonstationarity across the United States—Climate-Related Analyses

U.S. Department of the Interior
U.S. Geological Survey

Bulletin 17C

- England, J.F., Jr., Cohn, T.A., Faber, B.A., Stedinger, J.R., Thomas, W.O., Jr., Veilleux, A.G., Kiang, J.E., and Mason, R.R., Jr., 2018, Guidelines for determining flood flow frequency—Bulletin 17C: U.S. Geological Survey Techniques and Methods, book 4, chap. B5, 148 p., https://doi.org/10.3133/tm4B5.



Guidelines for Determining Flood Flow Frequency Bulletin 17C

Chapter 5 of
Section B, Surface Water
Book 4, Hydrologic Analysis and Interpretation

Techniques and Methods 4–B5

U.S. Department of the Interior
U.S. Geological Survey

USGS

Solutions Still Needed for Nonstationarity

Stationarity: a process that can be defined with a probability distribution with unchanging parameters, such as a peak-flow series used in flood-frequency analysis that has a defined, constant mean, variance, and skew.

Nonstationarity: a process that may exhibit gradual trends, sudden shifts (change points), or changes in variability. Regulation of a stream and natural or anthropogenic climate shifts can create one or more nonstationarities in a peak-flow series.

USGS

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

Research Questions and Approach

Where is change happening?

How are floods changing?

What is causing the change?

How to adjust flood frequencies for change?

Detection

Monotonic trends

Step trends

Peaks-over-threshold
- 2 events per year
- 1 event per 5 years

Attribution

Use national datasets of dams, land cover change, and precipitation to develop and test hypotheses for causal attribution of observed changes

Adjustment

Develop an assessment framework to evaluate different approaches to trend adjustment where the "true" trend is known.

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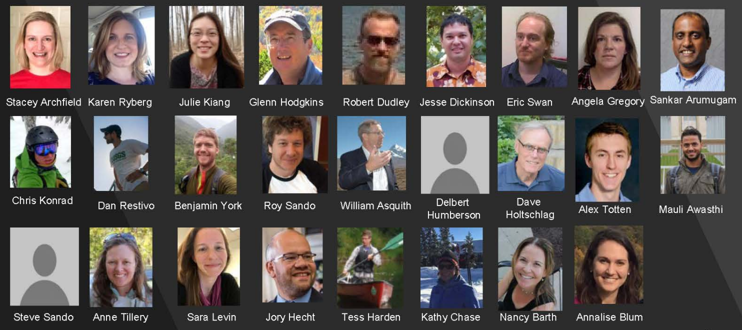
Research Team

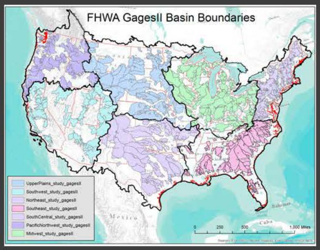
Research team and collaborators (N = 26)



Stacey Archfield
Karen Ryberg
Julie Kiang
Glenn Hodgkins
Robert Dudley
Jesse Dickinson
Eric Swan
Angela Gregory
Sankar Arumugam
Chris Konrad
Dan Restivo
Benjamin York
Roy Sando
William Asquith
Delbert Humberson
Dave Holtschlag
Alex Totten
Mauli Awasthi
Steve Sando
Anne Tillery
Sara Levin
Jory Hecht
Tess Harden
Kathy Chase
Nancy Barth
Annalise Blum

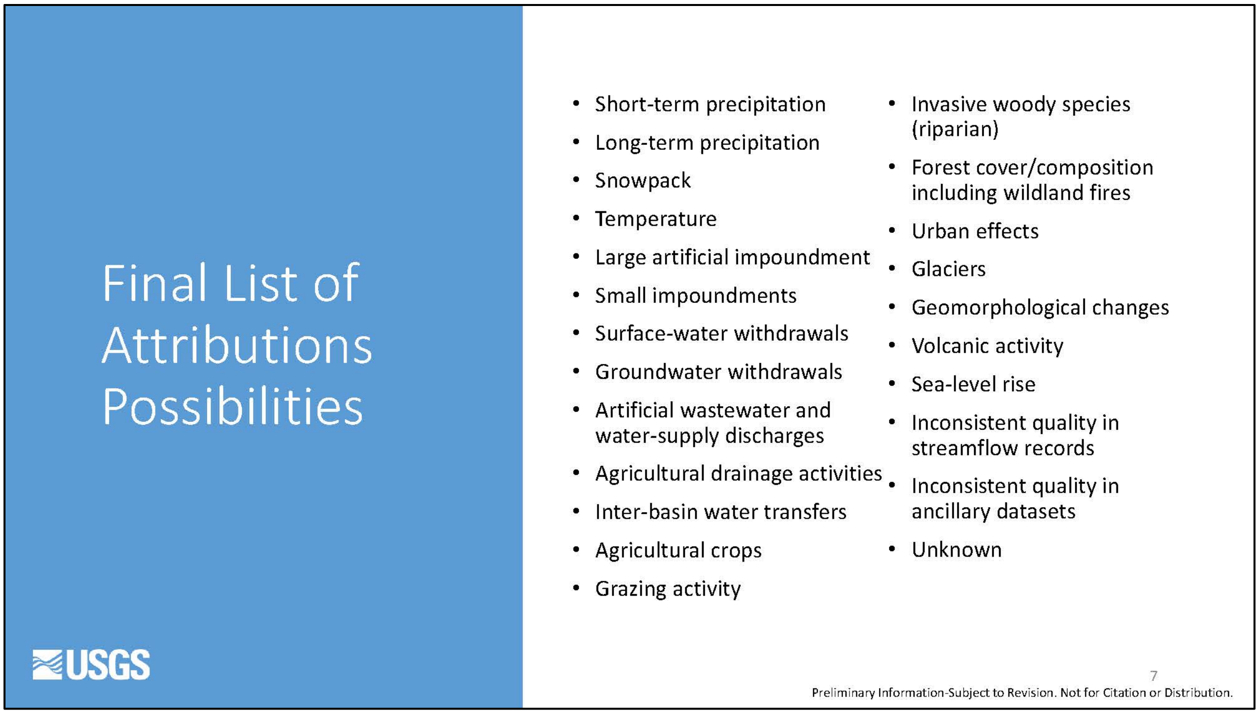
Attribution of Change – A Regional, Expert-Driven Approach using a Multiple Working Hypotheses Framework

75 years: 1941-2015 (n = 1464)



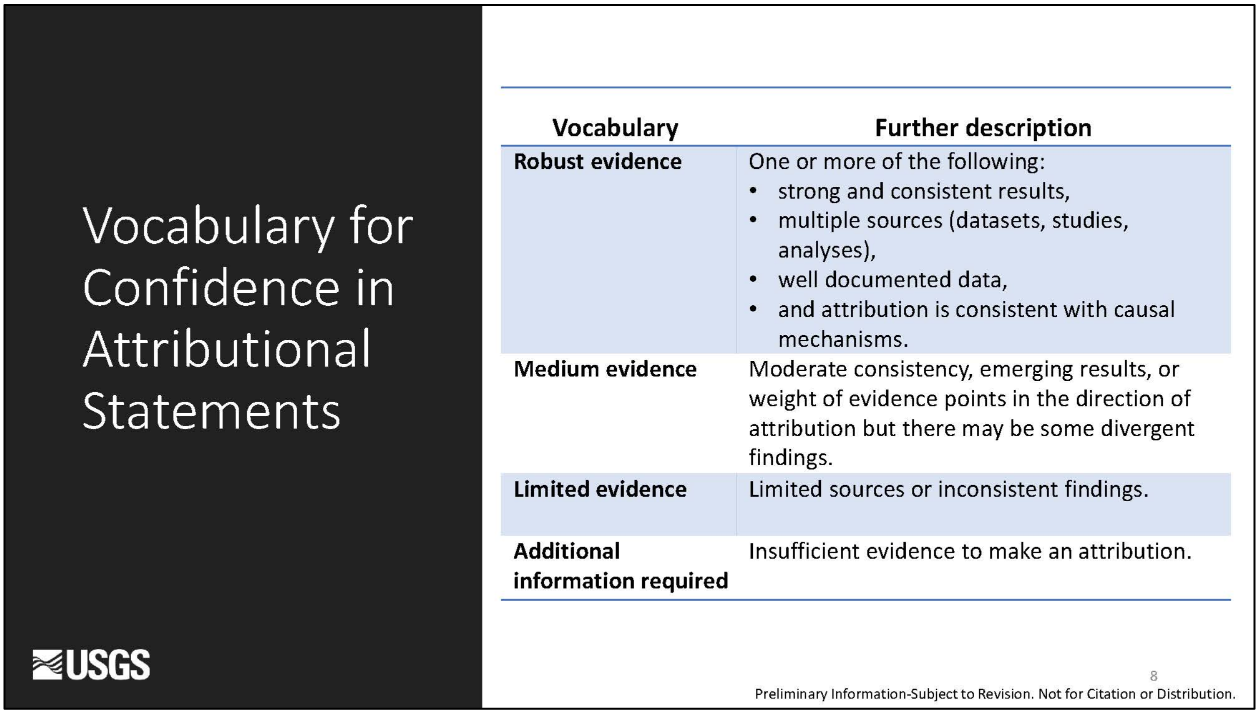
- Artificial Discharge
- Atmospheric Rivers
- Climate Variability
- Crop Type
- Data Quality
- Deforestation
- Developed Land
- Diversions
- Drainage
- Drought
- Fire
- Geomorphological Changes
- Grazing
- Groundwater Withdrawals
- Hurricanes and Tropical Storms
- Invasive Woody Species
- Percent Agricultural Land
- Population
- Precipitation
- Regulation
- Sea-level Rise
- Seismic Activity
- Temperature
- Seasonal Patterns of Change
- Volcanic Activity

The study is limited to national level analyses using attribution characteristics available at this scale. Further research is needed at the local and regional levels to understand drivers of flood change. The national results can be used as a starting place for detailed regional analyses that can leverage local expertise and regional model results.



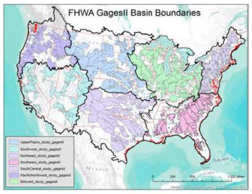
Final List of Attributions Possibilities

- Short-term precipitation
- Long-term precipitation
- Snowpack
- Temperature
- Large artificial impoundment
- Small impoundments
- Surface-water withdrawals
- Groundwater withdrawals
- Artificial wastewater and water-supply discharges
- Agricultural drainage activities
- Inter-basin water transfers
- Agricultural crops
- Grazing activity
- Invasive woody species (riparian)
- Forest cover/composition including wildland fires
- Urban effects
- Glaciers
- Geomorphological changes
- Volcanic activity
- Sea-level rise
- Inconsistent quality in streamflow records
- Inconsistent quality in ancillary datasets
- Unknown



Vocabulary for Confidence in Attributional Statements

Vocabulary	Further description
Robust evidence	One or more of the following: • strong and consistent results, • multiple sources (datasets, studies, analyses), • well documented data, • and attribution is consistent with causal mechanisms.
Medium evidence	Moderate consistency, emerging results, or weight of evidence points in the direction of attribution but there may be some divergent findings.
Limited evidence	Limited sources or inconsistent findings.
Additional information required	Insufficient evidence to make an attribution.



Gage #	Direction of trend	Primary attribution	Secondary attribution	Standard Confidence Statement	Attribution notes
ND05059500	Increase	Long-term precipitation		Regulation as cause of change refuted, Climate variability probable cause, Robust evidence	A dramatic increase in precipitation in this region has caused much larger flows (citations), despite regulation that would have made a decrease more likely - Since March 1993, flood flows that are diverted from the Sheyenne River just downstream from gaging station Sheyenne River above Sheyenne River Diversion near Horace (station 05059300) bypass this station (cite NWISWeb https://waterdata.usgs.gov/nwis/wys_rpt/?site_no=05059500).

Attribution of Change—Goals and an Example

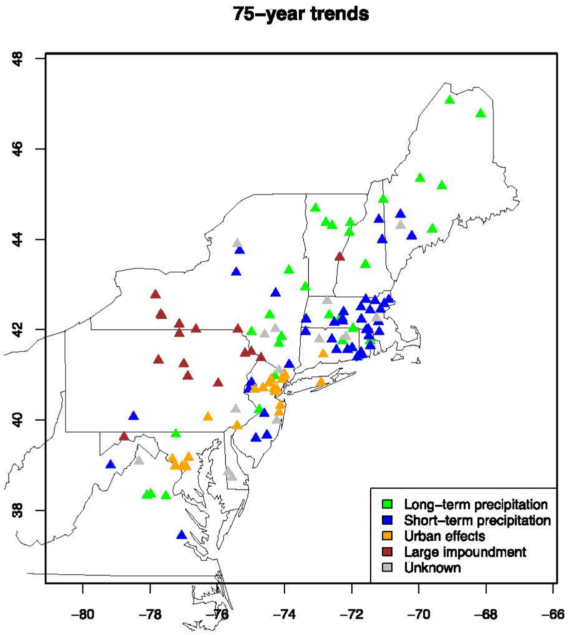
Each statistically significant result will have a primary attribution assigned to it with a statement of confidence and possibly a secondary attribution.

USGS

Examples

Climate-Related Attributions

Northeast Region Monotonic Trends



🟩 Long–term precipitation
🟦 Short–term precipitation
🟧 Urban effects
🟥 Large impoundment
⬜ Unknown

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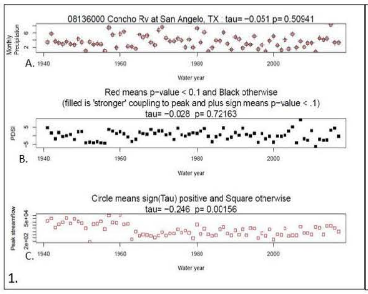
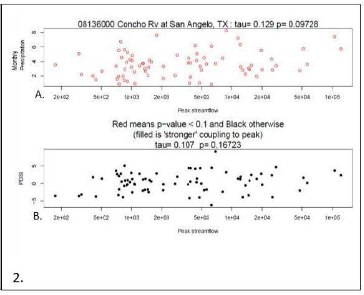
South Central Region



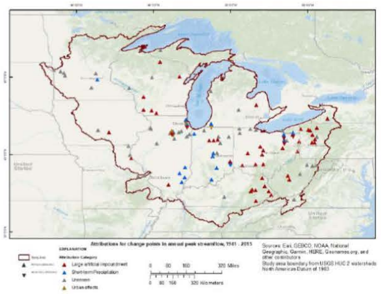
1.

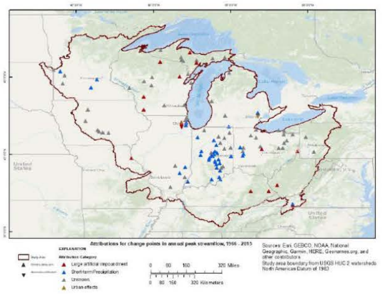


2.

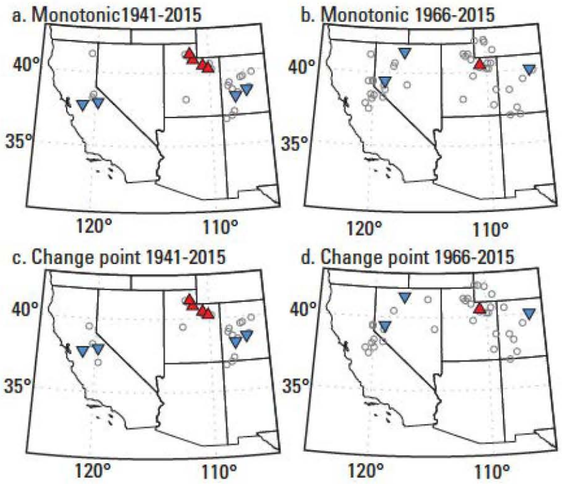
USGS

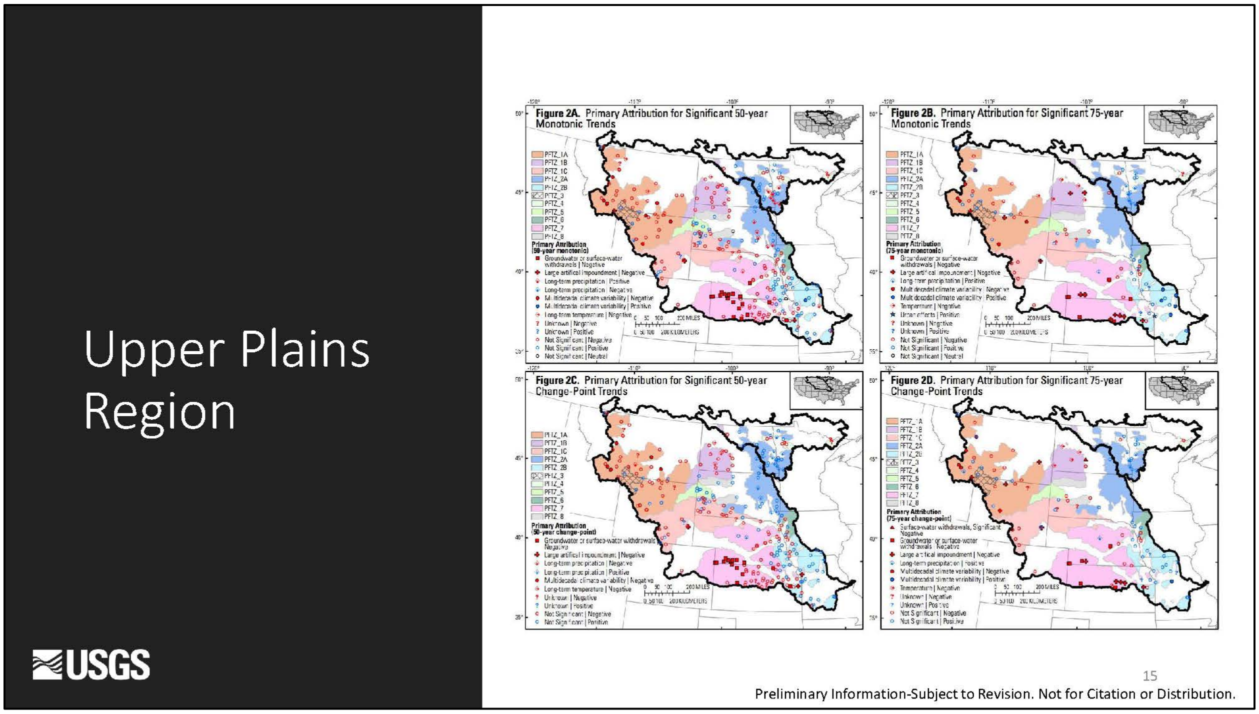
Midwest Region





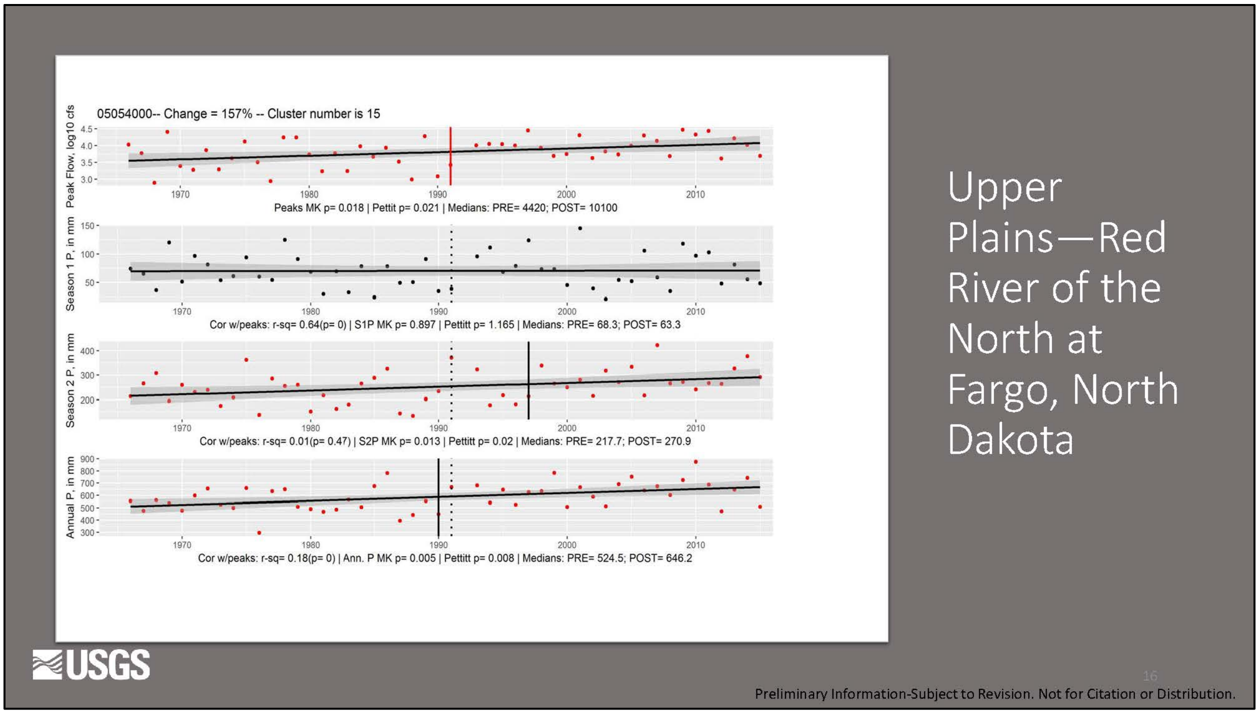
Southwest Region





Upper Plains Region

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



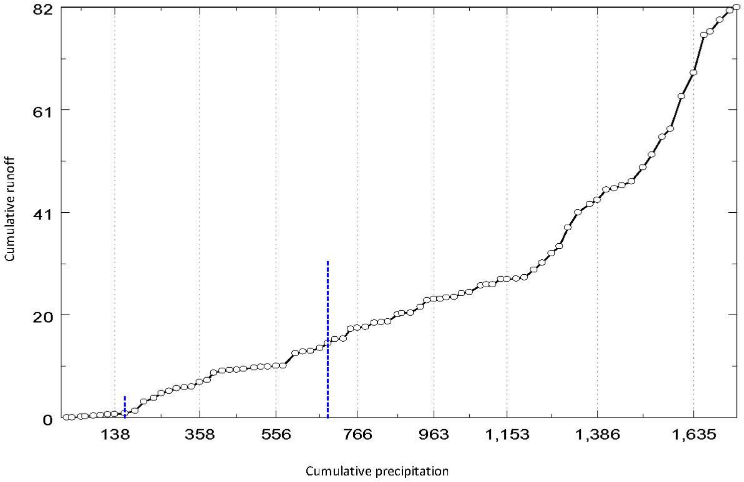
Upper Plains—Red River of the North at Fargo, North Dakota

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

Upper Plains—Double-Mass Curve

The theory of the double-mass curve is based on the fact that a graph of the cumulation of one quantity against the cumulation of an other quantity during the same period will plot as a straight line so long as the data are proportional; the slope of the line will represent the constant of proportionality between the quantities. A break in the slope of the double-mass curve means that a change in the constant of proportionality between the two variables has occurred or perhaps that the proportionality is not a constant at all rates of cumulation.

USGS Water Supply Paper 1541-B, 1960

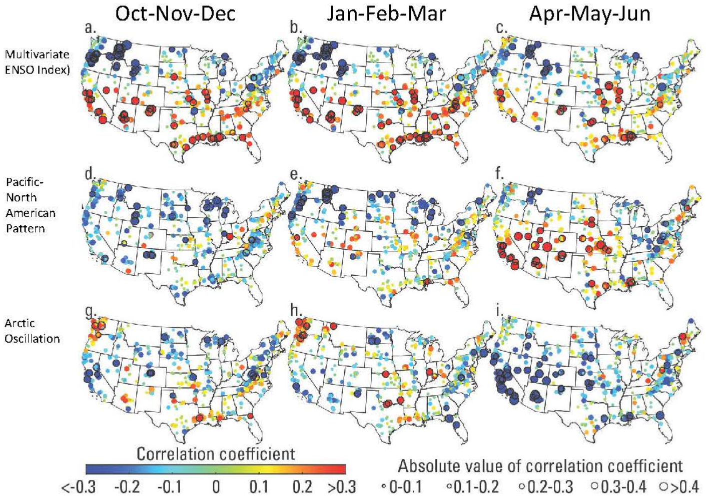


USGS

National Seasonal Patterns with Oceanic and Atmospheric Indices

Dickinson, J.E., Harden, T.M., and McCabe, G.J., 2019, **Seasonality of climatic drivers of flood variability in the conterminous United States**: Scientific Reports, v. 9, no. 1, 10 p., https://doi.org/10.1038/s41598-019-51722-8.

USGS



Phase II publications

- 8-chapter USGS Professional Paper providing trend and change point attribution for seven regions in the conterminous United States (chapters in review or editorial)
- A data release with the attributions and some supporting data (pending approval)
- Collaboration with Johns Hopkins University: Blum, Ferraro, Archfield, and Ryberg, *Causal effect of impervious cover on annual flood magnitude for the United States*, under revision

USGS

- Karen Ryberg
  Research Statistician
  USGS Dakota Water Science Center
  kryberg@usgs.gov

USGS

3.3 Day 1: Session 1C – Precipitation

Session Chair: Elena Yegorova, NRC/RES/DRA

3.3.1 Presentation 1C-1 (KEYNOTE): Planned Improvements for NOAA Atlas 14 Process and Products

Authors: Products. Sanja Perica, Hydrometeorological Design Studies Center, Office of Water Prediction, National Weather Service, National Oceanic and Atmospheric Administration (NOAA/NWS/OWP/HDSC); Sandra Pavlovic, Michael St. Laurent, Carl Trypaluk, and Dale Unruh, NOAA/NWS/OWP/HDSC and University Corporation for Atmospheric Research

Speaker: Sanja Perica

3.3.1.1 Abstract

Since 2004, the Hydrometeorological Design Studies Center (HDSC) of the National Oceanic and Atmospheric Administration's (NOAA) Office of Water Prediction has been in the process of updating outdated precipitation frequency estimates from the 1950s, 60s and 70s for U.S. states and affiliated territories in NOAA Atlas 14. NOAA Atlas 14 estimates are used for a variety of infrastructure design and planning activities under federal, state, and local regulations and are available for download from the Precipitation Frequency Data Server.

Funding for NOAA Atlas 14 work dictates that updates are done in volumes based on state boundaries. Volumes are typically produced in a serial workflow stretching over many years. This approach ultimately raises concerns over data continuity and currency among different volumes. Ideally, a well-defined, consistent, and reliable funding approach will be set to ensure that estimates are updated simultaneously for the whole country in 10-15 year cycles.

For future updates, HDSC proposes to develop an enhanced suite of products that will, in addition to current products, also have design storms, areal precipitation frequency estimates and confidence intervals of variable widths. All products will be produced using a newly developed non-stationary NOAA Atlas 14 frequency analysis modeling approach that can characterize the uncertainty due to non-stationary climate. As part of that effort, HDSC has been investigating the feasibility of incorporating future climate projections into the process and assessing the added value of new estimates with respect to traditional NOAA Atlas 14 estimates. Initial results indicate several issues that require further investigation; they will be discussed in the presentation.

3.3.1.2 *Presentation (ADAMS Accession No. ML20080M191)*

NATIONAL WEATHER SERVICE
Protecting Lives and Property for 150 Years

Planned Improvements for NOAA Atlas 14 Process and Products

Presenter: Sanja Perica

**Authors: Sanja Perica[1], Sandra Pavlovic[1,2], Michael St. Laurent[1,2]
Carl Trypaluk[1,2], Dale Unruh[1,2]**

[1] Hydrometeorological Design Studies Center (HDSC), Office of Water Prediction (OWP), NWS, NOAA

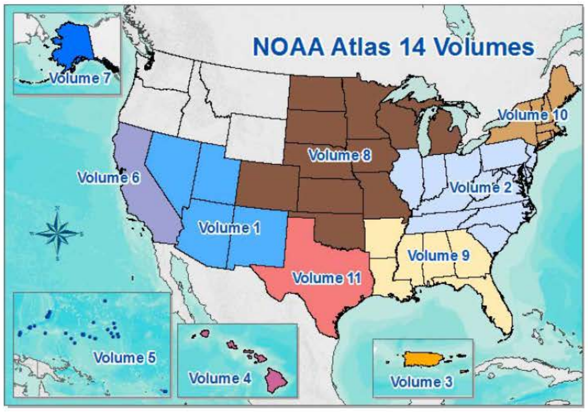
[2] University Corporation for Atmospheric Research

U.S. NRC Probabilistic Flood Hazard Assessment (PFHA) Research Workshop, 19 February 2020

What is NOAA Atlas 14?

- ❑ Since early 2000s HDSC has been updating precipitation frequency estimates for various parts of the United States and affiliated territories. Updated estimates with relevant supplementary information are published in NOAA Atlas 14 "Precipitation-Frequency Atlas of the United States."
- ❑ Atlas 14 supersedes NOAA publications HYDRO35, TP40, TP49 and Atlas 2 published in 1950s to 1970s.
- ❑ Funding model dictates that Atlas 14 updates are done in stages based on state boundaries.

  2004: Vols 1 & 2 (19 states)
  …
  2013: Vols 8 & 9 (17 states)
  2015: Vol 10 (7 states)
  2018: Vol 11 (TX)
  ????: Vol 12 (ID, MT, OR, WA, WY).



What are Precipitation Frequency Estimates?

- ❑ **Precipitation Frequency Estimate** (at a given location): Precipitation **D**epth (or **I**ntensity) for a specific **D**uration that has a certain **F**requency of occurring.

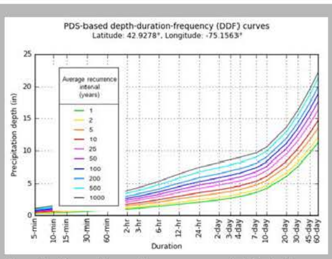
- ❑ **Frequency:**

Annual Exceedance Probability ("1-in-N event")

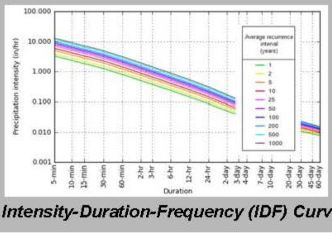
- Probability associated with exceeding a given amount of precipitation for a specified duration at least once in any given year.
- Ex. AEP of 1-in-100 equates to a 1% chance of the amount being exceeded at least once in any year.

Average Recurrence Interval, Return Period ("N-year event")

- Average time between precipitation events exceeding particular magnitude for a specified duration.
- Ex. 100-year amount on average occurs every 100 years.



Depth-Duration-Frequency (DDF) Curves



Intensity-Duration-Frequency (IDF) Curves

Where are Atlas 14 Estimates Used?

- ❑ NWS uses for monitoring observed/ forecasted rain to indicate flooding threats.

- ❑ Widely used to estimate severity of historic events.

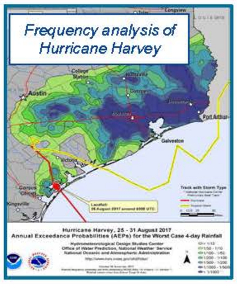
Forbes The Rainfall In Texas Is Changing And Here Is Proof

USA TODAY

Ellicott City rainstorm confirmed as 1-in-1,000 event — the second in two years

- ❑ HDSC analyzes severity of **selected** events

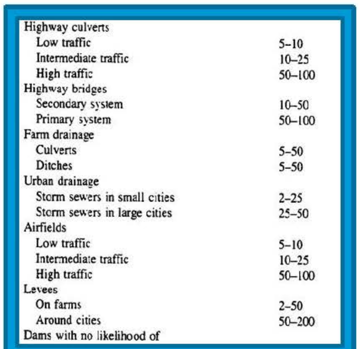
Frequency analysis of Hurricane Harvey



http://www.nws.noaa.gov/oh/hdsc/aep_storm_analysis/index.htm

- ❑ Estimates serve as the de-facto standards for designing, building and operating infrastructure to withstand the forces of heavy precipitation and floods.

- ❑ Selection of design criteria are governed by cities, municipalities, local or state governments and generally **depends on acceptable risk of failure.**



Highway culverts	
Low traffic	5–10
Intermediate traffic	10–25
High traffic	50–100
Highway bridges	
Secondary system	10–50
Primary system	50–100
Farm drainage	
Culverts	5–50
Ditches	5–50
Urban drainage	
Storm sewers in small cities	2–25
Storm sewers in large cities	25–50
Airfields	
Low traffic	5–10
Intermediate traffic	10–25
High traffic	50–100
Levees	
On farms	2–50
Around cities	50–200
Dams with no likelihood of	

Generalized design criteria for water-control structures.
From Chow, "Applied Hydrology"

Why Is It Important for Regulatory Authorities to Reference Most Recent Estimates?

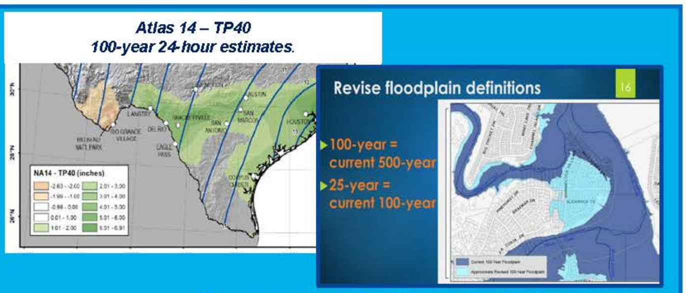
- ☐ Over-estimated precipitation frequency estimates can cause unnecessary cost to taxpayers or developers; under-estimated can result in destruction of property and loss of human life.
- ☐ Atlas 14 supersedes NOAA publications from 1950s to 1970s. New estimates are superior in terms of accuracy, reliability, and resolution.

Example from Volume 11 (TX)
City of Austin analysis (NA14 vs TP40)*:

500-year floodplain is now 100-year floodplain

100-year floodplain increased ~25%

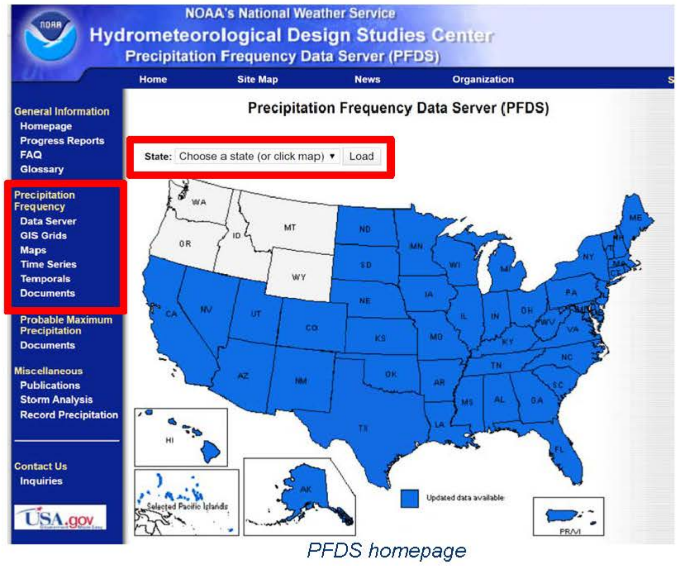
number of buildings in floodplain increased from ~3700 to ~6500



**Analysis does not include Colorado River floodplain*
Source: http://www.austintexas.gov/edims/document.cfm?id=302092

Where to Find Atlas 14 Estimates?

- ☐ NOAA Atlas 14 products can be downloaded from **Precipitation Frequency Data Server (PFDS)** hdsc.nws.noaa.gov/hdsc/pfds/index.html
- ☐ **Estimates for a specific location** can be retrieved by clicking on appropriate state on the map or selecting the state name from the drop-down menu
- ☐ **Estimates applicable across states in each volume** Can be retrieved from side menu under “Precipitation Frequency” tag

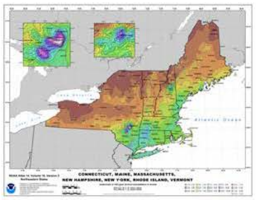


PFDS homepage

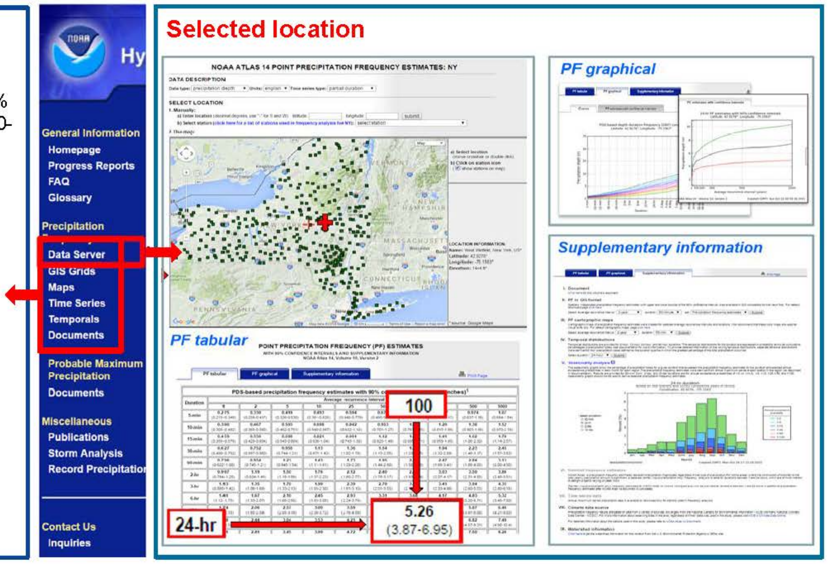
Atlas 14 Products

Whole project area

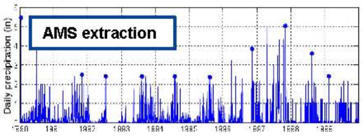
- GIS Grids. 30 arc sec grids of AMS-based and PDS-based estimates with 5% and 95% confidence limits for 5-min to 60-day durations and average recurrence intervals up to 1,000 years
- PF Maps. Cartographic maps for selected durations and ARI

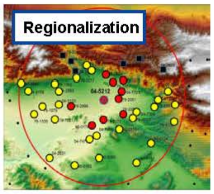


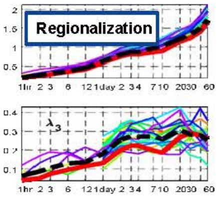
- Time Series
- Temporals
- Documents

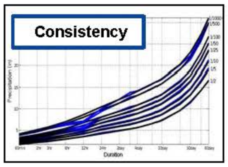


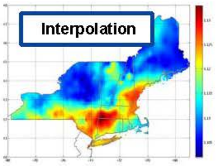
How are the Estimates Calculated?











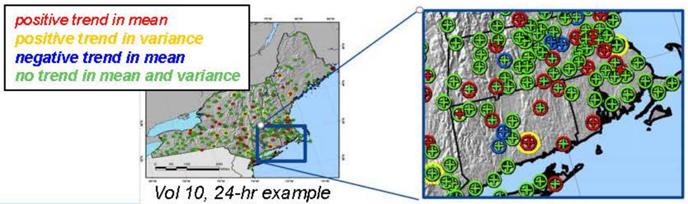
1. **Data collection, Annual Maximum Series (AMS) extraction and QC**
   - Data collection, digitization, formatting
   - Examination of geospatial data and station cleanup
   - AMS extraction for 17 durations and quality control
2. **At-station DDF/IDF curves**
   - Regionalization
   - Derivation of estimates and confidence limits, consistency checks
3. **Interpolation to 30 arc-sec grid**
   - PRISM statistical-geographic approach
4. **Peer review**
   - Funding agencies, HDSC list-server subscribers, others
5. **Revision** (back to steps 1 to 3)
6. **Supplementary information**
   - Documentation, confidence intervals, cartographic maps, etc.
7. **Web publication**

NA14 Stationary Process – Testing Stationarity Assumption

Stationarity is dead – whither water management?" (Milly et al. 2008)

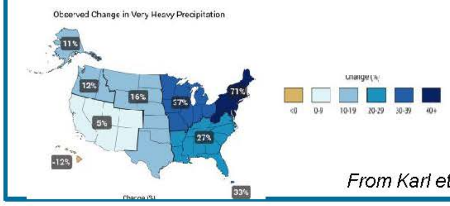
REGIONAL ANALYSIS:
H_0 : no correlation in regional normalized AMS regressed against time (5% level)

AT-STATION ANALYSIS:
Parametric and non-parametric tests



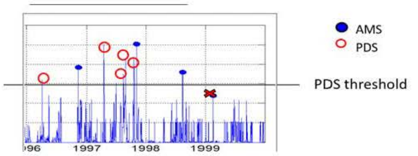
Vol 10, 24-hr example

Climate research indicates positive trends in frequency and magnitude of extreme events.



From Karl et al., 2009

So, why don't we detect consistent trends in NA14? Inadequate tests? Data?



Development of Non-Stationary NA14 Approach

❑ Current approach:

Stationary regional frequency analysis approach based on Generalized Extreme Value (GEV) distribution with parameters calculated from L-moment statistics from AMS (AMS assumed stationary).

❑ Goal:

To develop scientifically defensible non-stationary "NA14 method" that will be applicable across the whole US and valuable for engineering design.

❑ Non-stationary method to be used for future NA14 updates:

- Main modifications/enhancements to current NA14 method
  - ✓ Added new tests for trend detection
  - ✓ Partial Duration Series (PDS)-based Generalized Pareto Distribution (GPD) model replaced AMS-based GEV model
  - ✓ (Generalized) Maximum Likelihood replaced L-moment distribution parameterization approach
  - ✓ Distribution parameterization enabled to vary in time with a wide range of non-linear relationships
  - ✓ Framework flexible to allow for estimating future conditions using different approaches (next slide)

Work done in collaboration with Penn State University (Shaby, Mejia, Bopp).

Development of Non-Stationary NA14 Approach.
Estimating Future Precipitation Frequency Estimates (PFE)

❑ **Extrapolation using historical trends**

- Nonstationary model fitted to observational data; distribution parameterization modeled as function of time

For example, for the location parameter – μ:

- $\mu(t) = \mu_0$
- $\mu(t) = \mu_0 + a\,t$;
- $\mu(t) = \mu_0 + a_1\,t + a_2 t^2 + \ldots$
- $\mu(t) = \exp(a_1 + a_2 t)$
- μ(t) = any non-linear function of t; including sine fns

❑ **Using outputs from (downscaled) climate models**

a) Quasi-stationary “delta” method

- PFEs are estimated for several non-overlapping periods; stationarity is assumed within each period

b) Climate model outputs used directly as covariates for modeling distribution parameterization

For example:
$\mu(t) = a + b\,{*}\text{CMIP5}$
CMIP5 represents value from CMIP5 (downscaled) data chosen to be covariate

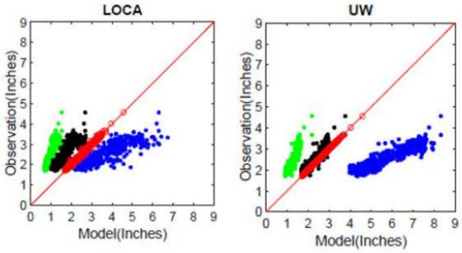
---

Development of Non-Stationary NA14 Approach.
Inclusion of Future Climate Projections

❑ *Work done in collaboration with University of Illinois at Urbana-Champaign (Markus, Angel, Grady) and University of Wisconsin-Madison (Shu, Wang, Lorenz)*

❑ **Evaluation of downscaled CMIP5 model data sets:**

- Period of evaluation: 1960-2005
- Models evaluated:
  - Statistically downscaled: LOCA (32 models); BCCAv2 (20),
    UWPD – University of Wisconsin Probabilistic Downscaling (24 models, >300 realizations)
  - Dynamically downscaled: NA-CORDEX (6)
- Compared: various modeled and observed extreme precipitatio ges, AMS & PDS climatology, AMS, corresponding PF estimates)
- LOCA and UWPD retained for further analysis.



Example. Scatterplot of 1960-2005 mean AMS calculated based on station observed data and modeled data (green: lowest values, black: medians; red: closest values to observations; blue: highest values).

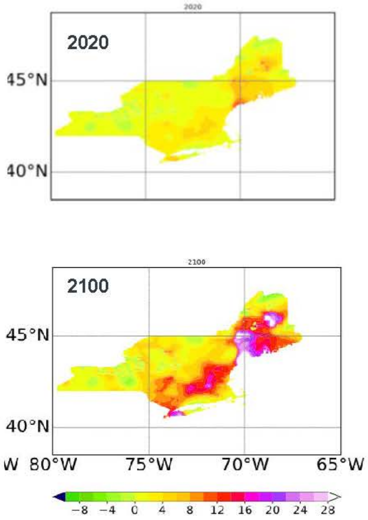
Development of Non-Stationary NA14 Approach. Inclusion of Future Climate Projections

☐ **Considered:**

- RCP4.5 and RCP8.5 emission scenarios.
- LOCA and UWPD downscaled CMIP5 datasets.

☐ **Main findings:**

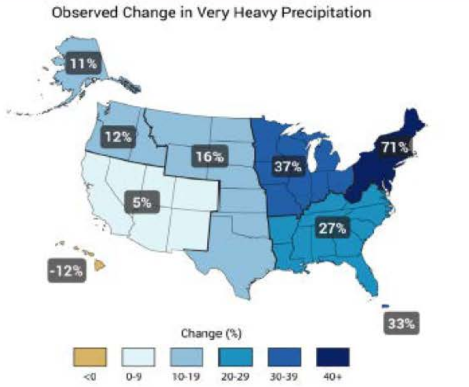
- Extrapolation of historical trends into future is usually not advisable.
- PF estimates for Volume 10 area will generally continue increasing, regardless of emission scenario or model used.
- There are considerable differences in projections depending on what dataset and what model are used.
- Projected PF spatial patterns are also quite dissimilar among different models/datasets.
- Uncertainties are significant; probabilistic approaches may be necessary.



Projected increases in % for 100-year 1-day estimates for years 2020 and 2100 under RCP4.5 scenario based on LOCA data and Delta method.

Addressing Climate Change – Some Considerations

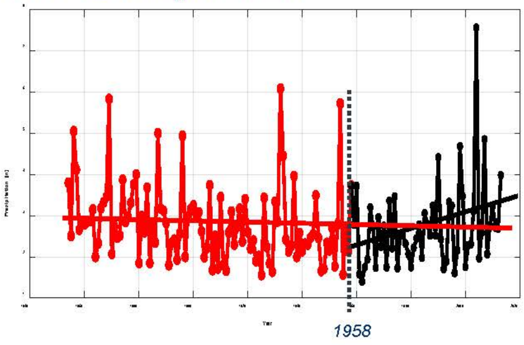
☐ Extrapolating historical trends. How far back to go in the analysis?



Percent increases in the amount of precipitation falling in very heavy events (defined as the heaviest 1% of all daily events) from 1958 to 2012 for each region (from Karl et al., 2009)

Amherst, MA 1-day AMS

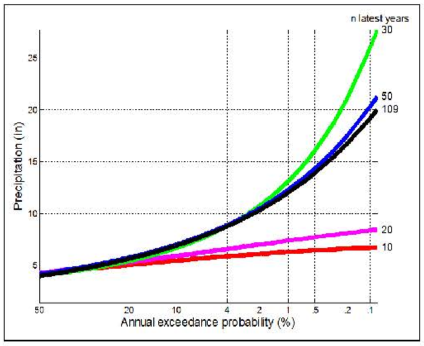
1958 – 2012 positive trend
1854 – 2012 negative trend



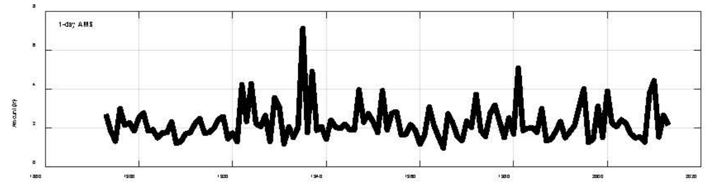
Addressing Climate Change – Some Considerations

❑ Is 30-year long record adequate for frequency analysis?

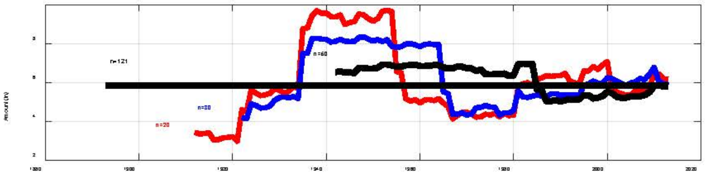
Effect of sample size on estimates



Amherst, NY



100-year estimates from 20-, 30- and 50 years of data over time.



Ensuring Accurate Assessment of Non-Stationary Climate Effects on Estimates

❑ Effects of methodology selection

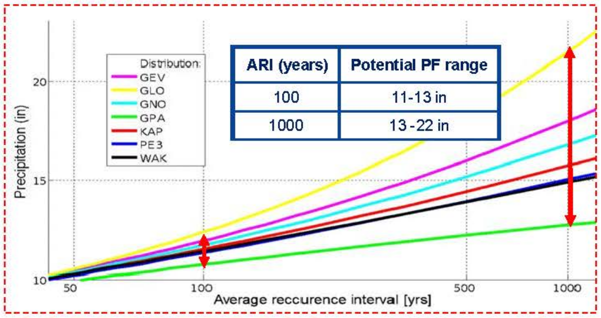
Example 1. Parameterization

24-hour 100-year estimates for BARRANQUITAS, PR station

- stationary NA14 (L-moments) vs. Non-stationary NA14 (MLE, μ(t)): 15.4 vs 20.7 in (34% increase)
- stationary NA14 (L-moments) vs. Stationary NA14 (MLE): 15.4 vs 19.9 in (29% increase)

Example 2. Distribution selection

- All distributions provide acceptable fit to data based on statistical tests.
- 13 inches of rain could be 1000-year or 100-year event (or anything in-between) depending on what distribution is selected.



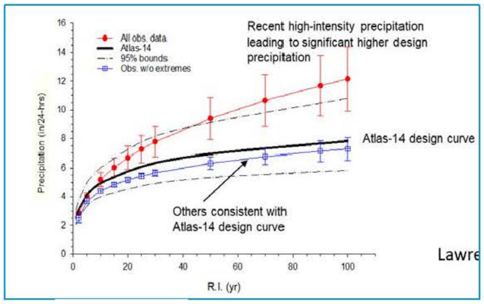
ARI (years)	Potential PF range
100	11-13 in
1000	13 -22 in

Ensuring Accurate Assessment of Non-Stationary Climate Effects on Estimates

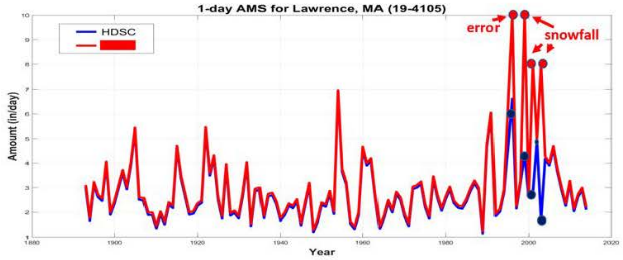
❑ Data issues

Example 1. External review of stationary NA14 estimates

24-hour estimates for Lawrence, MA station (from Volume 10)



Source: 🟥

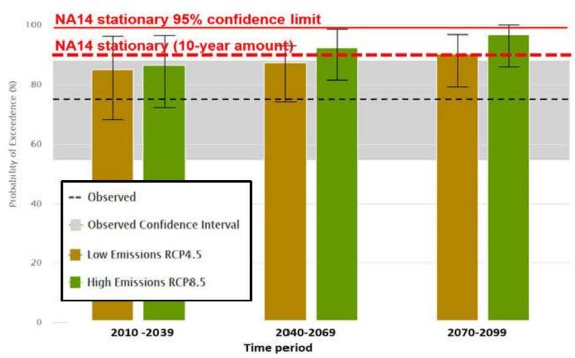

1-day AMS for Lawrence, MA (19-4105)

Increase in PFs almost entirely due to data errors.

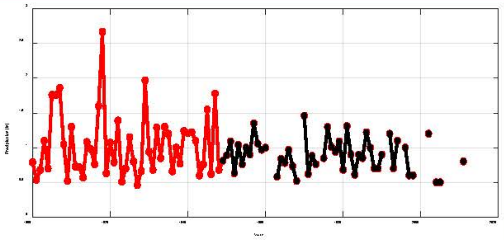
Accurate Assessment of Non-Stationary Climate Effects on Estimates

❑ Data issues

Probability of Exceeding 1.6 Inches of Precipitation in 1 Hours at Ithaca During Specified 30-Year Periods (%)



Cornell University, Northeast Regional Climate Center (NRCC)
web-based IDF projection tool: http://ny-idf-projections.nrcc.cornell.edu/



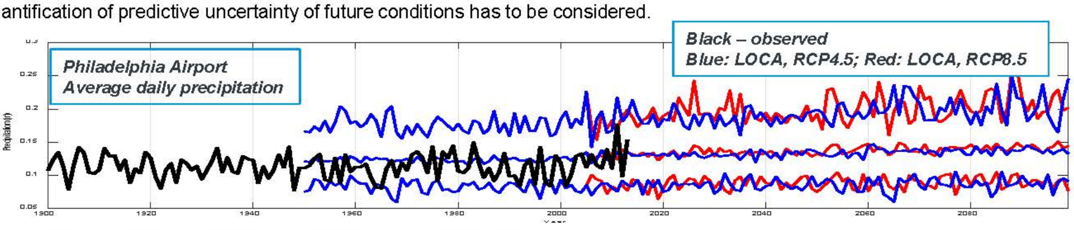
Ithaca, NY

49 years of additional hourly data digitized for NA14

Stationary NA14 estimates higher than most of projected estimates.

Addressing Climate Change – Some Considerations

- ☐ **Design standards will have to change under non-stationarity!**
  - Return period (ARI, AEP) risk and other reliability measures will have to explicitly account for a length of planning period (e.g., design life level, Rootzen and Katz, 2013).
  - Probabilistic approaches will have to replace current deterministic approaches if climate projections are considered. Quantification of predictive uncertainty of future conditions has to be considered.


Philadelphia Airport
Average daily precipitation

Black – observed
Blue: LOCA, RCP4.5; Red: LOCA, RCP8.5

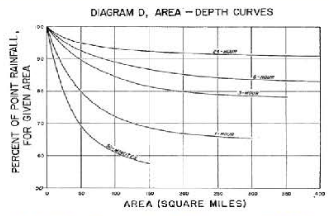
- ☐ **Effects of non-stationarity need to be accurately evaluated.**
- ☐ **Error contribution of stationarity assumption has to be evaluated relative to other sources of error.**

"Stationarity is dead – whither water management?" (Milly et al. 2008)
"Stationarity: wanted dead or alive?" (Lins and Cohn 2011)
"Comment on the announced death of stationarity" (Matalas 2012)
"Negligent killing of scientific concepts: the stationary case" (Koutsoyiannis and Montanari 2014)
"Modeling and mitigating natural hazards: Stationarity is immortal!" (Montanari and Koutsoyiannis 2014)
"Stationarity is undead: uncertainty dominates the distribution of extremes" (Serinaldi and Kilsby 2015)
"Stationarity should always remain the default assumption…" (Salas et al. 2017)

Atlas 14 Proposed Upgrades and Updates - Additional Products

☐ Areal Precipitation Frequency Estimates

- BACKGROUND: Atlas 14 estimates are point estimates. ARFs are used to convert point precipitation to average precipitation over a watershed. Many ARF methods have been proposed, but Weather Bureau's ARF curves from 1958 are still commonly used.
- PROPOSED: Develop location, duration and ARI specific ARF curves for states with NA14 coverage. Design PFDS web tool to delineate a watershed for a selected location and provide corresponding areal precipitation frequency estimates.



Weather Bureau's ARF curves (1958)

☐ Atlas 14 Design Storm

- BACKGROUND: Atlas 14 provides precipitation frequency estimates for a given duration, but designers often need information on how precipitation is distributed in time and not just the total amount.
- PROPOSED: Develop Atlas 14 design storm product with guidance on how to use the product.

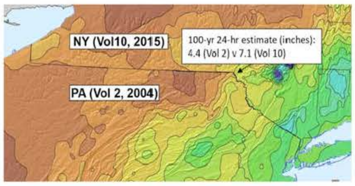
☐ Confidence Intervals

- BACKGROUND: Atlas 14 provides only bounds of 90% confidence interval.
- PROPOSED: Development of confidence intervals of variable width.

Atlas 14 Proposed Upgrades and Updates - Funding Approach

❑ **Current**

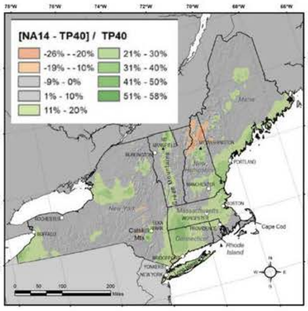
- Estimates are updated in Volumes as funding becomes available.
- Approach results in discontinuities at volumes' boundaries and creates issues for users that typically consider watershed (and not state-based) boundaries.



❑ **Proposed**

- Estimates should be updated on a regular cycle of ~10 years to take advantage of more stations with longer records, addition of most recent data in the analysis and use of modern methods.
- Boundary issues could be avoided by updating all states simultaneously.

Having a continuous and sustainable funding approach will be a small investment that would result in significant return and benefits for infrastructure design in the U.S.



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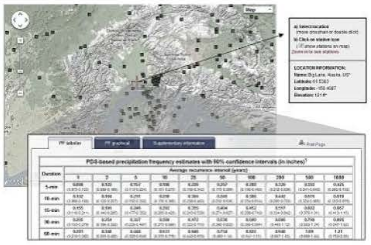
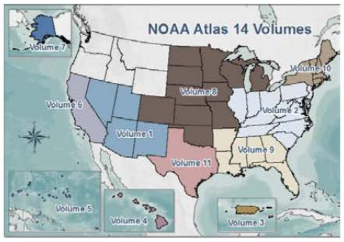
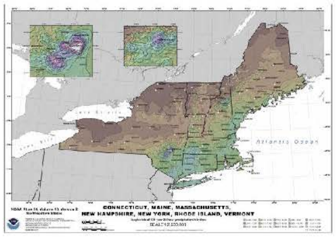






3.3.2 Presentation 1C-2: Application of Point Precipitation Frequency Estimates to Watersheds

Authors: Shih-Chieh Kao and Scott T. DeNeale, Oak Ridge National Laboratory (ORNL)

Speaker: Shih-Chieh Kao

3.3.2.1 Abstract

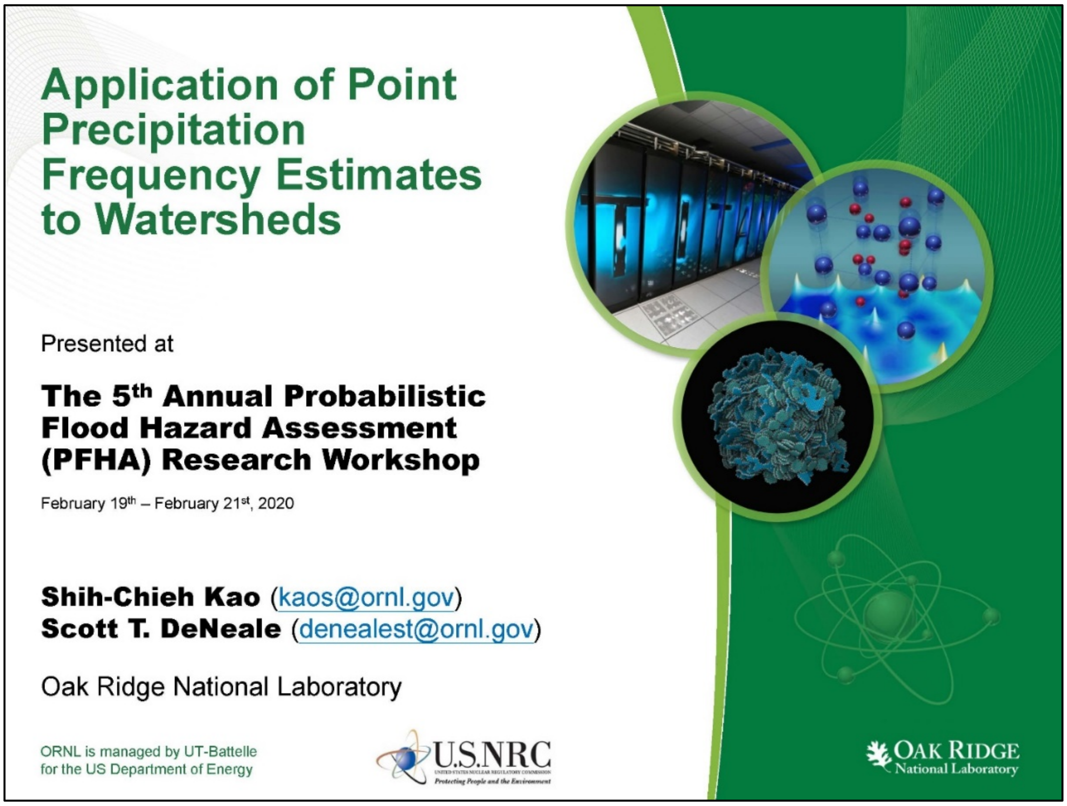
To support the probabilistic flood hazard assessment (PFHA), probabilistic estimates of areal extreme rainfall depth across various watershed sizes are required. Areal reduction factors (ARFs) have been widely used in hydrologic and hydraulic modeling applications to convert point-based precipitation frequency estimates (such as those found in NOAA Atlas 14) to watershed-scale precipitation frequency estimates. In turn, these watershed-scale precipitation frequency estimates are used to simulate extreme flood stage and discharge for infrastructure design and engineered systems operation. The use of ARF is necessary because high spatiotemporal resolution precipitation observations with long period of records, which are needed for accurate areal rainfall frequency estimation, are generally lacking and do not allow for an appropriate characterization of the associated spatial rainfall patterns.

However, compared to modern precipitation frequency analysis products (e.g., NOAA Atlas 14), the progress of ARF development in the U.S. is relatively slow, and the TP-29 ARFs published in the 1950s are still used in practice today. To improve the understanding of ARF variabilities across different precipitation products, ARF models, return periods, geographical locations, and seasons, this study conducts a comprehensive review of recent ARF research. The report summarizes potential precipitation products for ARF applications, and provides use case studies to demonstrate the derivation of ARF in several selected hydrologic regions in the U.S. Based on the results, ARF characteristics and PFHA application challenges are also summarized.

Our overall findings are in line with available literature which suggest ARFs decrease with increasing area, increase with increasing duration, and decrease with increasing return period. The results also show the importance of precipitation data source and ARF fitting method which both contribute to ARF uncertainty. In particular, we find that data length plays an important role in ARF estimation, especially for longer return period ARFs (e.g., greater than 100-year). The study demonstrates the need to improve ARFs with new data and methods for more reliable areal extreme precipitation estimates to support PFHA applications.

One objective of this study is to assist NRC in assessing different classes of fixed-area ARF methods in conjunction with available rainfall data sets to support the development of guidance for application of PFHA. The results of this study are for demonstration purposes only and are not intended to be used for ARF application. Additional research and development efforts, with thorough quality assurance and control performed, should be performed to develop a reliable national ARF product suitable for PFHA application.

3.3.2.2 Presentation (ADAMS Accession No. ML20080M193)



Application of Point Precipitation Frequency Estimates to Watersheds

Presented at

The 5th Annual Probabilistic Flood Hazard Assessment (PFHA) Research Workshop

February 19th – February 21st, 2020

Shih-Chieh Kao (kaos@ornl.gov)
Scott T. DeNeale (denealest@ornl.gov)

Oak Ridge National Laboratory

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Leverage Existing PFA Products

- **To avoid going through the entire chain of precipitation frequency analysis (PFA), we have often opted to look up pre-calculated *T*-year rainfall depths from existing PFA products**
  - TP-40 (Hershfield, 1961)
  - National Oceanic and Atmospheric Administration (NOAA) Atlas 14 (Bonnin et al., 2004 and other volumes)
- **However, most of the PFA products (including NOAA Atlas 14) provide frequency estimates of "point" precipitation**
  - This happens because the annual (or partial duration) maxima are usually identified independently in time.
  - Representative only for a small domain – not directly appropriate for large-scale watershed modeling applications.
  - Appropriate conversion factor is hence needed to derive areal-based extreme precipitation estimate.

Differences between Grid vs. Areal Maximum

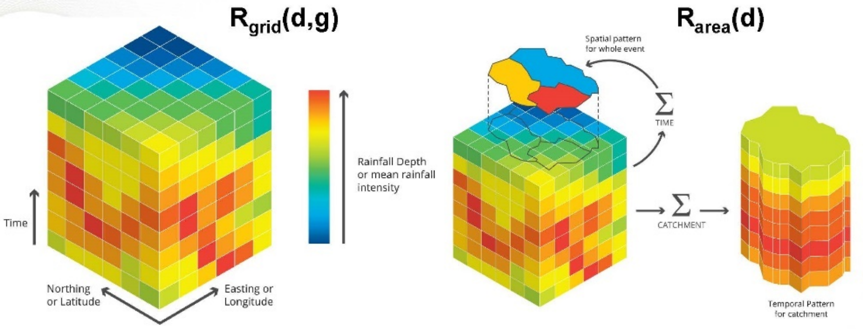
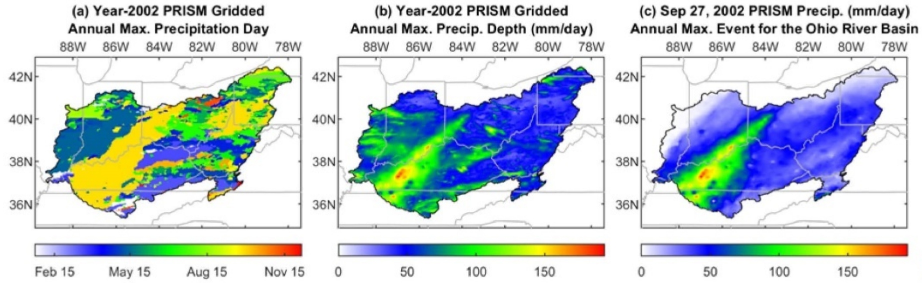


Image Source: Australian Rainfall and Runoff: A Guide to Flood Estimation http://book.arr.org.au.s3-website-ap-southeast-2.amazonaws.com/


(a) Year-2002 PRISM Gridded Annual Max. Precipitation Day

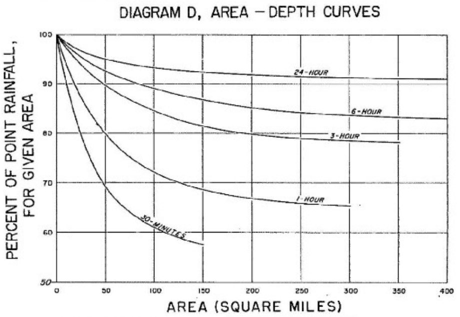
(b) Year-2002 PRISM Gridded Annual Max. Precip. Depth (mm/day)

(c) Sep 27, 2002 PRISM Precip. (mm/day) Annual Max. Event for the Ohio River Basin

Precipitation Areal Reduction Factor (ARF)

- **Existing PFA products (e.g., NOAA Atlas 14) are mostly developed for point rainfall**
- **Areal reduction factor (ARF) is defined as the ratio of areal extreme rainfall depth (P_{area}) to point-based extreme rainfall depth (P_{point})**
  - $P_{area} = P_{point} * ARF$
- **ARFs in common use suffer from several key limitations:**
  - Limited / outdated data
  - Small area sizes (up to 400 mi^2)
  - Do not vary with location, return period, or season

Example ARF curves (from TP-29)



Source: Technical Paper No. 29; noaa.gov

OAK RIDGE National Laboratory

Objectives of this Project

- **Understand and demonstrate how ARFs may vary when using different precipitation data products and ARF methods across different geographical locations, durations, areas, return periods, seasons, and etc.**
  - Task 1: Provide a summary of available precipitation products that can be used to develop ARFs.
  - Task 2: Provide a critical review of available ARF methods with a view to addressing the deficiencies in the commonly used empirical methods.
  - Task 3: Demonstrate use of the most promising method/dataset combinations through selected test cases.
- **Support Nuclear Regulatory Commission (NRC) on the development of future Probabilistic Flood Hazard Assessment (PFHA) guidance on ARFs used by NRC licensees**

OAK RIDGE National Laboratory

Fixed-area ARF

- **Following a watershed**
  - Find the maximum rainfall depth for a watershed
  - Maximum rainfall may capture one or multiple storms
  - More suitable for PHFA applications

Storm-centered ARF

- **Following a storm**
  - Describe the maximum rainfall depth of a moving storm
  - Storm may move across multiple watersheds
  - More suitable for deterministic storm analysis (e.g., PMP)

Given our specific focus of PFHA, this study only examined fixed-area ARF.

Watershed view of ARF

Storm view of ARF

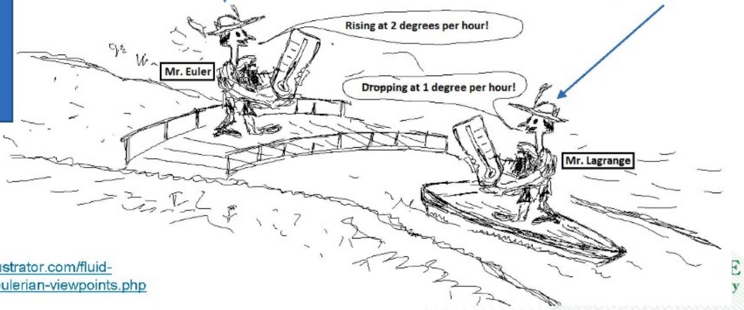


Image from http://www.flowillustrator.com/fluid-dynamics/basics/lagrangian-eulerian-viewpoints.php

Study Approach

- **Factors affecting ARFs**
  - Area, duration, and return period
  - Different ARF methods
  - Precipitation products to use
  - Geographical locations
  - Seasonality
- **Case study application**
  - Regional comparison
    - 3 hydrologic regions (HUC02), 5 precipitation products, and 6 ARF methods
  - National comparison
    - 18 hydrologic regions (HUC02), 1 precipitation product, and 1 ARF method
- **Evaluation through fitting statistics (e.g., NSE, RMSE, R^2)**
- **Only consider "geographically-fixed-area" ARF**

Key Metrics for Data Consideration

- **Accuracy/precision**
  - How reliable are the precipitation estimates available from the product, and what sources of error and uncertainty exist?
- **Temporal coverage**
  - For what time period are the precipitation estimates available, and are there any gaps in temporal coverage?
- **Data latency**
  - How regularly are the precipitation estimates uploaded online?
- **Spatial coverage**
  - For what regions are the precipitation estimates available?
- **Temporal resolution**
  - How frequently are precipitation estimates provided?
- **Spatial resolution**
  - For what horizontal spacing or area size are individual precipitation estimates available?

Selected Precipitation Products in Case Study

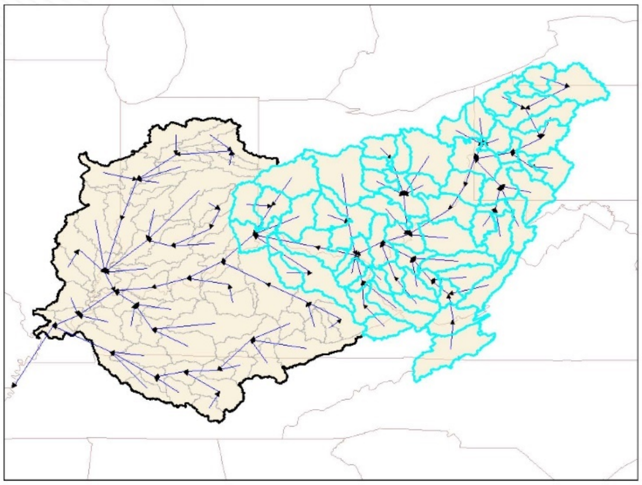
Precipitation Products	Provider	Dataset Type	Coverage Start	Coverage End	Data Latency	Spatial Coverage	Temporal Resolution	Spatial Resolution
Gauge-only Datasets								
Hourly Precipitation Data (DSI3240)	NOAA National Centers for Environmental Information (NCEI)	Gauge observation	1940	2013	Data since 2014 have not been released (checked 10/17/2017)	U.S. (including AK, HI, PR)	Hourly	Gauge
Gauge-driven Products								
Daymet version 3 (Daymet)	Oak Ridge National Laboratory (ORNL)	Gridded from gauge observation	1980	2017	Annual update	North America	Daily	1 km * 1 km
Daily PRISM Dataset (PRISM)	Oregon State University	Gridded from gauge observation (and partially with radar)	1981	present	Operational (updated automatically)	U.S. (48 states)	Daily	1/24 deg * 1/24 deg (~ 4 km * 4 km)
Livneh CONUS Near-surface Meteorological Data (Livneh)	University of Colorado, Boulder	Gridded from gauge observation	1950	2013	No scheduled update (checked 10/17/2017)	U.S. (48 states), Mexico, & Canada (south of 53N)	Daily	1/16 deg * 1/16 deg (~ 6 km * 6 km)
Radar-driven Products								
NCEP National Stage IV Analyses (ST4)	NOAA National Centers for Environmental Prediction (NCEP)	Merged radar and gauges (with QC)	2002	present	Operational (updated automatically)	U.S. (48 states), excluding California-Nevada & Northwest RFCs	Hourly	4 km * 4 km

- These precipitation products exhibit long temporal coverage, broad spatial coverage, and sufficient temporal/spatial resolution.
- DSI3240 is only analyzed for Region 05 (Ohio).

Case Study Assessment Procedures

- **Annual maximum series (AMS) searching**
  - *Data*
    - PRISM (1981–2017), Daymet (1980–2017), ST4 (2002–2017), Livneh (1950–2013), DSI3240 (1950–2013)
  - *Duration*
    - All: 1-day, 2-day, 3-day
    - Additionally for ST4 & DSI3240: 1-hr, 2-hr, 3-hr, 6-hr, 12-hr, 18-hr
  - *Season*
    - All season, Warm season (May–Oct), Cool season (Jan–Apr, Nov–Dec)
  - *Grid AMS* (P_{grid}): annually at each grid
  - *Areal AMS* (P_{area}): annually at each HUC08, HUC06, HUC04, HUCac
- **Sample ARF at each areal units (HUCs)**
  - Average AMS
    - (Temporal average of P_{area}) / (Temporal and spatial average of P_{grid})
  - T-year estimate
    - Fitting AMS by GEV, and getting T-year estimates (e.g., $P_{area,10yr}$)
    - $P_{area,Tyr}$ / (Spatial average of $P_{g11,Tyr}$)
- **Regional fitting by different ARF models**

Watershed-based AMS Searching Approach



- **Increase AMS samples to cover a wider range of watershed sizes**
- **Define additional spatial unit HUCac based on watershed connectivity**
  - For each HUC08, using its connectivity with other HUC08s to identify the entire upstream contributing watershed as HUCac
  - Use HUCac to search AMS
- **Use HUC08, HUC06, HUC04, and HUCac AMS to fit different ARF models**
  - 120 HUC08: 290 – 840 km²
  - 21 HUC06: 4,400 – 54,000 km²
  - 7 HUC04: 15,000 – 85,000 km²
  - 46 HUCac: 4,600 – 420,000 km²

Selected ARF Models

- **Empirical Methods**
  - M1: Leclerc & Schaake (1972) – fitted formula of US Weather Bureau TP-29

    $$ARF(A,D) = 1 - e^{aD^b} + e^{(aD^b - cA)}$$
  - M2: Koutsoyiannis and Xanthopoulos (1999) – fitted UK-NERC ARF relationship (NERC, 1975)

    $$ARF(A,D) = 1 - \frac{aA^{(b - c\ln A)}}{D^d}$$
  - M3: Hydrological Atlas of Switzerland Model (Grebner et al., 1998)

    $$ARF(A) = \frac{a_0}{(A + a_2)^{a_1}} + a_3 e^{-a_4 A}$$
  - M4: Australian Rainfall & Runoff (ARR) Guideline (Nathan and Weinmann, 2016)

    $$\begin{aligned} &ARF(A,D,AEP) \\ &= 1 - a\left(A^b - c\log_{10} D\right)D^{-d} \\ &+ eA^f D^g (0.3 + \log_{10} AEP) \\ &+ h10^{iAD}(0.3 + \log_{10} AEP) \end{aligned}$$
- **Dynamic Scaling Model**
  - M5: De Michele et al. (2001)

    $$ARF(A,D) = \left[1 + w\left(\frac{A^z}{D}\right)^b\right]^{-v/b}$$
- **Extreme Value Theory**
  - M6: Overeem et al. (2010)

    $$\begin{aligned} &ARF(A,D,AEP) = P(A,D,AEP)/P(A^*,D,AEP) \\ &P(A,D,AEP) = GEV^{-1}(1 - AEP|\mu,\gamma,\kappa) \\ &\mu(A,D) = aD^b + (c + d\ln D)A^e \\ &\gamma(A,D) = f\ln A + g\ln D + h \\ &\kappa(A) = i\ln A + j \end{aligned}$$

M5: De Michele Dynamic Scaling Model

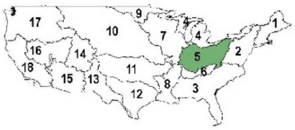
- **De Michele et al. (2001) and (2011)**
  - Uses the concepts of dynamic scaling and statistical self-affinity to find a general expression for the mean annual maxima precipitation as a function of the rainfall duration and area
- $\boldsymbol{ARF(A,D) = \left[1 + w\left(\frac{A^z}{D}\right)^b\right]^{-v/b}}$
  - *A*, area (km^2)
  - *D*, duration (hr)
  - Four parameters: *v*, *b*, *w*, *z*
- **ORNL Fitting**
  - Minimize the root mean square error (RMSE) between ARF samples and ARF model using Matlab *fminsearch* function (Nelder-Mead simplex algorithm; Lagarias et al., 1998)
  - Performance evaluated by Nash–Sutcliffe efficiency (NSE)
  - (4 fitted parameters) * (# of frequency levels)

Summary of Overall Findings

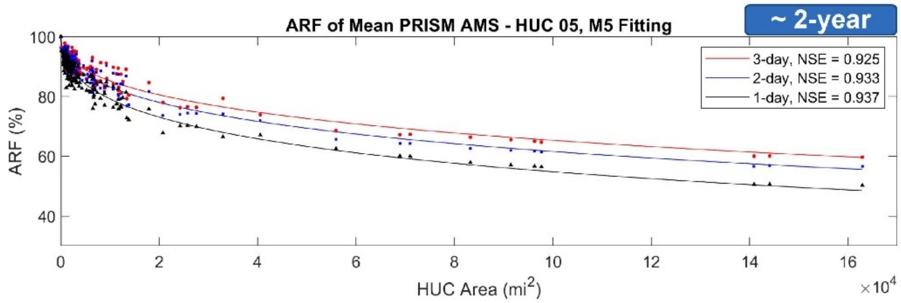
- **ARF decreases with (1) decreasing duration, (2) increasing area, and (3) increasing return period**
- ARF methods may cause significant differences.
- For data sources, smaller ARF differences are found, but the differences are not negligible.
- Cool season ARF > All season ARF > Warm season ARF
- ARF varies across different regions. Using one set of ARF everywhere across the country is not justified.
- High return level ARF remains a major challenge, mostly due to relatively short data record length.

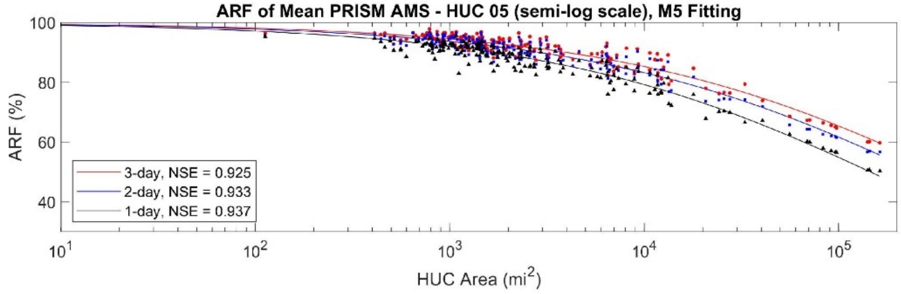
Region 05
M5 De Michele Model

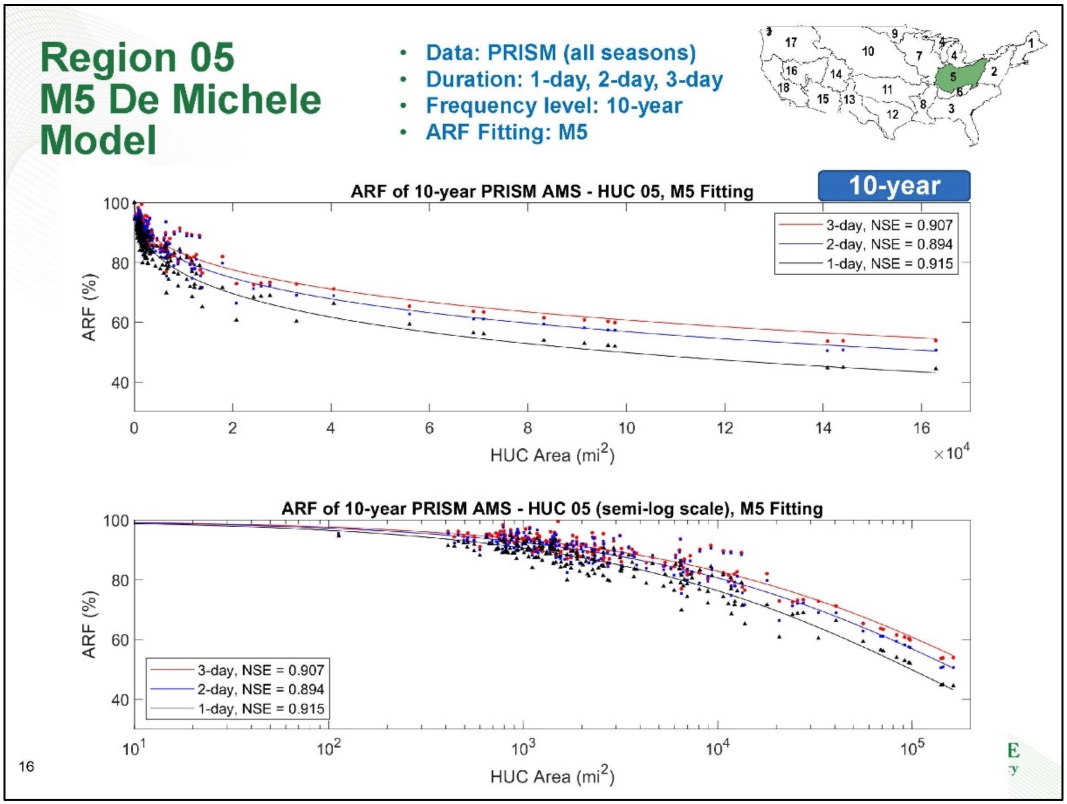
- **Data: PRISM (all seasons)**
- **Duration: 1-day, 2-day, 3-day**
- **Frequency level: AMS**
- **ARF Fitting: M5**



~ 2-year

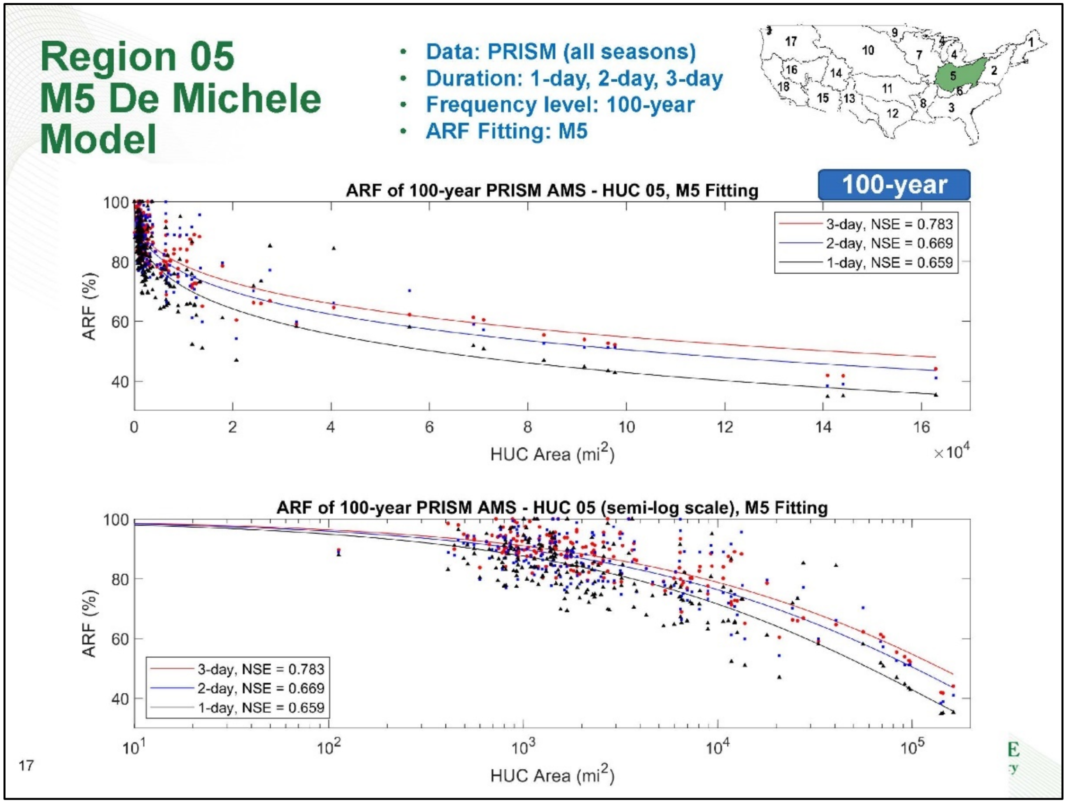






Region 05 M5 De Michele Model

- Data: PRISM (all seasons)
- Duration: 1-day, 2-day, 3-day
- Frequency level: 10-year
- ARF Fitting: M5

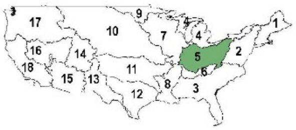


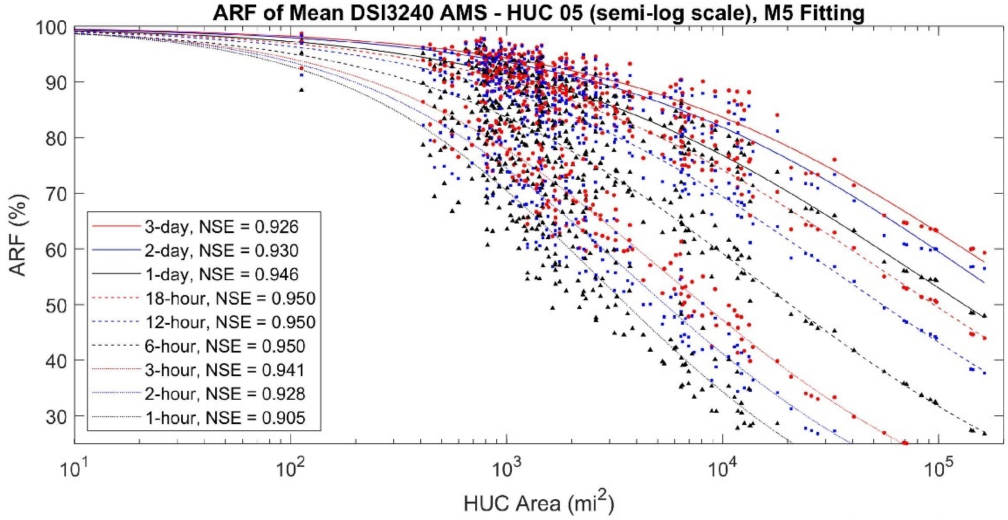
Region 05 M5 De Michele Model

- Data: PRISM (all seasons)
- Duration: 1-day, 2-day, 3-day
- Frequency level: 100-year
- ARF Fitting: M5

Differences across Durations

- Data: DSI3240 (all seasons)
- Duration: 3-day, 2-day, 1-day, 18-hr, 12-hr, 6-hr, 3-hr, 2-hr, 1-hr
- Frequency level: AMS
- ARF Fitting: M5





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Summary of Overall Findings

- ARF decreases with (1) decreasing duration, (2) increasing area, and (3) increasing return period.
- **ARF methods may cause significant differences.**
- For data sources, smaller ARF differences are found, but the differences are not negligible.
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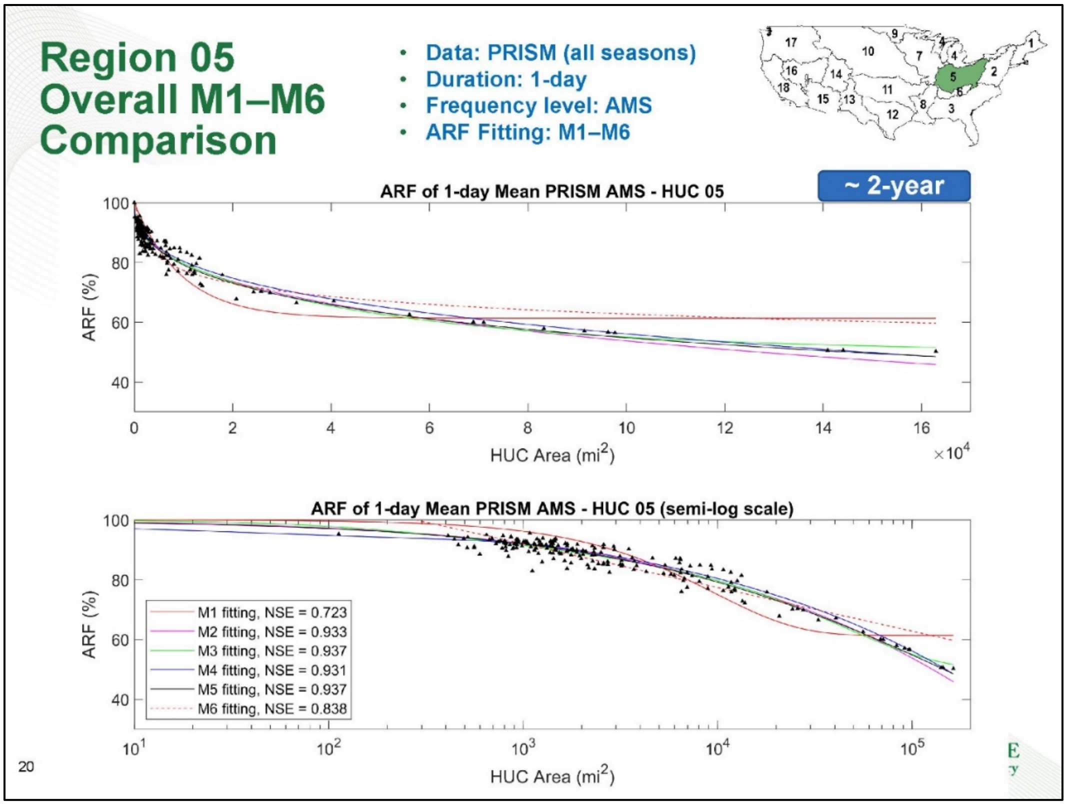


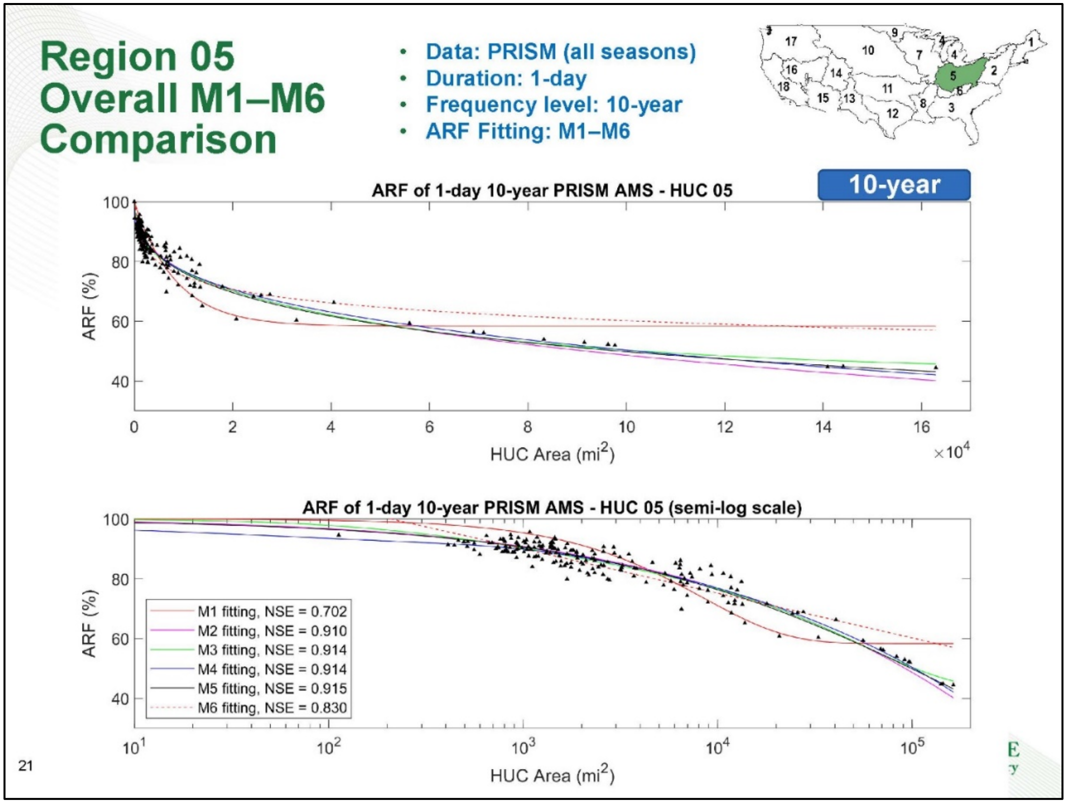
Region 05 Overall M1–M6 Comparison

- Data: PRISM (all seasons)
- Duration: 1-day
- Frequency level: AMS
- ARF Fitting: M1–M6

~ 2-year

ARF of 1-day Mean PRISM AMS - HUC 05

ARF of 1-day Mean PRISM AMS - HUC 05 (semi-log scale)



Region 05 Overall M1–M6 Comparison

- Data: PRISM (all seasons)
- Duration: 1-day
- Frequency level: 10-year
- ARF Fitting: M1–M6

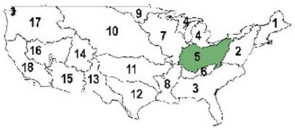
10-year

ARF of 1-day 10-year PRISM AMS - HUC 05

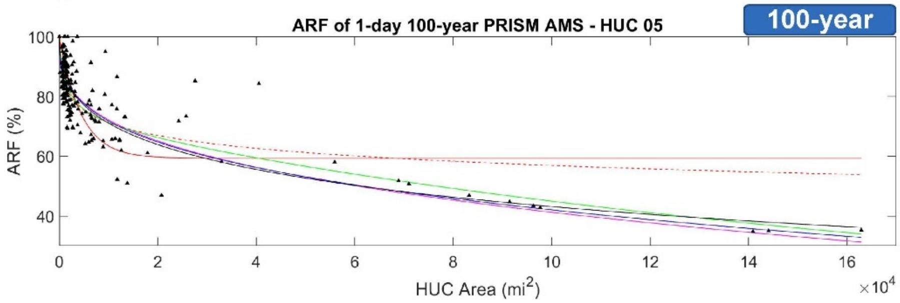
ARF of 1-day 10-year PRISM AMS - HUC 05 (semi-log scale)

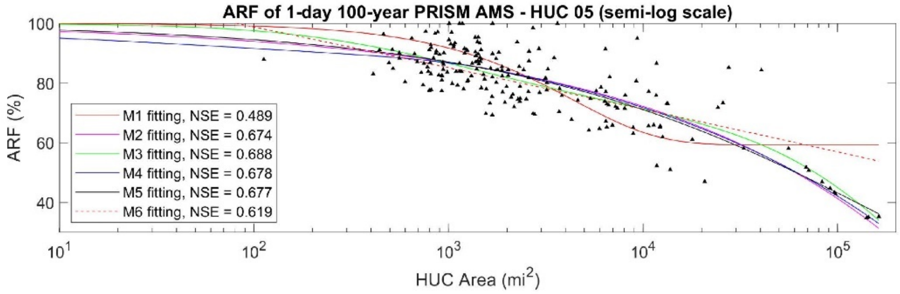
Region 05 Overall M1–M6 Comparison

- Data: PRISM (all seasons)
- Duration: 1-day
- Frequency level: 100-year
- ARF Fitting: M1–M6



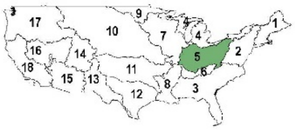
100-year





Region 05 Overall M1–M6 Comparison

- Data: PRISM (all seasons)
- Duration: 1-day, 2-day, 3-day
- Frequency level: AMS, 10-year, 100-year
- ARF Fitting: M1–M6



Duration	NSE					
	M1	M2	M3	M4	M5	M6
	Average AMS (approximately 2-year)					
1-day	0.72	0.93	0.94	0.93	0.94	0.84
2-day	0.76	0.93	0.93	0.93	0.93	0.77
3-day	0.75	0.92	0.93	0.92	0.93	0.67
	10-year					
1-day	0.70	0.91	0.91	0.91	0.91	0.83
2-day	0.69	0.89	0.90	0.89	0.89	0.75
3-day	0.73	0.90	0.91	0.91	0.91	0.70
	100-year					
1-day	0.48	0.67	0.69	0.68	0.68	0.62
2-day	0.45	0.70	0.70	0.70	0.70	0.61
3-day	0.59	0.80	0.81	0.81	0.80	0.71

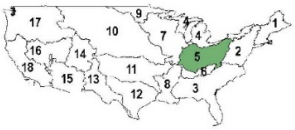
*Red cell highlights NSE < 0.5

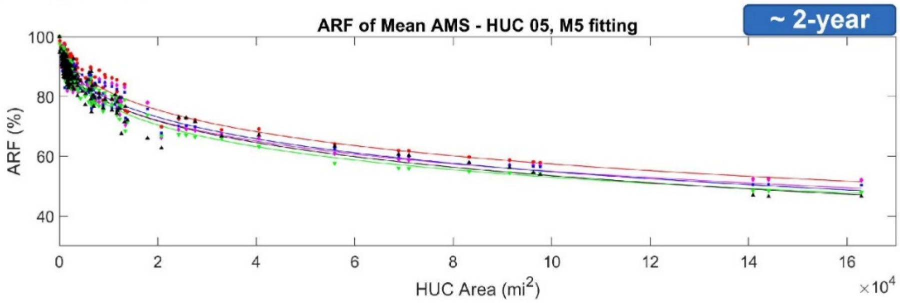
Summary of Overall Findings

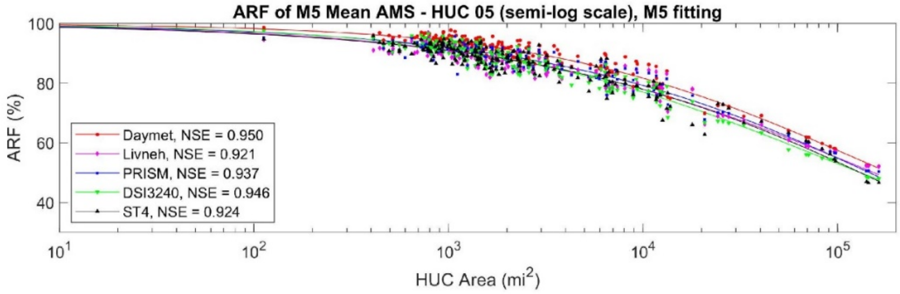
- ARF decreases with (1) decreasing duration, (2) increasing area, and (3) increasing return period.
- ARF methods may cause significant differences.
- **For data sources, smaller ARF differences are found, but the differences are not negligible.**
- Cool season ARF > All season ARF > Warm season ARF
- ARF varies across different regions. Using one set of ARF everywhere across the country is not justified.
- High return level ARF remains a major challenge, mostly due to relatively short data record length.

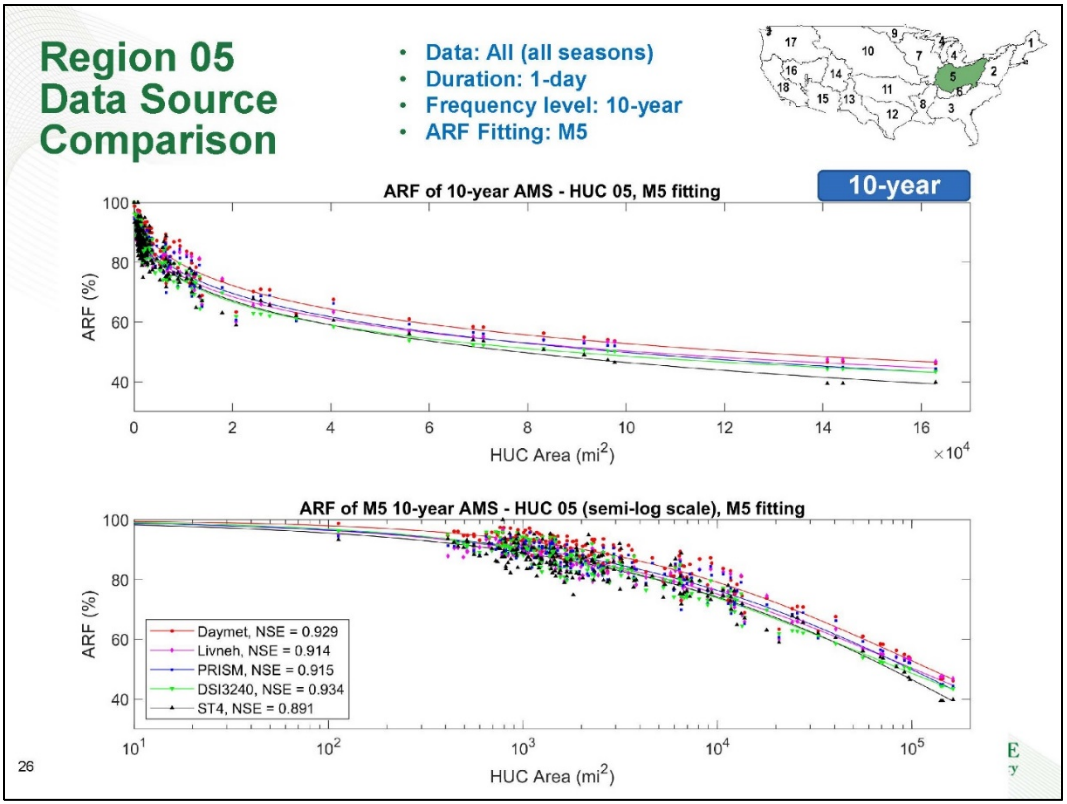
Region 05 Data Source Comparison

- **Data: All (all seasons)**
- **Duration: 1-day**
- **Frequency level: AMS**
- **ARF Fitting: M5**





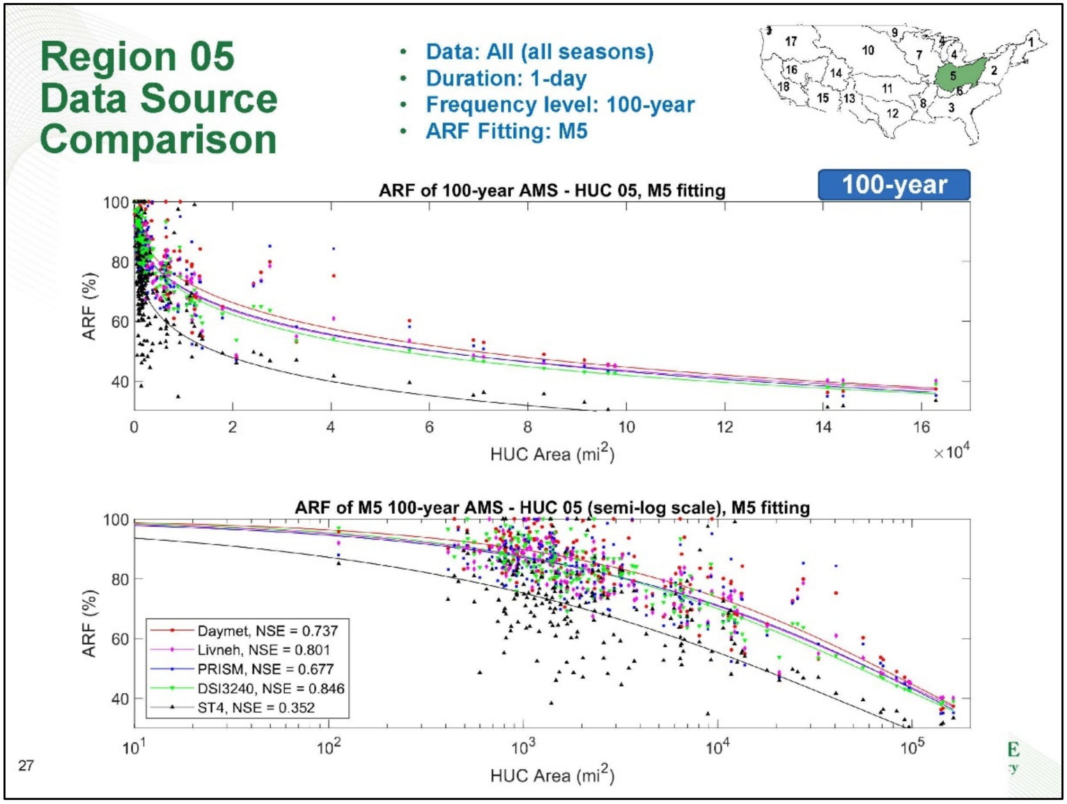




Region 05 Data Source Comparison

- Data: All (all seasons)
- Duration: 1-day
- Frequency level: 10-year
- ARF Fitting: M5

26



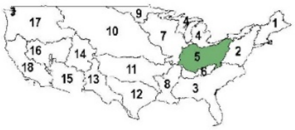
Region 05 Data Source Comparison

- Data: All (all seasons)
- Duration: 1-day
- Frequency level: 100-year
- ARF Fitting: M5

27

Region 05 Data Source Comparison

- Data: All (all seasons)
- Duration: 1-day, 2-day, 3-day
- Frequency level: AMS, 10-year, 100-year
- ARF Fitting: M5



Duration	NSE				
	PRISM (1981–2017)	Daymet (1980–2017)	ST4 (2002–2017)	Livneh (1950–2013)	DSI3240 (1950–2013)
	Average AMS (approximately 2-year)				
1-day	0.94	0.95	0.92	0.92	0.95
2-day	0.93	0.95	0.92	0.93	0.93
3-day	0.92	0.94	0.92	0.92	0.93
	10-year				
1-day	0.91	0.93	0.89	0.91	0.93
2-day	0.89	0.92	0.88	0.92	0.92
3-day	0.91	0.93	0.87	0.91	0.91
	100-year				
1-day	0.68	0.74	0.35	0.80	0.85
2-day	0.70	0.74	0.39	0.77	0.80
3-day	0.80	0.82	0.36	0.82	0.80

*Red cell highlights NSE < 0.5

Summary of Overall Findings

- ARF decreases with (1) decreasing duration, (2) increasing area, and (3) increasing return period.
- ARF methods may cause significant differences.
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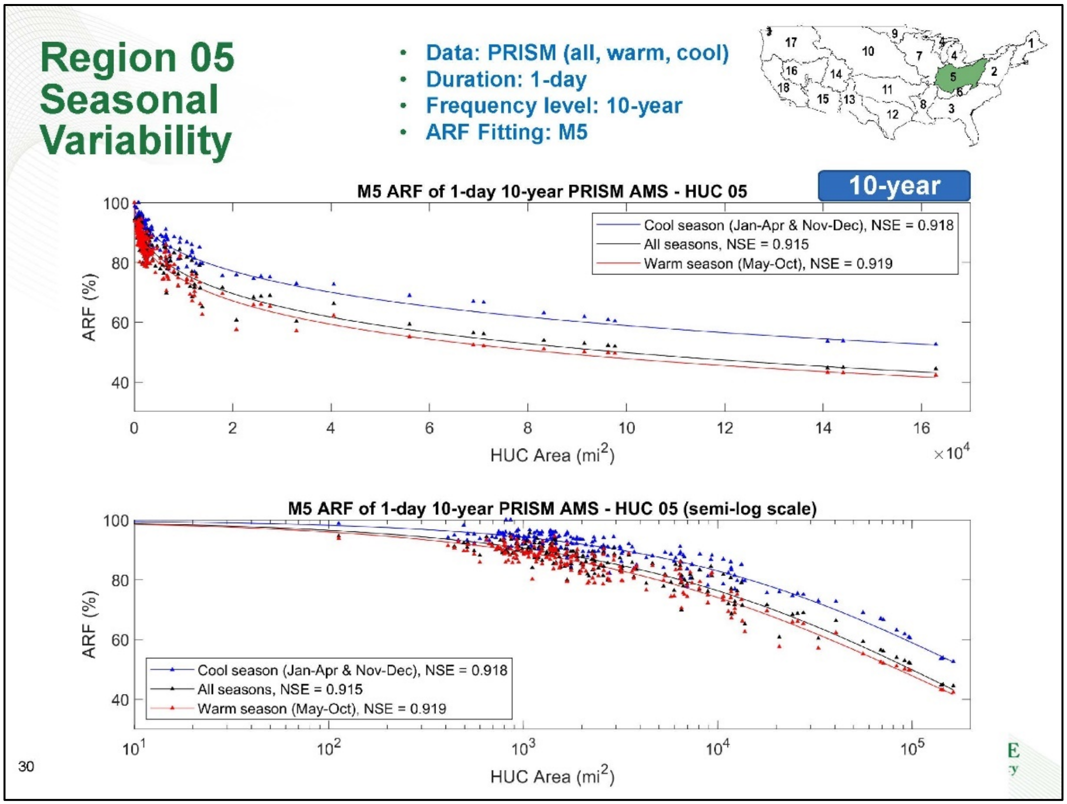

Region 05 Seasonal Variability

- Data: PRISM (all, warm, cool)
- Duration: 1-day
- Frequency level: 10-year
- ARF Fitting: M5

Summary of Overall Findings

- ARF decreases with (1) decreasing duration, (2) increasing area, and (3) increasing return period.
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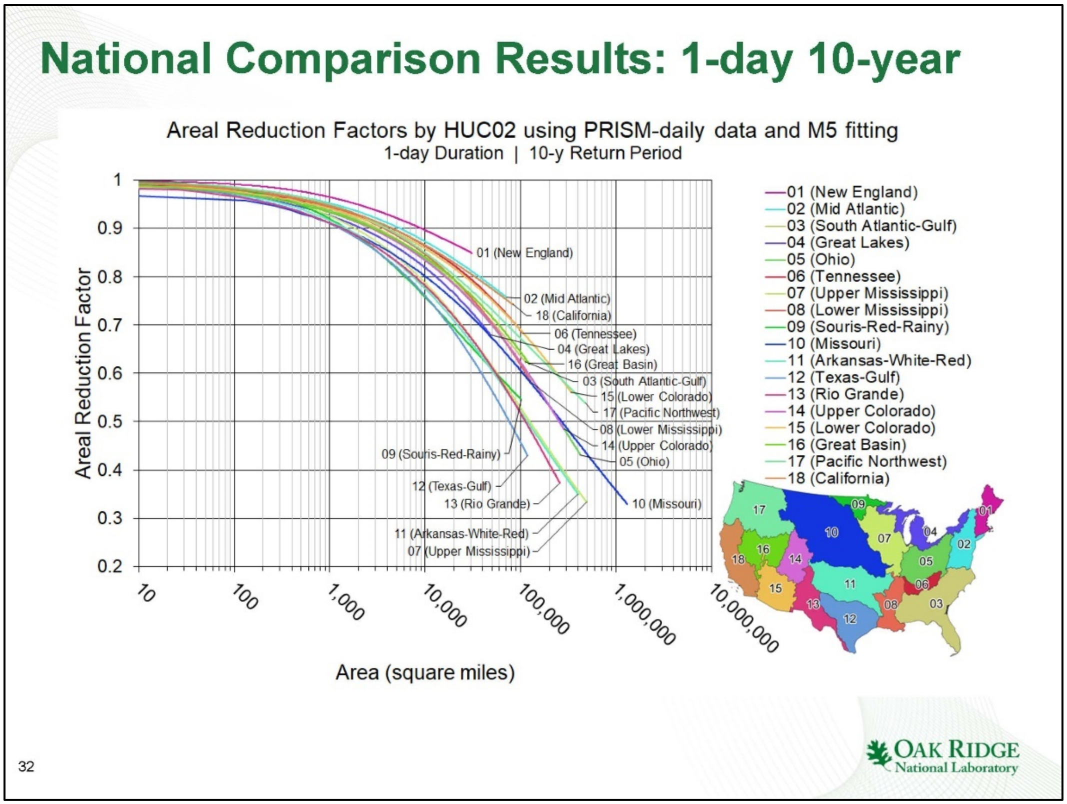
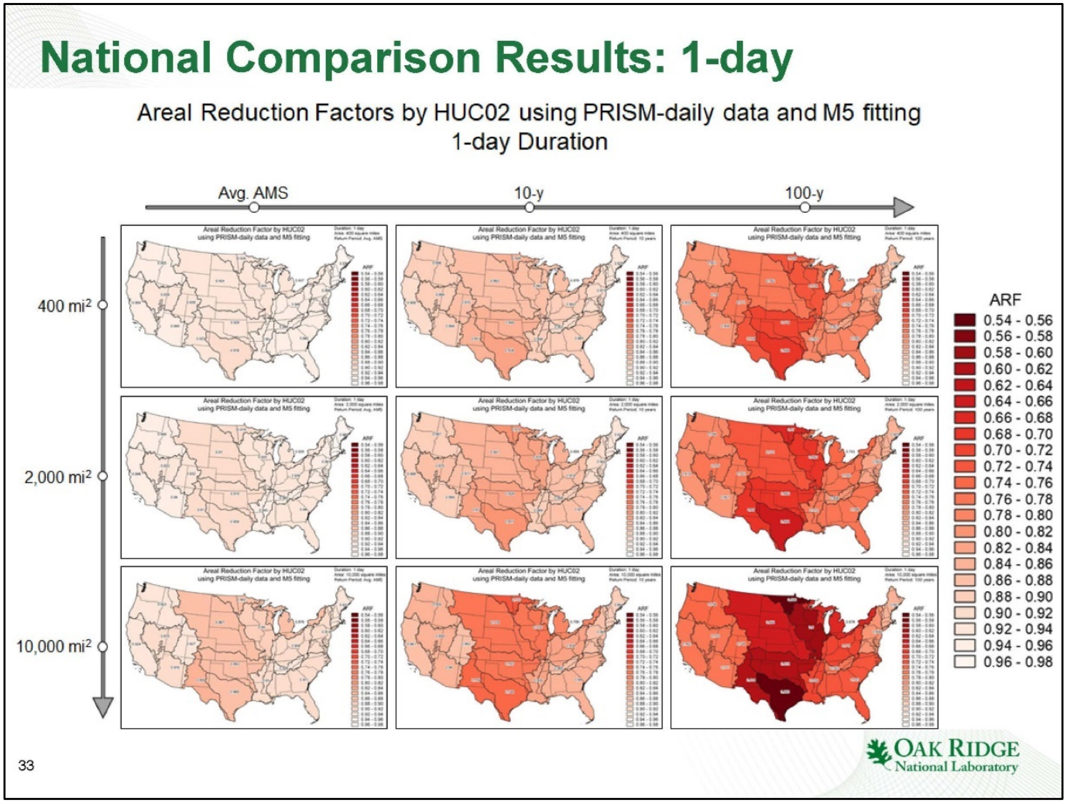


National Comparison Results: 1-day 10-year

Areal Reduction Factors by HUC02 using PRISM-daily data and M5 fitting
1-day Duration | 10-y Return Period



National Comparison Results: 1-day

Areal Reduction Factors by HUC02 using PRISM-daily data and M5 fitting
1-day Duration

National Comparison Results: 1-day NSE

Comparison of 1-day CONUS regional M5 ARF fitting using PRISM precipitation across different return periods.

Return Period	NSE																	
	Region Number																	
	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18
Avg. AMS	0.68	0.80	0.72	0.69	0.94	0.91	0.93	0.87	0.88	0.85	0.87	0.88	0.92	0.83	0.84	0.81	0.85	0.72
GEV 10-yr	0.66	0.67	0.72	0.58	0.91	0.89	0.90	0.83	0.85	0.78	0.81	0.89	0.90	0.81	0.79	0.77	0.84	0.74
GEV 100-yr	0.20	0.15	0.44	0.31	0.68	0.46	0.72	0.59	0.73	0.57	0.59	0.70	0.72	0.65	0.51	0.37	0.70	0.63

Summary of Overall Findings

- ARF decreases with (1) decreasing duration, (2) increasing area, and (3) increasing return period.
- ARF methods may cause significant differences.
- For data sources, smaller ARF differences are found, but the differences are not negligible.
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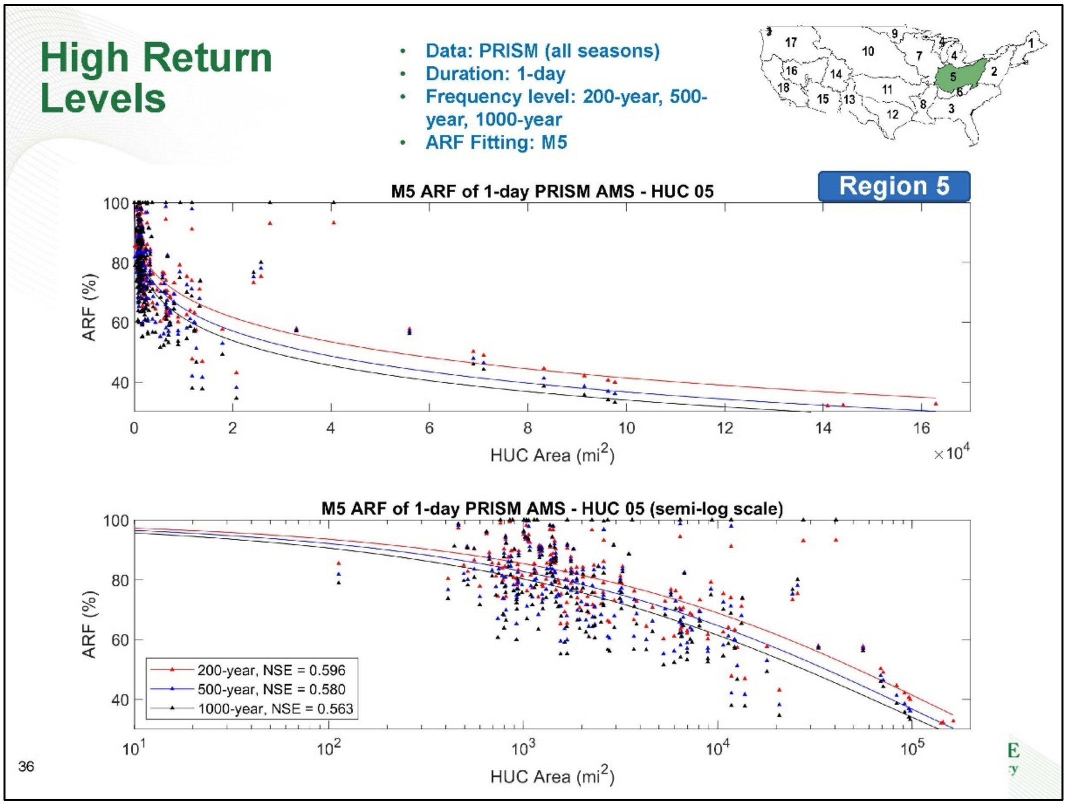
- ARF varies across different regions. Using one set of ARF everywhere across the country is not justified.
- **High return level ARF remains a major challenge, mostly due to relatively short data record length.**



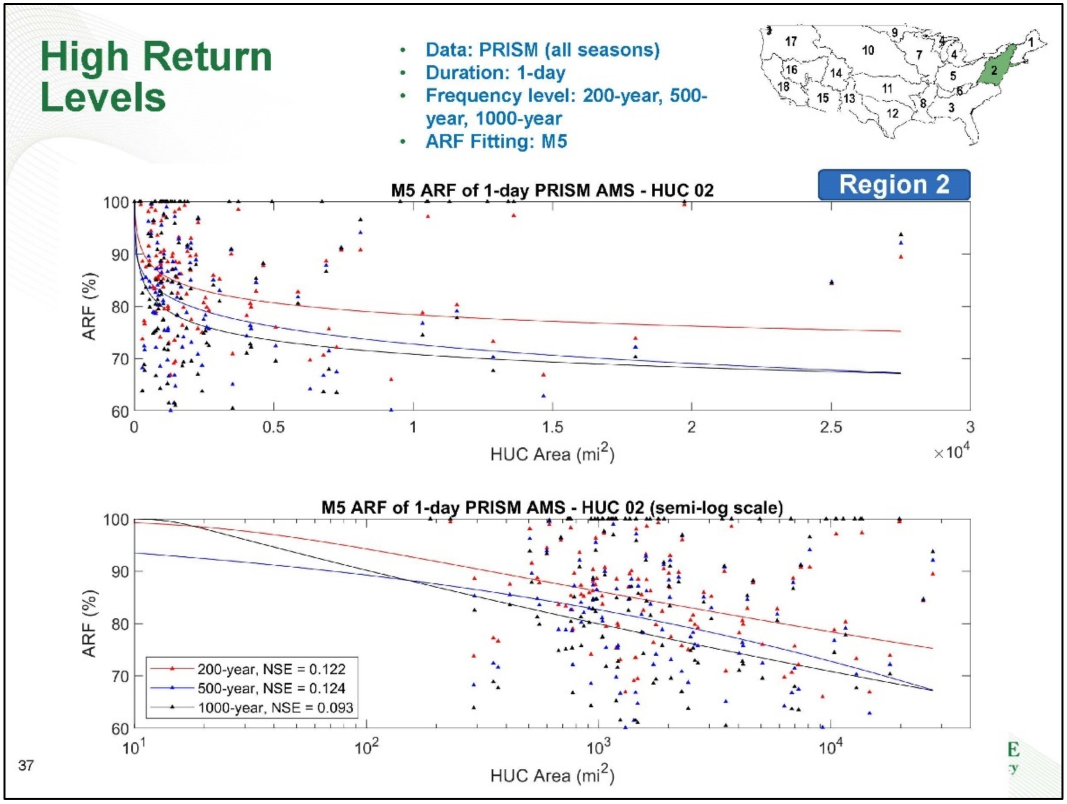
High Return Levels

- Data: PRISM (all seasons)
- Duration: 1-day
- Frequency level: 200-year, 500-year, 1000-year
- ARF Fitting: M5

Region 5

M5 ARF of 1-day PRISM AMS - HUC 05

M5 ARF of 1-day PRISM AMS - HUC 05 (semi-log scale)



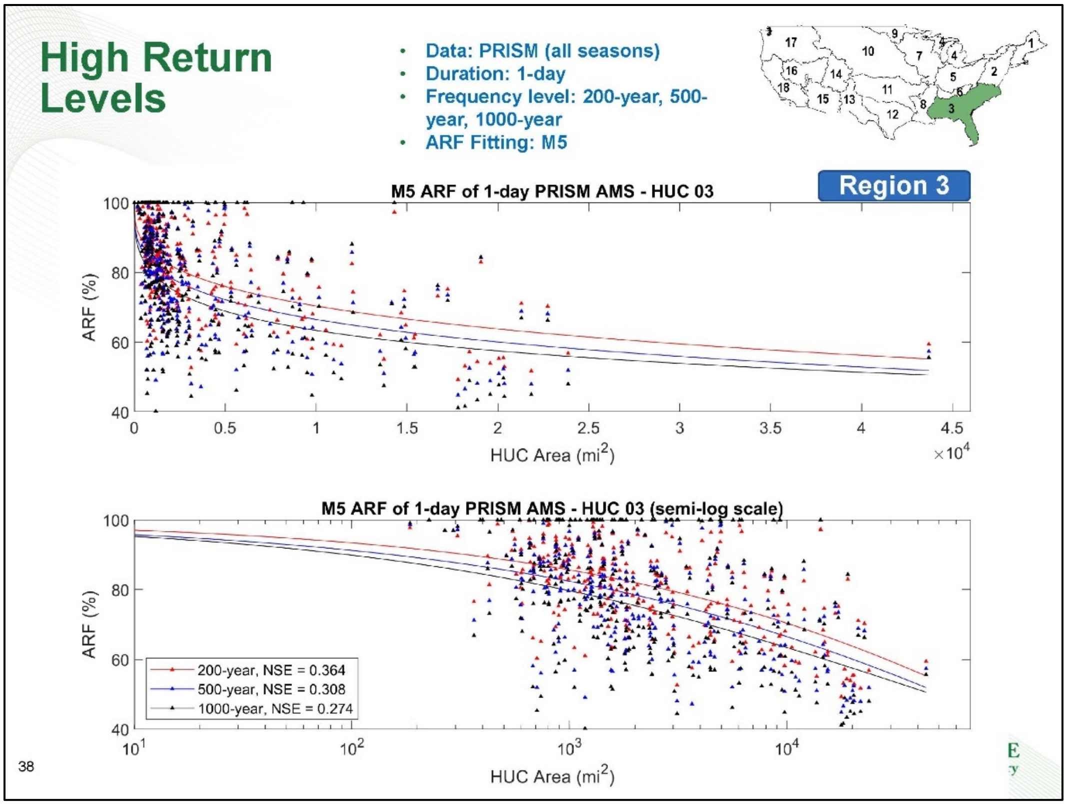
High Return Levels

- Data: PRISM (all seasons)
- Duration: 1-day
- Frequency level: 200-year, 500-year, 1000-year
- ARF Fitting: M5

Region 2

M5 ARF of 1-day PRISM AMS - HUC 02

M5 ARF of 1-day PRISM AMS - HUC 02 (semi-log scale)



High Return Levels

- Data: PRISM (all seasons)
- Duration: 1-day
- Frequency level: 200-year, 500-year, 1000-year
- ARF Fitting: M5

Issues to be Explored

- Development of ARF for long return period
- Uncertainty quantification
- Lack of long-term, high spatiotemporal resolution dataset
- Subwatershed application
- Need for a national ARF product

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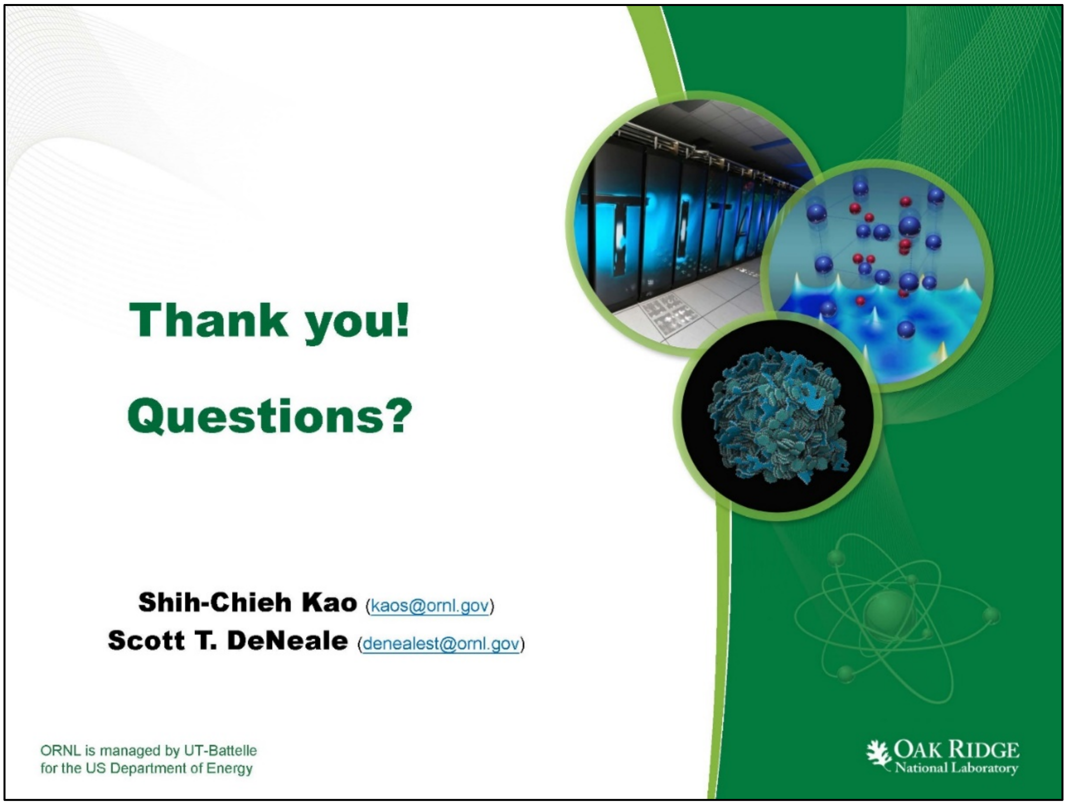

Thank you!

Questions?

Shih-Chieh Kao (kaos@ornl.gov)
Scott T. DeNeale (denealest@ornl.gov)

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3.3.3 Presentation 1C-3: How well can Kilometer-Scale Models Capture Recent Intense Precipitation Events?

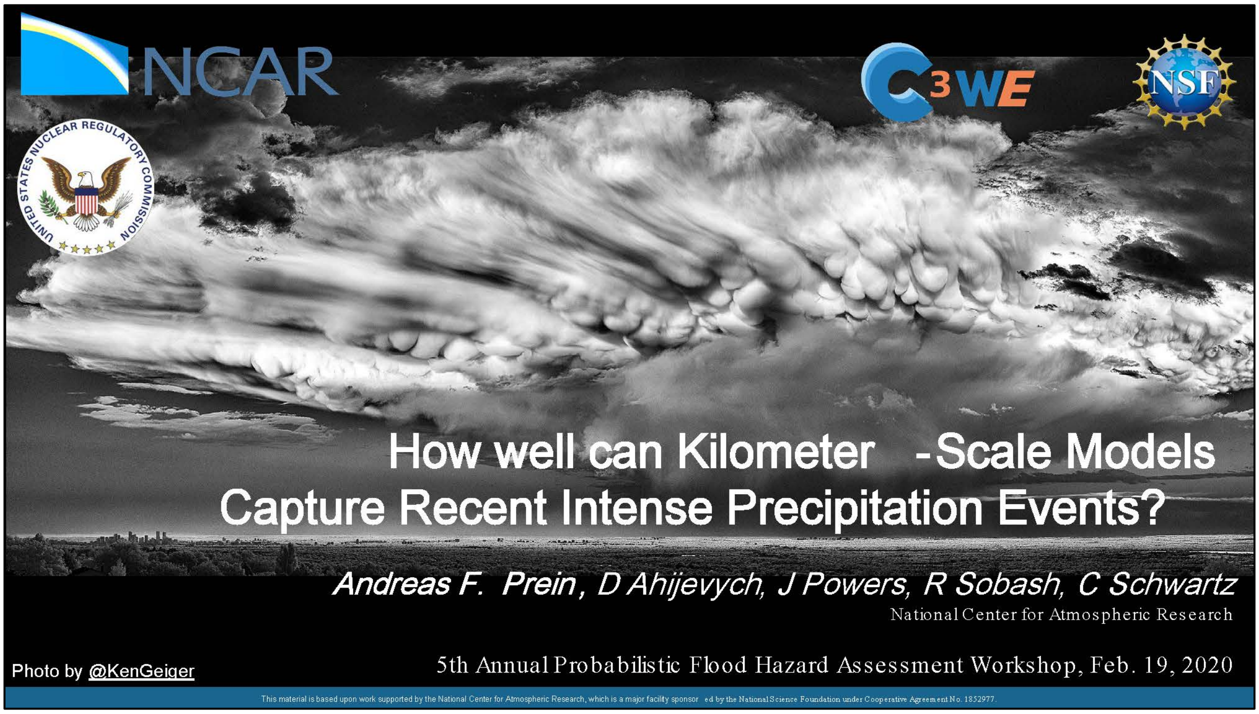
Authors: Andreas F. Prein, David Ahijevych, Jordan Powers, Ryan Sobash, and Craig Schwartz, National Center for Atmospheric Research (NCAR)

Speaker: Andreas F. Prein

3.3.3.1 Abstract

Planning for floods that are associated with very rare and intense precipitation events is challenging due to short observational records and changing climate conditions. Furthermore, shortcomings in traditionally-used estimators of extreme precipitation, such as Probable Maximum Precipitation (PMP) do not allow a quantification of uncertainties in hazard estimates in either a physical or a risk sense. Recent advancements in atmospheric modeling and computational science offers a promising way forward since they allow the simulation of intense precipitation events in unprecedented detail. These so-called convection-permitting models (CPMs) can explicitly simulate thunderstorms and can accurately represent orography on fine scales and thus are powerful tools for investigating extreme precipitation events. Here we will assess how well recent flood producing rainfall events can be captured by CPMs in different climate regions east of the U.S. continental divide. We use multisensory high-resolution precipitation datasets for the model evaluation and will assess the impact of model horizontal grid spacing (3-km and 1-km), initial conditions (up to 10-ensemble members), and observational uncertainties. Comparing results based on different types of storms (tropical cyclones, mesoscale convective systems, and orographic precipitation) provides a broad overview of skills and deficiencies in state-of-the-art CPMs and allow insights in how applicable they are for flood risk assessment.

3.3.3.2 Presentation (ADAMS Accession No. ML20080M195)



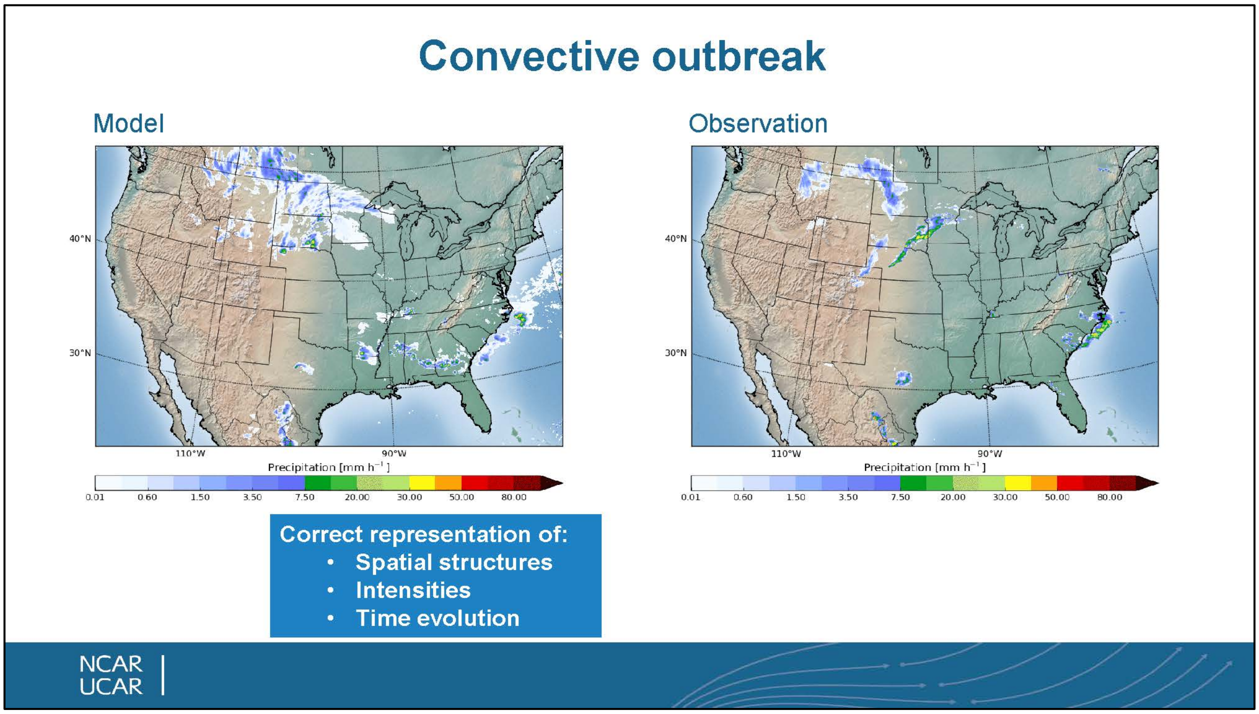
How well can Kilometer-Scale Models Capture Recent Intense Precipitation Events?

Andreas F. Prein, D Ahijevych, J Powers, R Sobash, C Schwartz
National Center for Atmospheric Research

5th Annual Probabilistic Flood Hazard Assessment Workshop, Feb. 19, 2020

Photo by @KenGeiger

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.



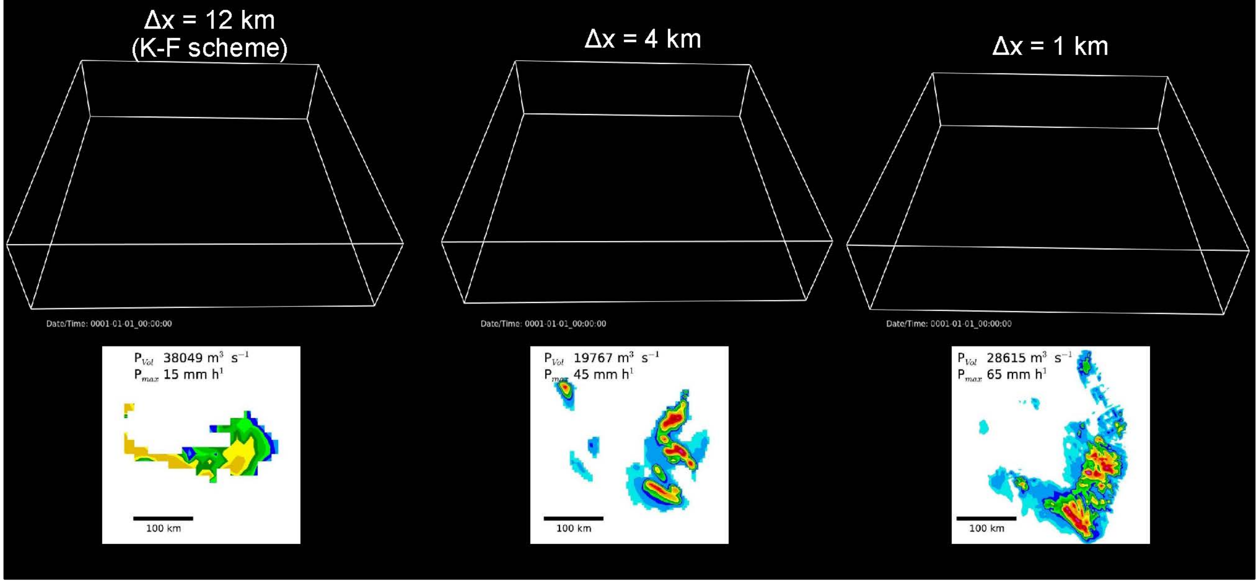
Convective outbreak

Model

Observation

Correct representation of:
- Spatial structures
- Intensities
- Time evolution

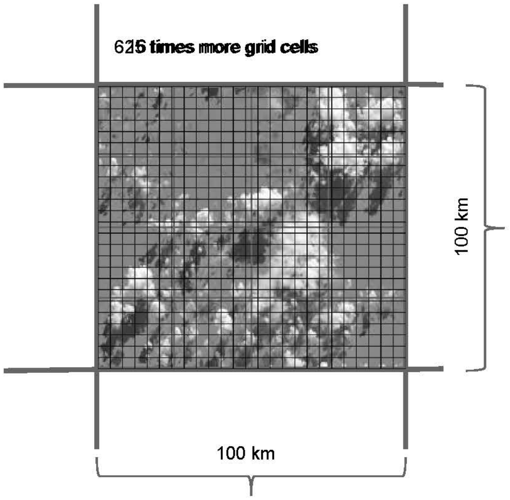
Step Improvement in Simulating Intense Rainfall Storms


Δx = 12 km (K-F scheme)

Δx = 4 km

Δx = 1 km

Deep convection in atmospheric models



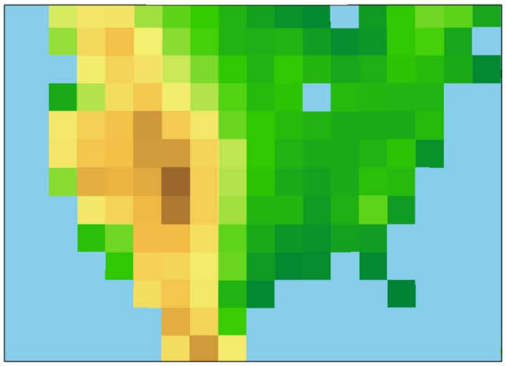
GCM grid spacing (~100 x 100 km)

- Deep convection is sub-gridscale process
- Needs cumulus parameterization

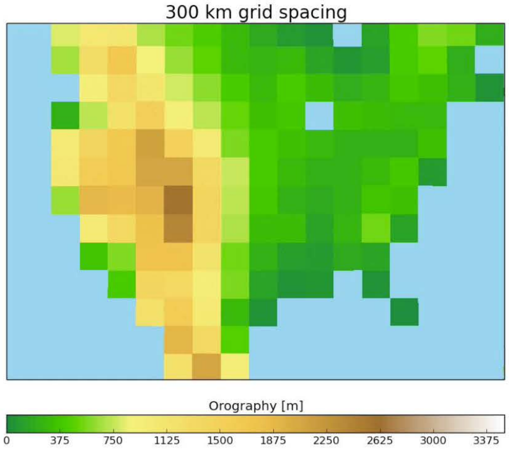
When do we start to resolve deep convection?

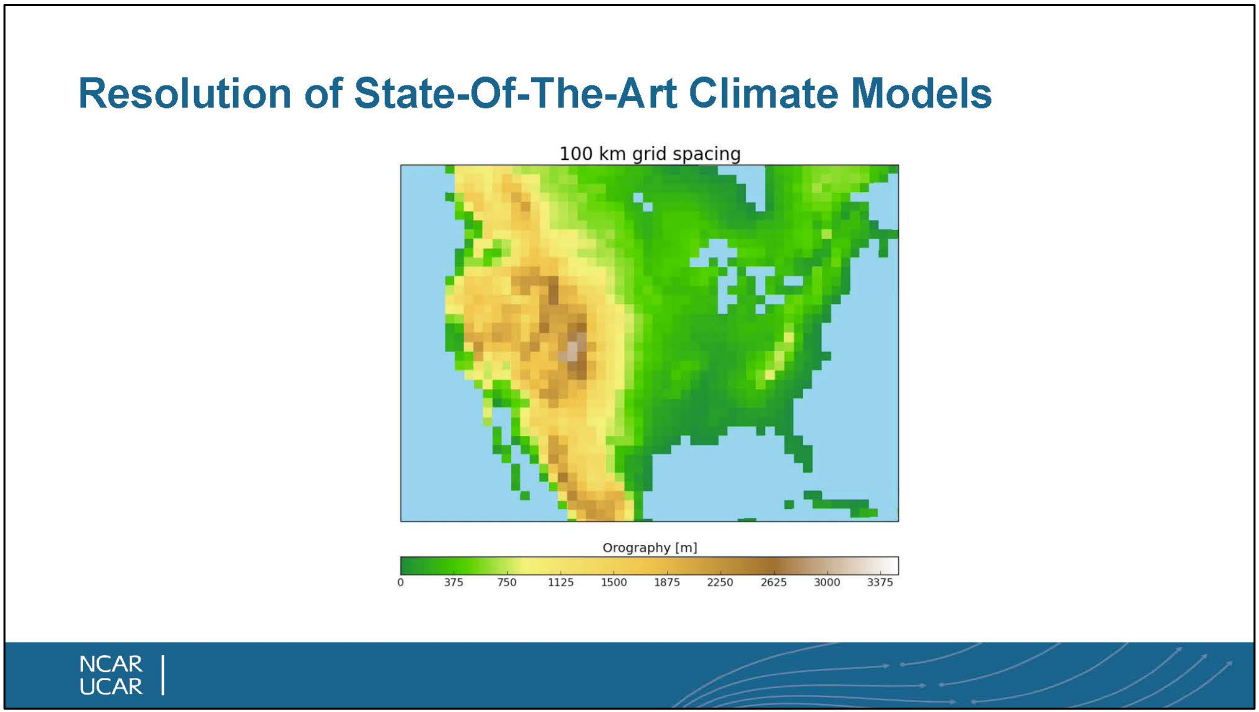
- ~4 km horizontal grid spacing (Weisman et al. 1997)

Resolution of State-Of-The-Art Climate Models



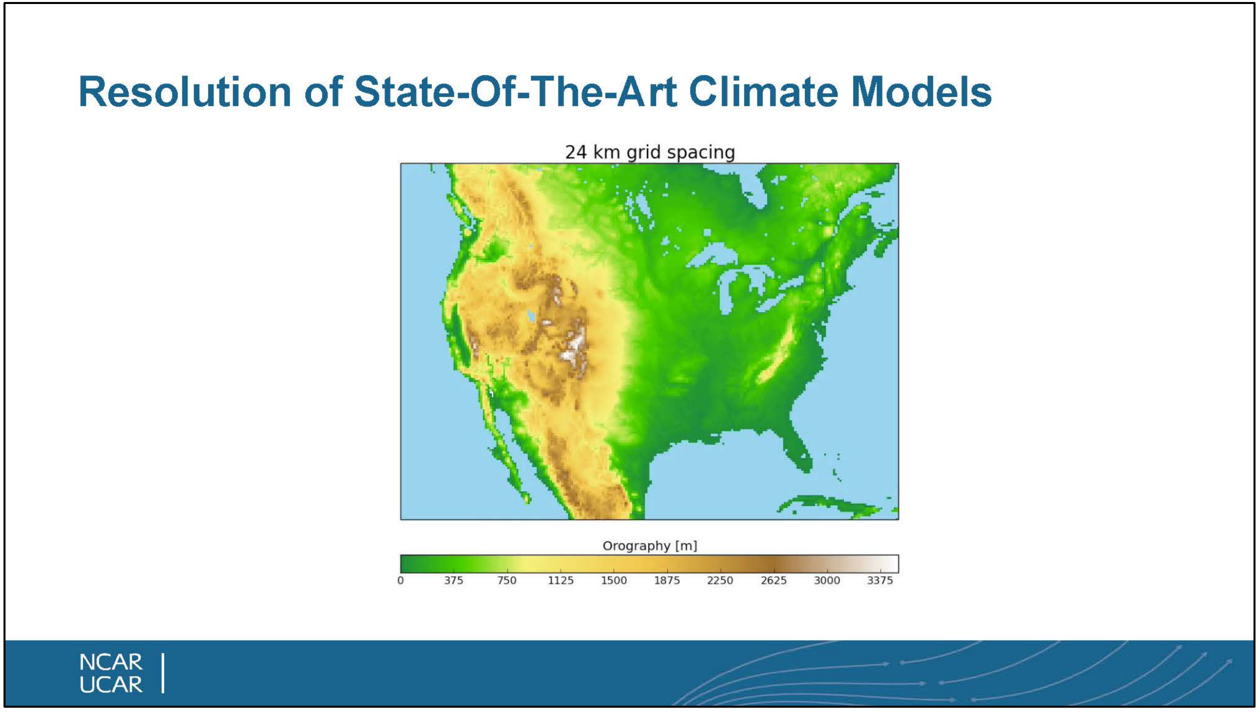
Resolution of State-Of-The-Art Climate Models


300 km grid spacing



Resolution of State-Of-The-Art Climate Models

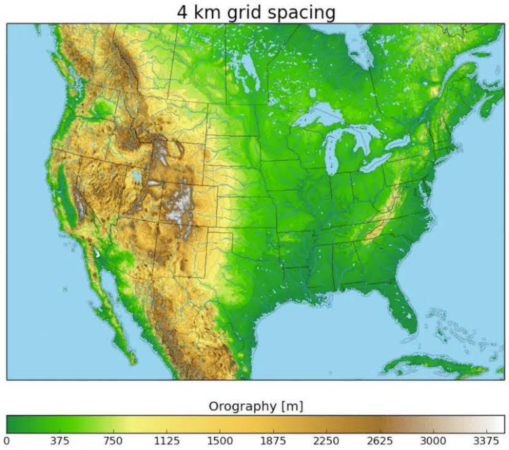
100 km grid spacing



Resolution of State-Of-The-Art Climate Models

24 km grid spacing

Resolution of State-Of-The-Art Climate Models



NCAR
UCAR

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.

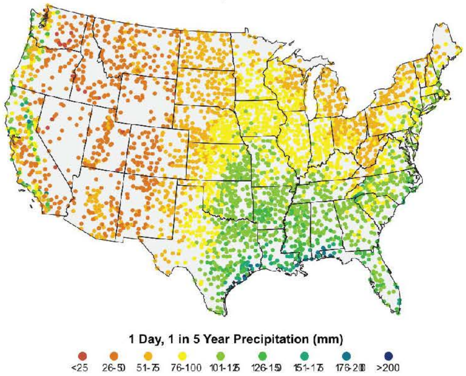
Convection-Permitting Models

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

NCAR
UCAR

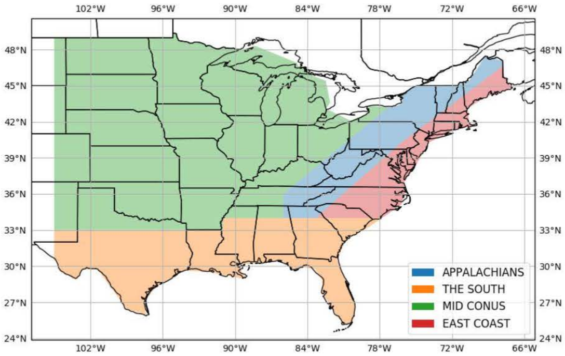
Intense Precipitation Events in Eastern CONUS

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



Kunkel et al. 2012

Evaluation in Four Regions



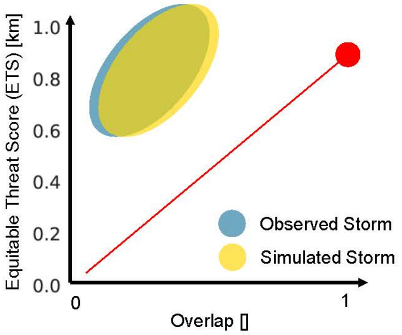
Convection-Permitting Model Simulations

Dataset	Δx	Elements	Period	Region	References
NCAR Real-time Ensemble	3 km	10-member ensemble forecasts	5/1/2015-12/31/2017	CONUS	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	Central / eastern U.S.	Schwartz et al. (2017)
NCAR Severe Weather Study	3 km & 1 km	Deterministic forecasts; 500 cases	2010-2017	Central / eastern U.S.	Sobash et al. (2019), Schwartz et al. (2019)

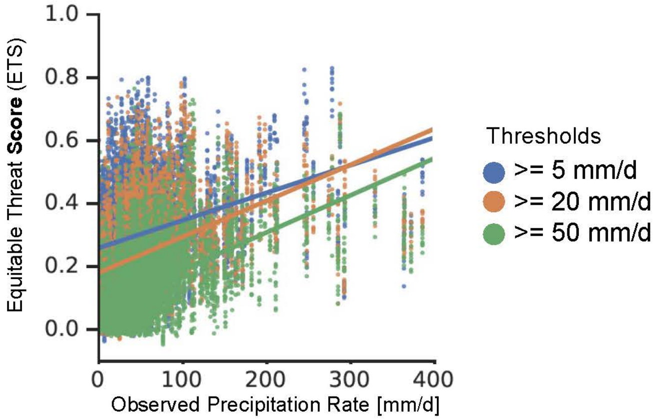
- 10,570 36-hour WRF simulations/forecasts at 3-km horizontal grid spacing (1.8 mi)
- 810 36-hour simulations at Δx=1 km (0.6 mi)

Are Intense Precipitation Events Harder to Simulate?

Equitable Threat Score (ETS)

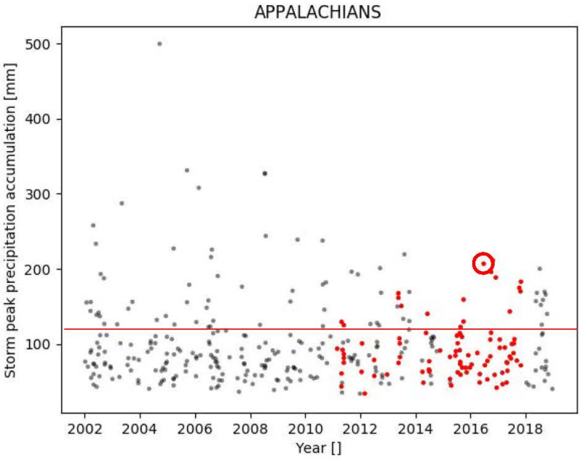


Southern U.S.

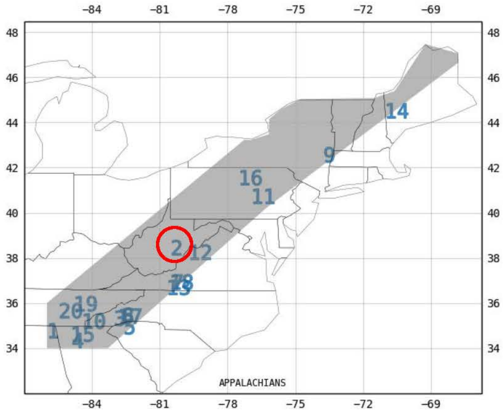


Model skill increases with intensity of event

Case Selection | Top 20 Events in Each Region

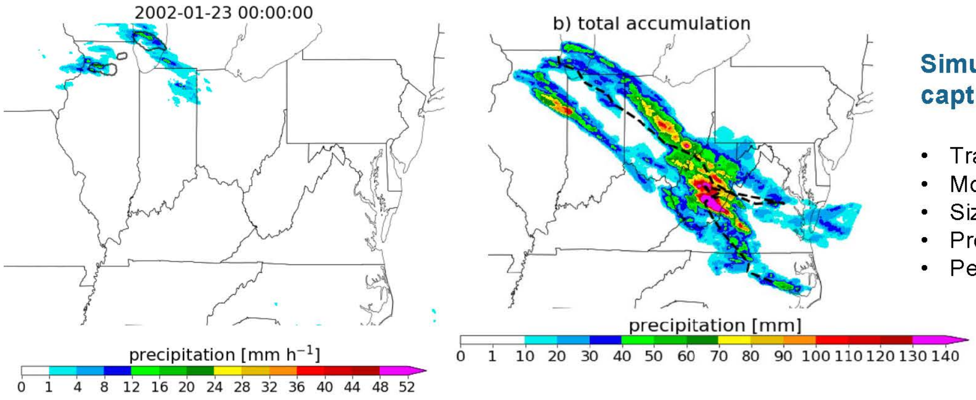


Top 20 Events in Appalachia Region



Lagrangian Evaluation Framework

West Virginia Flooding of 2016

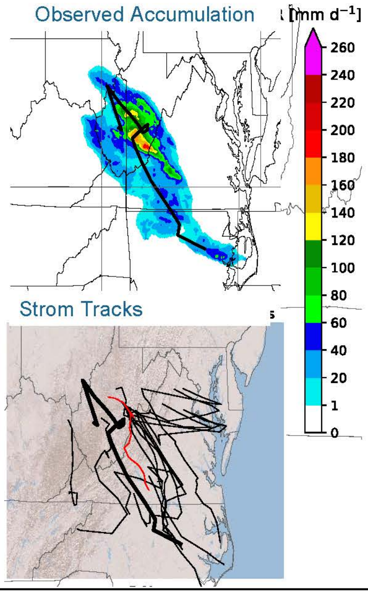


Simulation has to capture:

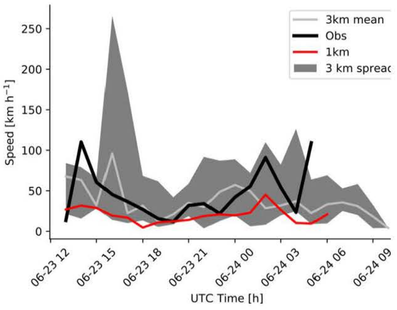
- Track
- Movement speed
- Size evolution
- Precipitation volume
- Peak accumulation

West Virginia Flooding of 2016

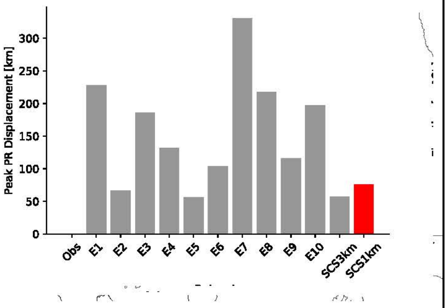
Observed Accumulation

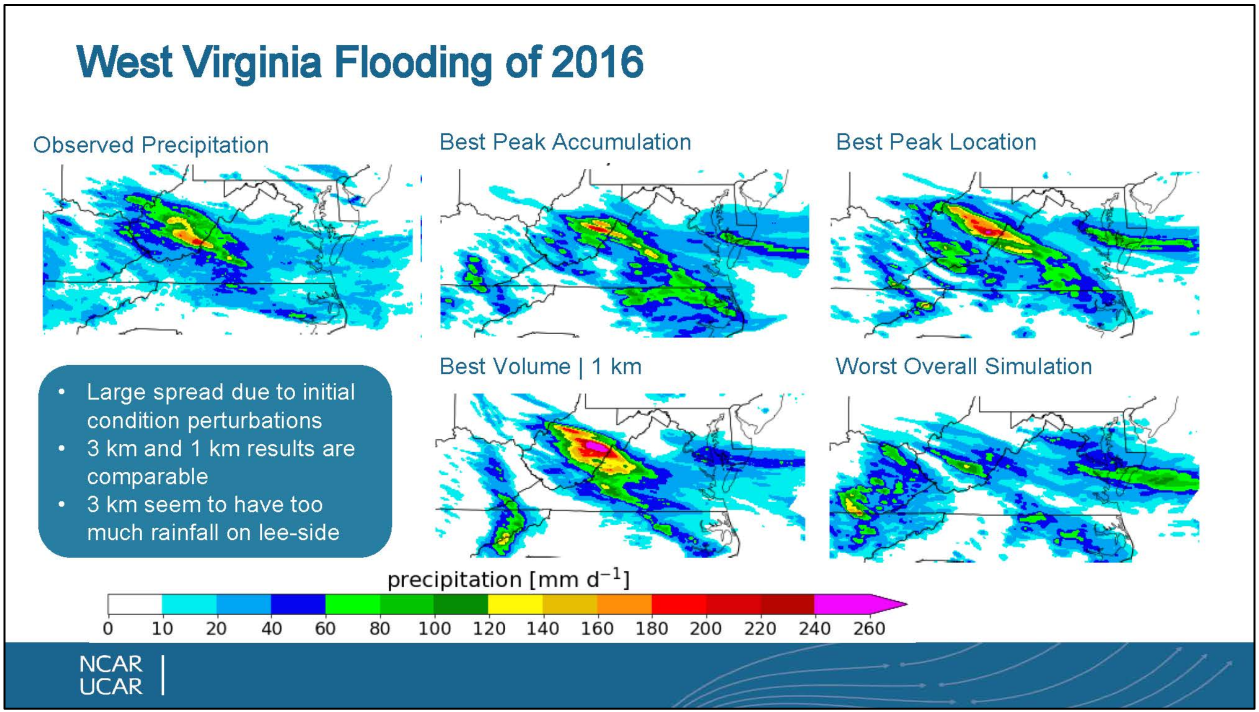


Storm Speed



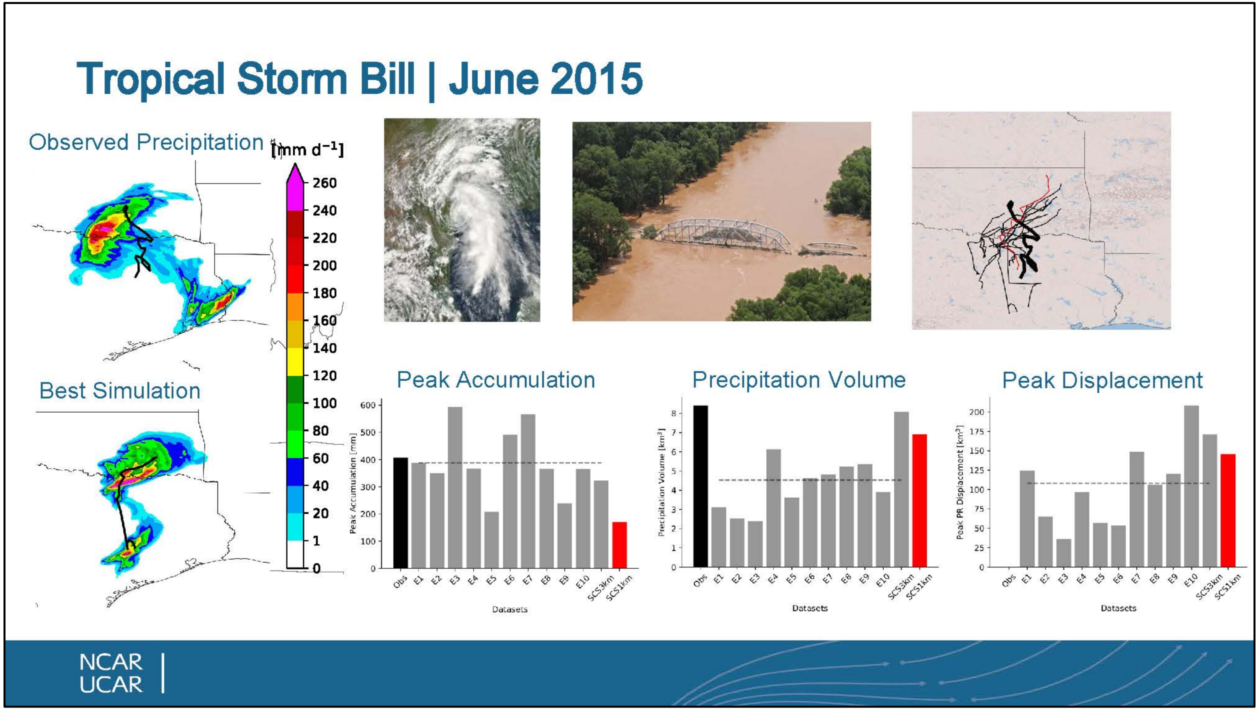
Peak Displacement





West Virginia Flooding of 2016

- Large spread due to initial condition perturbations
- 3 km and 1 km results are comparable
- 3 km seem to have too much rainfall on lee-side



Tropical Storm Bill | June 2015

Next Steps

- Assessment of model performance based on ensemble of intense events
- Quantification of systematic model biases
- Analyses of uncertainty sources to model performance
- Conceptual framework to use CPM simulations in Monte Carlo rainfall-runoff simulations

Uncertainty Source	Setting
Horizontal grid spacing (Δx)	3 km, 1 km (1.8 mi, 0.6 mi)
Precipitation observations	Stage-IV (Crosson et al. 1996, Fulton et al. 1998) Mosaic WSR-88D (Zhang and Gourley 2018) PRISM (Daly et al. 1994, 2002, 2008) Newman (Newman et al 2015)
Initial Conditions	Ensemble datasets to be used reflect initial condition perturbations

NCAR
UCAR

Summary and Conclusions

- Convection-permitting models can capture recently observed intense rainfall events east of the Continental Divide
- Predictability increases with rarity of event
- Sensitivity to initial condition perturbations is large
- 3 km and 1 km simulations show comparable results

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

NCAR
UCAR | prein@ucar.edu

3.3.4 Presentation 1C-4: Probabilistic Flood Hazard Assessment of NPP Site considering Extreme Precipitation in Korea

Authors: Kun-Yeun Han, Beom-Jin Kim, Kyungpook National University, Korea; Minkyu Kim, Korea Atomic Energy Research Institute (KAERI)

Speaker: Kun-Yeun Han

3.3.4.1 Abstract

The Probable Maximum Precipitation (PMP) considering the climate change scenarios of RCP4.5 and RCP8.5 is computed and compared with the probability rainfall to estimate the LIP (Local Intensive Precipitation) of Nuclear Power Plant site in Korea. The detailed topographic data with high resolutions DEM are constructed and the effects of building, road, and curb at NPP sites are analyzed through several times of walkdown.

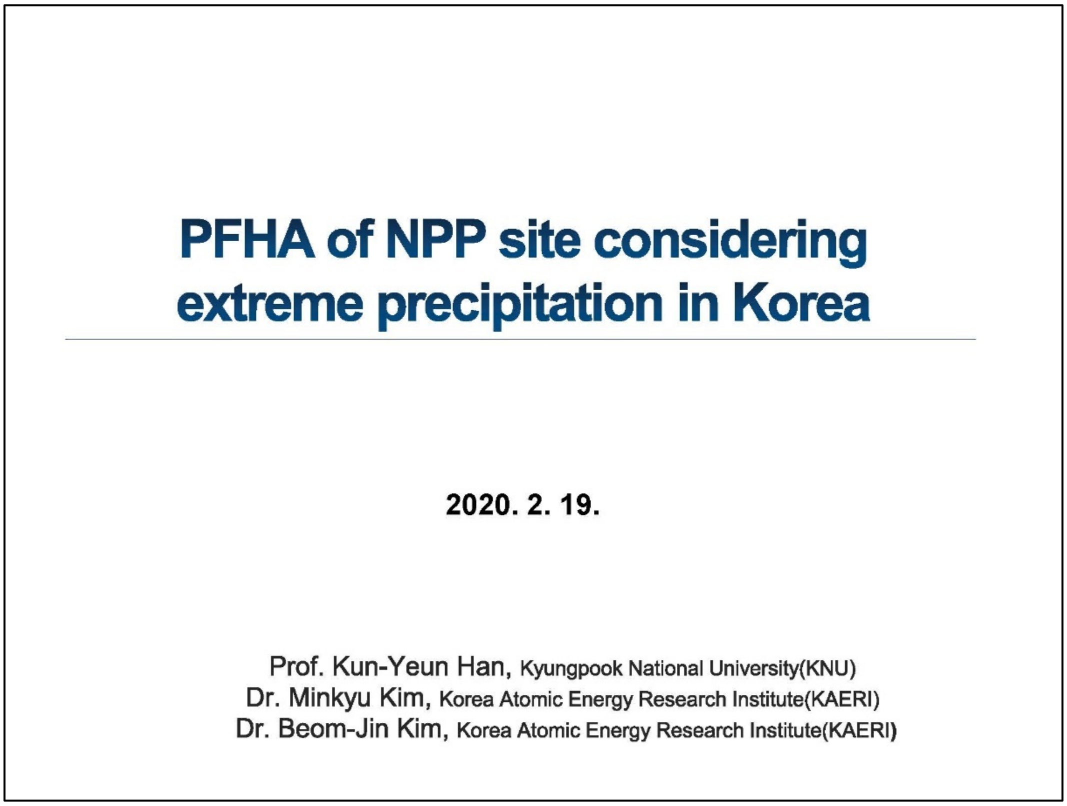
In order to evaluate the external flooding risk on NPP, hydrologic/hydraulic analysis are performed. For the external flood hazard analysis, 2D hydrodynamic model is carried out considering LIP and tidal level condition. Based on the simulation results of 2D analysis, flood hazard curves are developed for the inundation depth with frequency and rainfall duration. The internal flooding of SSC (Structure, System and Components) caused by external flooding of the major facilities are also evaluated. The result of this study is expected to be a basis for the waterproof design and planning of various types of flood prevention measures of NPP site.

Keywords: External Inundation; LIP; Hazard Curve; PFHA of NPP Sites

Acknowledgement

This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government (MSIP) (No. 2017M2A8A4015290)

3.3.4.2 Presentation (ADAMS Accession No. ML20080M196)



PFHA of NPP site considering extreme precipitation in Korea

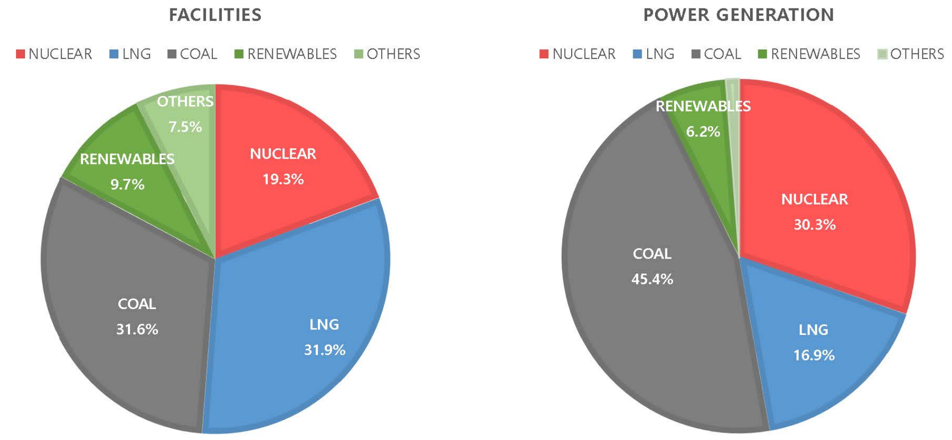
2020. 2. 19.

Prof. Kun-Yeun Han, Kyungpook National University(KNU)
Dr. Minkyu Kim, Korea Atomic Energy Research Institute(KAERI)
Dr. Beom-Jin Kim, Korea Atomic Energy Research Institute(KAERI)

Contents

1. Research Objectives
2. Local Intensive Precipitation Analysis
3. Detailed Hydrologic/Hydrodynamic Analysis
4. 2D External and Internal Flood Inundation
5. Conclusions

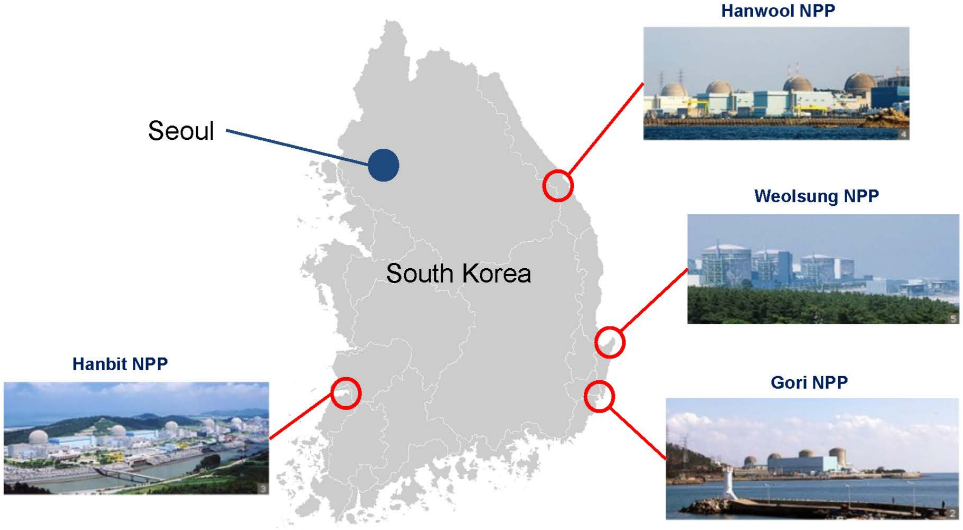
Power Generation Capacities in Korea(2017)



(Total Power Generation Capacities : 117GW)

(https://www.motie.go.kr)

Nuclear Power Plants in Korea(2017)



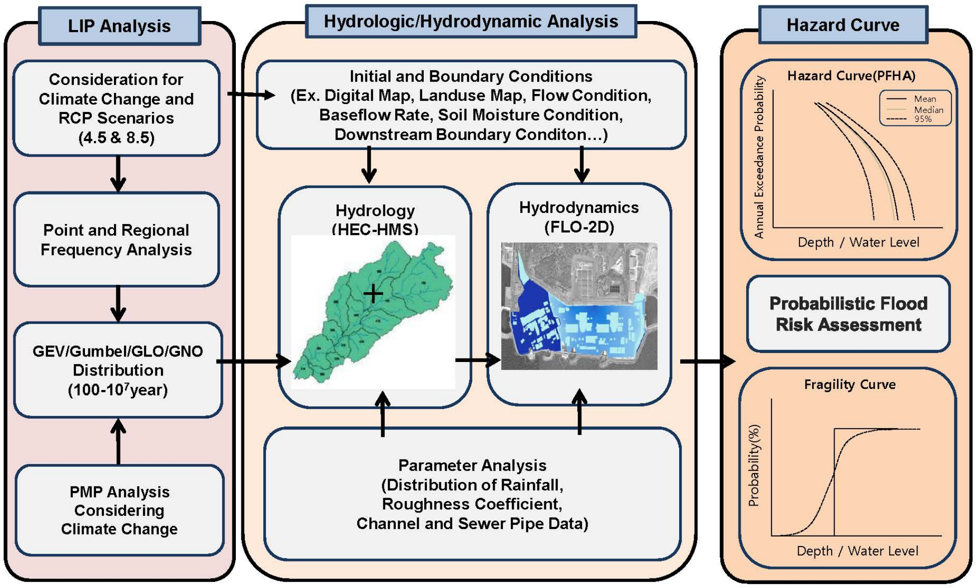
(https://terms.naver.com/entry.nhn?docId=3571558&cid=58941&categoryId=58960)

Research Objectives

Research Objectives

- ▶ In recent years, the risk of external/internal flooding of major national facilities such as NPP has increased significantly due to the local intensive precipitation under climate change.
- ▶ Refined walkdowns have been carried out at the site to investigate specifications for flood protection facilities, location, critical height and conditions of seals.
- ▶ Flood hazard curve by frequency has been developed through a quantitative analysis of extreme rainfall, inundation depth and inundation intensity by occurrence frequency.
- ▶ Fragility assessment has also been carried out for major structures, systems and components(SSC) by identifying flow paths through the results of walkdowns.

Research Method



LIP Analysis

Consideration for Climate Change and RCP Scenarios (4.5 & 8.5)

Point and Regional Frequency Analysis

GEV/Gumbel/GLO/GNO Distribution ($100-10^7$year)

PMP Analysis Considering Climate Change

Hydrologic/Hydrodynamic Analysis

Initial and Boundary Conditions (Ex. Digital Map, Landuse Map, Flow Condition, Baseflow Rate, Soil Moisture Condition, Downstream Boundary Conditon…)

Hydrology (HEC-HMS)

Hydrodynamics (FLO-2D)

Parameter Analysis (Distribution of Rainfall, Roughness Coefficient, Channel and Sewer Pipe Data)

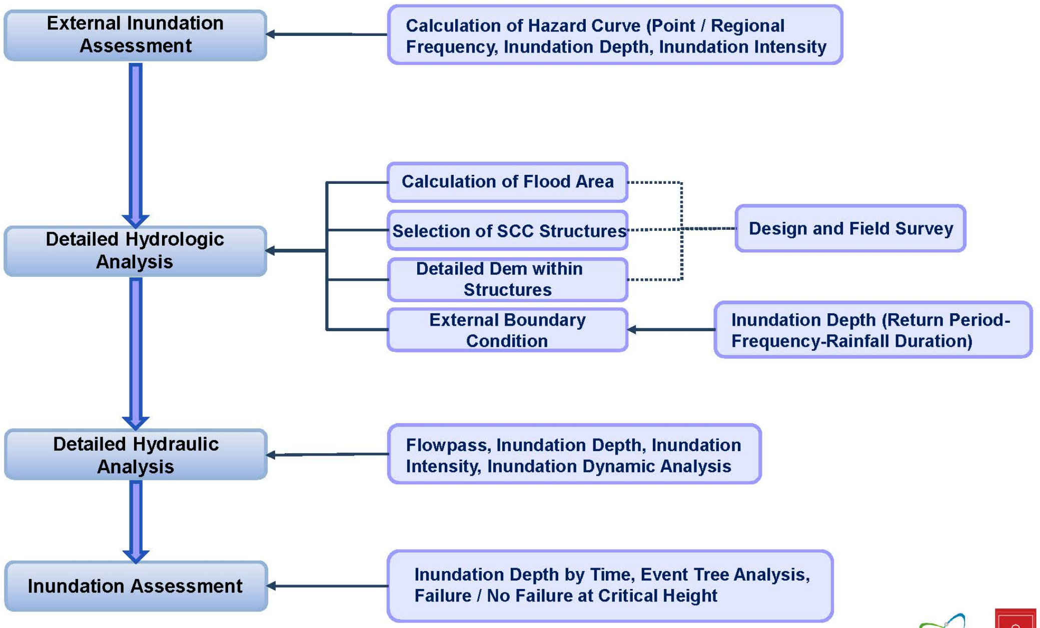
Hazard Curve

Probabilistic Flood Risk Assessment

Research Method

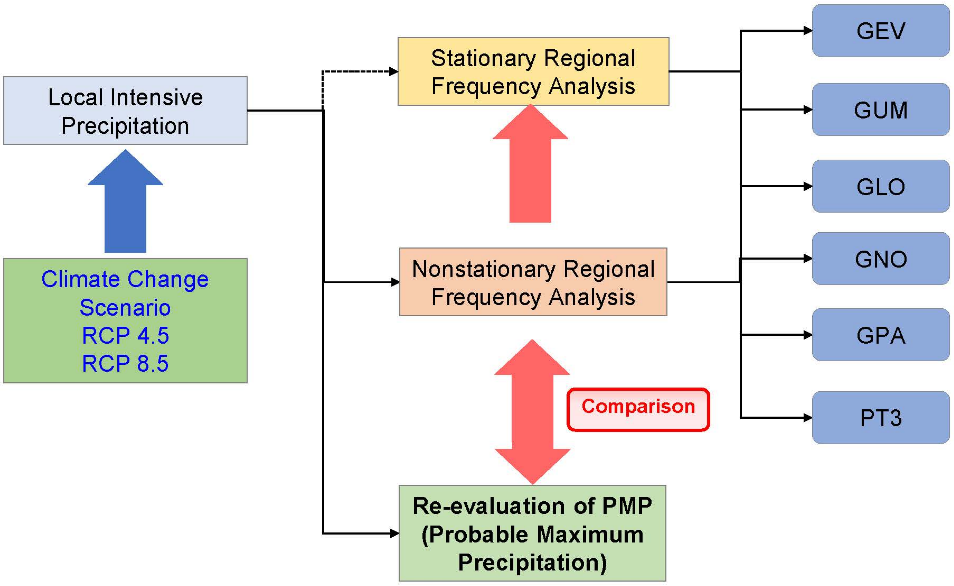
- ▶ Probable Maximum Precipitation(PMP) considering the climate change scenarios of RCP4.5 and RCP8.5 are computed and compared with the probability flood by frequency analysis to estimate the LIP.
- ▶ In order to evaluate the external flooding risk on these structures, 2D hydraulic analysis is performed and the frequency hazard curve is developed using the results of flood depth and velocity.
- ▶ To evaluate the flood risk, the safety factor of the performance function was calculated, then safety probability assessment was suggested under various risk conditions including the failure probability of system response, occurrence probability, exposure investigation and expected loss.

Research Method



Local Intensive Precipitation Analysis

Local Intensive Precipitation



Local Intensive Precipitation

Climate Change Scenario
RCP 4.5
RCP 8.5

Stationary Regional Frequency Analysis

Nonstationary Regional Frequency Analysis

Re-evaluation of PMP (Probable Maximum Precipitation)

Comparison

GEV
GUM
GLO
GNO
GPA
PT3

Local Intensive Precipitation

Type		Probability Density Function and Cumulative Distribution Function
Gumbel	PDF	$f(x) = \frac{1}{\alpha} exp\left[-\frac{x-\epsilon}{\alpha} - exp\{-\frac{x-\epsilon}{\alpha}\}\right] \; (-\infty < x < \infty)$
	CDF	$F(x) = exp\left[-exp\left[-\frac{(x-\epsilon)}{\alpha}\right]\right] (-\infty < x < \infty)$
GEV	PDF	$f(x) = \frac{1}{\alpha}\left\{1 - k(\frac{x-\epsilon}{\alpha})\right\}^{\left(\frac{1}{k}-1\right)} exp\left[-\left\{1 - k(\frac{x-\epsilon}{\alpha})\right\}^{\frac{1}{k}}\right]$
	CDF	$F(x) = exp\left\{-\left\{1 - k(\frac{x-\epsilon}{\alpha})\right\}^{\frac{1}{k}}\right\}$

(Source : Heo, J.H, Statistical Hydrology, 2016)

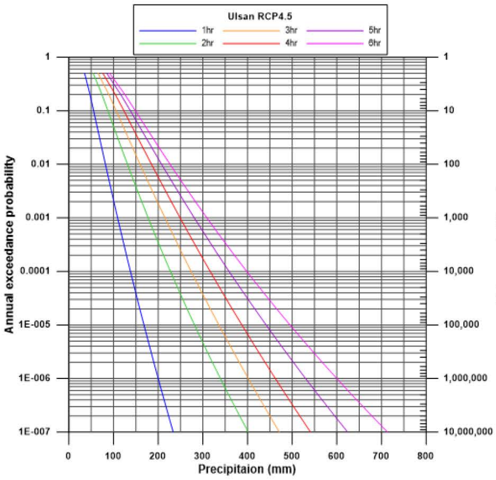
Local Intensive Precipitation

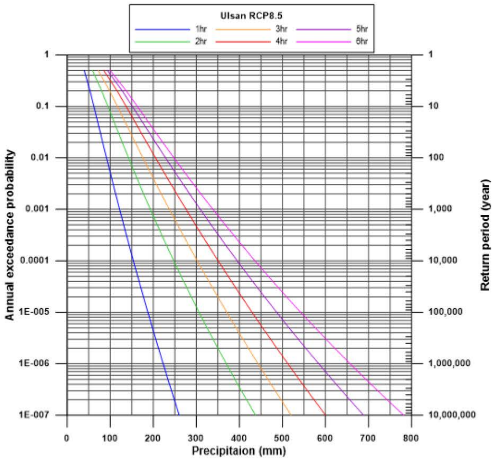
Type		Probability Density Function and Cumulative Distribution Function
GLO	PDF	$f(x) = \frac{1}{\alpha}\left\{1 - k(\frac{x-\epsilon}{\alpha})\right\}^{\left(\frac{1}{k}-1\right)}\left[1 + \left\{1 - k(\frac{x-\epsilon}{\alpha}\right\}^{\frac{1}{k}}\right]^{-2}$
	CDF	$F(x) = \frac{1}{\alpha}\left\{1 - k(\frac{x-\epsilon}{\alpha})\right\}^{\left(\frac{1}{k}-1\right)}\left[1 + \left\{1 - k(\frac{x-\epsilon}{\alpha}\right\}^{\frac{1}{k}}\right]^{-1}$
GNO	PDF	$f(x) = \frac{k}{2\alpha\Gamma(\frac{1}{k})} exp\{-\left\lvert\frac{x-\epsilon}{\alpha}\right\rvert^{k}\}$
	CDF	$F(x) = 1 - \frac{\Gamma(\frac{1}{\beta}, (\frac{x-\epsilon}{\alpha})^{\beta}}{2\Gamma(\frac{1}{\beta})}$

Local Intensive Precipitation

	Regional Frequency Analysis (Nonstationary-Climate change-R2 Region)						Regional Frequency Analysis (Nonstationary-Climate change-R2 Region)						PMP		
Scenario	RCP4.5			RCP8.5			RCP4.5			RCP8.5			Existing	RCP4.5	RCP8.5
Duration	GLO	GEV	GUM	GLO	GEV	GUM	GLO	GEV	GUM	GLO	GEV	GUM	-	-	-
10min	-	-	-	-	-	-	-	-	-	-	-	-	62.8	-	-
1hr	501.1	209.2	193.1	499.8	208.7	192.6	535.6	199.4	198.2	534.2	222.1	197.7	175.8	211.3	280.4
2hr	928.6	386.6	304.0	915.8	381.3	299.9	904.7	338.3	315.8	892.2	369.3	311.4	261.8	300.5	341.6
3hr	1363.8	571.6	374.8	1374.8	576.2	377.8	1066.4	402.1	387.7	1075.0	444.2	390.9	330.4	377.9	413.6
4hr	1776.1	751.0	433.7	1796.8	759.6	439.6	1222.0	461.8	447.1	1239.2	511.7	453.3	389.8	450.6	498.6
5hr	2144.6	913.8	485.9	2161.1	920.7	490.4	1401.3	529.5	499.8	1414.2	583.9	504.5	443.1	513.6	560.5
6hr	2450.9	1049.7	530.4	2463.9	1055.3	533.2	1585.0	600.1	543.9	1593.4	657.7	546.8	492.0	568.8	604.7
7hr	2683.4	1152.1	566.5	2704.6	1161.3	570.7	1760.5	669.9	578.4	1773.6	732.2	582.6	537.5	620.7	653.3
8hr	2858.4	1228.2	596.3	2895.5	1244.2	603.8	1942.3	741.1	606.2	1967.1	813.1	613.7	580.4	670.9	711.0
9hr	2999.1	1288.9	622.1	3052.3	1311.7	633.2	2151.7	817.2	630.9	2189.8	908.2	642.1	621.0	719.2	774.7
10hr	3124.5	1343.0	646.2	3188.4	1370.4	659.5	2399.5	901.5	655.5	2448.6	1020.7	669.0	659.8	765.3	840.0
11hr	3238.0	1391.9	668.8	3308.6	1422.3	683.5	2654.9	996.0	679.8	2712.9	1136.7	694.7	696.9	808.1	900.1
12hr	3338.8	1435.1	689.8	3415.7	1468.1	705.7	2876.7	1102.6	702.7	2942.9	1237.7	718.9	732.6	846.9	947.3

Hazard Curve with LIP(RCP 4.5 & 8.5)



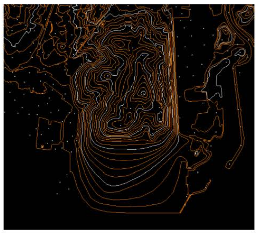


Detailed Hydrologic/Hydrodynamic Analysis

Topographic Analysis

Gori NPP site

- Study Area : Nuclear Power Plant site, Korea
- Area : 0.38km^2
- Precipitation : Probability Precipitation considering Climate Change



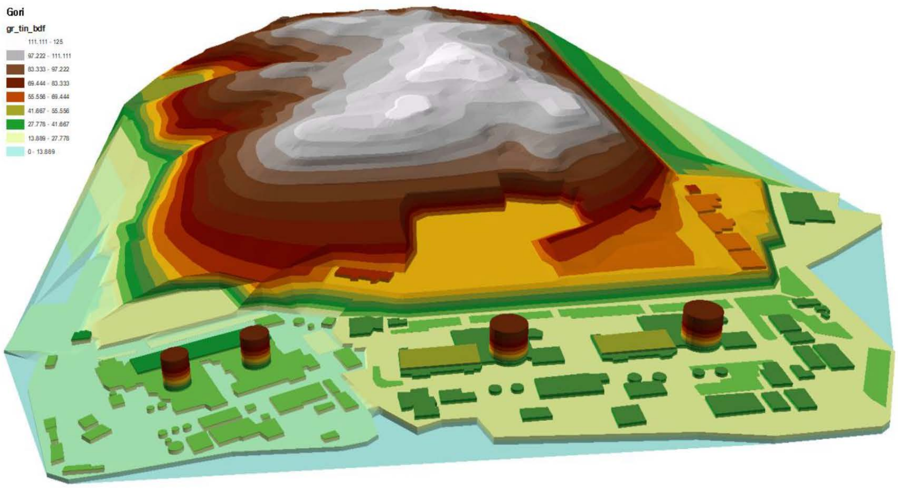
<1:5000 digital map>

<Satellite image>

<Topographic map>

Hydrologic Analysis

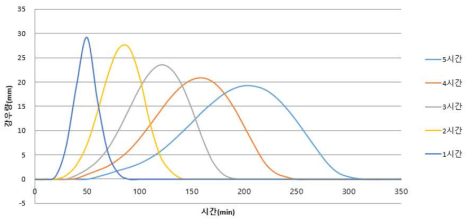
Topographic Map

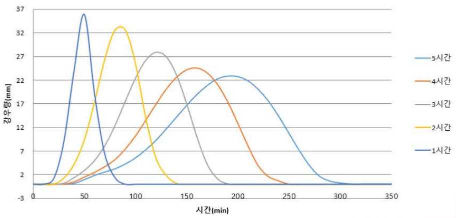


Hydrologic Analysis

- Based on the topographic data generated, 45 scenarios were constructed combining nine return periods from 100 year to $1x10^7$ year and rainfall duration conditions from 1 hour to 3 hours.

Subbasin-2	10^{-6} probability		10^{-7} probability	
	Rainfall(mm)	Peak Discharge(m^3/sec)	Rainfall(mm)	Peak Discharge(m^3/sec)
1hr	254.1	29.51	300.4	35.91
2hr	369.3	27.11	437.4	32.61
3hr	444.2	23.51	521.1	27.91
4hr	511.7	20.81	599.3	24.61
5hr	583.9	19.21	688.0	22.81



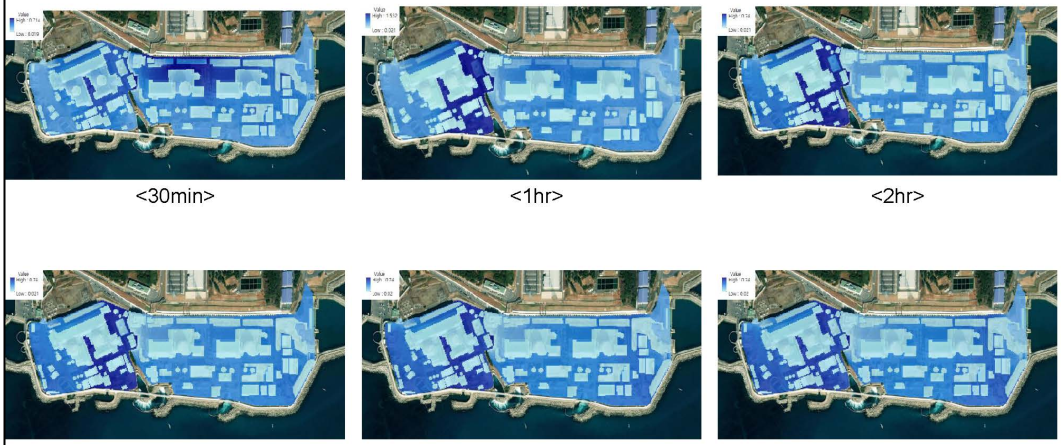


2D Hydrodynamic Analysis

External 2D Simulation and Hazard Analysis

- ▶ The grid size was 3m x 3m for two-dimensional analysis, and total simulation time was 12 hr.
- ▶ FLO-2D model was applied to external/internal flood inundation for the simulation of flood depth and velocity.

2D Hydrodynamic Analysis


<30min> <1hr> <2hr>

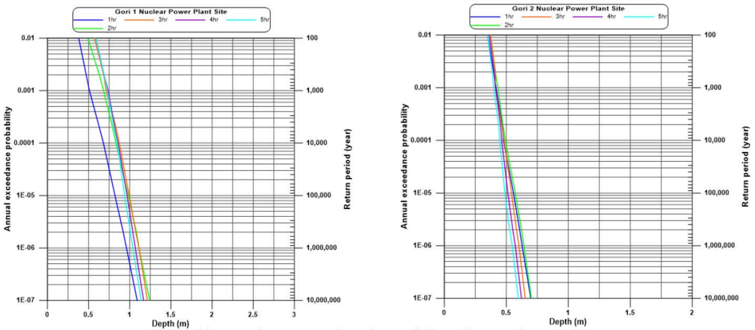
<3hr> <4hr> <5hr>

<Time variation of external flood inundation depth(10^7 year)>

Flood Hazard Analysis

Hazard Curve with 2D External Flood Analysis

▶ Based on the results of the 2D analysis, flood hazard curves for the inundation depth with the various frequency and duration conditions was developed at specific area of major facilities. The internal flooding within structure, system and components caused by external flood inundation in the major facilities was also evaluated.



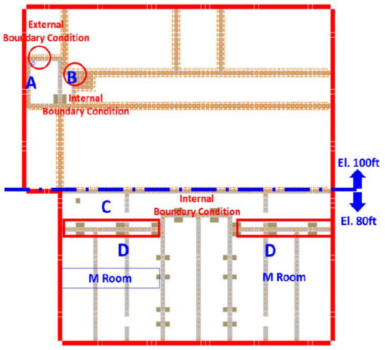
<Hazard curve of external flood event >

Flood Hazard Analysis

Internal Inundation and Hazard Analysis

▶ The grid size was 1m x 1m for 2D analysis, and total simulation time was 12 hr.

▶ A total of 4 areas form A to D in small flood areas.

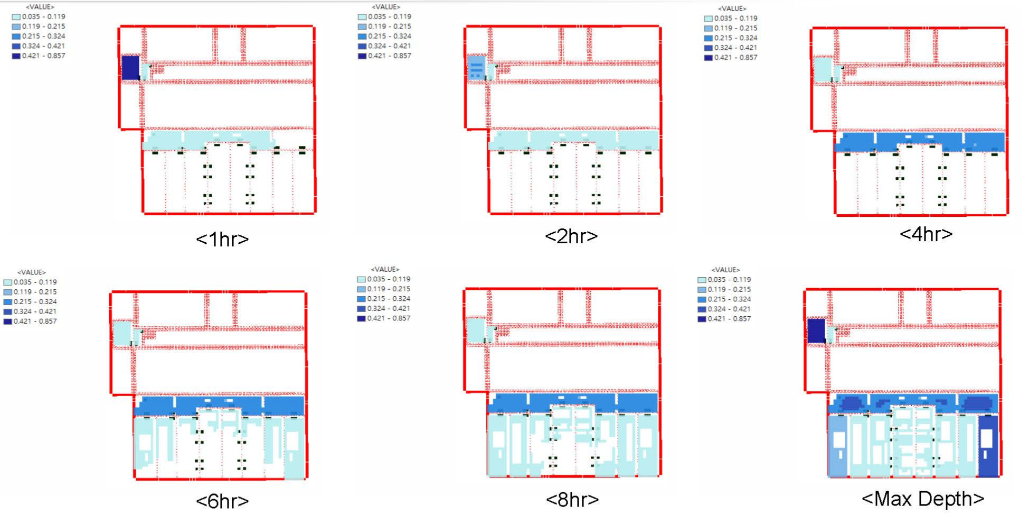


<Internal flood inundation analysis area>

Name of Building	100ft CB Door	100ft CB Stair Area	80ft M Facility Area	80ft M Facility Room
Area Mark	A	B	C	D

Flood Hazard Analysis

Result of Internal Flood Analysis(2D)



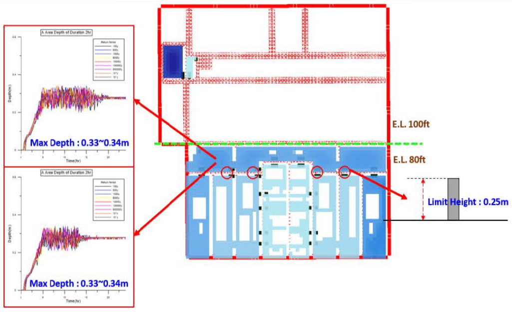
<1hr> <2hr> <4hr>

<6hr> <8hr> <Max Depth>

<Time variation of Internal inundation depth (10^7yr)>

Flood Hazard Analysis

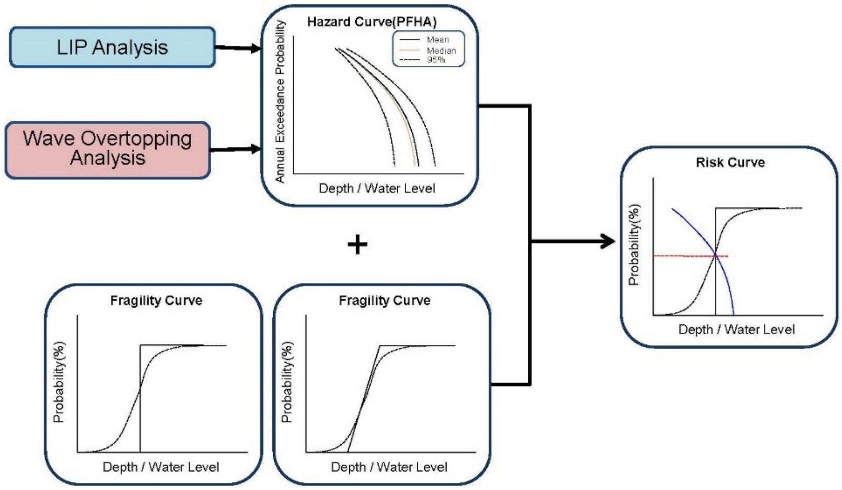
Result of Internal Flood Analysis(2D)



<Internal flood inundation depth (A to D area) >

- ▶ The maximum depth of NPP no. 3/4 of C area was 0.33 ~ 0.34m.
- ▶ In the design of nuclear structures, the average critical height of major equipment is 0.25m.
- ▶ Therefore, flooding in Zone C is likely to cause flooding into Zone D and Units 3 and 4 were considered vulnerable to internal flooding.

Future Study Plan



LIP Analysis

Wave Overtopping Analysis

Conclusions

Conclusions

- ▶ In order to estimate the probability rainfall of 1 million years and 10 million years at target NPP, it was judged that the Gumbel distribution of regional frequency analysis was most appropriate.
- ▶ In order to estimate the extreme flowrate through the topographic analysis and hydrologic analysis, each of the nine frequencies (100 years, 500 years, 1000 years, 5000 years, 10,000 years, 100,000 years, 500,000 years, 1 million years, 10 million years) were considered to calculate the runoff hydrograph for 1 to 5 hours durations.
- ▶ As a result of the calculations, the critical duration was found at 1 hour at all frequencies, and 29.5 m^3/s for 1 million years and 35.9 m^3/s for 10 million years were calculated respectively.

Conclusions

- ▶ As the results of this study, the basic data for the probabilistic risk assessment of external floods that could occur at the site of the NPP from the extreme flood conditions due to river and watershed flood were established.
- ▶ The probabilistic flood risk assessment method will be able to assess the risk associated with vulnerability at the site of the major NPP site, and it can be used as a technical basis for comprehensive and detailed quantitative risk assessment, as well as for establishing structural/non-structural measures and for various regulation tools against severe flooding at major NPP site.

Thanks for your attention.

kshanj@knu.ac.kr

3.3.5 Presentation 1C-5: Analysis of Heavy Multi-day Precipitation Events in CMIP6 Model Simulations in Support of the Fifth National Climate Assessment

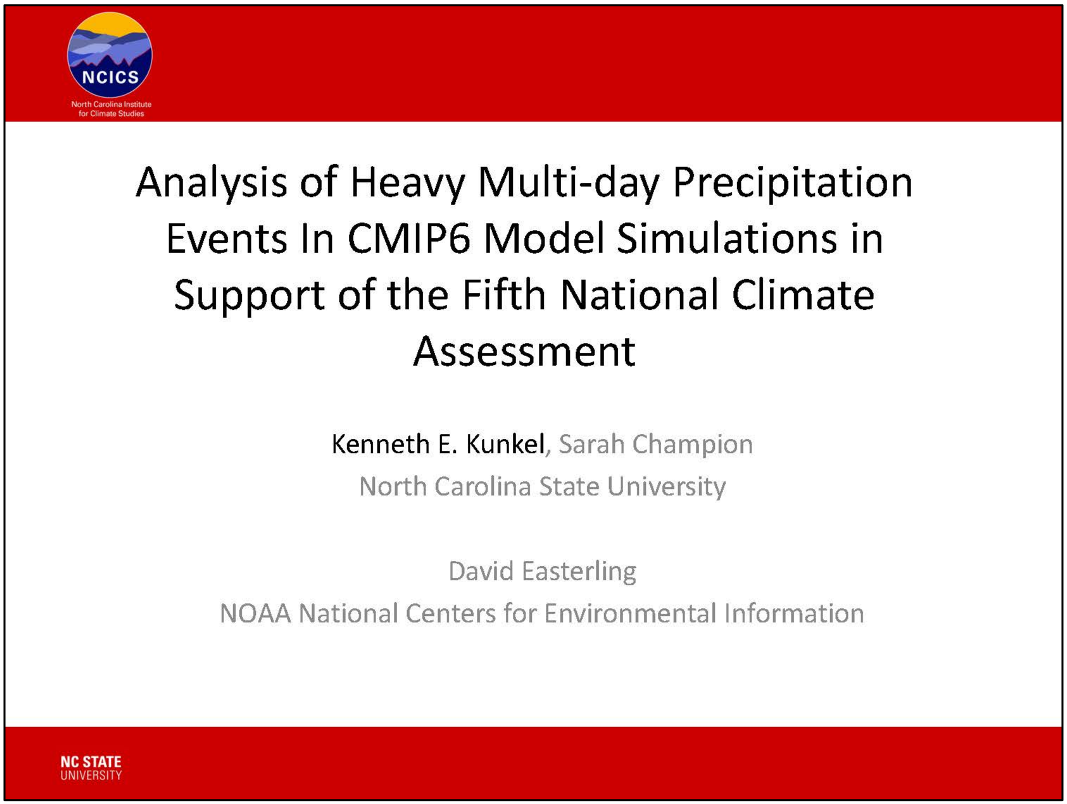
Authors: Kenneth Kunkel, North Carolina Institute for Climate Studies, North Carolina State University and David Easterling, NOAA National Centers for Environmental Information

Speaker: Kenneth Kunkel

3.3.5.1 Abstract

The Third U.S. National Climate Assessment (NCA3) mainly used climate scenarios generated using the CMIP3 suite of climate model simulations with some generated using CMIP5. The Fourth U.S. National Climate Assessment used the CMIP5 suite of simulations, and also used the Localized Constructed Analog (LOCA) statistical downscaling dataset to generate scenarios of extremes such as changes in heavy precipitation events. With the CMIP6 suite of simulations becoming available the intent of the U.S. Global Change Research Program is to utilize these simulations as much as possible for the Fifth U.S. National Climate Assessment. One major question raised during the NCA process is how extremes, such as hydrological extremes, have changed and will change in the future. Here we examine heavy precipitation events by finding the largest multi-day events for various sized areas (e.g. 50,000 km^2) in the observed record for the eastern United States, then examine both the simulations directly from CMIP5, two statistical downscaling methods driven by CMIP5 simulations, and two simulations from CMIP6 for their ability to produce similar precipitation events. Secondly, we examine the ability of both models and downscaling methods to reproduce the observed spatial coherence of the point precipitation amounts across the simulated precipitation events.

3.3.5.2 Presentation (ADAMS Accession No. ML20080M197)



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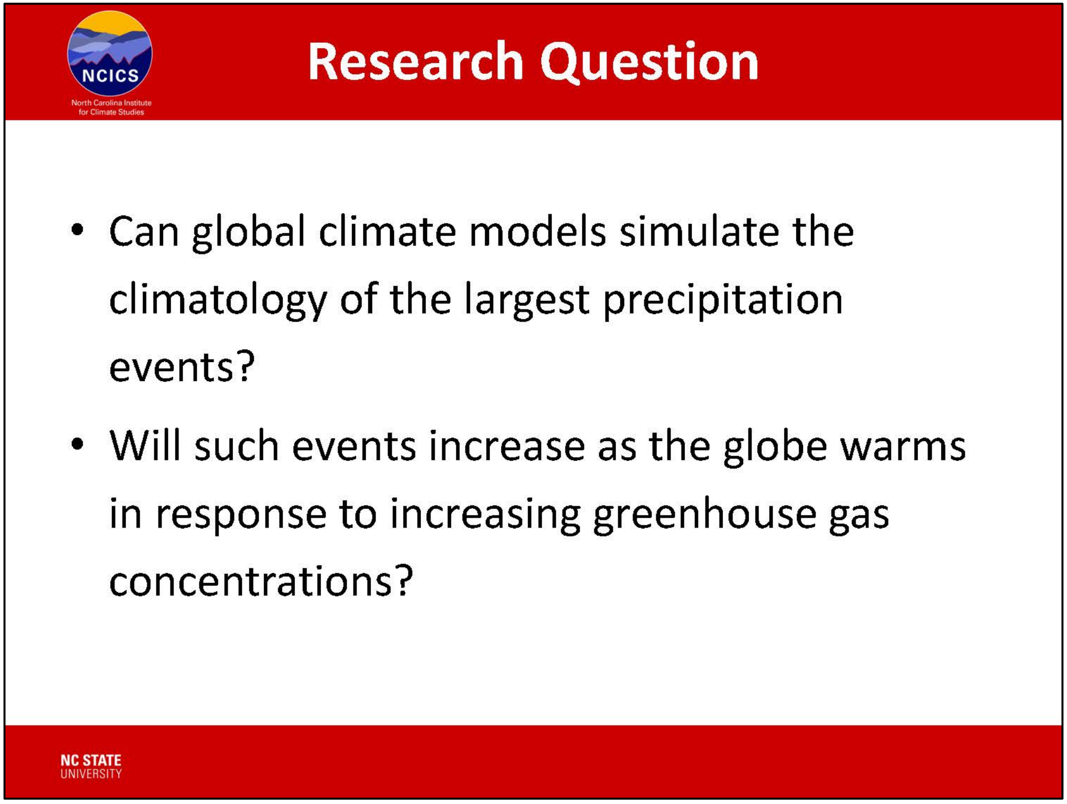
Analysis of Heavy Multi-day Precipitation Events In CMIP6 Model Simulations in Support of the Fifth National Climate Assessment

Kenneth E. Kunkel, Sarah Champion
North Carolina State University

David Easterling
NOAA National Centers for Environmental Information

NC STATE UNIVERSITY



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Research Question

- Can global climate models simulate the climatology of the largest precipitation events?
- Will such events increase as the globe warms in response to increasing greenhouse gas concentrations?

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Research Approach

- Analysis of historical precipitation data to identify the largest multi-day precipitation events in the U.S. historical record
- Analysis of select global climate model simulations from the new CMIP6 archive

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Historical Precipitation Analysis

- Examination of area-averaged rainfall in approximately square boxes
- 1949-2018
- Conterminous U.S.
- For temporal consistency, only used with less than 10% missing daily precipitation data from the Global Historical Climatology Network

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Historical Precipitation Analysis

- Defined an overlapping grid of cells separated by 1/5 degree in latitude and 1/5 degree in longitude covering conterminous U.S.
- Within the grid, considered all possible 2-degree by 2-degree (nominal) cells (all cells like the bold box in the following figure) (an approximate area of 20,000 mi^2)
- Computed daily precipitation for 1949-2018 as a simple average of all stations in each cell. All cells that are partly over water were not included in this analysis.

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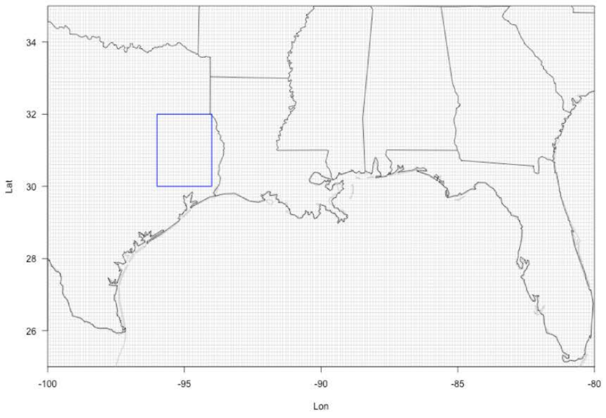
Grid Box Analysis



Historical Precipitation Analysis

- For each cell, identified the top (non-overlapping) **4-day precipitation** totals.
- Pooled everything (top events for all cells) together and identified the **top 100 events for 1949–2018** across the entire conterminous U.S., **eliminating** those that **overlap in time or space** with a larger event.
- Repeated analysis on several grid sizes from **1.0° to 3.0°**

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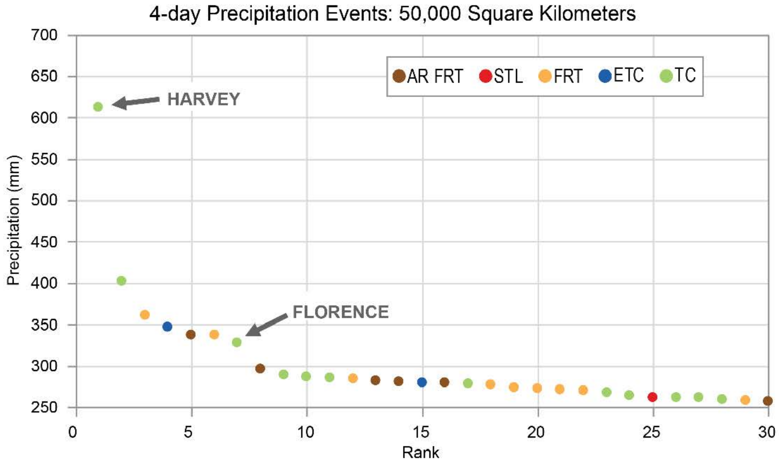
Top 30 Events-Ranked



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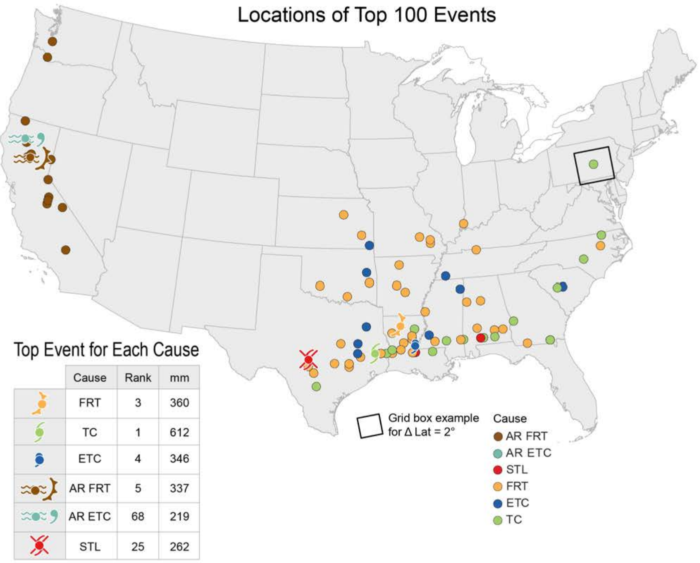
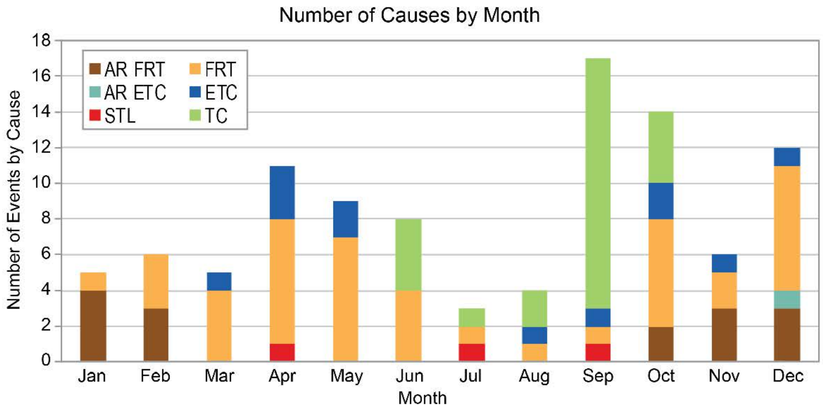
Locations and Causes



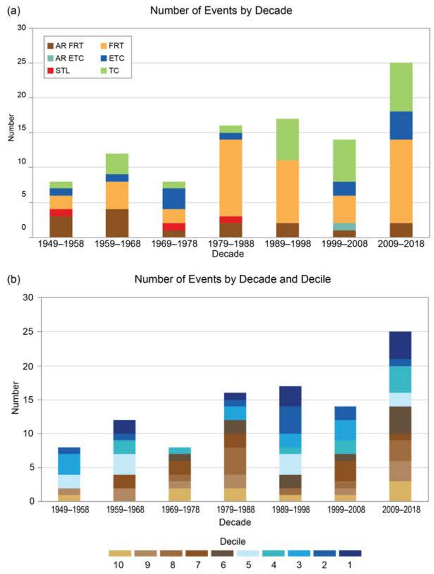
Top Event for Each Cause

	Cause	Rank	mm
	FRT	3	360
	TC	1	612
	ETC	4	346
	AR FRT	5	337
	AR ETC	68	219
	STL	25	262

Monthly Distribution



Temporal Distribution



Historical Analysis – Key Findings

- Events concentrated along the Gulf and West Coasts
- 59% of events caused by fronts and 25% by tropical cyclones
- Two peaks in monthly distribution – spring and early fall
- Upward trend in the number of events

Historical Analysis – Key Findings

- Kunkel, K.E. and S.M. Champion, 2019: An assessment of rainfall from Hurricanes Harvey and Florence relative to other extremely wet storms in the United States. *Geophys. Res. Lett.*, 46, 13,500–13,506. https://doi.org/10.1029/2019GL085034.

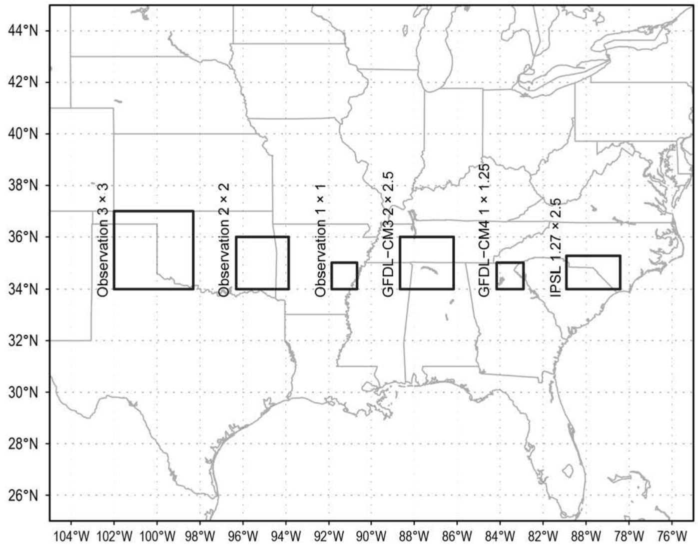
CMIP Precipitation Analysis

- Pilot analysis
- 1 model from CMIP5 and 2 from CMIP6
- NOAA GFDL
  - CM3: CMIP5, Pre-industrial control
  - CM4: CMIP6, Pre-industrial control
- IPSL
  - CMIP6, Pre-industrial control, Doubled CO_2

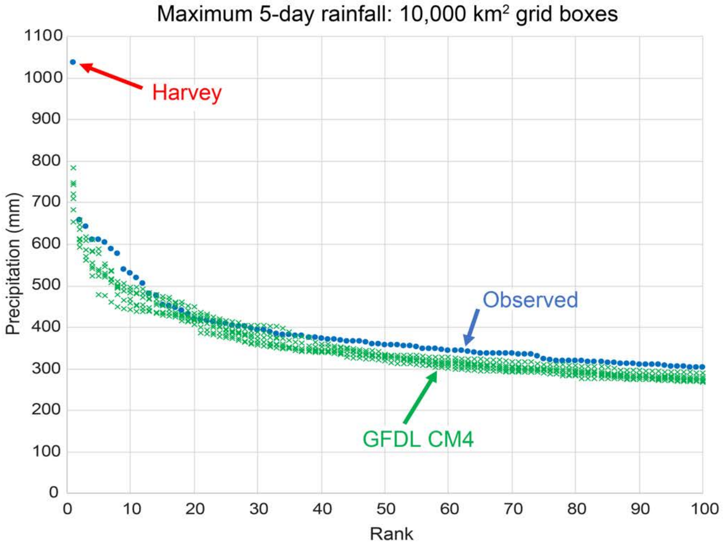
CMIP Precipitation Analysis

- Match historical analysis resolution with climate model native resolution
- Broke climate model simulations into 70-yr segments to match historical period length

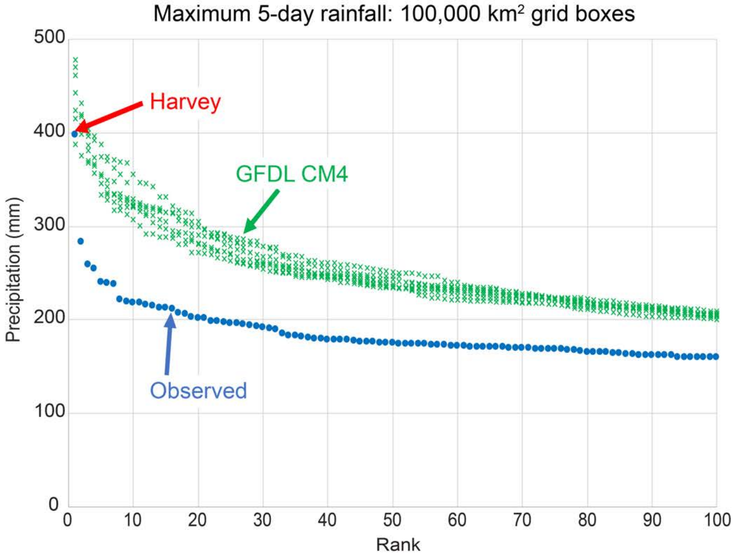
Grid Box Sizes

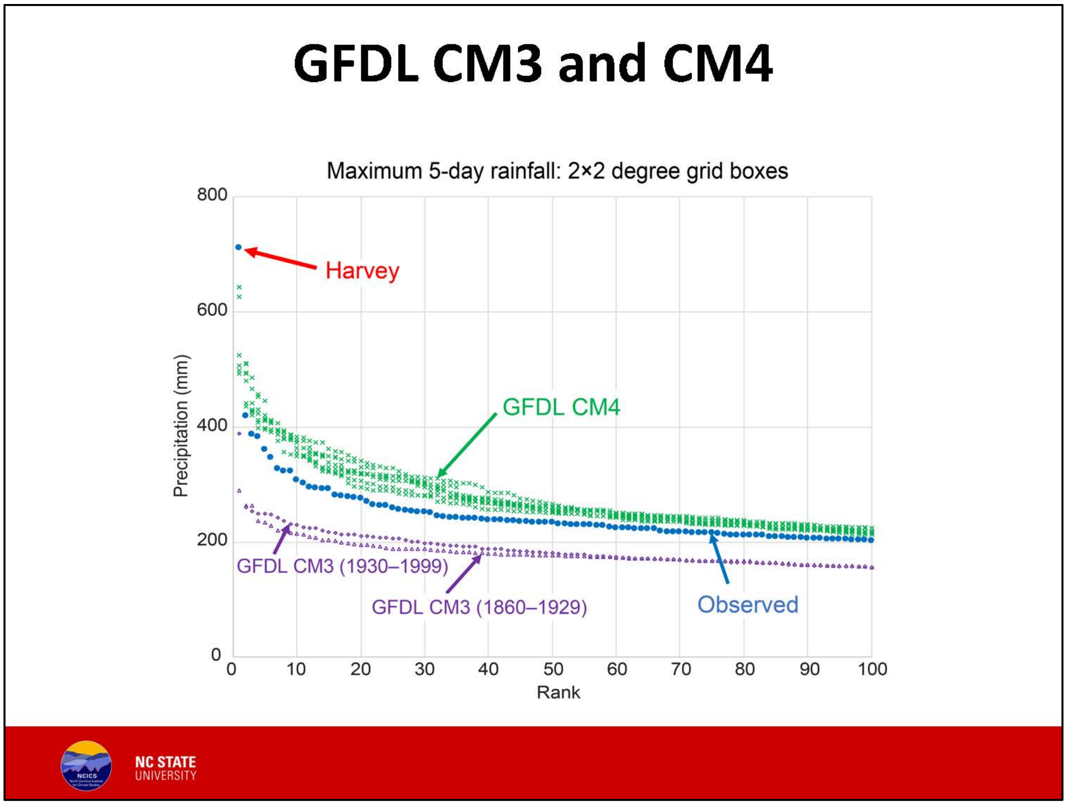


GFDL CM4 – native resolution



GFDL CM4 – 100,000 sq. km.





GFDL CM3 and CM4

Maximum 5-day rainfall: 2×2 degree grid boxes

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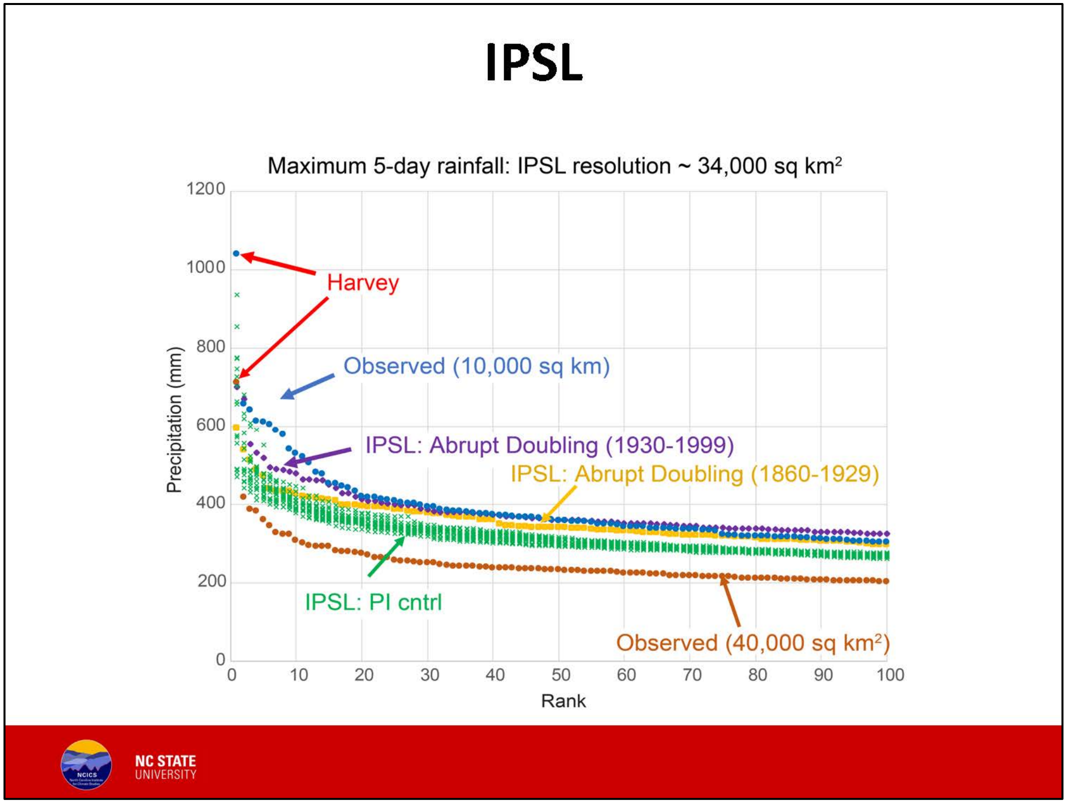

IPSL

Maximum 5-day rainfall: IPSL resolution ~ 34,000 sq km^2

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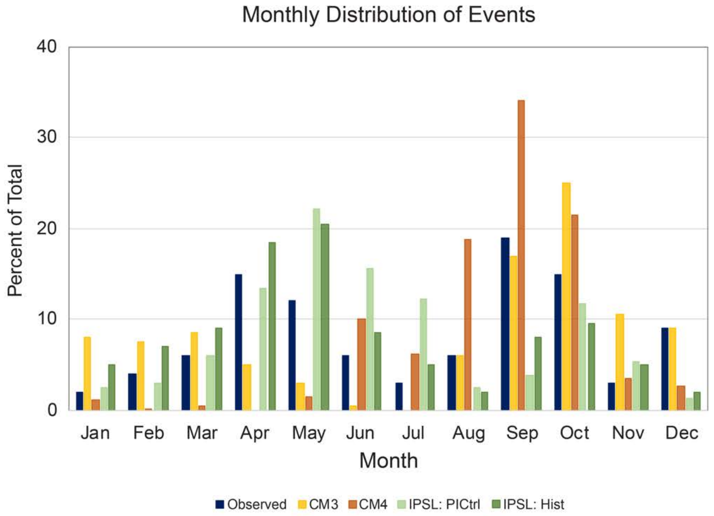
Monthly Distribution



CMIP Precipitation Analysis

- The GFDL CM4 models results are superior to GFDL CM3 model results in event magnitude, although the seasonal distribution is biased and events are too large at the 100,000 km^2 scale
- The IPSL model events are a little higher than observed when comparing similar box sizes
- At their native resolutions, none of the model simulations produce an event of the size of Harvey

3.4 Day 2: Session 2A – Riverine Flooding

Session Chair: Meredith Carr and Mark Fuhrmann, NRC/RES/DRA

3.4.1 Presentation 2A-1 (KEYNOTE): An Overview NOAA's National Water Model

Authors: Brian Cosgrove, Office of Water Prediction, National Weather Service, National Oceanic and Atmospheric Administration (NOAA/NWS/OWP); David Gochis, Research Applications Laboratory, National Center for Atmospheric Research (NCAR), Thomas Graziano, Ed Clark and Trey Flowers, NOAA/NWS/OWP

Speaker: Brian Cosgrove

3.4.1.1 Abstract

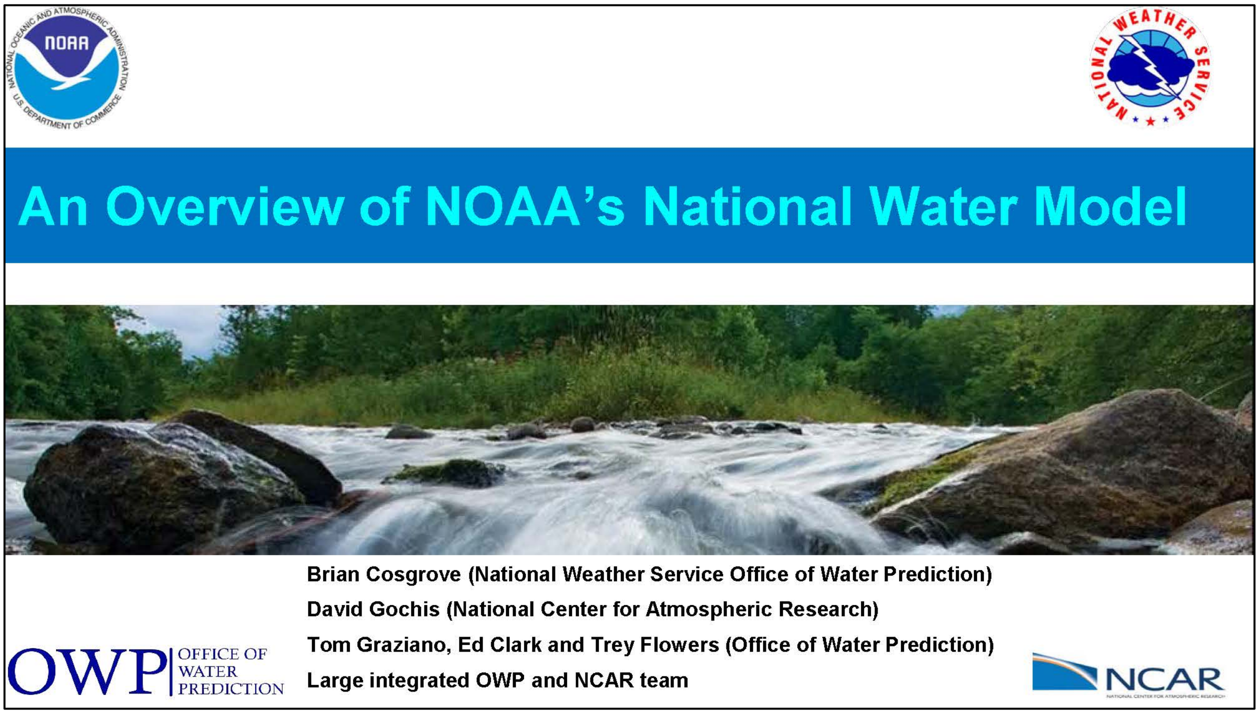
The National Water Model (NWM) has been running in National Weather Service (NWS) operations since August of 2016. Producing 24x7 guidance on streamflow, soil moisture, snowpack and other hydrologic components, the NWM supports the operational activities of NWS River Forecast Centers, the Federal Emergency Management Agency and other government entities, along with research and commercial sectors. Based on the community WRF-Hydro software architecture, it has been rapidly upgraded via a partnership between the NWS Office of Water Prediction (OWP), the National Center for Atmospheric Research and the National Centers for Environmental Prediction. As with prior versions V2.0, implemented in June of 2019, is underpinned by a network of 2.7 million vector-type river reaches for river routing, a 1km land surface grid for land surface modeling, and a 250m grid for surface and subsurface routing of runoff. This latest operational version builds on prior capabilities to provide improved accuracy and first-time ensemble forecast guidance. Additionally, the NWM's expansion to Hawaii marks the first ever provision of operational streamflow guidance to this island domain.

Following on from V2.0, V2.1 will be implemented into operations in early 2021. This significant upgrade will include the assimilation of reservoir outflow data which will greatly improve the accuracy of downstream forecasts. Domain expansion will continue via the inclusion of the Great Lakes drainage area, along with Puerto Rico and the US Virgin Islands. Additionally, calibration will be improved via the use forcings from the new Analysis of Record for Calibration. Improving upon the existing 25-year NWM retrospective, this same forcing dataset will be used to underpin a new 40-year retrospective simulation.

Looking further into the future, subsequent versions will contain upgrades needed to support a variety of additional activities within the NWS and broader hydrologic community. These include a model extension to simulate combined impact of freshwater and coastal flooding, a shallow groundwater model, and an improved NextGen collaborative development infrastructure.

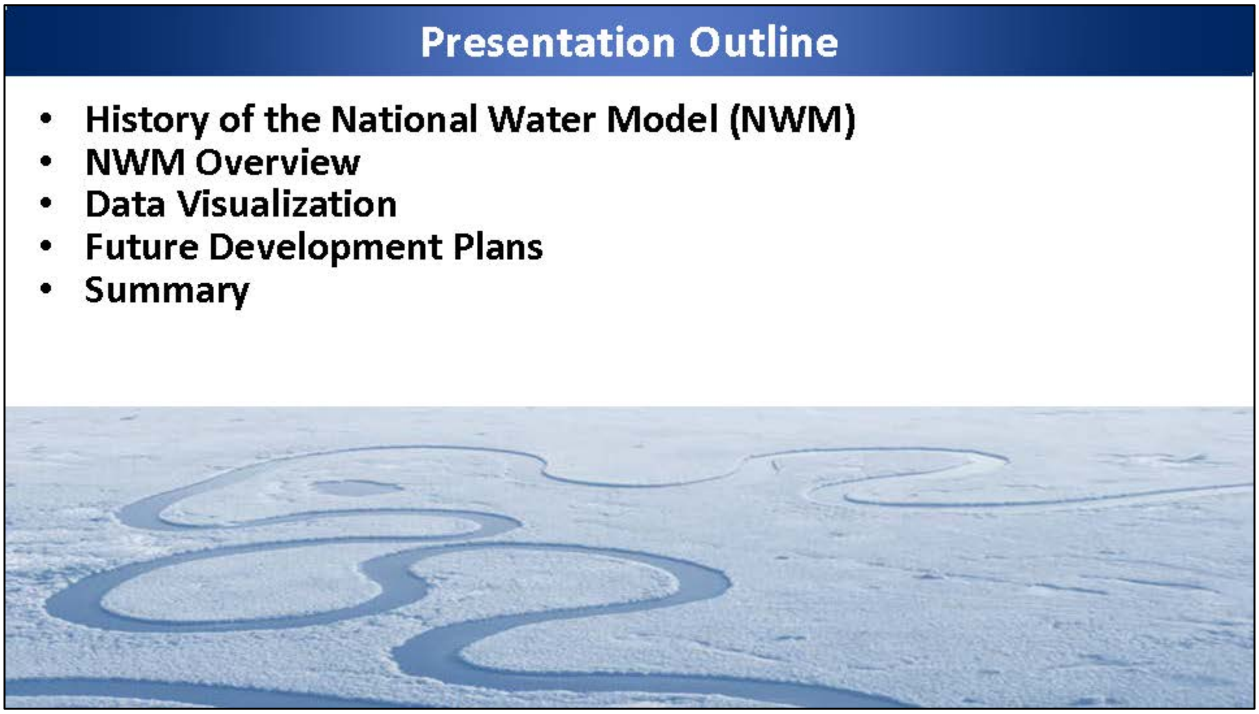
This presentation will provide a brief history of the NWM, give a general overview of the current system, and cover current and emerging NWM products. It will highlight recent and planned NWM upgrades, along with updates on community development and other hydrologic activity areas.

3.4.1.2 *Presentation (ADAMS Accession No. ML20080M200)*



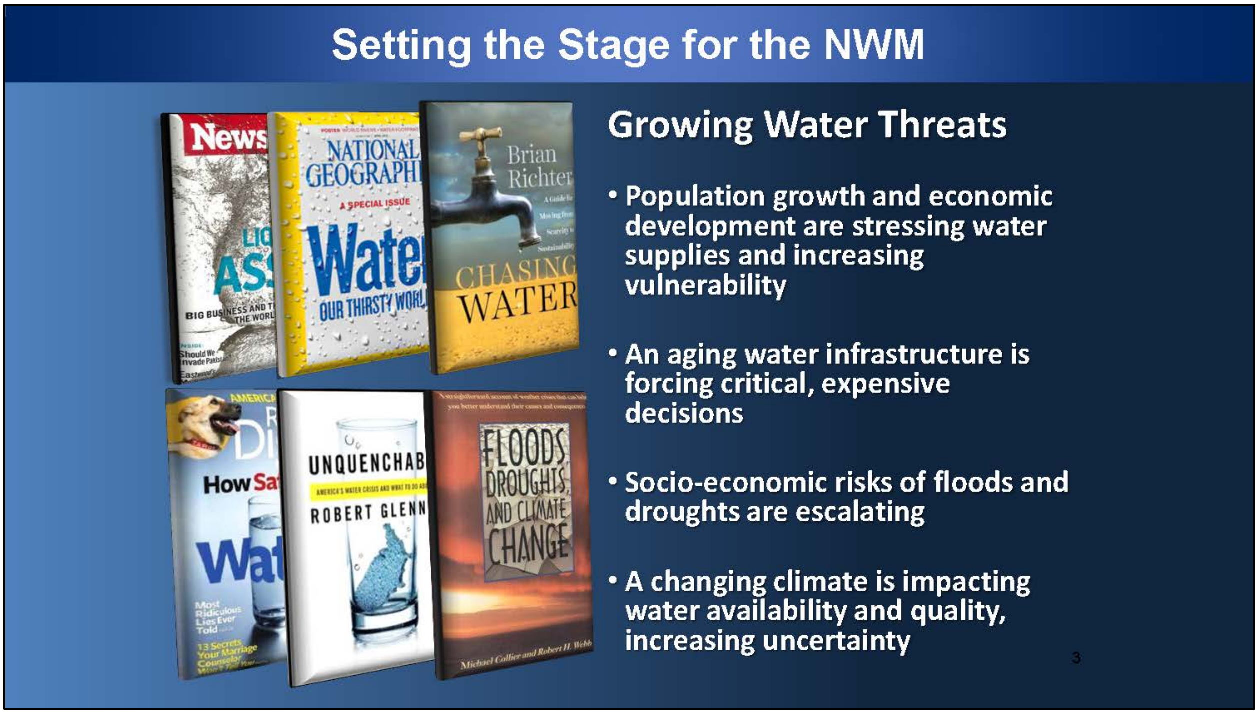
An Overview of NOAA's National Water Model

Brian Cosgrove (National Weather Service Office of Water Prediction)
David Gochis (National Center for Atmospheric Research)
Tom Graziano, Ed Clark and Trey Flowers (Office of Water Prediction)
Large integrated OWP and NCAR team



Presentation Outline

- History of the National Water Model (NWM)
- NWM Overview
- Data Visualization
- Future Development Plans
- Summary



Setting the Stage for the NWM

Growing Water Threats

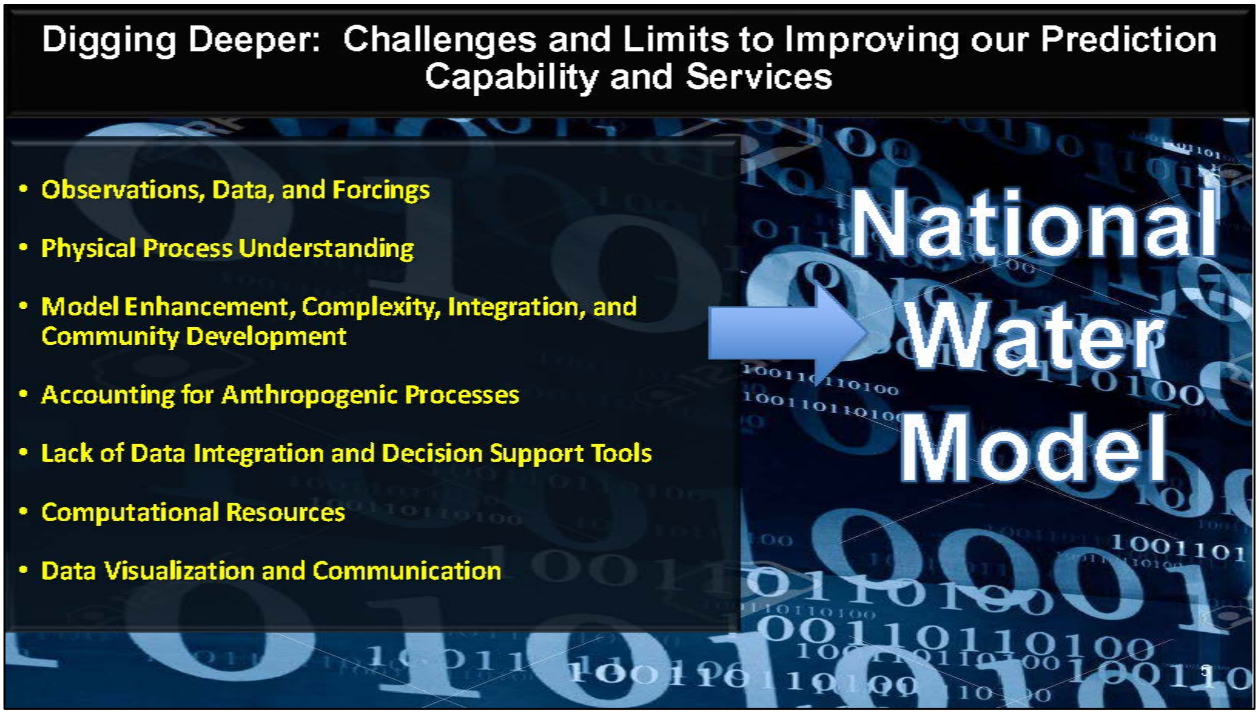
- Population growth and economic development are stressing water supplies and increasing vulnerability
- An aging water infrastructure is forcing critical, expensive decisions
- Socio-economic risks of floods and droughts are escalating
- A changing climate is impacting water availability and quality, increasing uncertainty

Focusing Requirements: Stakeholder Input

Flooding	Water Quality	Water Availability	Drought	Climate Change

Need integrated understanding of near- and long-term outlook and risks

- Provide consistent, high resolution (“street level”), integrated water analyses, predictions and data to address critical unmet information and service gaps
- Transform information into intelligence by linking hydrologic, infrastructural, economic, demographic, environmental, and political data
- Integrate Social Science to create *Actionable Water Intelligence*
- Also: Major National Academy of Sciences report highlighting capability gaps



Digging Deeper: Challenges and Limits to Improving our Prediction Capability and Services

- Observations, Data, and Forcings
- Physical Process Understanding
- Model Enhancement, Complexity, Integration, and Community Development
- Accounting for Anthropogenic Processes
- Lack of Data Integration and Decision Support Tools
- Computational Resources
- Data Visualization and Communication

National Water Model

Key Supporting Partnerships

- Federal Agencies including Integrated Water Resources Science & Services (IWRSS)

USGS science for a changing world	Water Information and Science
US Army Corps of Engineers	Water Management
NOAA	Water Prediction
FEMA	Response and Mitigation

- Academia/Research including National Academy of Sciences, National Science Foundation, CUAHSI, UCAR, NCAR
- Water Resources Managers, Emergency Managers, and other Enterprise Stakeholders

Key Supporting Facility: National Water Center

Initial Operating Capacity: May 26, 2015

- Center of excellence for water resources science and prediction
- Catalyst to transform water prediction through enterprise collaboration
- Operations Center for water resources common operating picture and decision support services on all time scales

March 21, 2019

NWC has hosted more than 80 scientific meetings with over 3000 participants

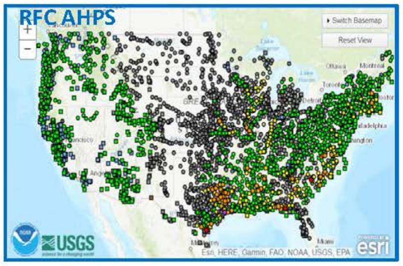
National Water Model (NWM) Overview

- Full spectrum hydrologic model, providing complementary NWS hydrologic guidance
- NWM was upgraded to V2.0 in June 2019 by OWP, NCEP and NCAR

River Forecast Centers: Authoritative forecasts at ~3,600 RFC Points

NWM: Guidance at 2.7 million NHDPlus river segments, filling in coverage

V1.0 2016 ● V2.0 2019 ● V3.0 2022 ● Next Gen



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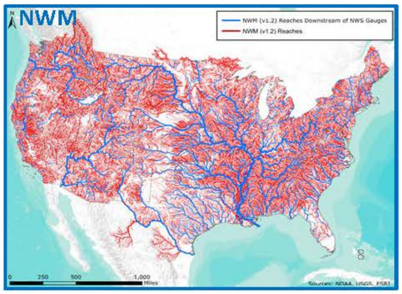
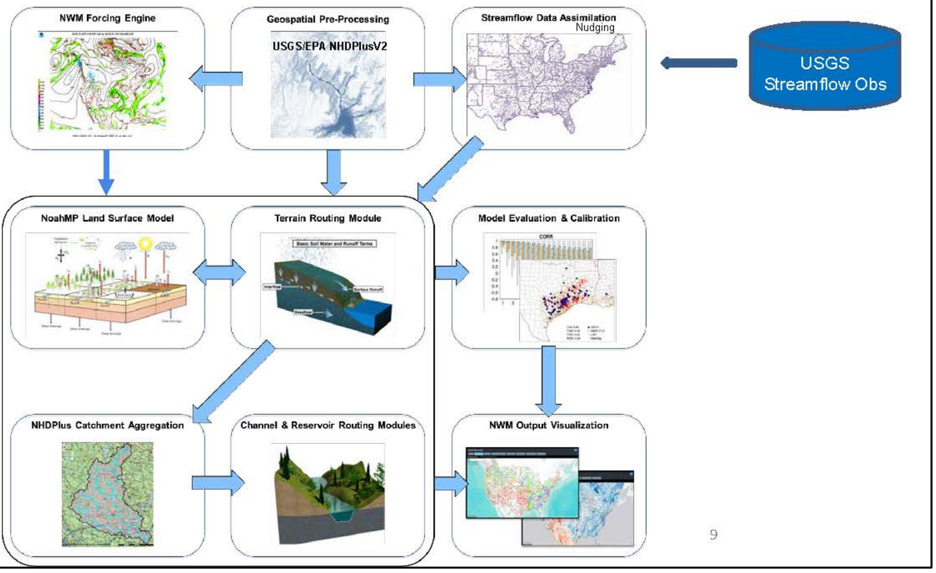


National Water Model System Structure

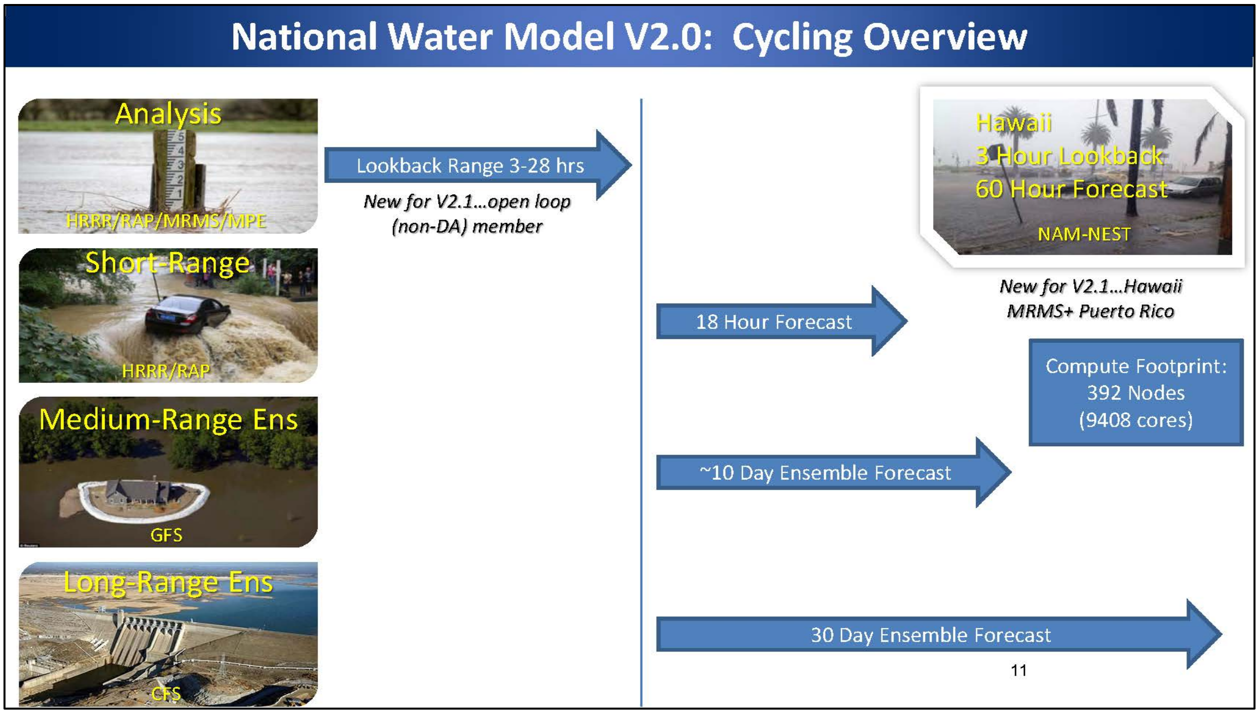
Fusion of column structure of land surface models, distributed structure of hydrologic models and national USGS/EPA NHDPlusV2 stream network within WRF-Hydro framework. Supported by verification and visualization.

NWM Hydrography
Medium Resolution
NHDPlusV2



NWM Operational Computing Environment

- The NWM runs on the NOAA Weather and Climate Operational Supercomputing System (WCOSS)
  - The model runs in a fully automated fashion with no interactive user modifications allowed between upgrades
  - Main data ingest sources should be operational themselves
- NWM Compute and disk usage
  - NWM V2.0 uses 32 nodes per model run (768 cores), and reaches a high water mark of 360 nodes (8,640 cores) due to overlapping jobs
  - V2.1 will use ~392 nodes
- NWM annual upgrade cycle can vary with internal/external factors



National Water Model V2.0: Cycling Overview

Analysis
HRRR/RAP/MRMS/MPE
Lookback Range 3-28 hrs
New for V2.1…open loop (non-DA) member

Short-Range
HRRR/RAP
18 Hour Forecast

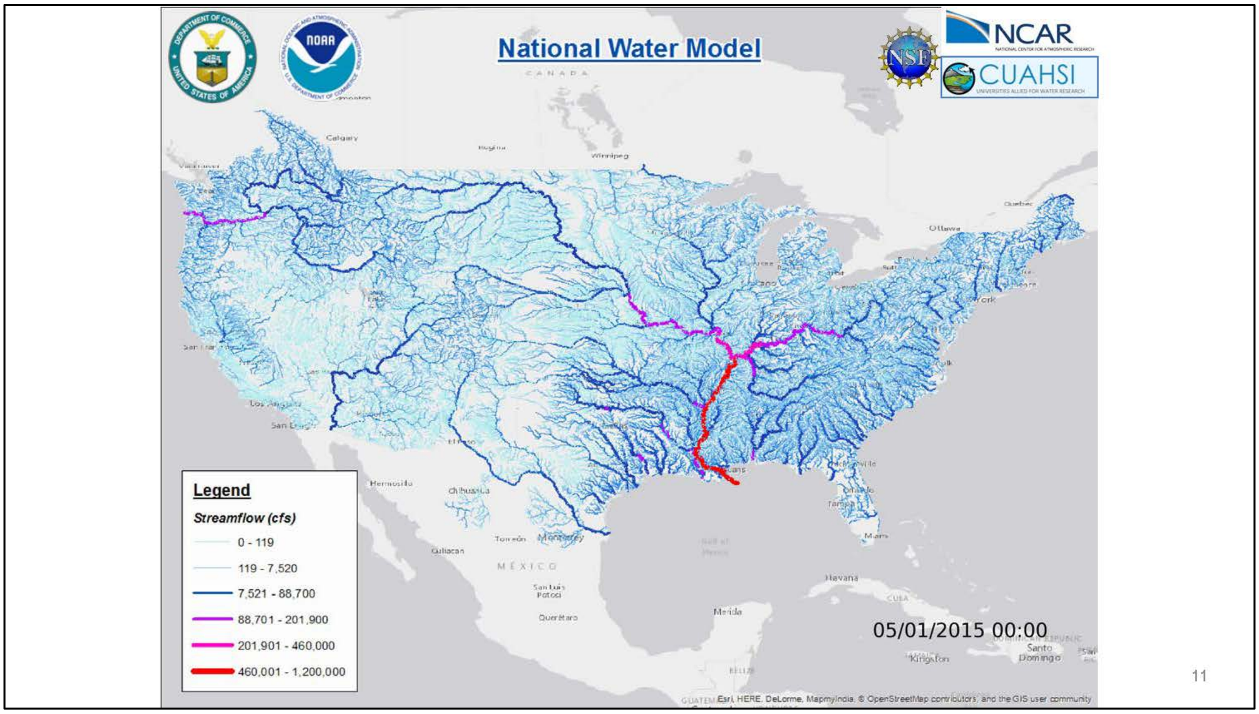
Medium-Range Ens
GFS
~10 Day Ensemble Forecast

Long-Range Ens
CFS
30 Day Ensemble Forecast

Hawaii
3 Hour Lookback
60 Hour Forecast
NAM-NEST

New for V2.1…Hawaii MRMS+ Puerto Rico

Compute Footprint:
392 Nodes
(9408 cores)



National Water Model

Legend

Streamflow (cfs)

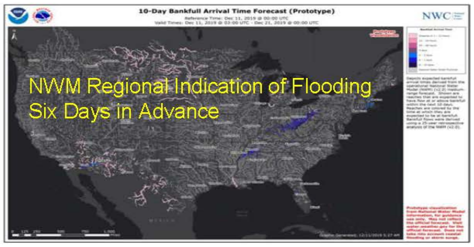
- 0 - 119
- 119 - 7,520
- 7,521 - 88,700
- 88,701 - 201,900
- 201,901 - 460,000
- 460,001 - 1,200,000

05/01/2015 00:00

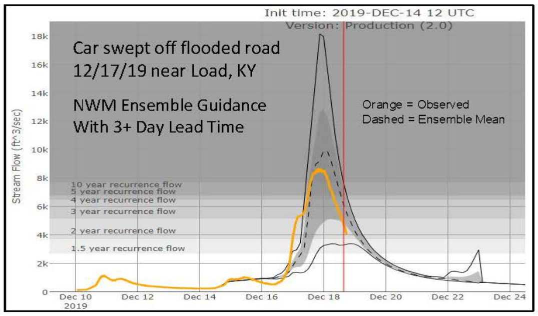
Esri, HERE, DeLorme, MapmyIndia, © OpenStreetMap contributors, and the GIS user community

Current Core Capability: Complementary Guidance

- No traditional NWS RFC river forecasts are available for many smaller streams
- Regional NWM signals over underserved areas can be leveraged days in advance
- Closer to event, ensemble guidance valuable for specific rivers



NWM Regional Indication of Flooding Six Days in Advance



Car swept off flooded road 12/17/19 near Load, KY

NWM Ensemble Guidance With 3+ Day Lead Time

- Daily NWS briefings
- National Water Center operations
- WPC mesoscale precip discussions
- FEMA disaster response support

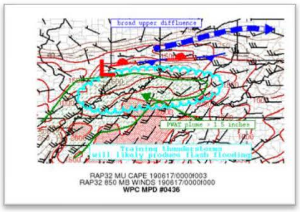
Current Core Capability: Complementary Guidance

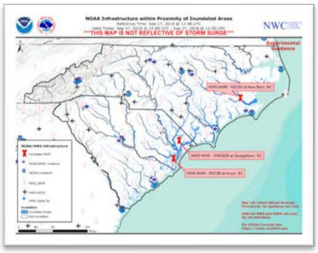
- NWM guidance is used by NWS forecasters, Water Prediction Operations staff, as well as partner agencies

Daily NWS Briefings

WPC Metwatch Desk

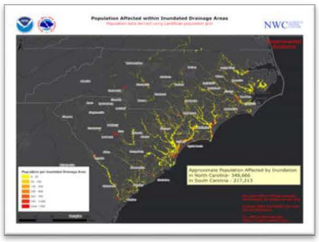
FEMA Disaster Response





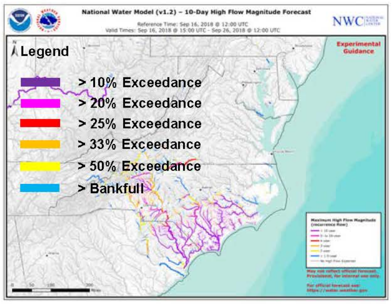
…but the heavy rates into sensitive terrain where NWM 40cm soil moisture is already at least 80% saturated suggests flash flooding will be likely…

….flash flooding noted by 14-day rainfall of 150-300%, and high NWM streamflow anomalies. High-res guidance is in good agreement…

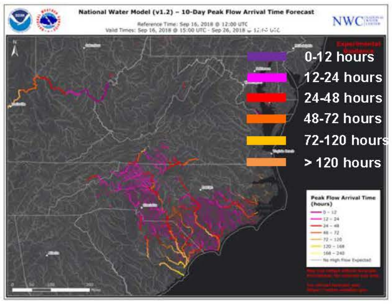


Further Leveraging NWM Model Output: Flow Forecast Mapping

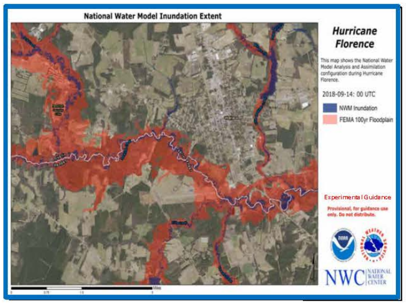
A Look Ahead to Experimental Visualizations



10-Day High Flow Magnitude Full Domain



10-Day High Flow Arrival Time Full Domain

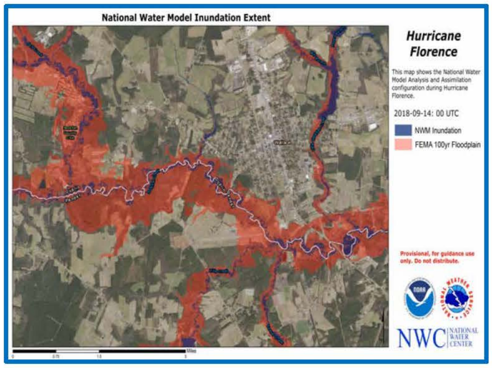


Inundation Extent Texas now, CONUS by ~2021

Where is the event? When will it occur? How likely is it?

NWM Output Visualization: Flood Inundation Mapping

- Goal: Develop Real-time Flood Inundation Mapping Systems
- FY18/19 APG: Two sources of data
  - Official WGRFC Forecasts
    - NWM "Replace and Route"
    - Available below AHPS points
  - NWM Forecasts
    - Operational NWM used as input
    - Available for ~2.7 million reaches
  - Use Height Above Nearest Drainage (HAND) method to translate streamflow to inundation forecasts
- Proposed DOC FY20/21 APG
  - Replace and Route over CONUS domain
  - NWM-based FIM Maps over NERFC



Communication is key: Multiple visualizations being prototyped

Provides actionable information as to the timing and extent of flood waters

Enhancing the NWM: Development Trajectory

v1.0

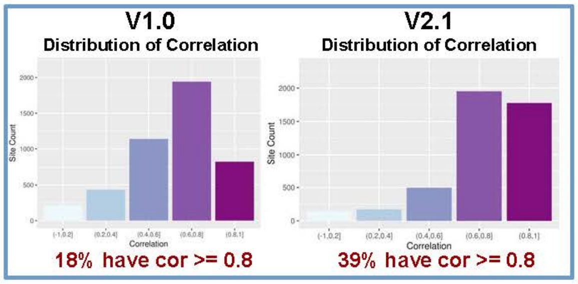
Foundation: 2016
Water resource model
2.7 million reaches

v1.1/1.2/2.0

Upgrades: 2017/2018/2019
Hawaii, medium range ens., physics upgrades, improved modularity, MPE ingest

v2.1

Next Upgrade: Early 2021
Expansion to PR and Great Lakes, reservoir modules, forcing upgrades, open-loop, and improved Hawaii forcing



18% have cor >= 0.8

39% have cor >= 0.8

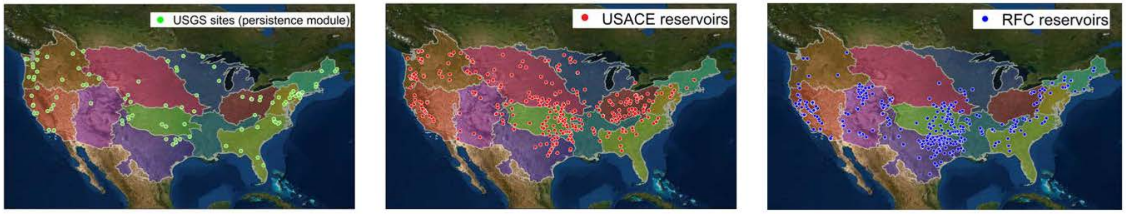
v3.0

Future Upgrade: 2022
Coastal coupling, expansion to Alaska, improved groundwater and infiltration, hydro-fabric upgrades

NWM V2.1 Future Development: Improved Treatment of Reservoir Outflow

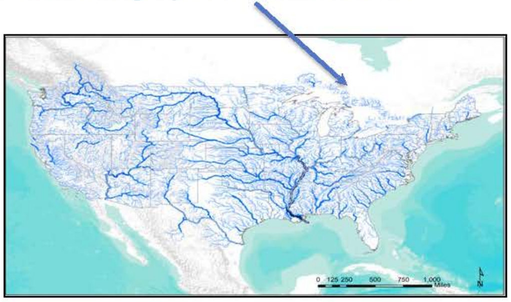
- Reservoir outflows are key to overall NWM streamflow accuracy
- Several thousand reservoirs represented in NWM, but in basic fashion
- NWM V2.1 will have two data ingest upgrades to improve outflows
  - Persistence-based data assimilation approach
    - USACE Observations from CWMS RADAR service
    - USGS Observations from existing WCOSS USGS stream gauge feed
  - Use of RFC reservoir discharge time series
    - Forecasts from each RFC transferred to NWM on WCOSS supercomputer

Potential Sites - Refining with Partners



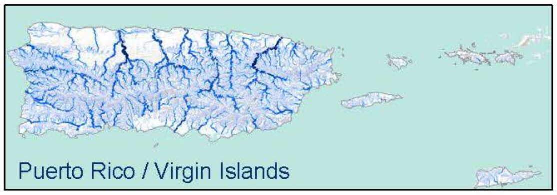
NWM V2.1 Future Development: Domain Expansion to Great Lakes

- NWM V2.1 channel routing domain expanded to include Great Lakes and Lake Champlain drainage basins
- NCAR and Great Lakes Environmental Research Lab (GLERL) collaboration with onboarding by OWP and NCAR



CONUS

- NWM V2.1 domain expanded to include Puerto Rico / US Virgin Islands
- Designed in partnership with SERFC and Puerto Rico WFO

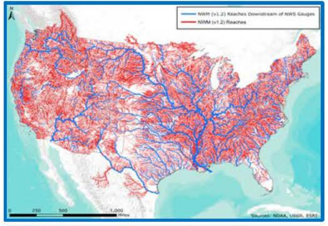


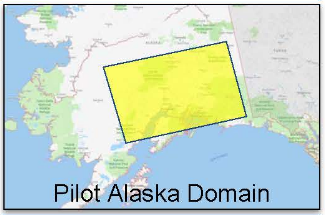
Puerto Rico / Virgin Islands

NWM V3.0 and Beyond (2022+): Expanded Partnerships and Activities

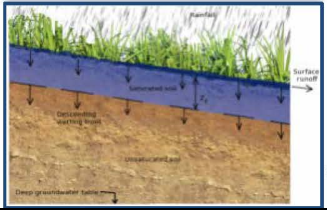
- ★ Coastal Coupling
  - Freshwater-estuary-ocean model coupling
  - Simulate compound flooding—freshwater/surge/tides
- ★ Expansion to south-central Alaska (with APRFC)
  - Beginning with Cook Inlet/Copper River Basin
  - Accompanying cold land physics upgrades
- ★ Inland Hydrologic and Hydraulic Routing
  - Improved routing for backwater and complex channels
  - Accompanying hydrofabric upgrades for routing and FIM
- Improved infiltration scheme for partitioning rainfall
  - ★ Optimization of existing infiltration options
  - Foundational physics upgrade, evolving Noah-MP
- Improved treatment of groundwater
  - ★ Enhancement of groundwater approach, calibration
  - Shallow groundwater model with USGS
  - Key to simulating low-flow conditions

★ = V3.0



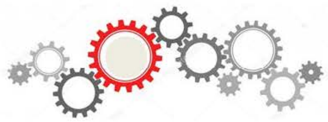


Pilot Alaska Domain



Accelerating Improvement: Next Gen NWM Framework

- New, purpose-built modular NWM software architecture will aid collaboration and maximize development efficiency, increasing the rate of model improvement
- Design underway with USGS and NCAR, leveraging GSA 18F group
  - Need for re-design informed by the Community Advisory Committee for Water Prediction (CAC-WP)
  - GSA 18F process leverages agile development process; code sprints will be transparent with broader community
  - Will more easily support addition of appropriate models for any surface discretization
  - Capability for TIN/unstructured mesh and heterogenous physics will support coupling and scaling of NWM and will enable linkage to new NWS Unified Forecast System
- Complemented by a new model-as-a-service initiative



Closing Thoughts

- With three upgrades in three years, the NWM is rapidly advancing
- Complements information where already available and provides first-ever guidance at underserved locations
- What exists now is a foundation that will continue to be built upon
  - v2.0 implemented into operations in June: Domain expansion, ensembles
  - v2.1 is anticipated in early 2021: Domain expansion, reservoir upgrades
  - v3.0 is anticipated in 2022: Coastal coupling, AK domain, improved sub-sfc
  - Next Gen NWM planning underway
- Along with upgrades, flood inundation mapping, replace-and-route, model-as-a-service and partnerships with Big Data are key elements moving NWM forward
- The key to advancing the NWM is a rich and vibrant partnership with the research community, along with federal, state and private entities

3.4.2 Presentation 2A-2: Moving Beyond Streamflow: Quantifying Flood Risk and Impacts through Detailed Physical Process and Geospatial Representation using the WRF-Hydro Modeling System

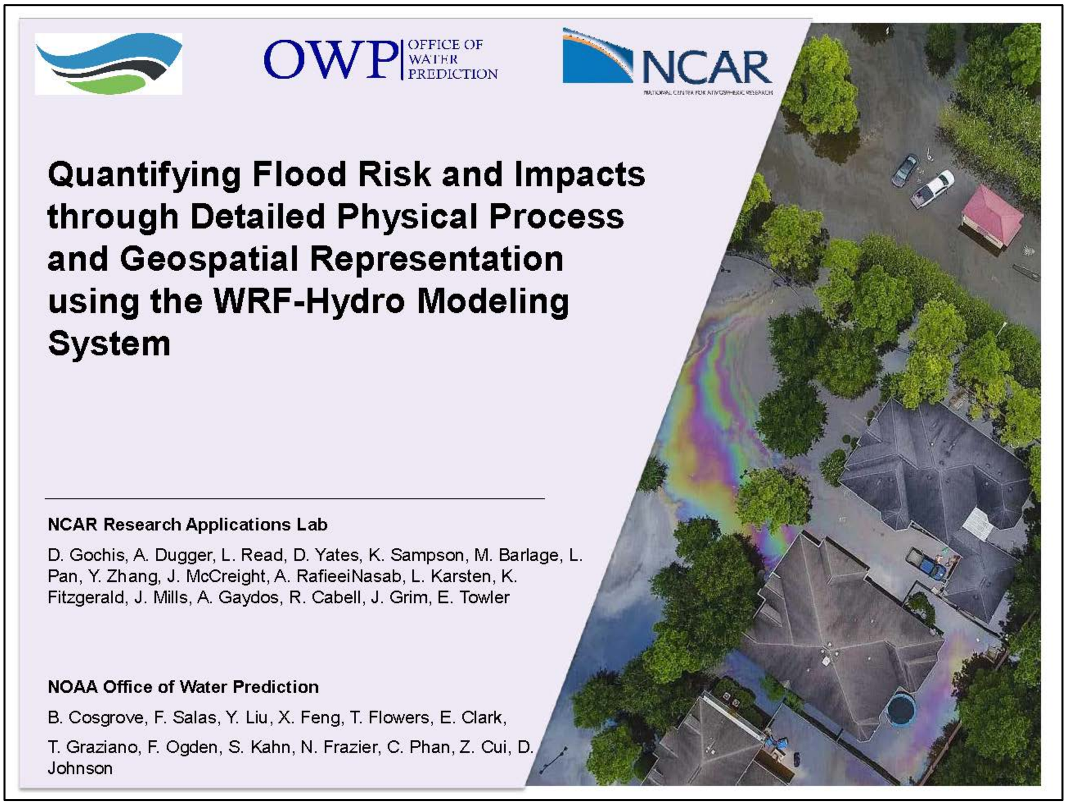
Authors: David Gochis, Aubrey Dugger and Laura Read, National Center for Atmospheric Research (NCAR)

Speaker: David Gochis

3.4.2.1 Abstract

Operational flood and flash flood prediction models, such as the NOAA National Water Model, offer a stable, reliable forecasting service providing complete continental coverage in a 24/7/365-time delivery. However, various requirements and constraints associated with operational systems can limit their tailoring to specific types of water-related risks, particularly when it comes to understanding changes in future flooding risk. Dynamics associated with changing weather and climate patterns, changing sea levels, and changing land cover/land use conditions can drive dramatic changes in flood risk and often need to be characterized using a risk-based approach. In this presentation we will present a number of different configurations and applications of the community WRF-Hydro modeling system that demonstrate the system's capability to provide meaningful information regarding water-related environmental risks.

3.4.2.2 Presentation (ADAMS Accession No. ML20080M202)



OWP OFFICE OF WATER PREDICTION

NCAR

Quantifying Flood Risk and Impacts through Detailed Physical Process and Geospatial Representation using the WRF-Hydro Modeling System

NCAR Research Applications Lab

D. Gochis, A. Dugger, L. Read, D. Yates, K. Sampson, M. Barlage, L. Pan, Y. Zhang, J. McCreight, A. RafieeiNasab, L. Karsten, K. Fitzgerald, J. Mills, A. Gaydos, R. Cabell, J. Grim, E. Towler

NOAA Office of Water Prediction

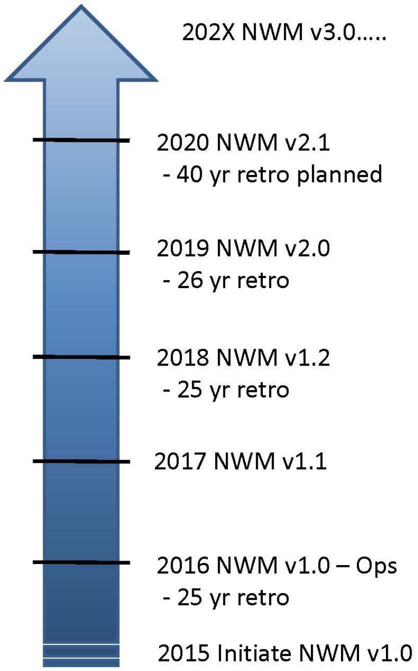
B. Cosgrove, F. Salas, Y. Liu, X. Feng, T. Flowers, E. Clark, T. Graziano, F. Ogden, S. Kahn, N. Frazier, C. Phan, Z. Cui, D. Johnson

Outline

- Recap of NCAR role in current role/structure
- Value added NWM applications and emerging WRF-Hydro research areas:
  - Archive of long term simulation fields for statistical use
  - Downscaled flood inundation products
  - Hyper-resolution modeling
  - Constituent transport/tracer modeling

Supporting the NOAA National Water Model

- NCAR Role:
  - Build and maintain underlying WRF-Hydro modeling architecture
  - Enhance physics options and input data into NWM
  - Conduct training and capacity building services
  - Perform version-over-version evaluation and assessment
  - Execute long-term retrospective model integrations for statistical benchmarking
- 25- and 40-year retrospective runs aligned with v2.0 and v2.1 of the NWM respectively



202X NWM v3.0.....

2020 NWM v2.1
- 40 yr retro planned

2019 NWM v2.0
- 26 yr retro

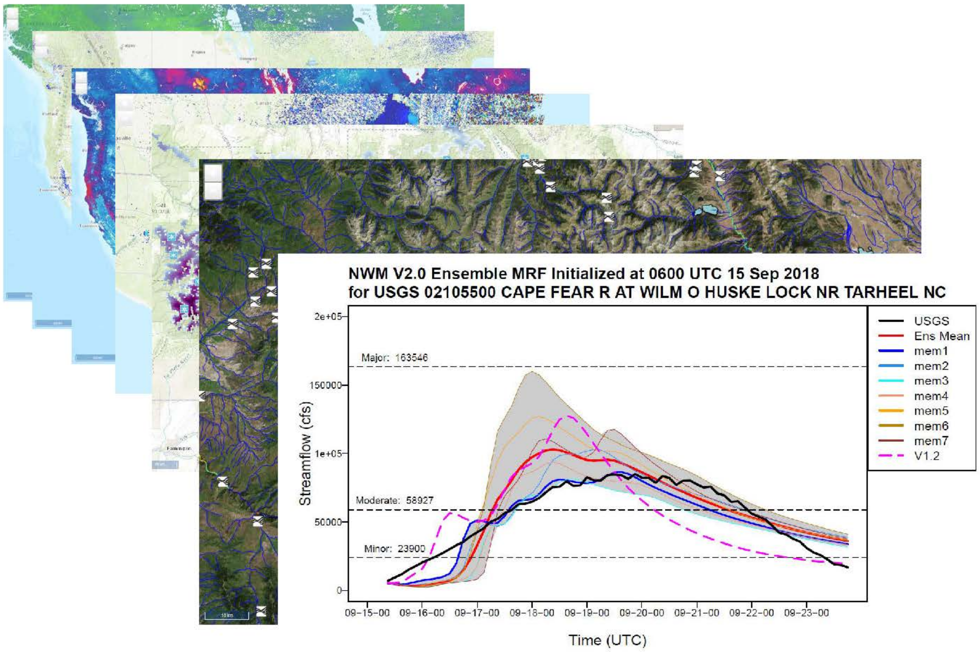
2018 NWM v1.2
- 25 yr retro

2017 NWM v1.1

2016 NWM v1.0 – Ops
- 25 yr retro

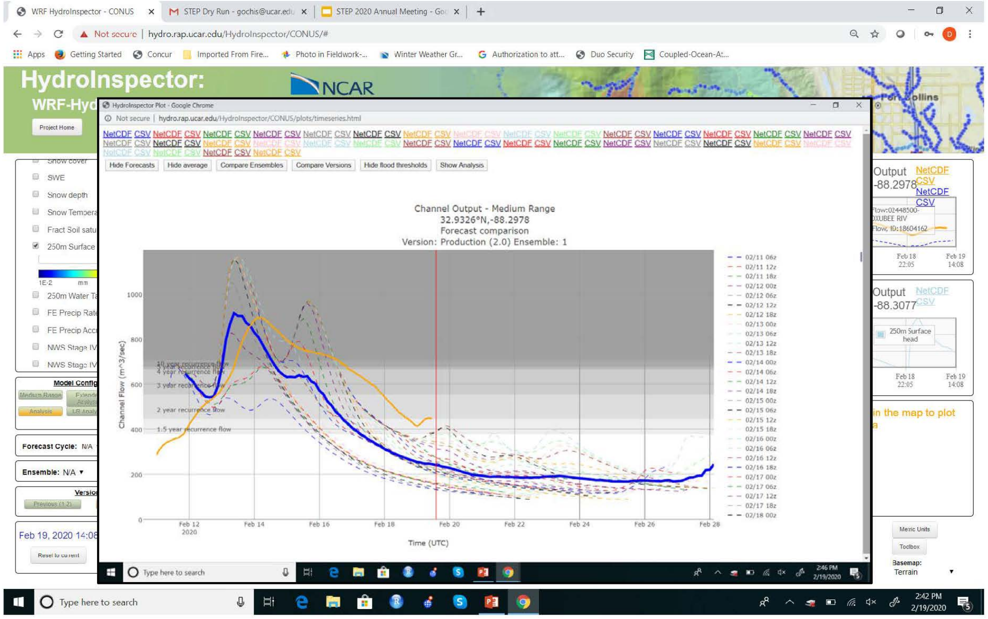
2015 Initiate NWM v1.0

Model Outputs

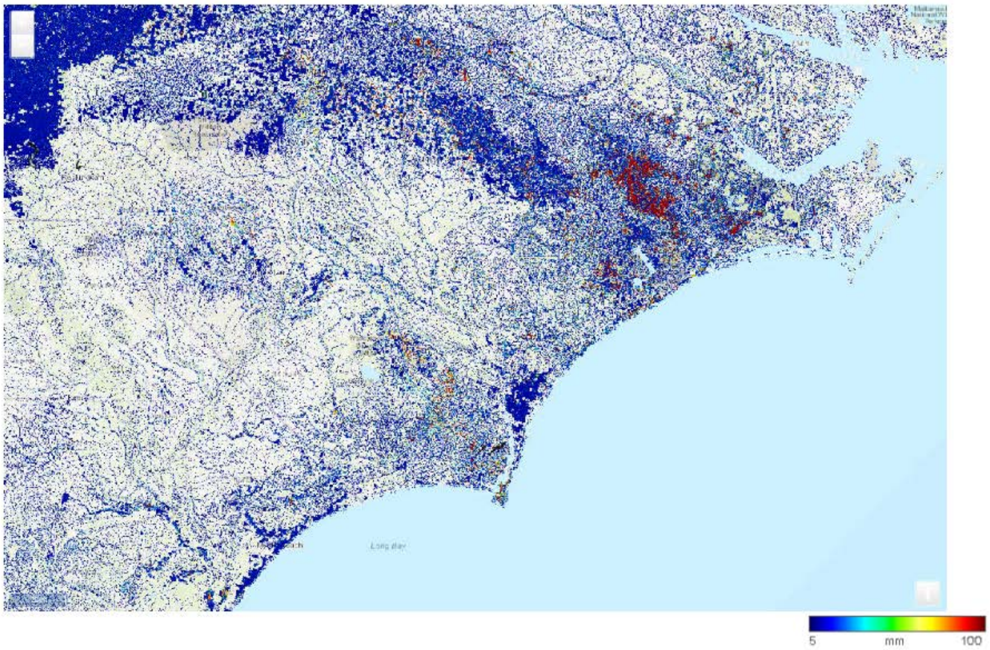


Ensemble streamflow predictions

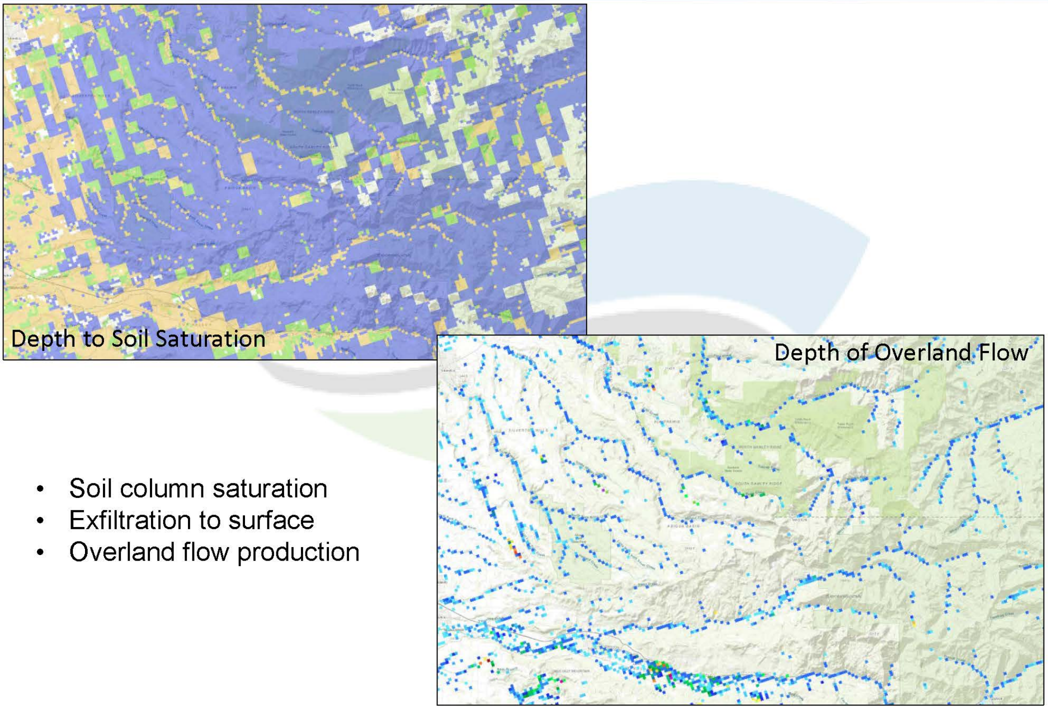
WRF-Hydro Research: Flood Frequency Exceedance Products



NWM v1.2 Medium Range Forecast Surface Overland Flow Water Depth (mm):
Eastern N. Carolina, Hurricane Florence….Forecast guidance up to 6 days in advance

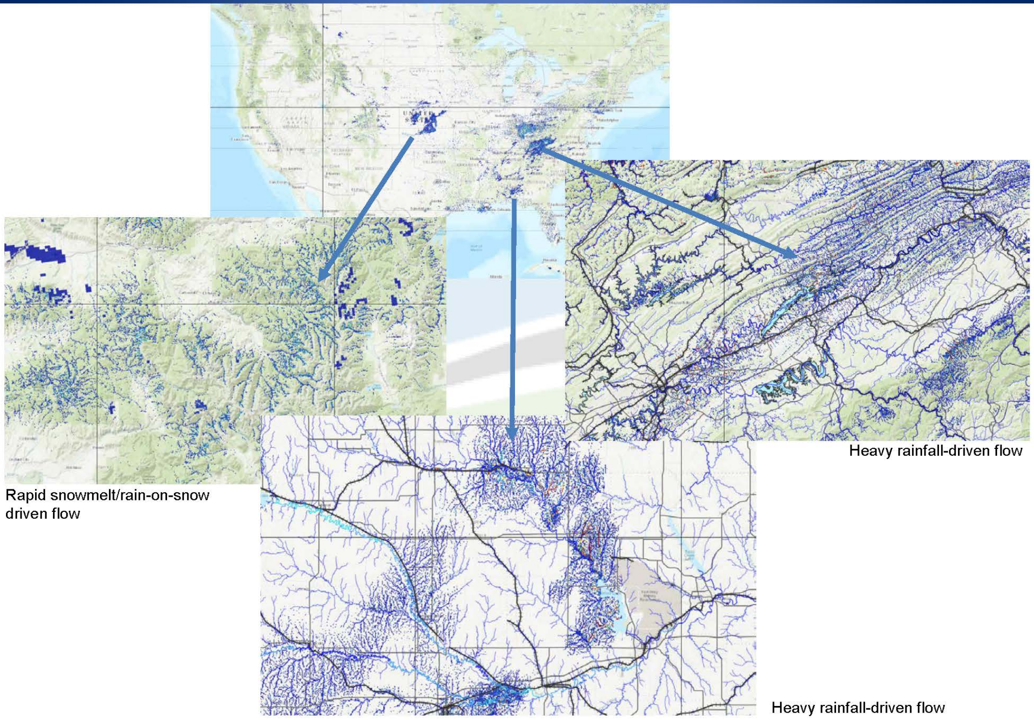


WRF-Hydro Research: Capturing multiple flooding mechanisms



- Soil column saturation
- Exfiltration to surface
- Overland flow production

WRF-Hydro Research: Capturing multiple flooding mechanisms



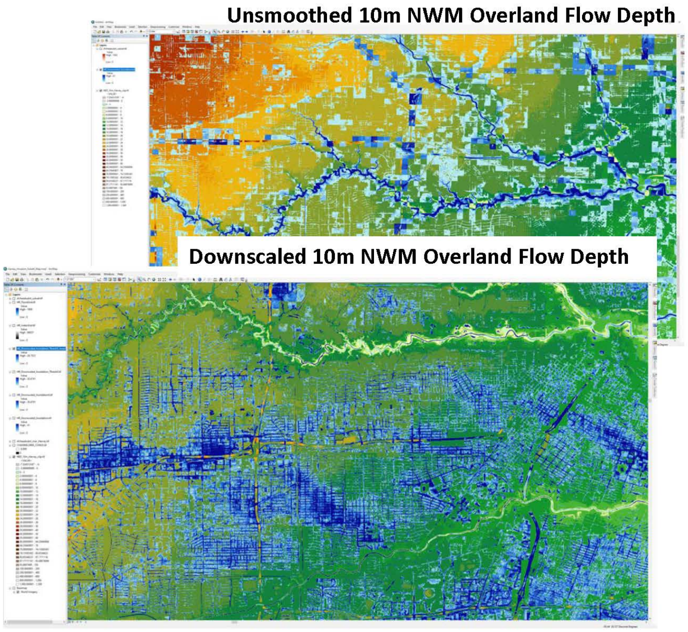
Rapid snowmelt/rain-on-snow driven flow

Heavy rainfall-driven flow

Heavy rainfall-driven flow

WRF-Hydro Research: Flood Inundation Products

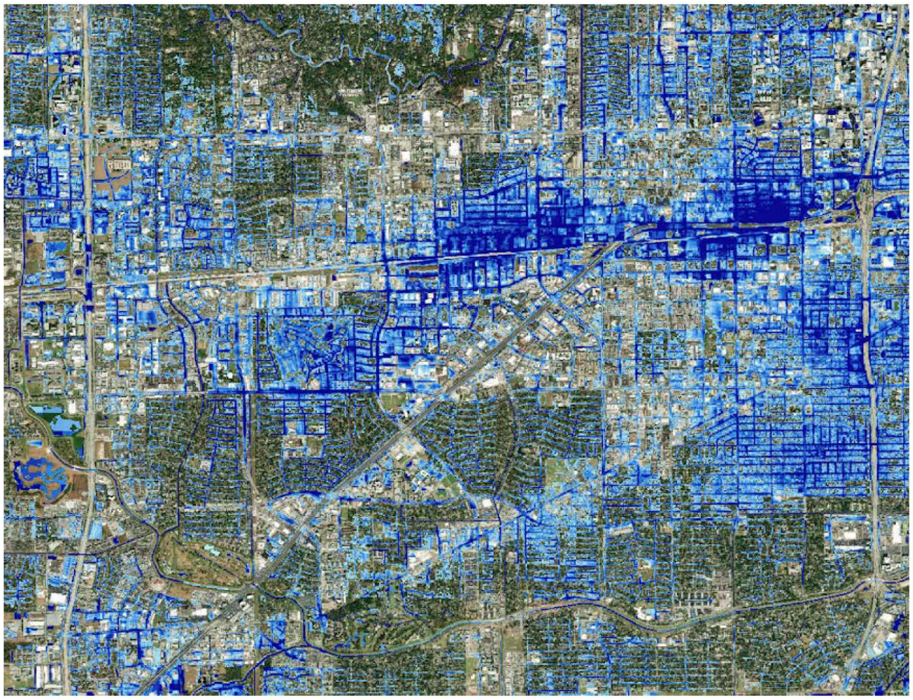
- Terrain-downscaled inundation maps
- 2-step hybrid blended product:
  - Downscaled max. overland flow depth
  - Riverine inundation
  - Utilize ensembles forecasts to make probabilistic product
  - Adopt workflow to 'on-demand' service via HydroInspector
- Applications in:
  - Operational prediction
  - Long term risk analysis



Unsmoothed 10m NWM Overland Flow Depth

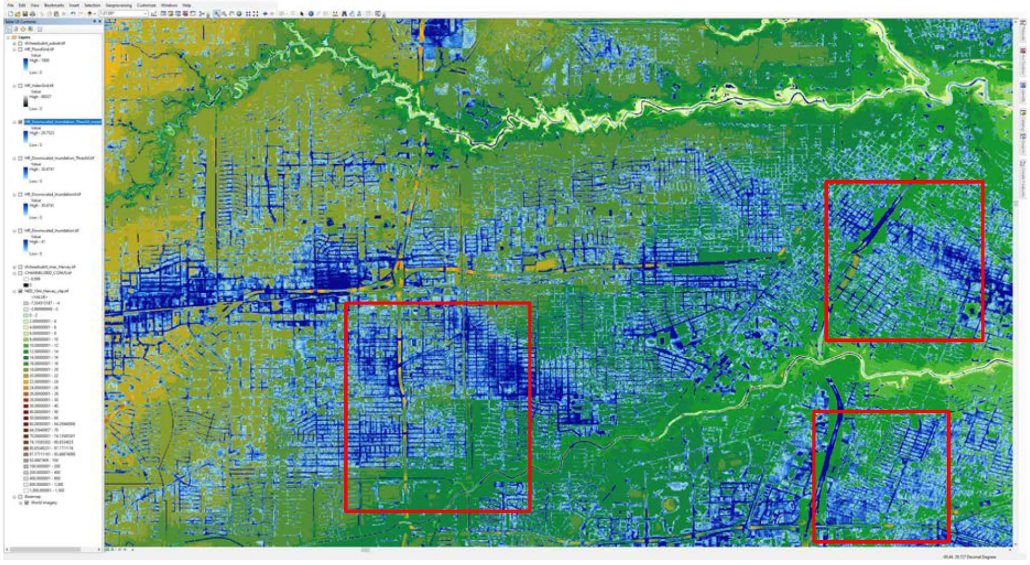
Downscaled 10m NWM Overland Flow Depth

WRF-Hydro Research: Flood Inundation Products



WRF-Hydro Research: Flood Inundation Products

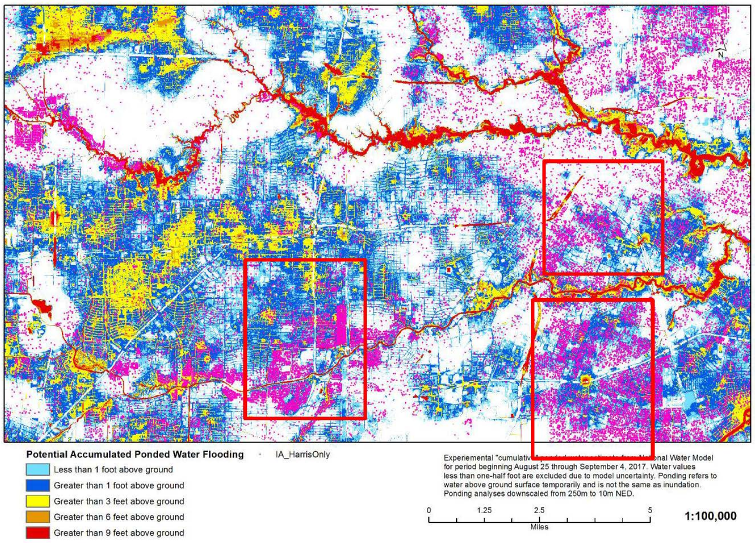
Downscaled 10m NWM Overland Flow Depth



- Work to blend overland flow with riverine flood inundation products is ongoing

WRF-Hydro Research: Flood Inundation Products

- Guidance for validating FEMA damage claims
- Building capability for cloud-based, on-demand production



Potential Accumulated Ponded Water Flooding

- 🟦 Less than 1 foot above ground
- 🟦 Greater than 1 foot above ground
- 🟨 Greater than 3 feet above ground
- 🟧 Greater than 6 feet above ground
- 🟥 Greater than 9 feet above ground

Experiemental "cumulativ[illegible] National Water Model for period beginning August 25 through September 4, 2017. Water values less than one-half foot are excluded due to model uncertainty. Ponding refers to water above ground surface temporarily and is not the same as inundation. Ponding analyses downscaled from 250m to 10m NED.

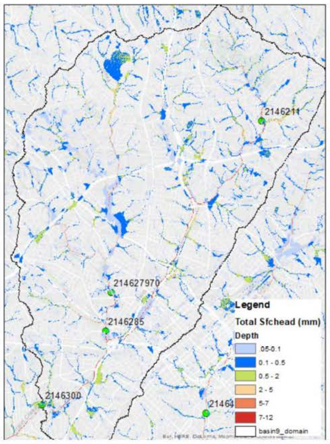
Costumized, portable viewing applications for 'on-demand' intel

1. Clouc
2. Servi
3. Mobi

WRF-Hydro Hyper-Resolution Modeling:

- Explicit characterization of landscape-constrained inundation modeling
  - Spatial scale of 1's to 10s' of meters explicit modeling
  - Akin to Large Eddy Simulation for atmosphere (not CFD though…)

10m model of Charlotte, NC

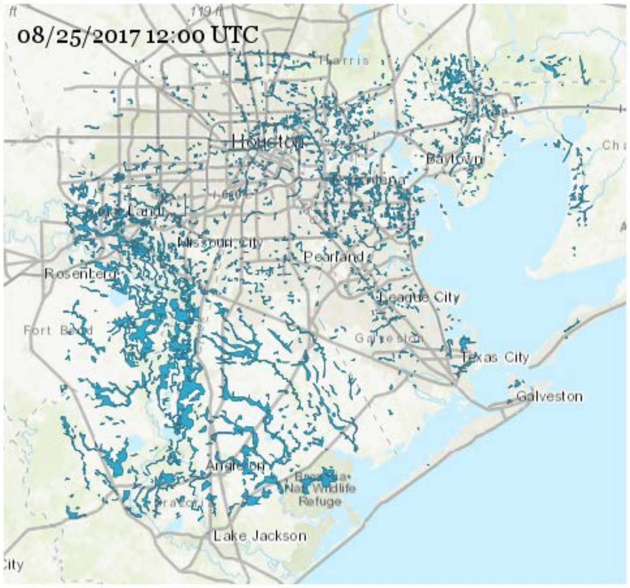


30m model of 2013 Colorado Floods

Hurricane Harvey Inundation Area Hyper-Resolution Modeling:

2D Grid Evaluation (example: hyper-resolution inundation):

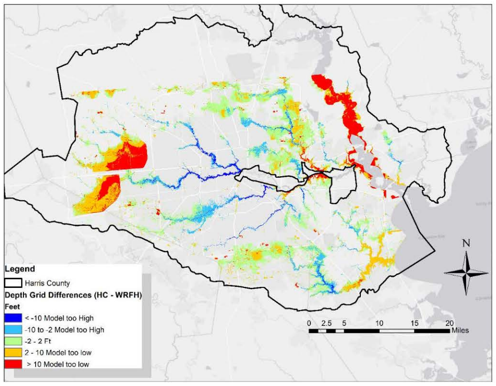
Inundation now being evaluated using CYGNSS retrievals via UCAR President's Fund project

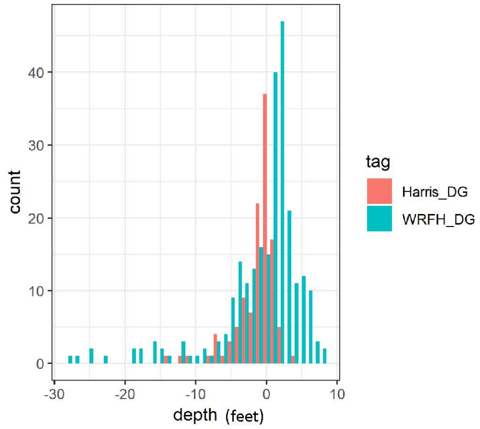


Hurricane Harvey hyper-resolution simulation

WRF-Hydro Research: Evaluating depths in Hurricane Harvey

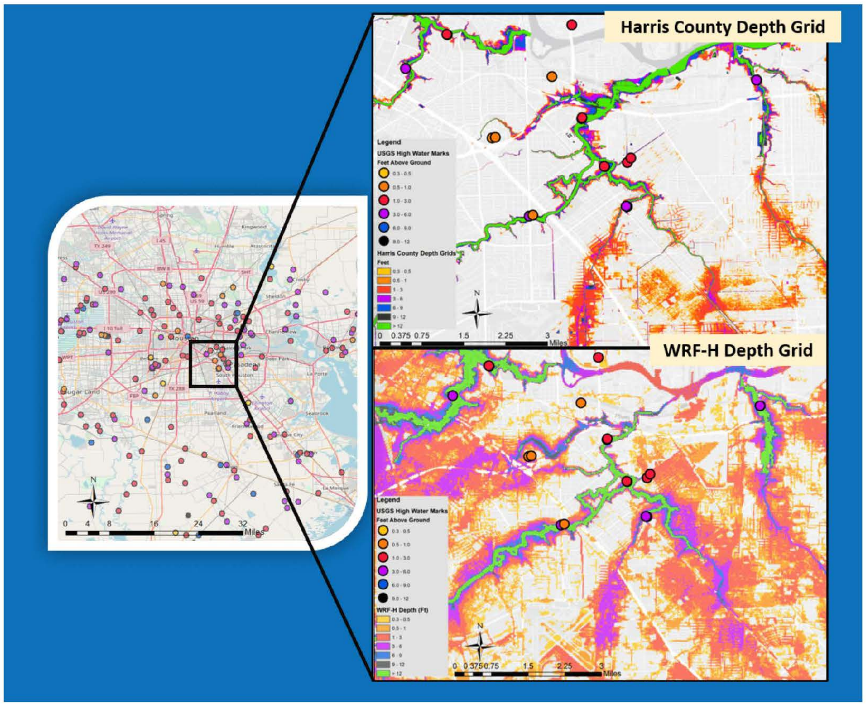
Maximum inundation in Harris County. WRF-Hydro simulation compared with Harris Co. depth grids.



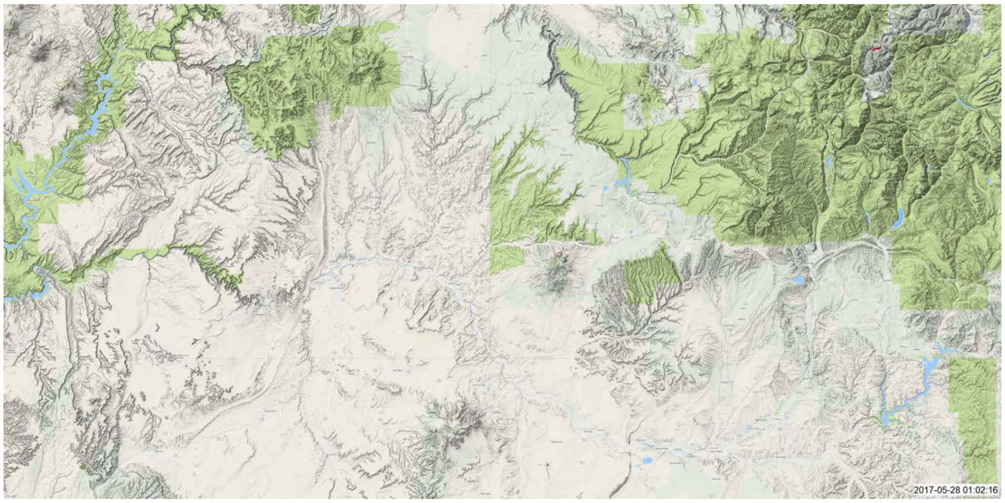


WRF-Hydro shows some areas of under prediction, mainly in detention ponds that were not initialized properly.

WRF-Hydro Research: Capturing multiple flooding mechanisms

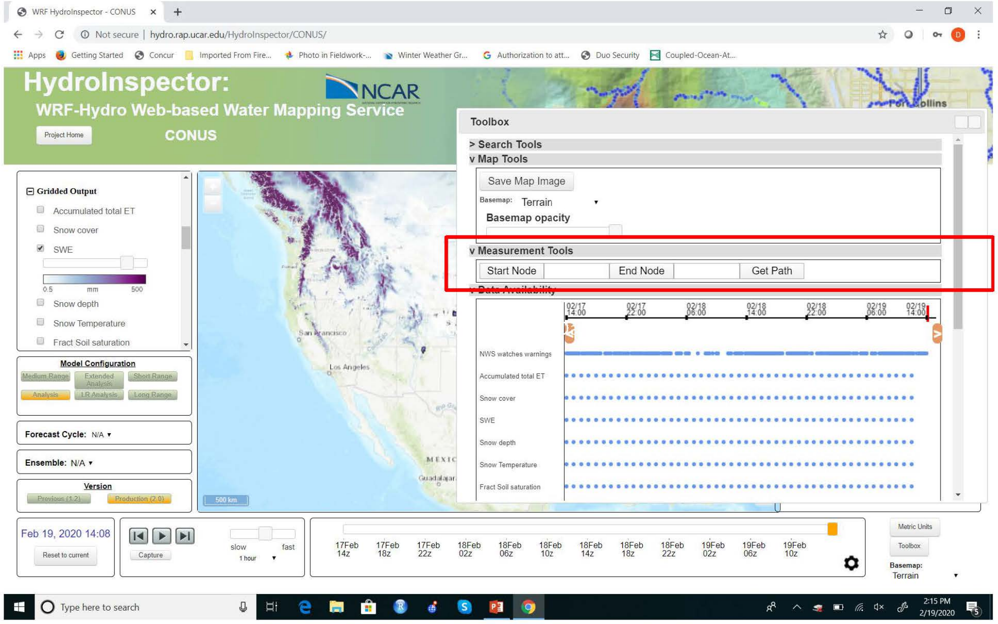


Real-time, on-demand flow path tracing:



- Environmental tracers for transport timing prediction
- On-demand capability using existing operational NWM
- Nearly instantaneous response
- Amenable to stochastic perturbation of flows to generate probabilisitc guidance
- Example of the Gold King Mine Spill

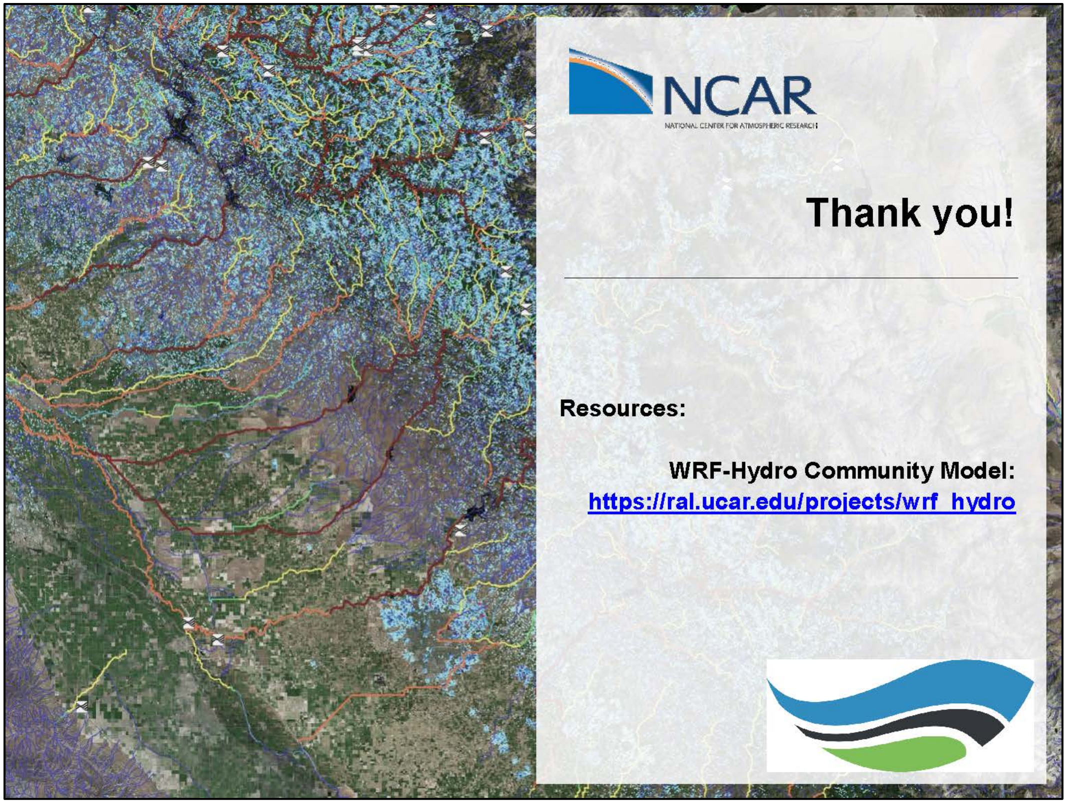
Real-time, on-demand flow path tracing:



Summary:

- NCAR continues to support development of the baseline operational National Water Model

- Numerous value-added products and services are being developed using NWM outputs OR custom configurations of the WRF-Hydro system
  - Statistical analysis of 25 & 40-year retrospective runs
  - Downscaled flood inundation maps
  - On-demand, hyper-resolution modeling
  - Constituent tracing through model fields
  - Portable, cloud based web mapping services and analysis applications



NCAR
NATIONAL CENTER FOR ATMOSPHERIC RESEARCH

Thank you!

Resources:

WRF-Hydro Community Model:
https://ral.ucar.edu/projects/wrf_hydro

3.4.3 Presentation 2A-3: Extreme Flood Hazard Assessment – Overview of a probabilistic methodology and its implementation for a Swiss river system.

Authors: V.N. Dang and C.A. Whealton; Paul Scherrer Institute, Switzerland

Speaker: V.N. Dang

3.4.3.1 Abstract

The project Extreme Floods in the Aare River (EXAR) has recently been completed in Switzerland[1]. The main objectives of this project were to: 1) provide a simulated hydrological dataset that can be used for flood hazard analysis throughout the Aare River Basin, 2) account for processes that are induced or correlated with flooding events in the hazard analysis, and 3) implement the methodology for multiple sites to assess the flood hazard in the frequency range of 1E-3 to 1E-7/a.

A simulated hydrological dataset was taken as the basis for assigning frequencies to flows with exceedances of less than 1E-3/a. This data was a result of a modeling chain that included a weather generator (GWEX), runoff model (HBV), and simplified routing model of the river system to route the flows from each catchment into the main river (RS Minerve). The result was approximately 300,000 years of hourly flow values simulated with three parameter sets (~900,000 years of data).

In the hazard analysis, each structure was analyzed not only for the possible impacts to the downstream sections of the river but also for local impacts at sites of interest as well. The main structures considered were levees (failure), bridges (clogging with driftwood), weirs (clogging and gate operation failure), and landslides (partial or full blockage of channel). All relevant and non-negligible events were retained in an event tree analysis for the sites and scenarios were simulated with a 2-D hydraulic model (BASEMENT).

The project characterized epistemic uncertainties from each of the models or analyses used in this project; a number of these were quantified and propagated while the significance of others were addressed with sensitivity analyses. Frequency uncertainty was considered from the different parameterizations of the runoff model, which led to different exceedance curves, uncertainty in the probability of landslides, and in some cases the likelihood of driftwood clogging at structures. The water level uncertainty included uncertainty from the hydrologic simulation and possible effects from landslides. The presentation will also discuss the key limitations of the methodology based on the comprehensive implementation experience gained in the project

---

[1] Andres N., Badoux A., Hegg Ch. (Ed.) 2019: Grundlagen Extremhochwasser Aare. Hauptbericht Projekt EXAR. Methodik und Resultate. (*Bases for the extreme flood hazard on the Aare River. Main report of project EXAR.*) Swiss Federal Institute for Forest, Snow and Landscape Research WSL. (in German, forthcoming.)

3.4.3.2 Presentation (ADAMS Accession No. ML20080M204)

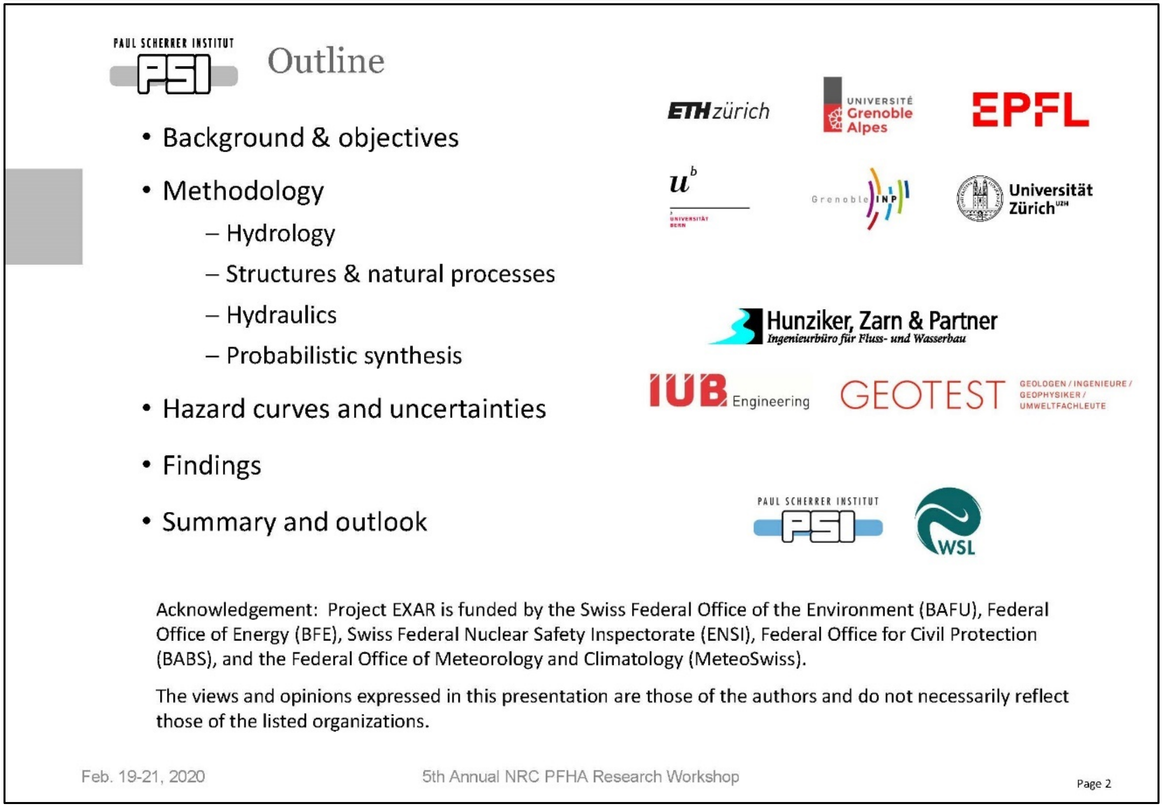
PAUL SCHERRER INSTITUT

WIR SCHAFFEN WISSEN – HEUTE FÜR MORGEN

Vinh N. Dang & Calvin Whealton :: Risk & Human Reliability Group :: Paul Scherrer Institute

Extreme Flood Hazard Assessment
Overview of a probabilistic methodology and its implementation for a Swiss river system

5th Probabilistic Flood Hazard Assessment Research Workshop
19-21 February 2020. USNRC, Rockville, MD



PAUL SCHERRER INSTITUT

Outline

- Background & objectives
- Methodology
  - Hydrology
  - Structures & natural processes
  - Hydraulics
  - Probabilistic synthesis
- Hazard curves and uncertainties
- Findings
- Summary and outlook

Acknowledgement: Project EXAR is funded by the Swiss Federal Office of the Environment (BAFU), Federal Office of Energy (BFE), Swiss Federal Nuclear Safety Inspectorate (ENSI), Federal Office for Civil Protection (BABS), and the Federal Office of Meteorology and Climatology (MeteoSwiss).

The views and opinions expressed in this presentation are those of the authors and do not necessarily reflect those of the listed organizations.

Feb. 19-21, 2020 5th Annual NRC PFHA Research Workshop Page 2

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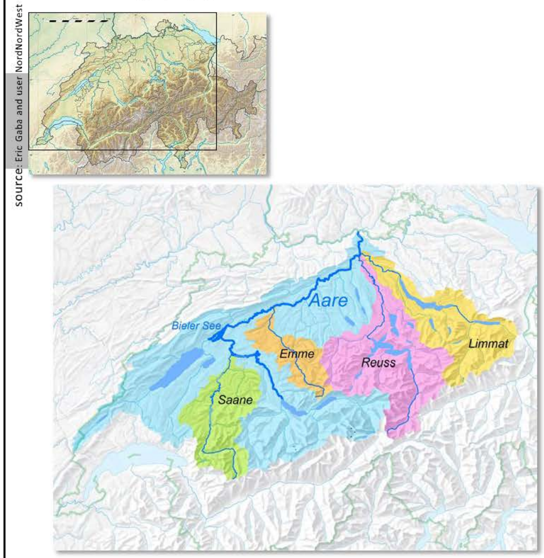
Aare River Watershed



source: Eric Gaba and user NordNordWest

- Develop consistent methodology for probabilistic flood hazard assessment (PFHA)
  - Develop hydrological dataset for PFHA
  - Hazard assessment for selected sites on Aare
    - Frequency range of 1E-3 to 1E-7/a
    - Including conditional events

- The Aare catchment
  - 295 km (183 mi) to Rhine (at Koblenz, CH)
  - Catchment area 17’675 km² (6’870 sq. mi.)
    - 43% of surface area of Switzerland
    - High alpine to farmland and urban
    - 4 major subcatchments
    - Highly engineered system

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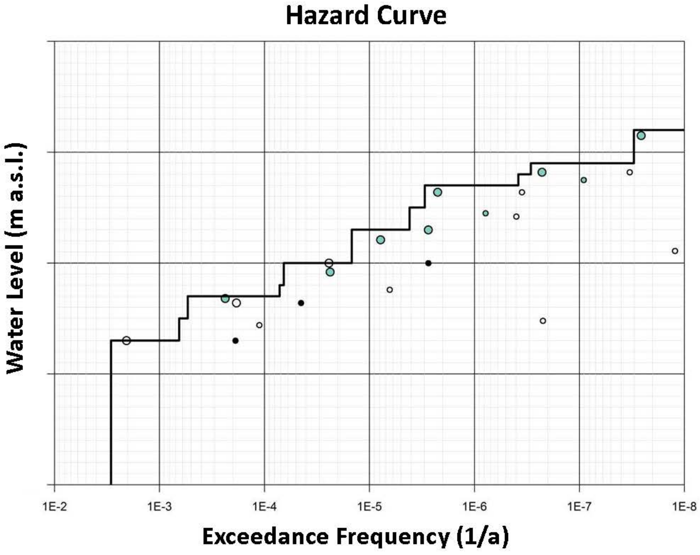
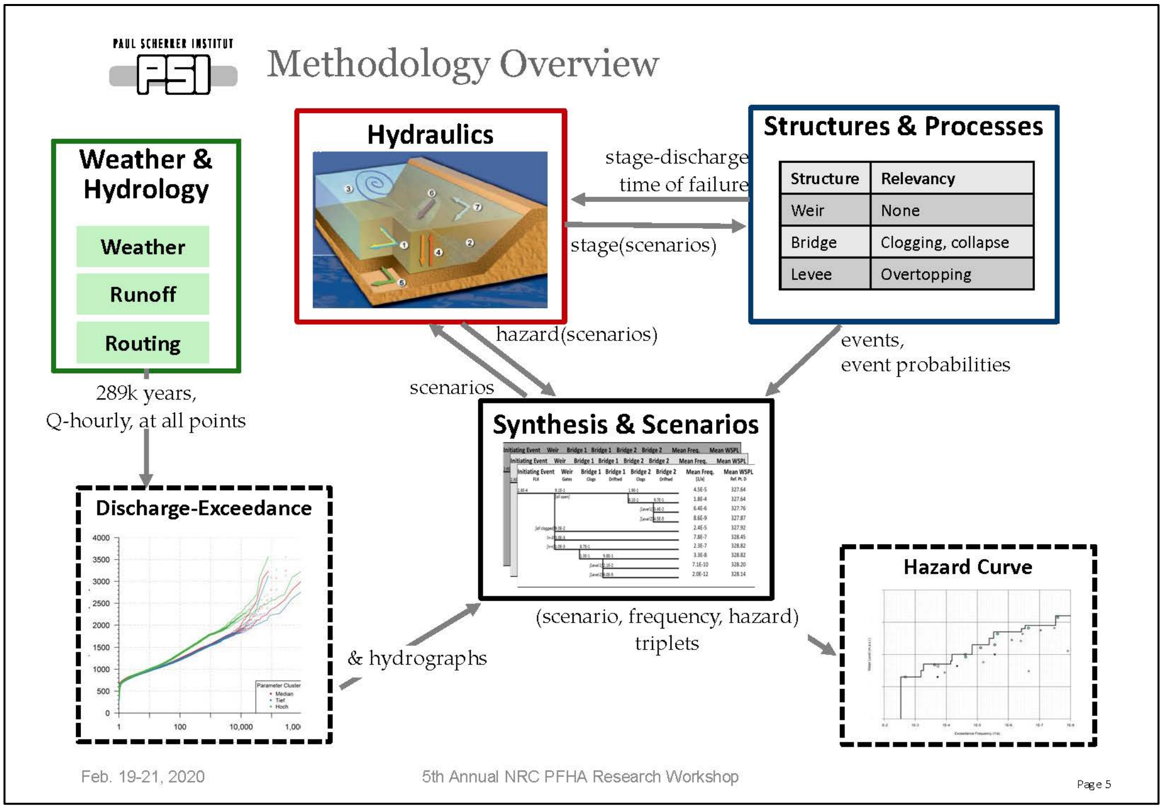
Hazard Curve

Hazard measure

- ➢ Elevation head (in m.a.s.l.)
- ○ Total head
- ○ Velocity
- ○ Shear stress



Input: triplets (scenario, frequency, hazard level)



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Methodology Overview

Weather & Hydrology
- Weather
- Runoff
- Routing

289k years,
Q-hourly, at all points

Discharge-Exceedance

Hydraulics

stage-discharge
time of failure

stage(scenarios)

Structures & Processes

Structure	Relevancy
Weir	None
Bridge	Clogging, collapse
Levee	Overtopping

hazard(scenarios)

scenarios

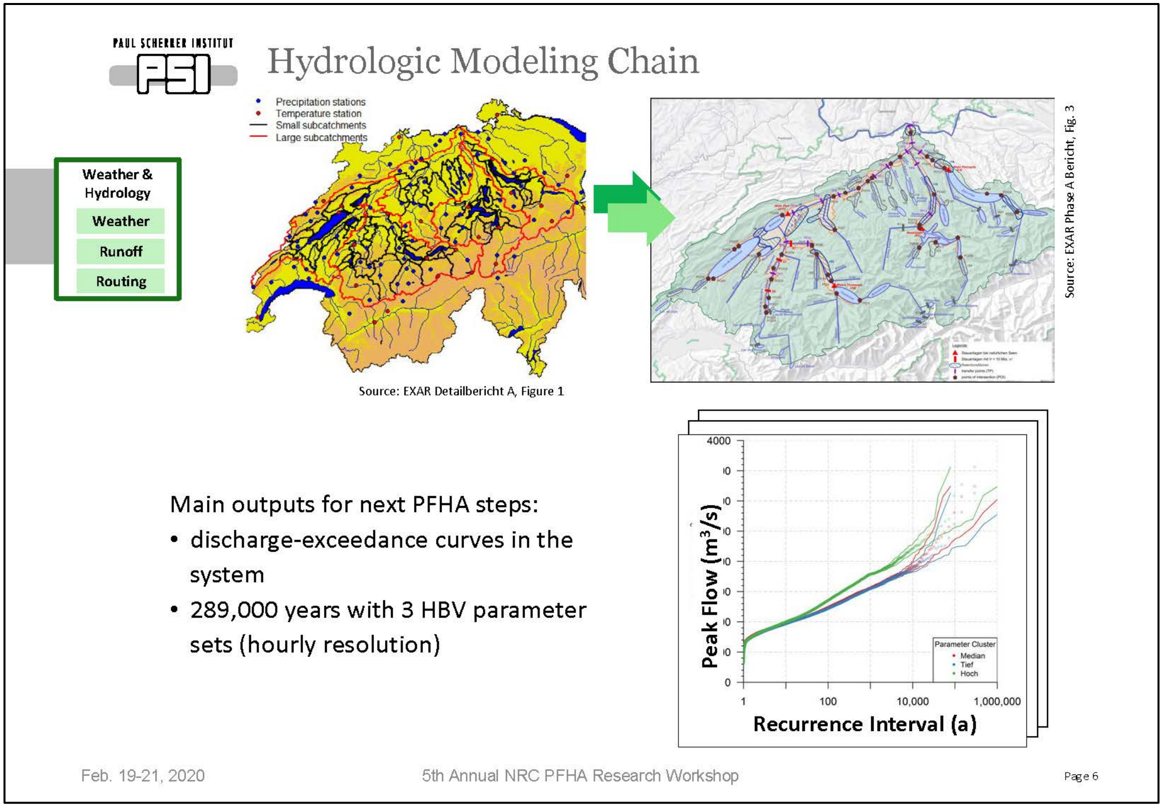
events,
event probabilities

Synthesis & Scenarios

& hydrographs

(scenario, frequency, hazard)
triplets

Hazard Curve



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Hydrologic Modeling Chain

Weather & Hydrology
- Weather
- Runoff
- Routing

Source: EXAR Detailbericht A, Figure 1

Source: EXAR Phase A Bericht, Fig. 3

Main outputs for next PFHA steps:
- discharge-exceedance curves in the system
- 289,000 years with 3 HBV parameter sets (hourly resolution)

Hydrologic Modeling Chain

Weather & Hydrology
Weather
Runoff
Routing

Weather **GWEX**: mean average precipitation and temperature (MAP & MAT)
- Precipitation (105 stations) modeled using Extended GPD distribution
- Temperature (26 stations) modeled as MAR(1) process
- Spatially disaggregated to catchments using Thiessen polygons
- Temporally disaggregated from 3-days to 1-hr using meteorological analog

Runoff **HBV**: hourly runoff values for each elementary catchment
- Semi-distributed catchment model
- 89 elementary catchments in the system (40 ungauged)
- Cluster analysis used to define lower, median, and higher simulated floods

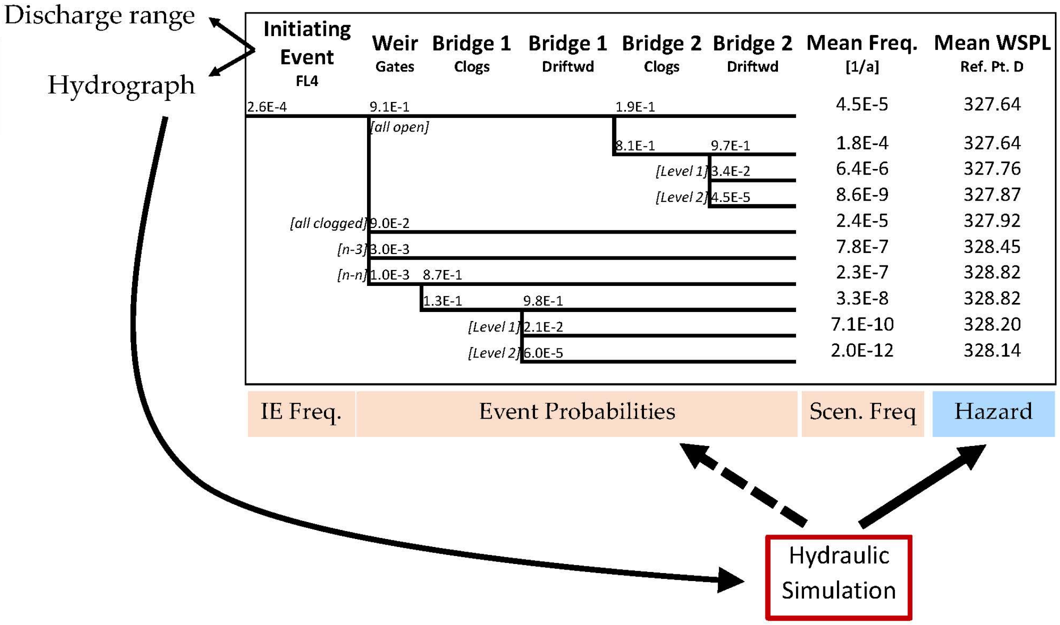
Routing **RS Minerve**: hourly flow values at transfer points
- Aggregated elementary catchment runoff to flow in main tributaries and Aare
- Includes lake regulation
- Calibrated to 2005 flood and validated to 2007 flood (both ~100-yr return period)

Probabilistic Scenario Modeling

scenario,
frequency,
hazard level

	Scenario	
	Initiating event	*Top events*
Hydraulic simulation	**Representative hydrograph**	• **Natural process** • **Structure-related** induced, correlated, independent
Quantification (estimation of probabilities)	**Discharge range frequency**	**Event probabilities**
Basis	Discharge exceedance frequency curve	Fragilities, estimated occurrence, …

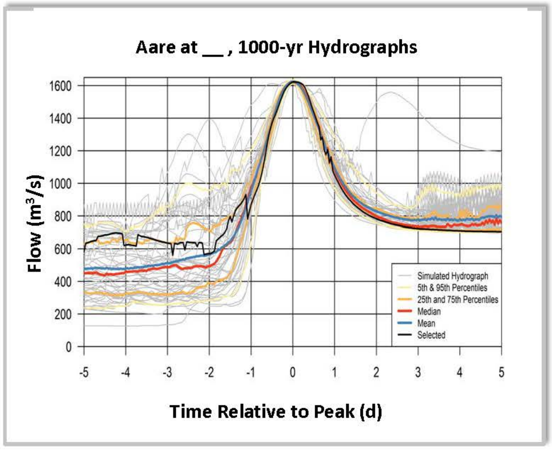
Event Tree



Initiating Event FL4	Weir Gates	Bridge 1 Clogs	Bridge 1 Driftwd	Bridge 2 Clogs	Bridge 2 Driftwd	Mean Freq. [1/a]	Mean WSPL Ref. Pt. D
2.6E-4	9.1E-1 *[all open]*			1.9E-1		4.5E-5	327.64
				8.1E-1	9.7E-1	1.8E-4	327.64
					[Level 1] 3.4E-2	6.4E-6	327.76
					[Level 2] 4.5E-5	8.6E-9	327.87
	[all clogged] 9.0E-2					2.4E-5	327.92
	[n-3] 3.0E-3					7.8E-7	328.45
	[n-n] 1.0E-3	8.7E-1				2.3E-7	328.82
		1.3E-1	9.8E-1			3.3E-8	328.82
			[Level 1] 2.1E-2			7.1E-10	328.20
			[Level 2] 6.0E-5			2.0E-12	328.14

Hydrograph selection

- Each initiating event is a discharge range with a frequency.
- To compute the hazard, a hydrograph is needed



➢ Three discharge ranges

Discharge range IE	Freq. [/yr]	Qpeak Fexc [/yr]
FL3	~ 3E-3	1E-3
FL4	~ 3E-4	1E-4
FL5	~ 3E-5	1E-5

➢ More difficult cases: confluence, peak-duration

Structures & Processes

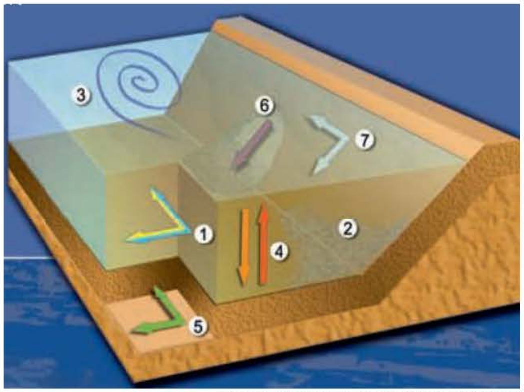
Relevance criteria

1) ability to change downstream frequencies or hydrograph behavior
2) impact on hazard at local assessment site

- Weirs/Dams
  - Waves from collapse (Q -> h[reservoir] -> P)
  - Backwater from closed/clogged gates (scoping P)
- Levees (Q -> h at levee -> P)
  - New flowpaths
  - Retention changing hydrograph timing or peak
- Landslides (higher water table -> P)
  - Backwater from channel blockage
  - Local flowpaths
- Driftwood (Q -> flow at structure -> P)
  - Backwater
  - Local flowpaths

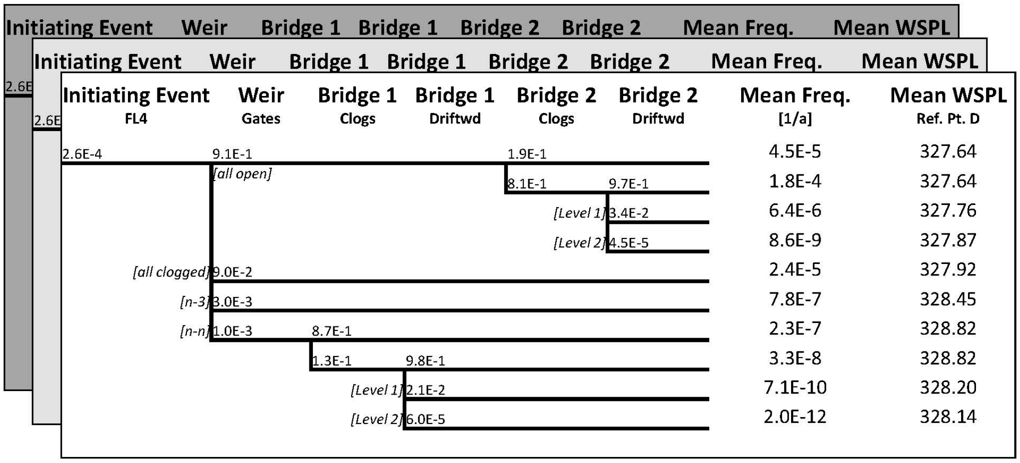
Hydraulic Simulation

- 2-D model of reach using BASEMENT v3 (https://basement.ethz.ch/)
  - Saint-Venant equations
  - Morphology model
  - Main inputs: DEM and roughness values
- Parameters calibrated using surrogate modeling
- Morphology capabilities used for small set of scenarios
  - bed load transport, aggradation, resuspension



Source: https://basement.ethz.ch/about.html

Scenarios to hazard curves…

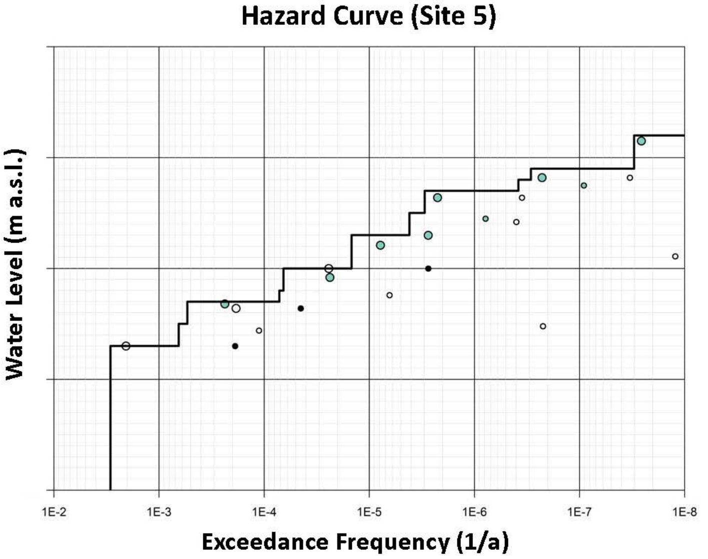


Initiating Event FL4	Weir Gates	Bridge 1 Clogs	Bridge 1 Driftwd	Bridge 2 Clogs	Bridge 2 Driftwd	Mean Freq. [1/a]	Mean WSPL Ref. Pt. D
2.6E-4	9.1E-1 *[all open]*			1.9E-1		4.5E-5	327.64
				8.1E-1	9.7E-1	1.8E-4	327.64
					[Level 1] 3.4E-2	6.4E-6	327.76
					[Level 2] 4.5E-5	8.6E-9	327.87
	[all clogged] 9.0E-2					2.4E-5	327.92
	[n-3] 3.0E-3					7.8E-7	328.45
	[n-n] 1.0E-3	8.7E-1				2.3E-7	328.82
		1.3E-1	9.8E-1			3.3E-8	328.82
			[Level 1] 2.1E-2			7.1E-10	328.20
			[Level 2] 6.0E-5			2.0E-12	328.14

Hazard Curve

Point estimate hazard curve:

Exceedance plotted from scenario points at (mean frequency, mean hazard value)

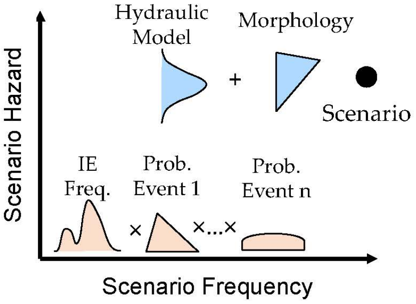


Hazard Curve Uncertainty

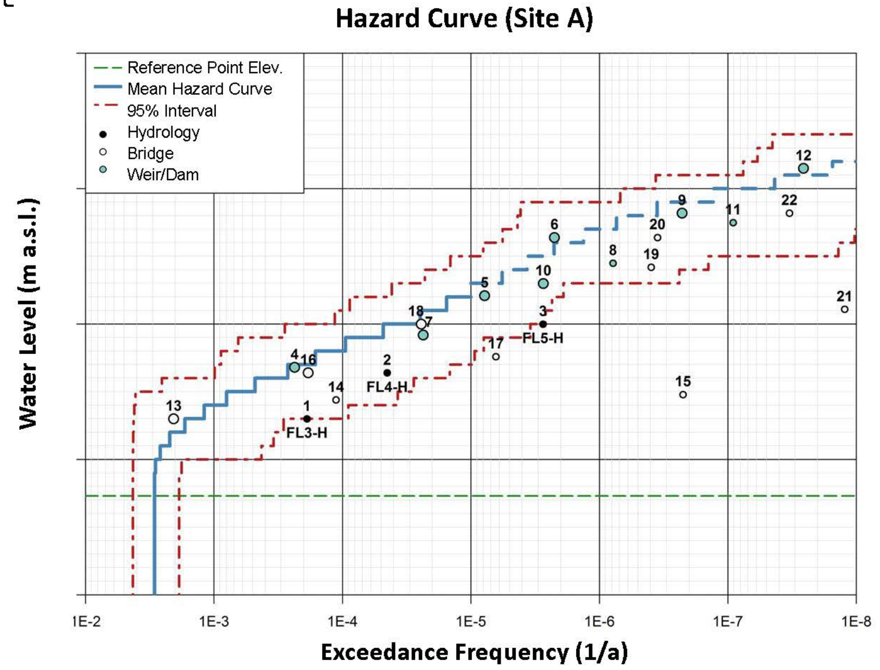
- Uncertainties in frequency space
  - Initiating Event Frequency (HBV parameter set curves)
  - Probabilities (uncertainty of failure models, clogging models, etc.)
- Uncertainties in hazard space
  - Water Levels (water levels from 2-D model and morphology)

➢ Need to transform hazard space uncertainty into frequency space

- Monte Carlo approach
  - Each sample of the set of uncertainty distributions => realization of the 3 event trees
  - 5000 samples => 5000 hazard curves
  - Statistics obtained from 5,000 curves : mean curve, frequency quantiles



Hazard Curve: Mean & Envelope from Uncertainty



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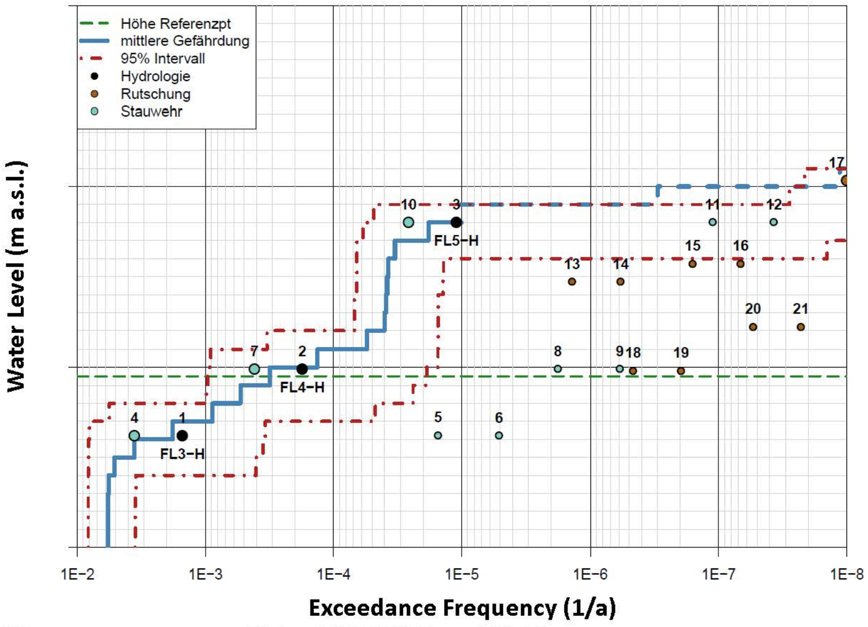
Hazard Curve: Mean & Envelope from Uncertainty

Hazard Curve (Site B)



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Core findings – flood hazard

Key Findings:

- Dominant sources of site hazard “hydrological” or “natural processes + engineered structures”
- Also dependent on frequency range of interest
- Some scenarios and results on hazard below 1E-5/yr but incomplete picture due to lack of credible estimate for 1E-6/yr hydrological flood

Site-specific Findings

- For the assessed sites, levee failures are not dominant
  (and overtopping more important than duration/volume)
- No dominant scenarios with landslides (co-occurrence with flood event is low)
- At multiple sites, driftwood volume and clogging are important contributors
- Flood management failure important to risk (at extreme end of hazard curve) at one site.

Summary & Outlook

- State-of-the-art models in hydrologic chain, in hydraulics, structural analysis
- Experts in the relevant disciplines periodically reviewed methodology and implementation and provided suggested modifications and verifications
- Interdisciplinarity enhanced verification and plausibility checks throughout project

- Measurement records essential but some difficulties (e.g. representation of extreme floods for calibration, engineering of the catchment)
- Discharge exceedance curves were judged to be plausible
- More hydrological parameter sets recommended to address (HBV) uncertainty better – at lowest frequencies

  Rare/extreme hazard is based on top 0.1% of annual maxima (1E-3/yr, 300 events, 300’000 annual maxima)

- 3 discharge ranges (IEs) sufficient to characterize hazard

Outlook

- Better characterization driftwood generation and retention, as well as clogging is required
- Flood management strategy and implementation during extreme floods
  - Modeling
  - Strategy
- Computational challenge for morphology

- Scope: Upper catchment floods (mountain regions) ; Rhine

Wir schaffen Wissen – heute für morgen

My thanks go to the EXAR Team

WSL
IUB Engineering
GEOTEST GEOLOGEN / INGENIEURE / GEOPHYSIKER / UMWELTFACHLEUTE
Hunziker, Zarn & Partner Ingenieurbüro für Fluss- und Wasserbau
Universität Zürich
Universität Bern
Grenoble INP
Université Grenoble Alpes
EPFL
ETH zürich
PAUL SCHERRER INSTITUT PSI

References and further reading

Andres N., Badoux A., Hegg Ch. (Ed.) 2019: Grundlagen Extremhochwasser Aare. Hauptbericht Projekt EXAR. Methodik und Resultate. (*Bases for the extreme flood hazard on the Aare River. Main report of project EXAR.*) Swiss Federal Institute for Forest, Snow and Landscape Research WSL. (in German, forthcoming.)

EXAR Detailed reports (in English)

- Staudinger, M., Viviroli, D. 2019: Extremhochwasser an der Aare. Detailbericht A Projekt EXAR. Hydrometeorologische Grundlagen [EN: *Hydrometeorological Elements*]. Universität Zürich. Zürich: 382 S.

- Sutter, A., Karrer, T., Whealton, C. 2019: Extremhochwasser an der Aare. Phase B. Detailbericht C: Rutschungen und Schwemmholz [EN: *Landslides and Driftwood*]. ARGE GEOTEST-HZP-IUB. Zollikofen: 85 S. [Landslides and part of Driftwood in English]

- Dang, V.N., Whealton, C. 2019: Extremhochwasser an der Aare. Detailbericht G Projekt EXAR. Ereignisbaumanalyse und Gefährdungskurven [EN: *Event Trees and Hazard Curves*]. Paul Scherrer Institut PSI. 113 S.

[Journal Articles in Preparation]

References and further reading

GWEX

- Evin, G.; Favre, A.C.; Hingray, B. (2018). Stochastic generation of multi-site daily precipitation focusing on extreme events. *Hydrology and Earth System Sciences 22*(1):655-672. doi: 10.5194/hess-22-655-2018

HBV

- Bergström, S. (1992). The HBV Model: Its Structure and Applications,Swedish Meteorological and Hydrological Institute (SMHI), Hydrology,Norrköping, 35 pp.
- Seibert, J.; Vis, M.J.P., 2012: Teaching hydrological modeling with a user-friendly catchment-runoffmodel software package. *Hydrology and Earth System Sciences 16*: 3315-3325. doi:10.5194/hess-16-3315-2012

RS Minerve (www.crealp.ch/fr/accueil/outils-services/logiciels/rs-minerve.html)

- García Hernández, J., Paredes Arquiola, J., Foehn, A., Roquier, B., 2016: RS MINERVE – Technical Manual v2.7. For Software version 2.4.2.0. , Centre de recherche sur l'environnement alpin (CREALP); HydroCosmos SA [manuals in English].

BASEMENT (basement.ethz.ch/about.html)

- Versuchsanstalt für Wasserbau, Hydrologie und Glaziologie (VAW) der ETH Zürich (2019). BASEMENT v3 Reference Manual [in English].

PMP/PMF vs. Simulation

- EXAR hydrologic modeling chain is not based on the PMP/PMF concept
- Several studies have computed PMP/PMF for smaller catchments (table below)
- Maximum simulated floods from EXAR are close to PMP/PMF estimates, with larger differences being for the small catchments that have more variable precipitation distributions
- EXAR simulations are not implausible compared to PMP/PMF

River, location	Study	TP or catchment	PMF [m³/s]	Q_{max} GWEX [m³/s]
Aare, Bern	Felder&Weingartner2016,2017, Zischg et al.2018	SSASSB	1296	1250
Emme, Wiler	Felder et al.2019	SSKSSD	1388	1356
Kander, Hondrich	Felder et al. 2019	KanHon	830	1050
Sihl, Zürich	Kienzler et al.2015	SihZue	975	772

EXAR Detailbericht A, Table 4

Felder G. & Rolf Weingartner R. (2016) An approach for the determination of precipitation input for worst-case flood modelling. *Hydrological Sciences Journal,* 61:14, 2600-2609. doi: 10.1080/02626667.2016.1151980

Felder G., Weingartner R. (2017) Assessment of deterministic PMF modelling approaches. *Hydrological Sciences Journal,* 62:10, 1591-1602. doi: 10.1080/02626667.2017.1319065

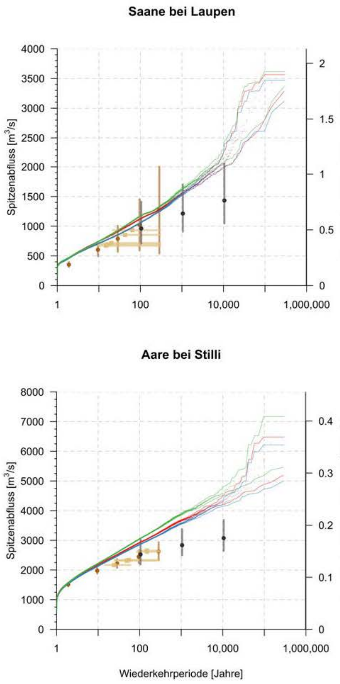
Felder G., Paquet E., Penot D., Zischg A., Weingartner R. (2019) Consistency of Extreme Flood Estimation Approaches. *J. Hydrol. Eng.,* 24(7): 04019018. doi: 10.1061/(ASCE)HE.1943-5584.0001797

Kienzler P., Andres N., Näf-Huber D., Zappa M. (2015) Herleitung extremer Niederschläge und Hochwasser im Einzugsgebiet des Sihlsees für einen verbesserten Hochwasserschutz der Stadt Zürich. *Hydrologie und Wasserbewirtschaftung HyWa,* 59, 48-58. doi: 10.5675/HyWa_2015,2_1

Zischg A. P., Felder G., Weingartner R., Quinn N., Coxon G., Jeffrey N., Freer J., Bates P. (2018) Effects of variability in probable maximum precipitation patterns on flood losses. *Hydrol. Earth Syst. Sci.,* 22, 2759–2773. doi: 10.5194/hess-22-2759-2018

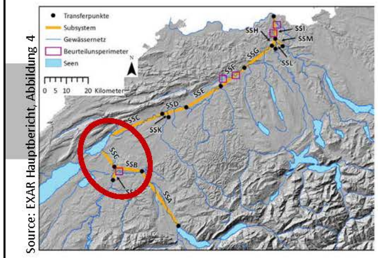
Comparison of Simulation & Gauged Record

- Many transfer points show good agreement between the gauged record, extrapolations from the gauged record, and the simulations within that range
  - Aare above Saane confluence
  - Major Tributaries: Emme, Reuss, Limmat
- A few transfer points (Saane Outlet, Aare after Wasserschloss) show markedly higher simulation than extrapolation values (figures right)
  - Superposition is very strong in the extreme events, with over 95% being common
  - Superposition is not typically estimated for single gauge extrapolations

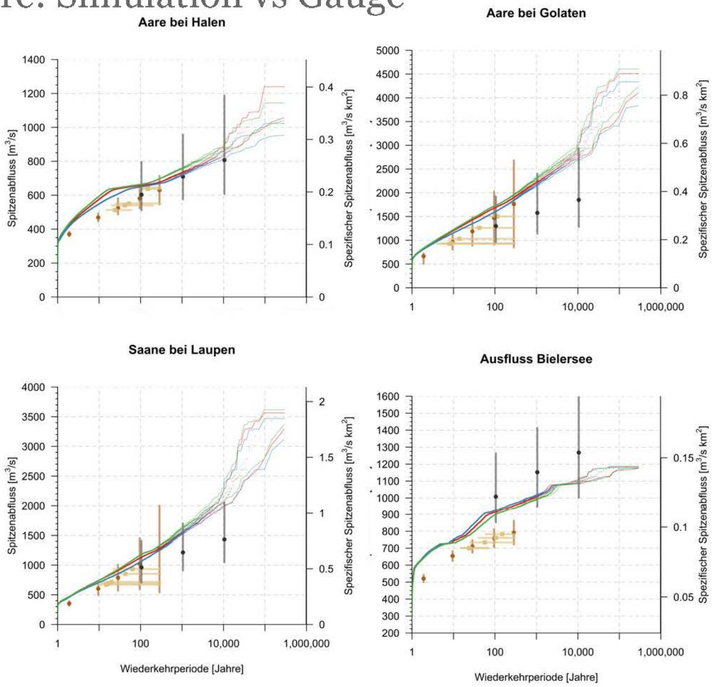


Source: EXAR Detailbericht A, Figure 119

Upper Aare: Simulation vs Gauge



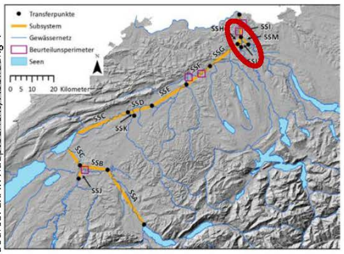
Source: EXAR Hauptbericht, Abbildung 4



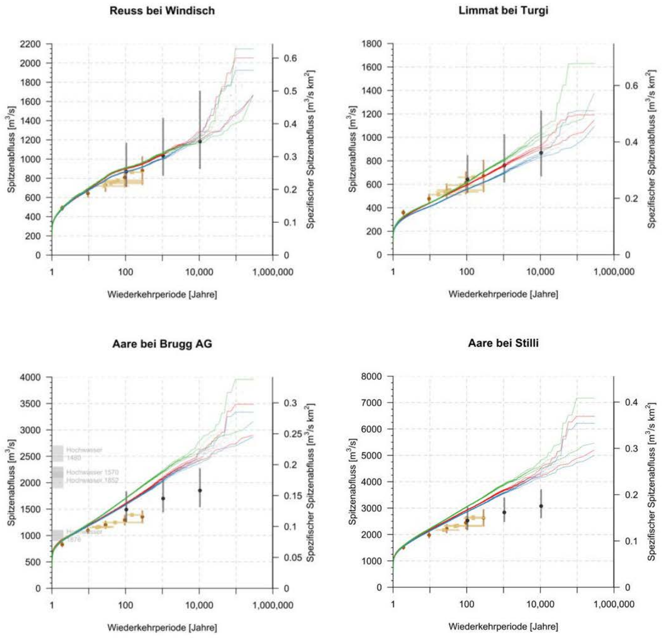
- Aare at Halen (SSASSB) is close to EPFL estimate
- Saane (SSJSSB) shows steeper trend than prediction
- Outflow of Bielersee is on low end of EPFL estimate

Source: EXAR Detailbericht A, Figure 119

Lower Aare: Simulation vs Discharge



Source: EXAR Hauptbericht, Abbildung 4

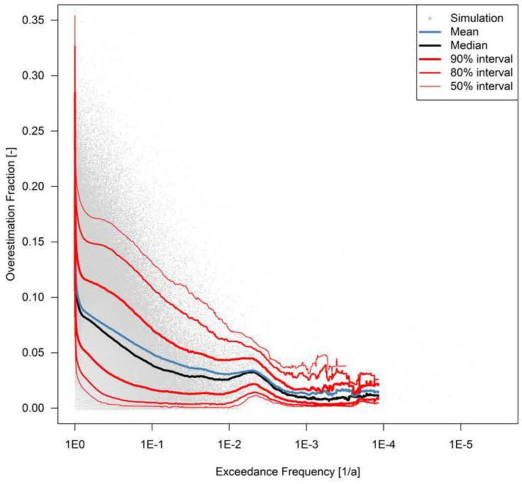


- Reuss and Limmat tributaries very close to estimates
- Aare shows steeper slop, diverges after 100-yr flood
- After confluence, major differences in estimates and simulation
- Analysis shows +95% superposition is common in extreme events

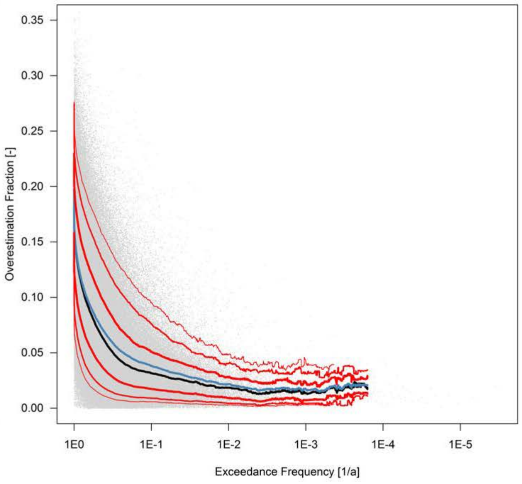
Source: EXAR Detailbericht A, Figure 119

Superposition of Flood Peaks

Aare & Saane Confluence

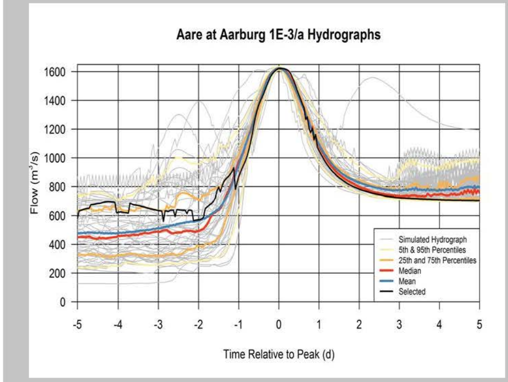


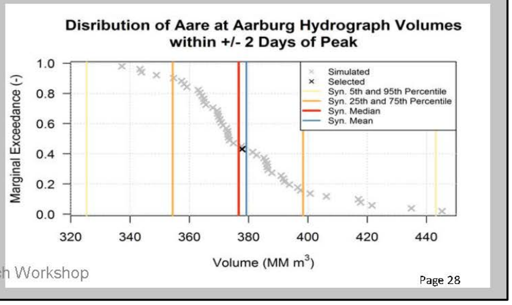
Aare, Reuss & Limmat Confluence



Hydrograph Selection

- Preliminary initiating events chosen to be 1E-3, 1E-4, and 1E-5/a floods (peak flow exceedance criteria)
- Representative or typical hydrographs had to be chosen
  - Project intended to provide best estimate
  - Avoids overly conservative approximations
- Failures and hazard levels dominated by peak flow mechanisms
  - Possible to select hydrograph based on volume, e.g. for levees
  - Analysis showed that most instances of volume/duration failure also peak flow failure





Driftwood Model

P(clog volume) = P(clog initiates)*P(wood volume)

- P(clog initiates) from Shalko's lab experiments

  depends on flow at site, number of pillars in the channel, distance between water surface and bridge deck, etc

- P(wood volume) determined from the expected range of driftwood volume

  GIS analysis with factors for 30-year and 300-year driftwood volumes used to determine 5th and 95th percentiles of lognormal distribution

Conservative principle applied (Bruttoprinzip)

- Lakes retain all driftwood from upstream
- No retention along the Aare River outside of lakes
- Some retention attributed to tributaries

In event tree model, probability of clogging at downstream structures depends on whether clogging occurred at upstream structures that are in the same event tree

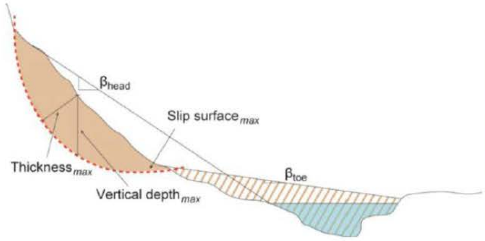
Landslides

General frequency determined using a hazard mapping approach

Method of slices with numerical model (Slide2D) for water table (WT) sensitivity

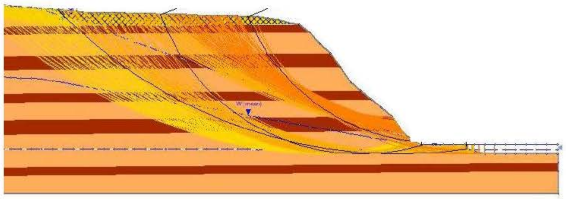
- Hazard mapping frequency assumed WT ~ 13.5 deg
- Elevated WT of 27 deg assumed for EXAR events
- Most landslides not sensitive to WT (<4x change in frequency)

Estimation of Maximum Volume and Intrusion into Channel

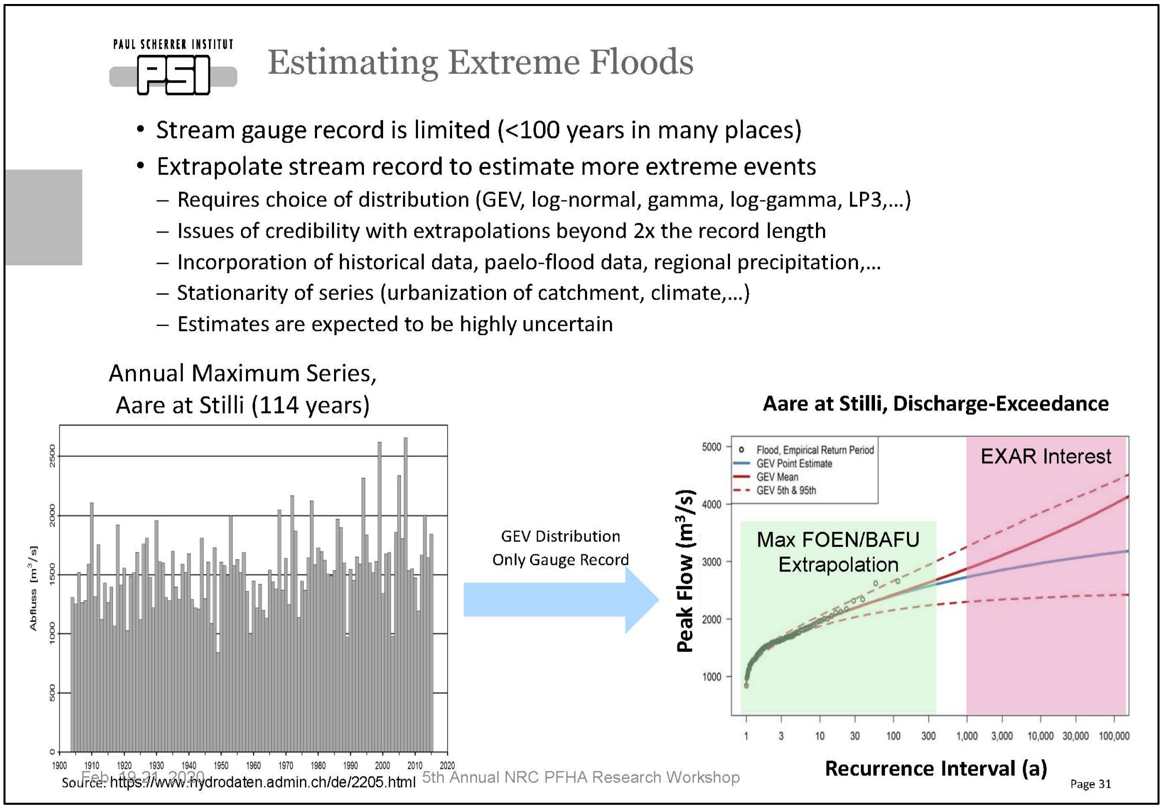


EXAR Detailbericht C, Abbildung 37

Water Table Sensitivity Method of Slices for Different Volumes



EXAR Detailbericht C, Abbildung 39



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Estimating Extreme Floods

- Stream gauge record is limited (<100 years in many places)
- Extrapolate stream record to estimate more extreme events
  - Requires choice of distribution (GEV, log-normal, gamma, log-gamma, LP3,…)
  - Issues of credibility with extrapolations beyond 2x the record length
  - Incorporation of historical data, paelo-flood data, regional precipitation,…
  - Stationarity of series (urbanization of catchment, climate,…)
  - Estimates are expected to be highly uncertain

Annual Maximum Series,
Aare at Stilli (114 years)

Source: https://www.hydrodaten.admin.ch/de/2205.html

GEV Distribution
Only Gauge Record

Aare at Stilli, Discharge-Exceedance

3.4.4 Presentation 2A-4: Practical Approaches to Probabilistic Flood Estimates: an Australian Perspective

Speaker: Rory Nathan, University of Melbourne, Australia

3.4.4.1 Abstract

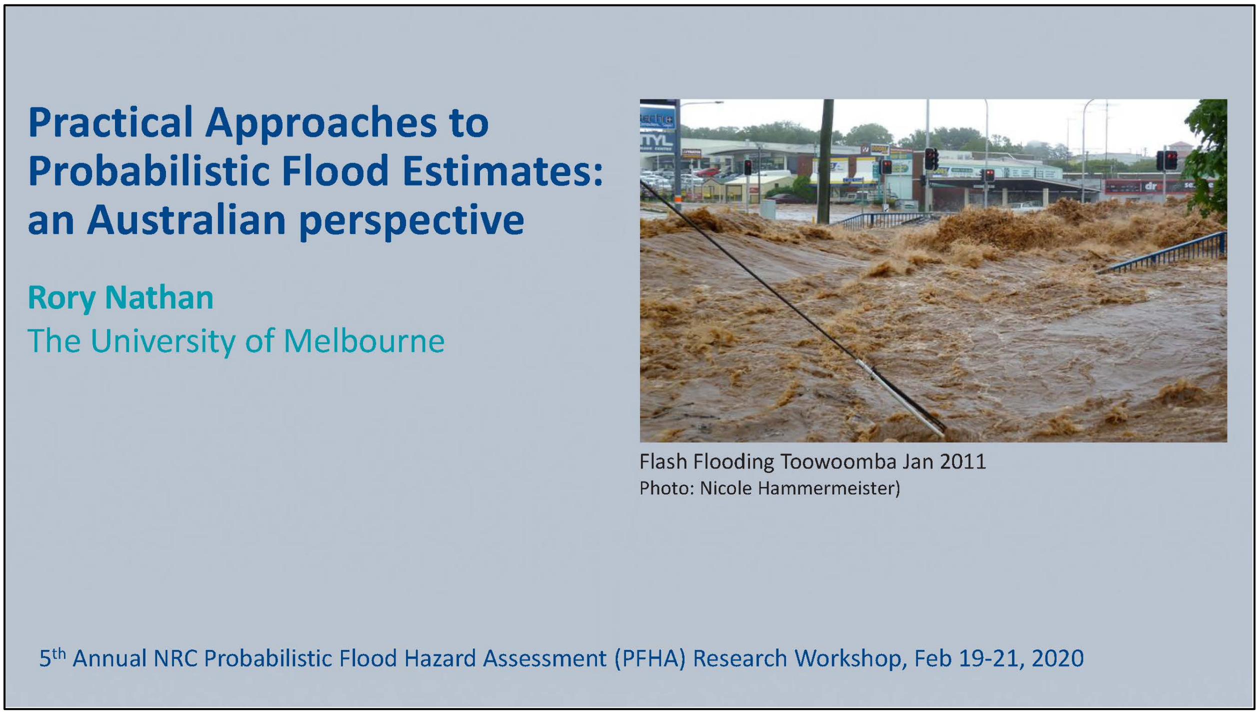
The influence of hydrologic variability on flood estimates has traditionally been accommodated using simple approaches based on the use of “averaged” inputs and simplified assumptions about their joint interaction. Such simplifications can be configured to reproduce probabilistic estimates of flood risk, though without independent verification such estimates must be regarded as an “act of faith”. And even where the means to independently verify probabilistic estimates exist, their extrapolation to conditions beyond those found in the observed record introduces additional uncertainty that is not easily defended.

The Australian national flood guidelines have just been revised after ten years of effort by a large team of specialist practitioners and academics. A key focus of the revised guidelines has been the development and promulgation of practical methods for the explicit consideration of the joint probabilities involved in the transformation of rainfall to flood runoff. The objective of these methods is to achieve a “probability-neutral” transformation of rainfall probabilities to flood probabilities. At its simplest, the guidelines advocate for the use of an ensemble of temporal patterns, which in many instances is the dominant influence (after rainfall) that influences the magnitude (and/or rarity) of the resulting flood. For more complex problems Monte Carlo approaches are recommended for use with event-based approaches; at their simplest, these approaches can consider the joint occurrence of variable antecedent catchment wetness and temporal patterns, though these frameworks are easily extended to consider the joint interaction with variable spatial patterns of rainfall, antecedent snowpack, and other factors relevant to the site-specific nature of the problem.

The emphasis of these approaches is to consider the influence of aleatory rather than epistemic sources of uncertainty; that is, factors arising from natural hydrologic variability rather than those arising from measurement errors and limitations in our understanding. To support these approaches, a national data base has been developed that provides information on ensembles of point and areal temporal patterns, probabilistic behaviour of antecedent and continuing losses, areal reduction factors, baseflows, and pre-burst rainfalls. This includes tools for the joint probability modelling of estuarine regions, regional estimates of flood quantiles, and a multi-site rainfall simulator for the stochastic generation of daily rainfall at multiple locations.

While the Australian guidelines are supported by an extensive suite of design products, the underlying nature of the methods are generically applicable, and for many practical problems the information required to accommodate the primary sources of uncertainty are readily found in the observed records.

3.4.4.2 Presentation (ADAMS Accession No. ML20080M205)



Practical Approaches to Probabilistic Flood Estimates: an Australian perspective

Rory Nathan

The University of Melbourne

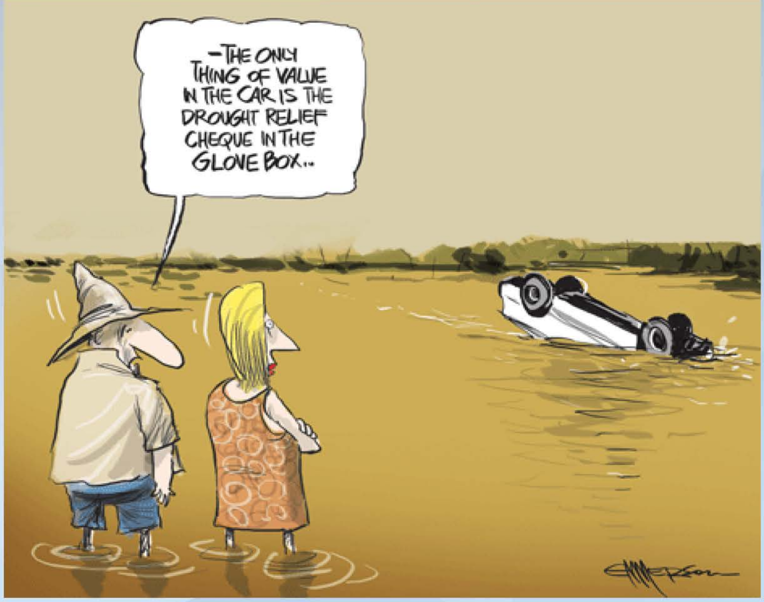
Flash Flooding Toowoomba Jan 2011

Photo: Nicole Hammermeister)

5th Annual NRC Probabilistic Flood Hazard Assessment (PFHA) Research Workshop, Feb 19-21, 2020

I love a sunburnt country
A land of sweeping plains
Of ragged mountain ranges
Of droughts and flooding rains

Dorothea Mackellar (1904)



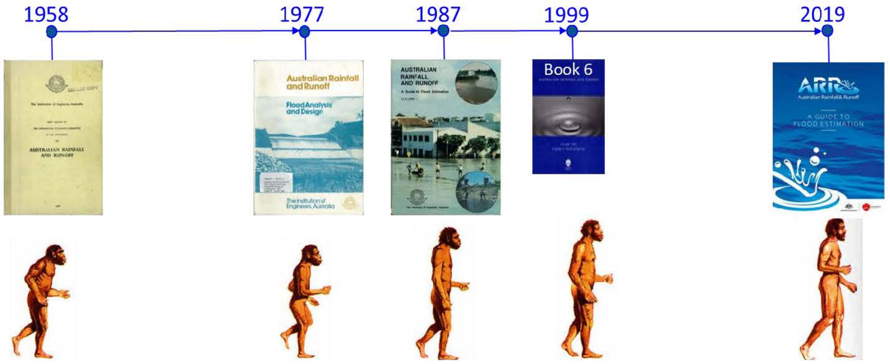
I love a sunburnt country
A land of sweeping plains
Of ragged mountain ranges
Of droughts ^ and flooding rains
bushfires

Dorothea Mackellar (1904)

Brisbane City flood, January 2011
Photo: Felicity Wilson
USD$20 billion damages

Townsville flood, January 2019
Photo: Courier Mail
USD$4 billion damages

Timeline of "Australian Rainfall and Runoff" national flood guidelines



Increasing defensibility, & focus on joint probabilities

1958 — *Hydrol robustus*

1977 — *Hydrol habilis*

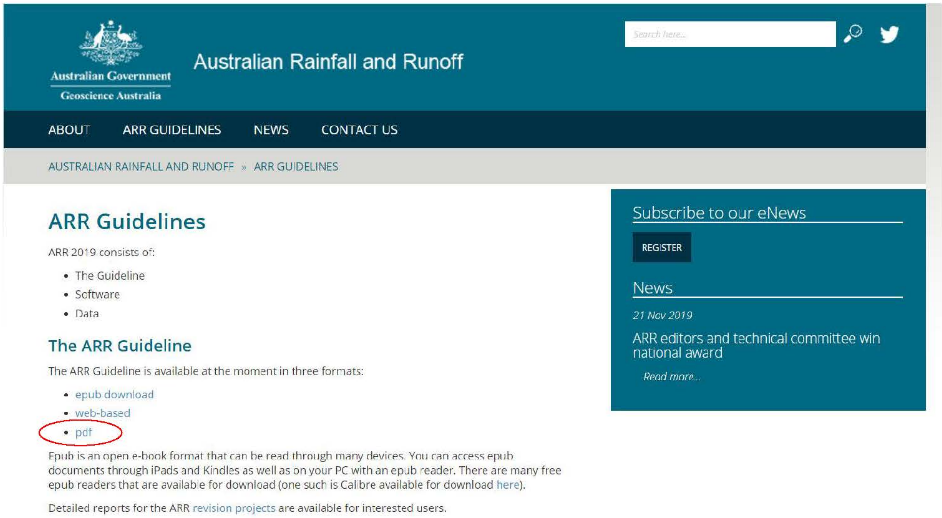
1987 — *Hydrol erectus*

1999 — *Hydrol neand-erthalensis*

2019 — *Hydrol sapiens*

- 22 research projects
- 9 books (~1500 pp)
- ~$13.5M (& equal in-kind)

Australian Rainfall and Runoff (ARR2019)
http://arr.ga.gov.au/arr-guideline



ARR Guidelines

ARR 2019 consists of:

- The Guideline
- Software
- Data

The ARR Guideline

The ARR Guideline is available at the moment in three formats:

- epub download
- web-based
- pdf

Epub is an open e-book format that can be read through many devices. You can access epub documents through iPads and Kindles as well as on your PC with an epub reader. There are many free epub readers that are available for download (one such is Calibre available for download here).

Detailed reports for the ARR revision projects are available for interested users.

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News

21 Nov 2019

ARR editors and technical committee win national award

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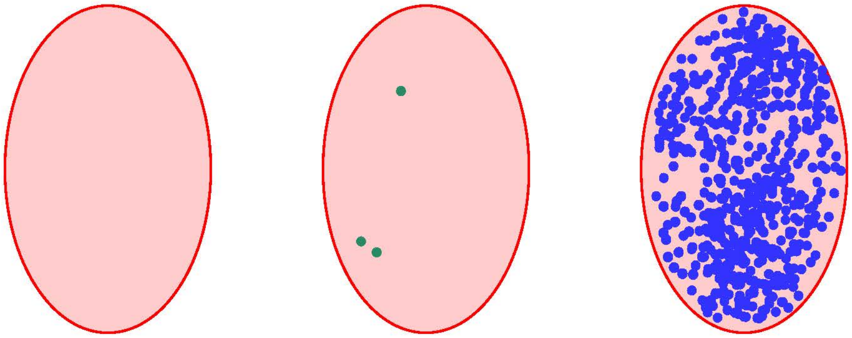
Availability of Data

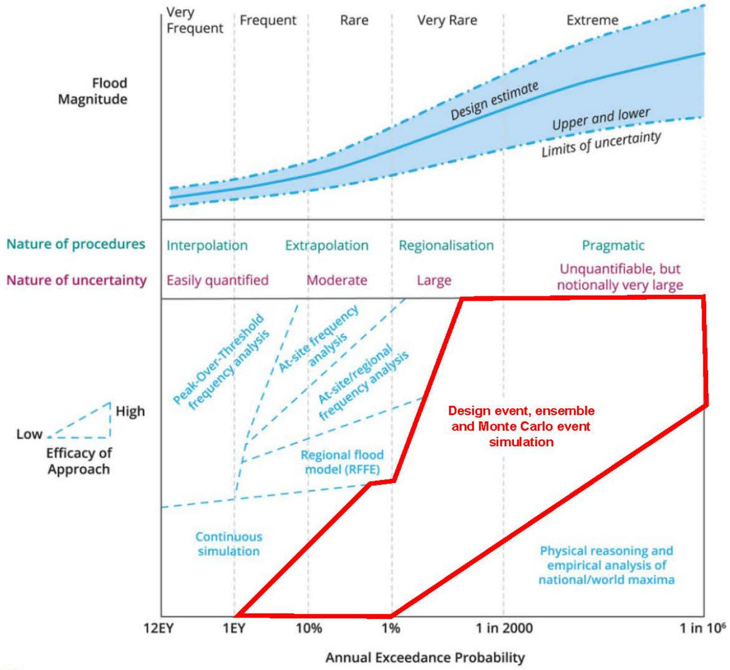


Where info is required

Available flood data

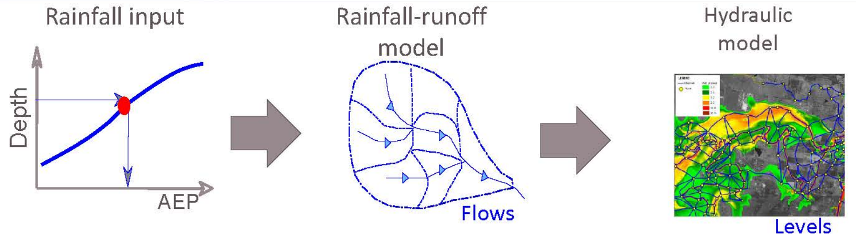
Available rainfall data

Efficacy of different approaches



ARR2019: Book 1, Ch 3
Approaches to Flood Estimation
Nathan and Ball

Rainfall-based methods



- Statistical parameters
- Spatial pattern?
- Temporal pattern?
- Pre-burst?

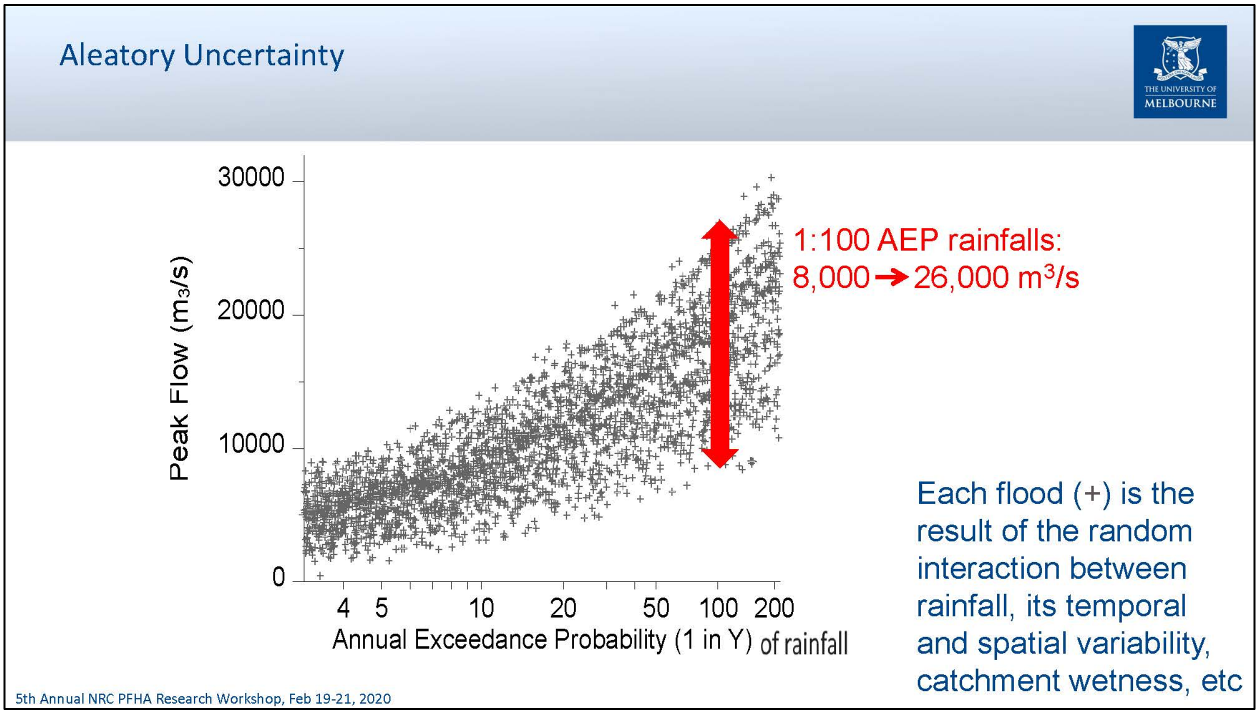
- Stream network
- Routing params
- Antecedent wetness?
- Event losses?

- Bathymetry
- Floodplain/structures
- Roughness params
- Boundary conditions?

Epistemic uncertainty
(data, parameters)

Aleatory uncertainty
(natural variability)

Probability-neutral focus is on aleatory uncertainty with aim of ensuring a 1:Y rainfall yields a 1:Y flood.

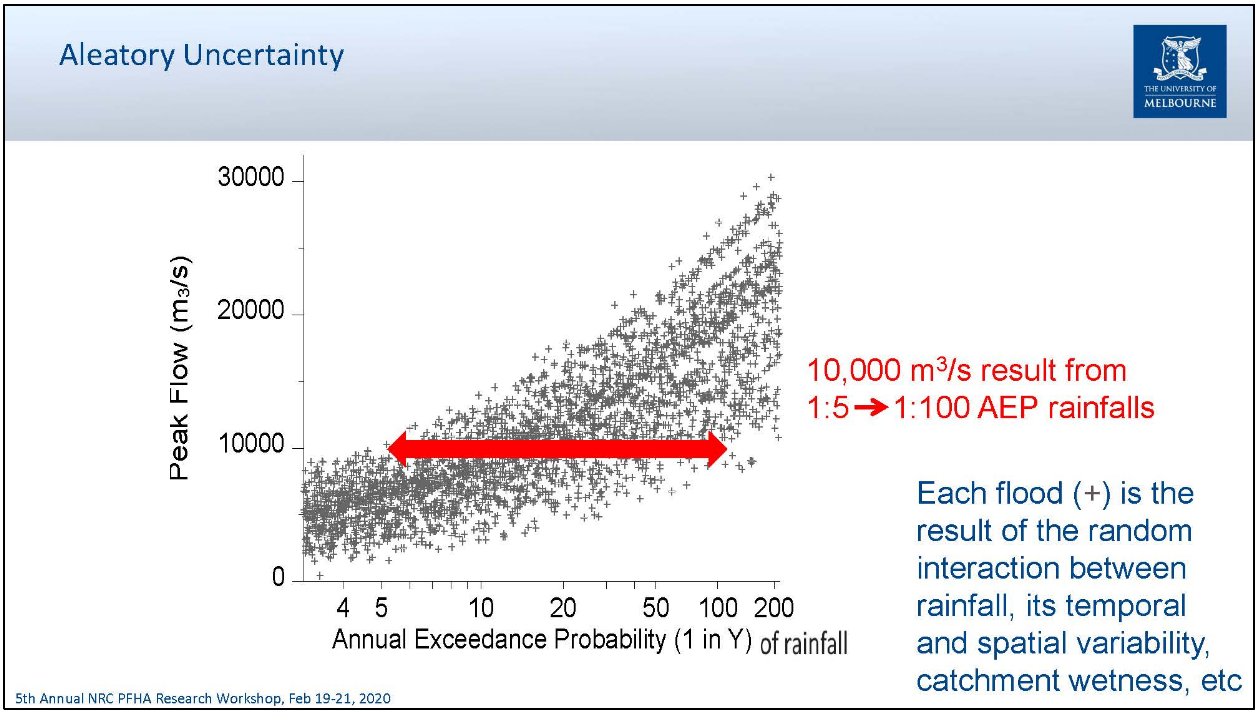


Aleatory Uncertainty

1:100 AEP rainfalls:
8,000 → 26,000 m^3/s

Each flood (+) is the result of the random interaction between rainfall, its temporal and spatial variability, catchment wetness, etc

5th Annual NRC PFHA Research Workshop, Feb 19-21, 2020



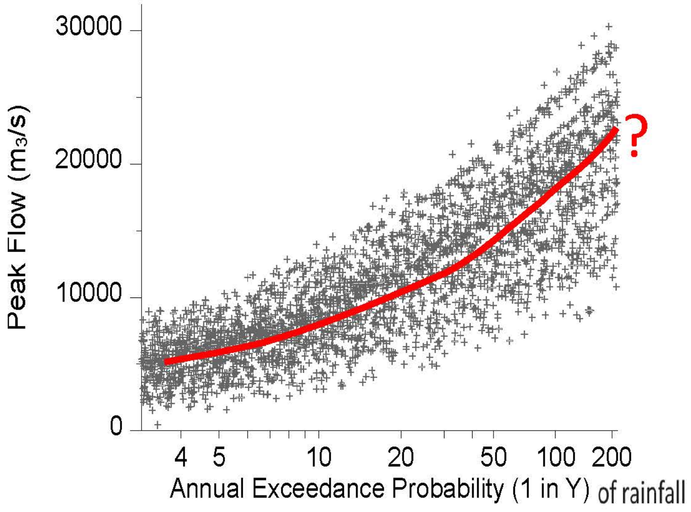
Aleatory Uncertainty

10,000 m^3/s result from
1:5 → 1:100 AEP rainfalls

Each flood (+) is the result of the random interaction between rainfall, its temporal and spatial variability, catchment wetness, etc

5th Annual NRC PFHA Research Workshop, Feb 19-21, 2020

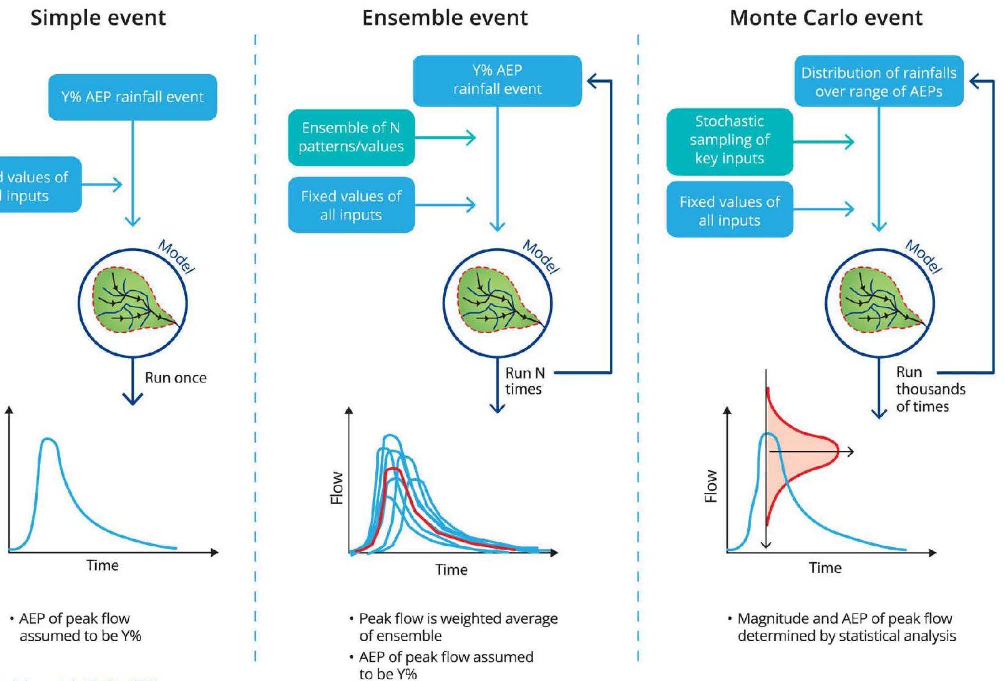
Aleatory Uncertainty



Each flood (+) is the result of the random interaction between rainfall, its temporal and spatial variability, catchment wetness, etc

---

Three approaches of increasing complexity:



Simple event

Y% AEP rainfall event

Fixed values of all inputs

Run once

- AEP of peak flow assumed to be Y%

Ensemble event

Y% AEP rainfall event

Ensemble of N patterns/values

Fixed values of all inputs

Run N times

- Peak flow is weighted average of ensemble
- AEP of peak flow assumed to be Y%

Monte Carlo event

Distribution of rainfalls over range of AEPs

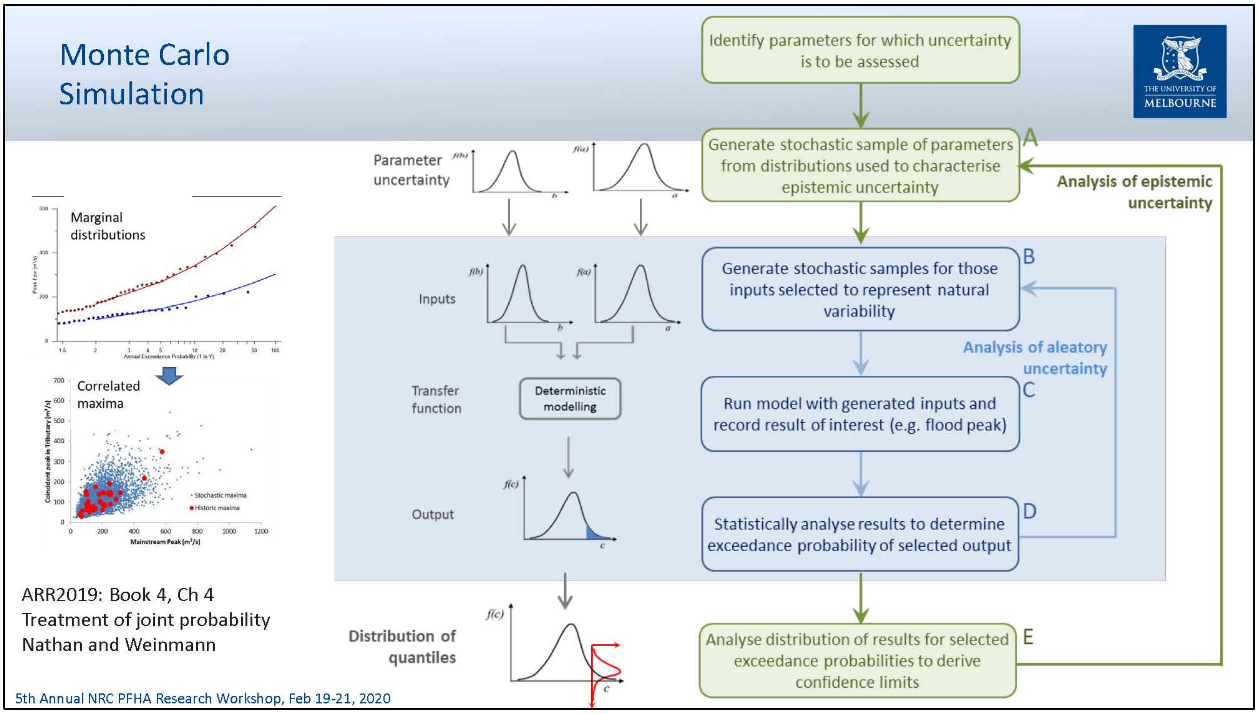
Stochastic sampling of key inputs

Fixed values of all inputs

Run thousands of times

- Magnitude and AEP of peak flow determined by statistical analysis

ARR2019: Book 4, Ch 3
Types of simulation approaches
Nathan and Ling



Monte Carlo Simulation

Identify parameters for which uncertainty is to be assessed

A Generate stochastic sample of parameters from distributions used to characterise epistemic uncertainty

B Generate stochastic samples for those inputs selected to represent natural variability

C Run model with generated inputs and record result of interest (e.g. flood peak)

D Statistically analyse results to determine exceedance probability of selected output

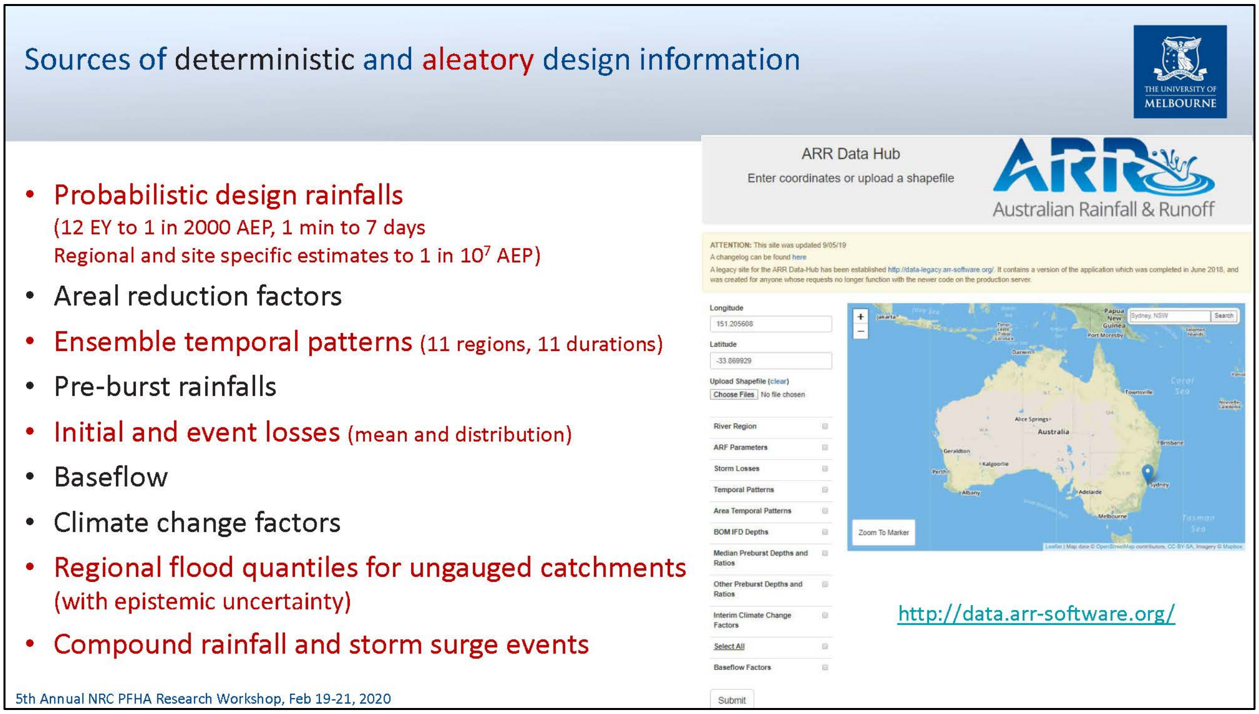
E Analyse distribution of results for selected exceedance probabilities to derive confidence limits

Analysis of epistemic uncertainty

Analysis of aleatory uncertainty

ARR2019: Book 4, Ch 4
Treatment of joint probability
Nathan and Weinmann

5th Annual NRC PFHA Research Workshop, Feb 19-21, 2020



Sources of deterministic and aleatory design information

- Probabilistic design rainfalls
  (12 EY to 1 in 2000 AEP, 1 min to 7 days
  Regional and site specific estimates to 1 in 10^7 AEP)
- Areal reduction factors
- Ensemble temporal patterns (11 regions, 11 durations)
- Pre-burst rainfalls
- Initial and event losses (mean and distribution)
- Baseflow
- Climate change factors
- Regional flood quantiles for ungauged catchments
  (with epistemic uncertainty)
- Compound rainfall and storm surge events

ARR Data Hub

Enter coordinates or upload a shapefile

ATTENTION: This site was updated 9/05/19

A changelog can be found here

A legacy site for the ARR Data-Hub has been established http://data-legacy.arr-software.org/. It contains a version of the application which was completed in June 2018, and was created for anyone whose requests no longer function with the newer code on the production server.

Longitude: 151.205608

Latitude: -33.869929

Upload Shapefile (clear)

Choose Files No file chosen

River Region ☐
ARF Parameters ☐
Storm Losses ☐
Temporal Patterns ☐
Area Temporal Patterns ☐
BOM IFD Depths ☐
Median Preburst Depths and Ratios ☐
Other Preburst Depths and Ratios ☐
Interim Climate Change Factors ☐
Select All ☐
Baseflow Factors ☐

Submit

Sydney, NSW

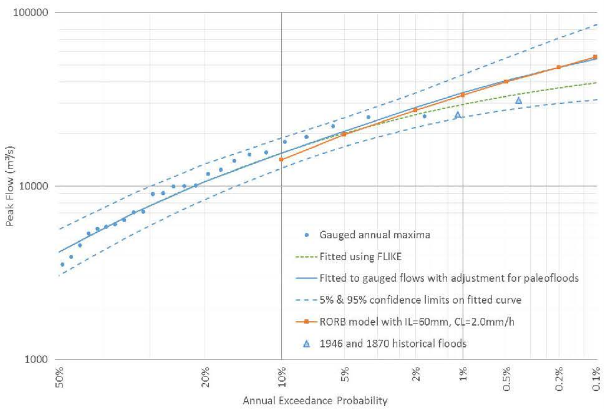
Leaflet | Map data © OpenStreetMap contributors, CC-BY-SA, Imagery © Mapbox

http://data.arr-software.org/

5th Annual NRC PFHA Research Workshop, Feb 19-21, 2020

Reconciliation/derivation of flood frequency curves

- "Frequent to Rare" flood risk design for floodplain planning and major infrastructure
  - — Design risks from 1 in 2 AEP to 1 in 2000 AEP
  - — Books 2, 3, 4, 5 & 7
- "Very Rare to Extreme" flood risk design for critical infrastructure and dams
  - — Design risks from 1 in 100 AEP to 1 in 10^7 AEP
  - — Book 8 (includes PMP -> PMF)
  - — AEP of PMP:
    - Regional - Laurenson-Kuczera (based on area)
    - Site specific - Nathan et al (2016), *J Hydrol* v543, pp706-720
    - Lang et al (2019) ANCOLD conf proc, Auck NZ
- FLIKE – Bayesian flood frequency analysis (Kuczera)
  https://flike.tuflow.com/
- RORB – storage-routing event-based Monte-Carlo modelling based on stratified sampling
  https://www.harc.com.au/software/rorb/



Conclusions

- Guidelines finalised in 2019
- Considerable improvement in available design information
- Major methodological shift to joint probability treatment of rainfall, temporal patterns, losses (and storm surge)
- Required extensive engagement with industry
- User-friendly "data hub" repository for regional data sets
- Design information expected to be refined with experience and further testing

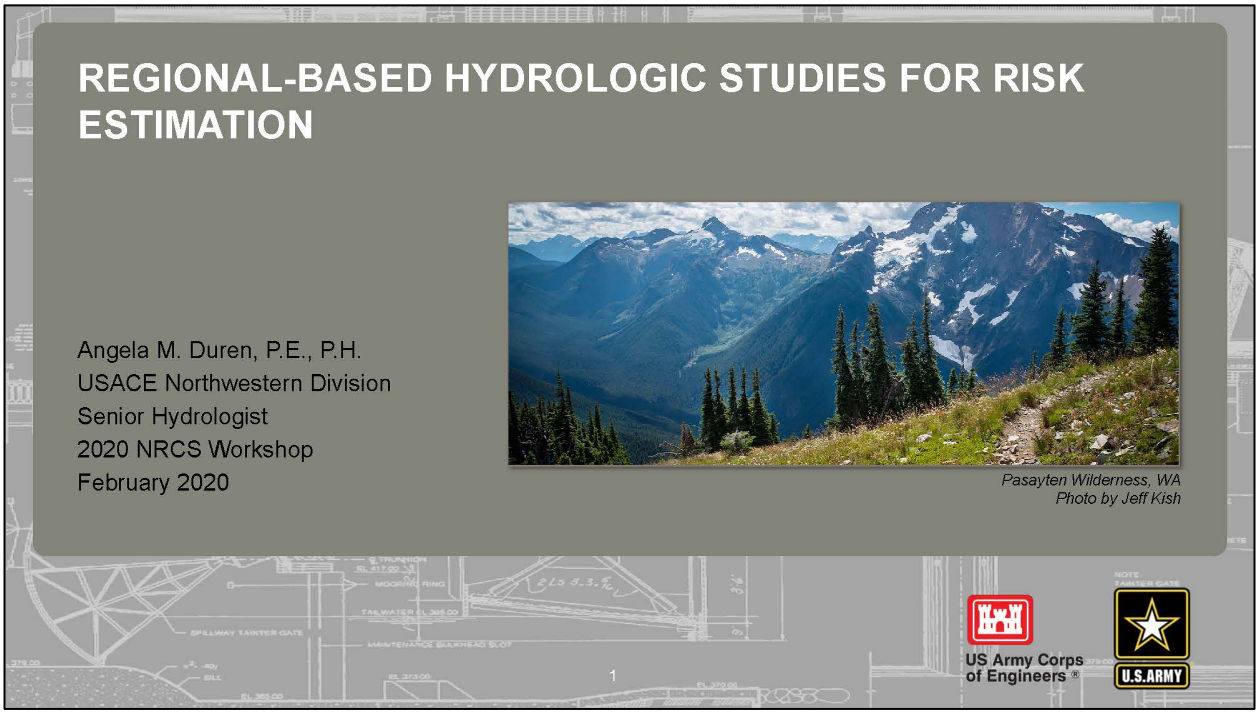
3.4.5 Presentation 2A-5: Columbia River Basin Regional Hydrology Studies: Regional Statistical Analyses for Flood Risk Assessment

Speaker: Angela M. Duren*, U.S. Army Corps of Engineers, Northwestern Division

3.4.5.1 Abstract

A regional-based approach was used in the development of the stage frequency curves for 7 of the 13 dams in the Willamette Basin, part of the larger Columbia River Basin, for use in an Issue Evaluation Study (IES)-level dam safety analysis. This saved both money and time and also allowed for larger regional studies used as the basis of the stage frequency curves to be developed for use in future studies. This includes a regional volume skew study for flow frequency analysis, a regional precipitation frequency curve analysis, regional site-specific Probable Maximum Precipitation (PMP) analysis, and basin-wide hydrologic and reservoir operations modeling via HEC-HMS and HEC-ResSim linkage in a holistic watershed HEC-WAT model. The Willamette work formed the basis of the design for the larger on-going Columbia River Basin (CRB) hydrology studies, in which a regional precipitation and snow water equivalent (SWE) frequency analyses have been done, numerical modelling is being performed for improved period of record meteorologic data and PMP estimation, and regional modeling is being performed for development of synthetic hydrology and stage frequency curves that account for meteorologic and hydrologic uncertainty.

3.4.5.2 Presentation (ADAMS Accession No. ML20080M208)



REGIONAL-BASED HYDROLOGIC STUDIES FOR RISK ESTIMATION

Angela M. Duren, P.E., P.H.
USACE Northwestern Division
Senior Hydrologist
2020 NRCS Workshop
February 2020

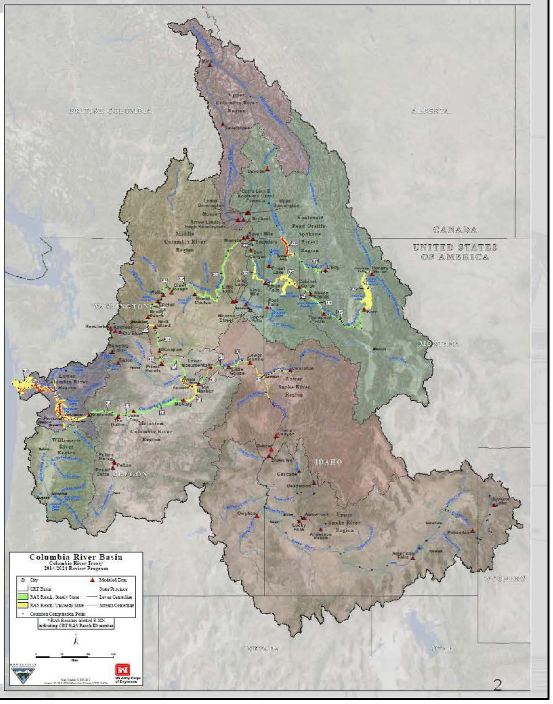
Pasayten Wilderness, WA
Photo by Jeff Kish

US Army Corps of Engineers ®

U.S.ARMY

OUTLINE

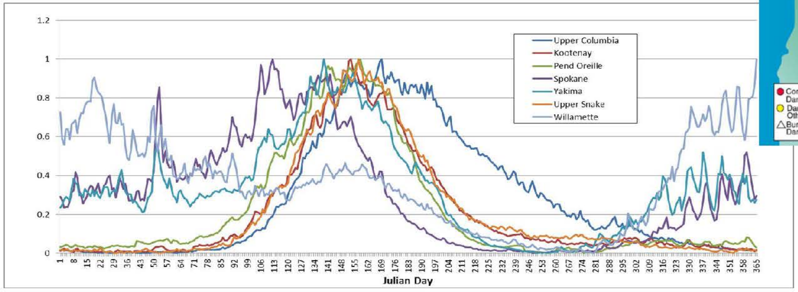
- Flood Risk Assessment
  - Synthetic Hydrographs
  - Synthetic Stage
- Key Components of Stage/Regulated Flow Frequency Curves
- Willamette Stage Frequency Curve Analysis – Key Lessons Learned
- Moving Forward: Columbia River Basin Hydrology Studies



COLUMBIA RIVER BASIN

❖ 260,000 square miles and extending throughout the Pacific Northwest and into Canada.

❖ There are more than 250 reservoirs and around 150 hydroelectric projects in the basin, including 18 mainstem dams on the Columbia and its main tributary, the Snake River.



Basin-wide Average Runoff Signal

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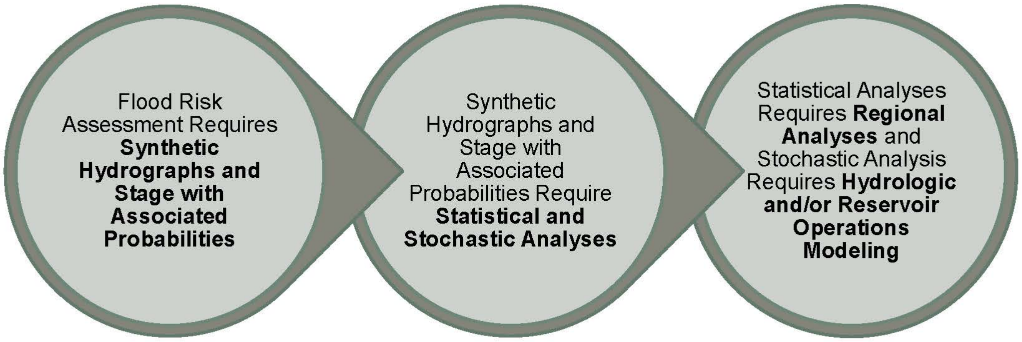
USACE MISSION: FLOOD RISK



Flood Risk Assessment Requires **Synthetic Hydrographs and Stage with Associated Probabilities**

Synthetic Hydrographs and Stage with Associated Probabilities Require **Statistical and Stochastic Analyses**

Statistical Analyses Requires **Regional Analyses** and Stochastic Analysis Requires **Hydrologic and/or Reservoir Operations Modeling**

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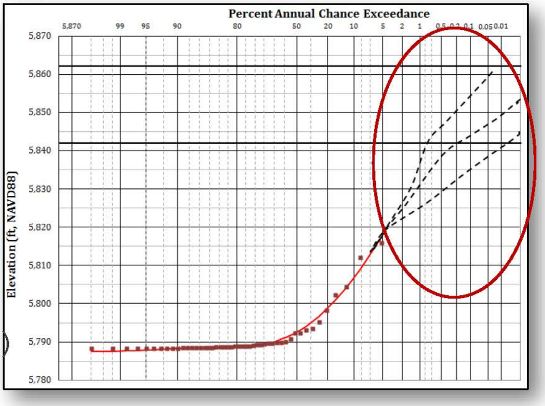
STAGE/REGULATED FLOW FREQUENCY CURVE (RESERVOIR OR RIVER CHANNEL)
(STAGE/REGULATED FLOW, UNCERTAINTY VS PROBABILITY)

Some Factors that Affect the Peak Flow and Elevation for Any Given Event

- Temperature
- Precipitation intensity
- Spatial/temporal distribution of precipitation
- Antecedent snowpack
- Antecedent elevations
- Operations
- Baseflow
- Soil infiltration capacity
- Rainfall-runoff transformation (unit hydrograph)



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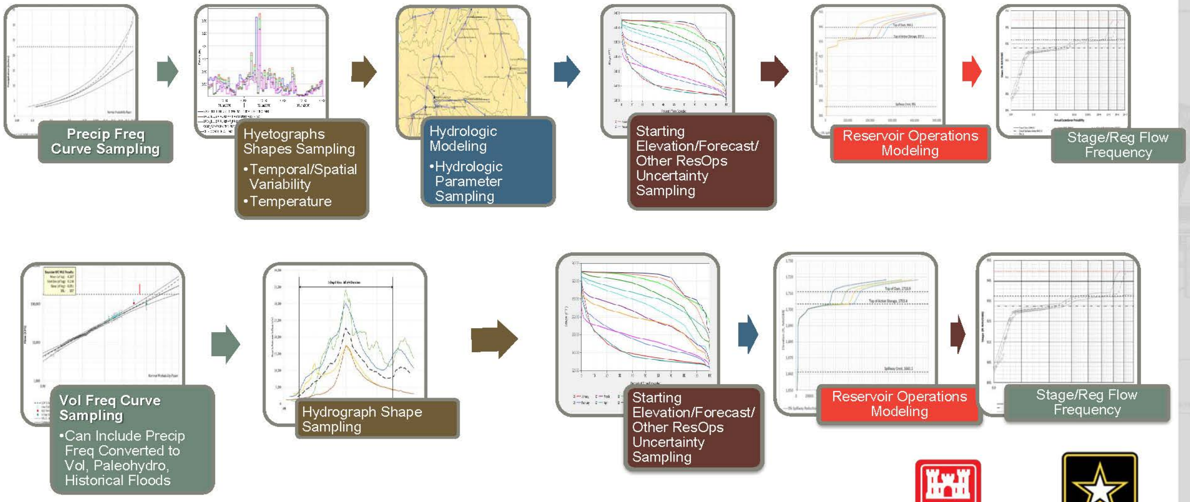
KEY COMPONENTS OF STAGE FREQUENCY CURVES

WILLAMETTE BASIN STAGE FREQUENCY CURVES



Precip Freq Curve Sampling

Hyetographs Shapes Sampling
- Temporal/Spatial Variability
- Temperature

Hydrologic Modeling
- Hydrologic Parameter Sampling

Starting Elevation/Forecast/ Other ResOps Uncertainty Sampling

Reservoir Operations Modeling

Stage/Reg Flow Frequency

Vol Freq Curve Sampling
- Can Include Precip Freq Converted to Vol, Paleohydro, Historical Floods

Hydrograph Shape Sampling

Starting Elevation/Forecast/ Other ResOps Uncertainty Sampling

Reservoir Operations Modeling

Stage/Reg Flow Frequency

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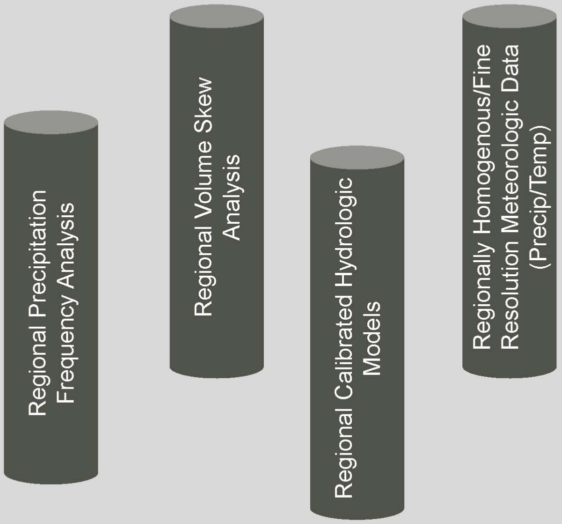
WILLAMETTE DAM SAFETY STUDY: LESSONS LEARNED

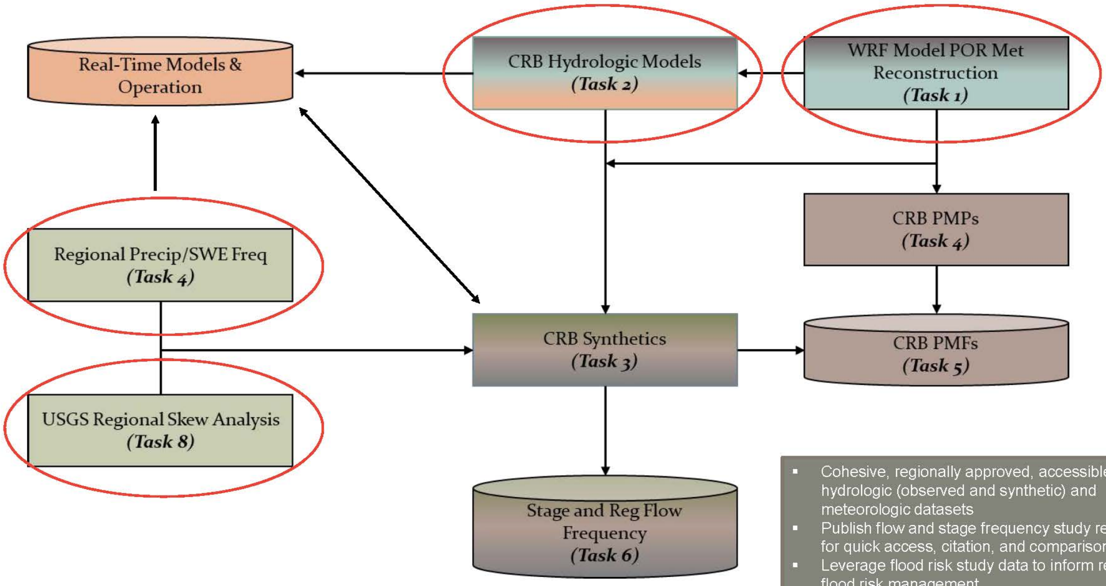
Pillars of Optimal Flood Risk Management Hydrology



Optimal Hydrologic Studies for Risk Estimation Includes Regional Corroboration and a Solid Foundation:

- Regionally Homogenous/Fine Resolution Spatial/Temporal/Temperature Data
- Regional Hydrologic Models
- Regional Precipitation Frequency
- Regional Volume Frequency Curve Analysis

COLUMBIA RIVER BASIN (CRB) HYDROLOGIC STUDIES



Real-Time Models & Operation

CRB Hydrologic Models *(Task 2)*

WRF Model POR Met Reconstruction *(Task 1)*

CRB PMPs *(Task 4)*

Regional Precip/SWE Freq *(Task 4)*

CRB Synthetics *(Task 3)*

CRB PMFs *(Task 5)*

USGS Regional Skew Analysis *(Task 8)*

Stage and Reg Flow Frequency *(Task 6)*

- Cohesive, regionally approved, accessible hydrologic (observed and synthetic) and meteorologic datasets
- Publish flow and stage frequency study results for quick access, citation, and comparison
- Leverage flood risk study data to inform real-time flood risk management
- Update hydrology from original design

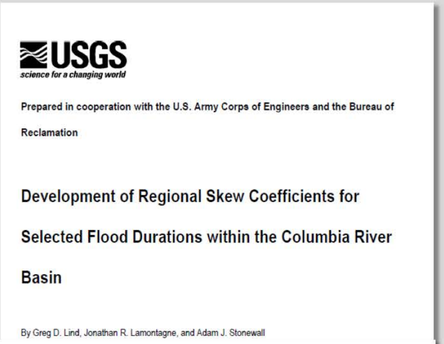
CRB DURATION FLOW FREQUENCY CURVES REGIONAL SKEW ANALYSIS

Key Points:

- Durations 1-day through 60-day; flooding season only

- This report utilized Bayesian statistical methods, which have been used for numerous flood-frequency studies, to develop and analyze regional models based on hydrologically significant basin characteristics.

- Using incremental steps of mean annual precipitation while developing skew models, it was found that 40 inches of annual precipitation seemed to be a natural breakpoint for the relationships between basins and their skew coefficients. As such, a regression model was fitted to precipitation with a sigmoidal function used to smoothly transition the boundary of 40 inches of precipitation a year.

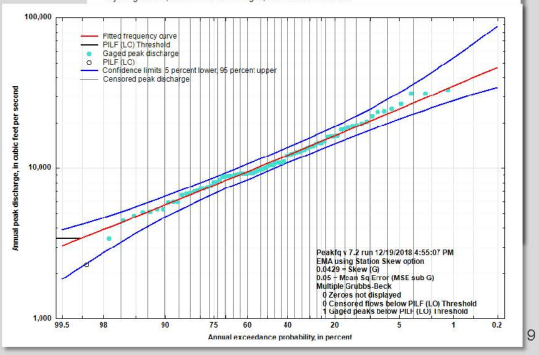


USGS
science for a changing world

Prepared in cooperation with the U.S. Army Corps of Engineers and the Bureau of Reclamation

Development of Regional Skew Coefficients for Selected Flood Durations within the Columbia River Basin

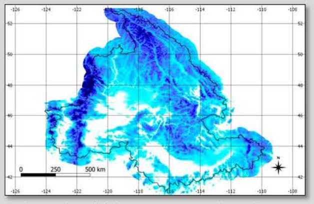
By Greg D. Lind, Jonathan R. Lamontagne, and Adam J. Stonewall

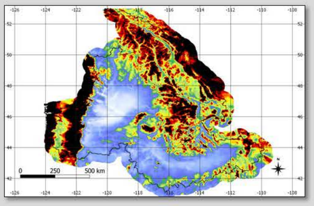


CRB DURATION PRECIPITATION AND SNOW WATER EQUIVALENT (SWE) FREQUENCY CURVES REGIONAL ANALYSIS

Key Points:

- Durations 1-day through 60-day
- Warm season & cool season for precipitation; cool season for SWE
- Pointwise and areal-based exceedance probabilities of precipitation and SWE using a spatial max-stable process model and observed pointwise maxima data.
- Each max-stable modeling analysis leverages extreme value theorem (EVT), at-site estimates of extreme PREC/SWE, physiographic and climatological covariate data, and recent advances in model calibration.
- No areal reduction factors required





Point-wise 100-year return level maps for SWE (top) and precipitation (right)

Title: Spatial Analysis of Precipitation and Snow Water Equivalent Extremes for the Columbia River Basin

Authors:

Brian E. Skahill, Research Civil Engineer, US Army Corps of Engineers, Engineer Research and Development Center, Coastal and Hydraulics Laboratory, Portland, Oregon

Angela M. Duren, Senior Hydrologist, US Army Corps of Engineers, Northwestern Division, Portland, Oregon

Luciana Cunha, Senior Engineer, WEST Consultants, Folsom, California

Chris Bahner, Senior Project Manager, WEST Consultants, Salem, Oregon

Abstract:

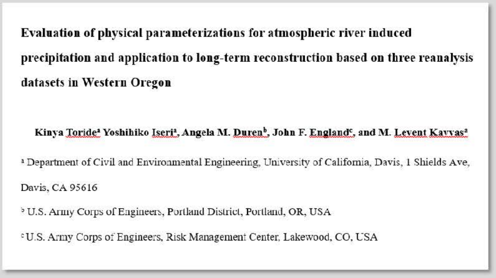
Recent advances in the spatial statistics of extremes and model calibration were applied to develop and deliver areal-exceedance estimates for precipitation, by season and duration, and snow water equivalent, by cool season month and for the water year, for 758 delineated sub-basins of the Columbia River Basin which correspond to a new Columbia River Basin hydrology model watershed delineation. Understanding that future USACE-NWD mission requirements may change, project execution also included the development and delivery of an application guidance document to credibly compute areal-exceedance estimates, including uncertainty, for PREC or SWE for any arbitrary area within the CRB. R, a free software environment for statistical computing and graphics (https://www.r-project.org/), and QGIS, a free and open source geographic information system (https://qgis.org/en/site/index.html), were the primary tools used for product development and delivery. The following R software packages were primarily used during project execution: evd, Glmnet, maps, raster, rgdal, SDMTools, sp, and SpatialExtremes.

CRB NUMERICAL ATMOSPHERIC MODEL (WEATHER RESEARCH AND FORECAST (WRF)) FOR:

❖ HISTORIC DATA RECONSTRUCTION
❖ PMP
❖ SYNTHETIC STORMS

Key Points:

- Dynamical downscaling of reanalysis datasets to reconstruct high resolution historical meteorologic data (1929-2017) (4km x 3 hr)
  - Used for calibration and continuous simulation of hydrologic models
- Calibration and validating of WRF model using historical events (PRISM; Corroborating with Regional WRF models)
- Maximization of the integrated vapor transport jet
- stream and lateral boundary shifting for maximization of storms over a given region for PMP and synthetic events (publication pending).



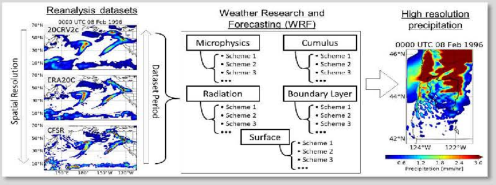
Evaluation of physical parameterizations for atmospheric river induced precipitation and application to long-term reconstruction based on three reanalysis datasets in Western Oregon

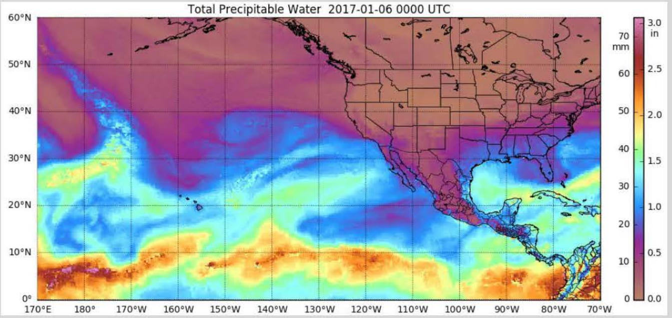
Kinya Toride[a] Yoshihiko Iseri[a], Angela M. Duren[b], John F. England[c], and M. Levent Kavvas[a]

[a] Department of Civil and Environmental Engineering, University of California, Davis, 1 Shields Ave, Davis, CA 95616

[b] U.S. Army Corps of Engineers, Portland District, Portland, OR, USA

[c] U.S. Army Corps of Engineers, Risk Management Center, Lakewood, CO, USA

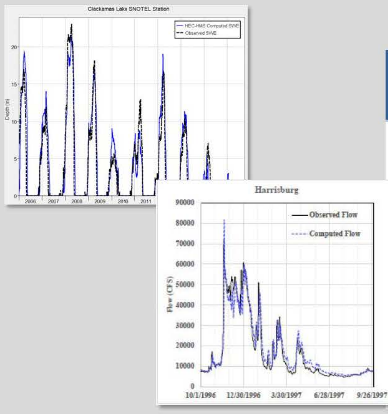


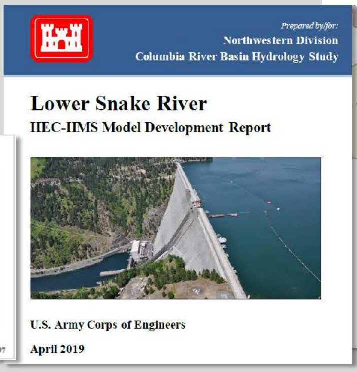


CRB BASIN-WIDE CALIBRATED HYDROLOGIC MODELS

Key Points:

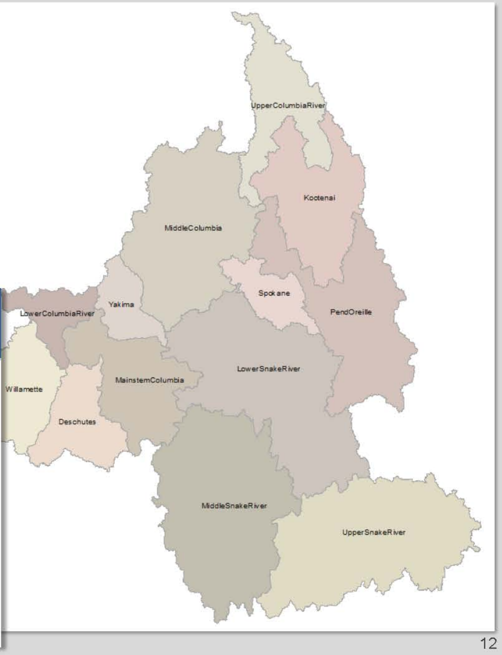
- Columbia River Basin (260,000 square miles) broken out into 13 models by tributary
- Coarse-level Calibration to four key water years in terms of variability in meteorology and water management challenges
- Models reflect both rainflood and snowmelt (dominant) seasons
- Models being used for both real-time and planning/dam safety efforts
- Regionally-approved




Prepared by/for:
Northwestern Division
Columbia River Basin Hydrology Study

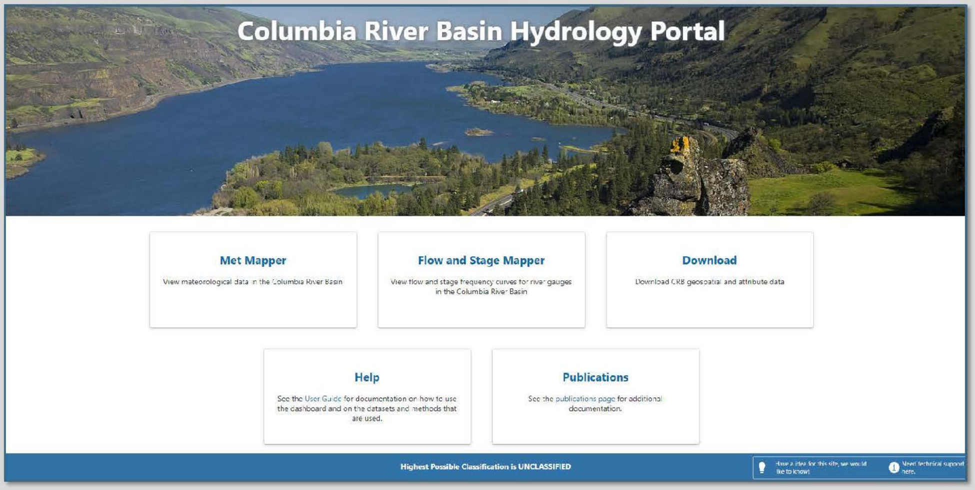
Lower Snake River
HEC-HMS Model Development Report

U.S. Army Corps of Engineers
April 2019



CRB HYDROLOGY STUDIES: THE END GAME

✓ Cohesive, regionally approved, accessible hydrologic (observed and synthetic) and meteorologic datasets
✓ Publish flow and stage frequency study results for quick access, citation, and comparison
✓ Leverage flood risk study data to inform real-time flood risk management
✓ Update hydrology from original design


Columbia River Basin Hydrology Portal

Met Mapper
View meteorological data in the Columbia River Basin

Flow and Stage Mapper
View flow and stage frequency curves for river gauges in the Columbia River Basin

Download
Download CRB geospatial and attribute data

Help
See the User Guide for documentation on how to use the dashboard and on the datasets and methods that are used.

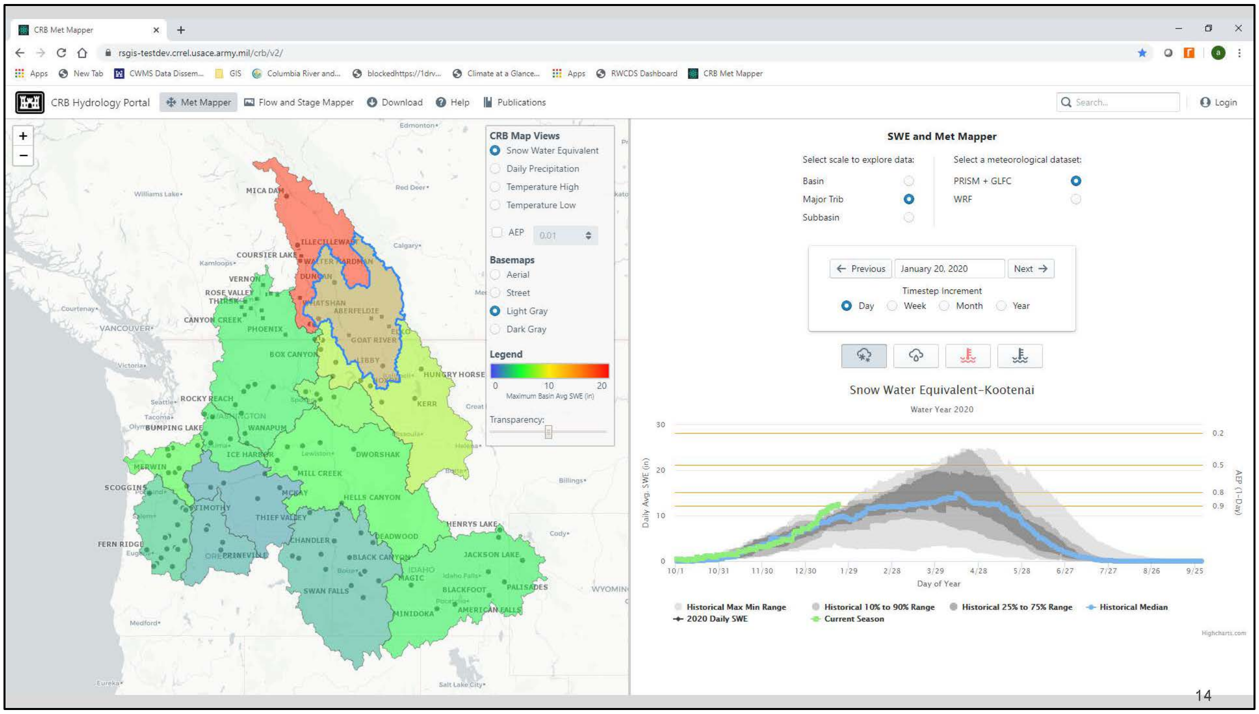
Publications
See the publications page for additional documentation.

Highest Possible Classification is UNCLASSIFIED

Have a idea for this site, we would like to know!

Need technical support here.

https://rsgis-testdev.crrel.usace.army.mil/crb/v2/

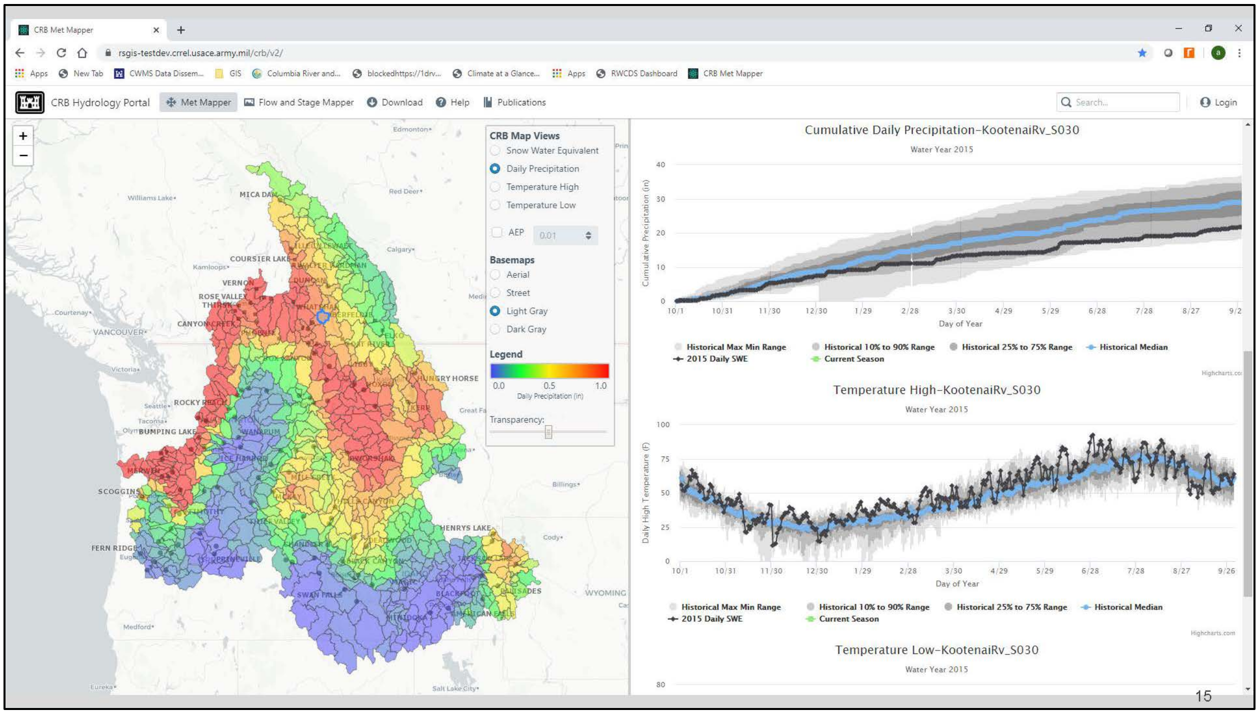


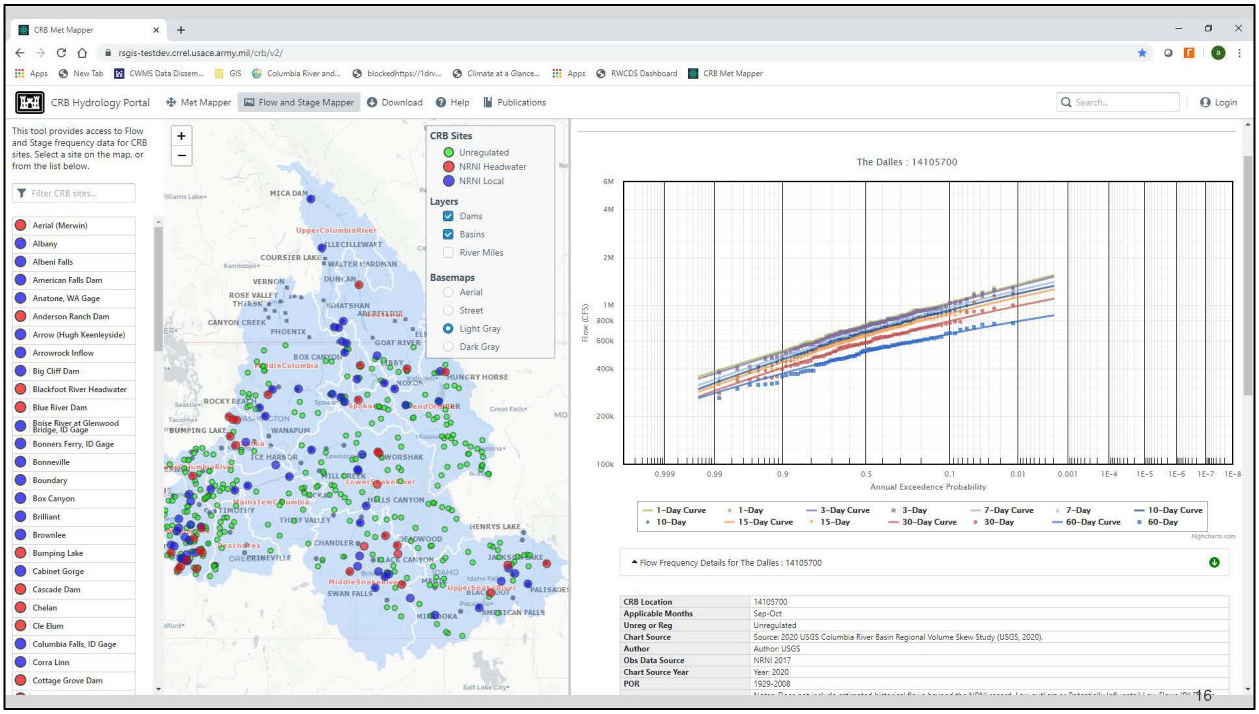
Select scale to explore data: ○ Basin ● Major Trib ○ Subbasin

Select a meteorological dataset: ● PRISM + GLFC ○ WRF

January 20, 2020

● Day ○ Week ○ Month ○ Year



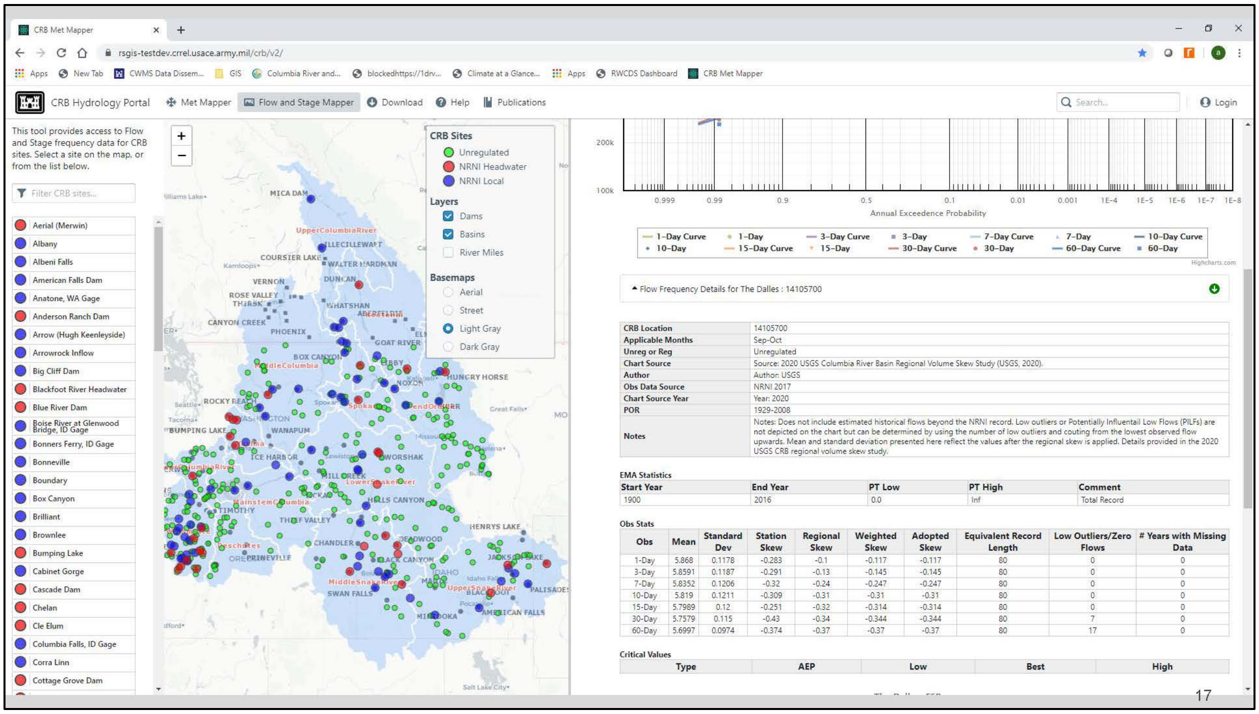


This tool provides access to Flow and Stage frequency data for CRB sites. Select a site on the map, or from the list below.

▲ Flow Frequency Details for The Dalles : 14105700

CRB Location	14105700
Applicable Months	Sep-Oct
Unreg or Reg	Unregulated
Chart Source	Source: 2020 USGS Columbia River Basin Regional Volume Skew Study (USGS, 2020).
Author	Author: USGS
Obs Data Source	NRNI 2017
Chart Source Year	Year: 2020
POR	1929-2008

16



This tool provides access to Flow and Stage frequency data for CRB sites. Select a site on the map, or from the list below.

▲ Flow Frequency Details for The Dalles : 14105700

CRB Location	14105700
Applicable Months	Sep-Oct
Unreg or Reg	Unregulated
Chart Source	Source: 2020 USGS Columbia River Basin Regional Volume Skew Study (USGS, 2020).
Author	Author: USGS
Obs Data Source	NRNI 2017
Chart Source Year	Year: 2020
POR	1929-2008
Notes	Notes: Does not include estimated historical flows beyond the NRNI record. Low outliers or Potentially Influentail Low Flows (PILFs) are not depicted on the chart but can be determined by using the number of low outliers and couting from the lowest observed flow upwards. Mean and standard deviation presented here reflect the values after the regional skew is applied. Details provided in the 2020 USGS CRB regional volume skew study.

EMA Statistics

Start Year	End Year	PT Low	PT High	Comment
1900	2016	0.0	Inf	Total Record

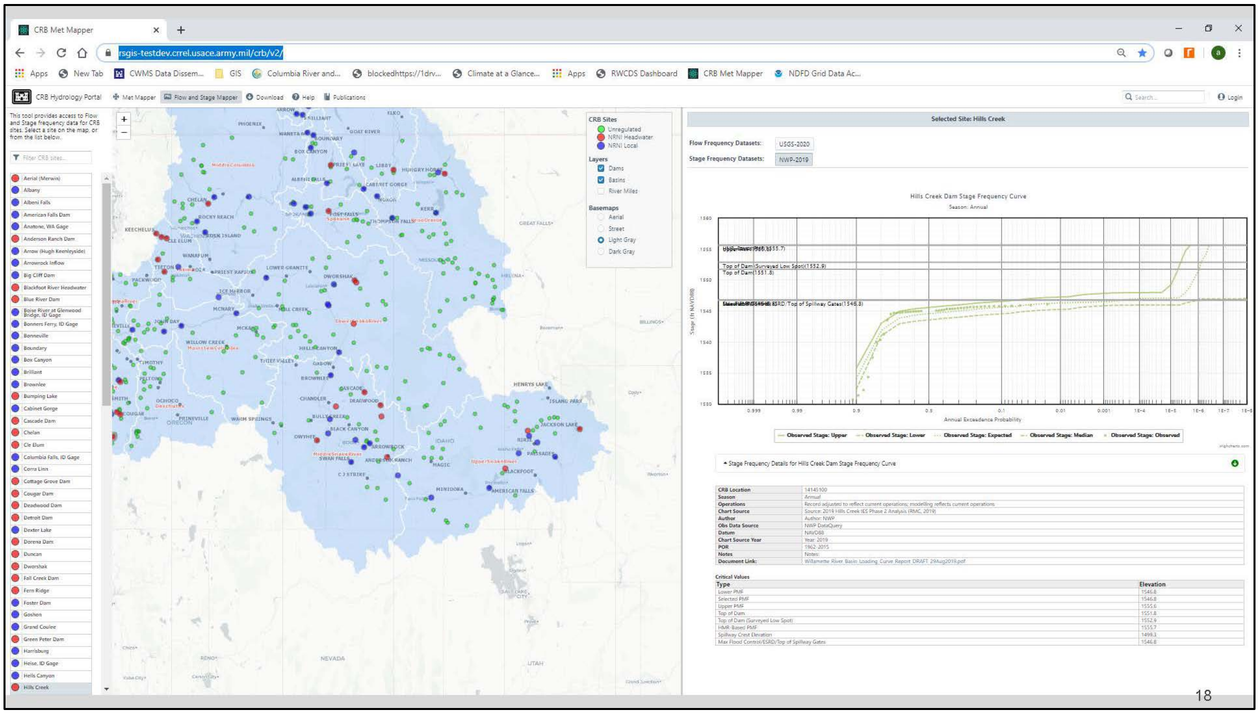
Obs Stats

Obs	Mean	Standard Dev	Station Skew	Regional Skew	Weighted Skew	Adopted Skew	Equivalent Record Length	Low Outliers/Zero Flows	# Years with Missing Data
1-Day	5.868	0.1178	-0.283	-0.1	-0.117	-0.117	80	0	0
3-Day	5.8591	0.1187	-0.291	-0.13	-0.145	-0.145	80	0	0
7-Day	5.8352	0.1206	-0.32	-0.24	-0.247	-0.247	80	0	0
10-Day	5.819	0.1211	-0.309	-0.31	-0.31	-0.31	80	0	0
15-Day	5.7989	0.12	-0.251	-0.32	-0.314	-0.314	80	0	0
30-Day	5.7579	0.115	-0.43	-0.34	-0.344	-0.344	80	7	0
60-Day	5.6997	0.0974	-0.374	-0.37	-0.37	-0.37	80	17	0

Critical Values

Type	AEP	Low	Best	High

17



This tool provides access to Flow and Stage frequency data for CRB sites. Select a site on the map, or from the list below.

- 🔴 Aerial (Merwin)
- 🔵 Albany
- 🔵 Albeni Falls
- 🔵 American Falls Dam
- 🔵 Anatone, WA Gage
- 🔴 Anderson Ranch Dam
- 🔵 Arrow (Hugh Keenleyside)
- 🔵 Arrowrock Inflow
- 🔵 Big Cliff Dam
- 🔴 Blackfoot River Headwater
- 🔴 Blue River Dam
- 🔵 Boise River at Glenwood Bridge, ID Gage
- 🔵 Bonners Ferry, ID Gage
- 🔵 Bonneville
- 🔵 Boundary
- 🔵 Box Canyon
- 🔵 Brilliant
- 🔵 Brownlee
- 🔴 Bumping Lake
- 🔵 Cabinet Gorge
- 🔴 Cascade Dam
- 🔴 Chelan
- 🔴 Cle Elum
- 🔵 Columbia Falls, ID Gage
- 🔵 Corra Linn
- 🔴 Cottage Grove Dam
- 🔴 Cougar Dam
- 🔴 Deadwood Dam
- 🔴 Detroit Dam
- 🔵 Dexter Lake
- 🔴 Dorena Dam
- 🔴 Duncan
- 🔴 Dworshak
- 🔴 Fall Creek Dam
- 🔴 Fern Ridge
- 🔵 Foster Dam
- 🔵 Goshen
- 🔵 Grand Coulee
- 🔴 Green Peter Dam
- 🔵 Harrisburg
- 🔵 Heise, ID Gage
- 🔵 Hells Canyon
- 🔴 Hills Creek

CRB Sites
- 🟢 Unregulated
- 🔴 NRNI Headwater
- 🔵 NRNI Local

Layers
- ☑ Dams
- ☑ Basins
- ☐ River Miles

Basemaps
- ○ Aerial
- ○ Street
- ● Light Gray
- ○ Dark Gray

Selected Site: Hills Creek

Flow Frequency Datasets: USGS-2020

Stage Frequency Datasets: NWP-2019

▲ Stage Frequency Details for Hills Creek Dam Stage Frequency Curve

CRB Location	14145100
Season	Annual
Operations	Record adjusted to reflect current operations; modelling reflects current operations
Chart Source	Source: 2019 Hills Creek IES Phase 2 Analysis (RMC, 2019)
Author	Author: NWP
Obs Data Source	NWP DataQuery
Datum	NAVD88
Chart Source Year	Year: 2019
POR	1962-2015
Notes	Notes:
Document Link:	Willamette River Basin Loading Curve Report DRAFT 29Aug2019.pdf

Critical Values

Type	Elevation
Lower PMF	1546.8
Selected PMF	1546.8
Upper PMF	1555.6
Top of Dam	1551.8
Top of Dam (Surveyed Low Spot)	1552.9
HMR-Based PMF	1555.7
Spillway Crest Elevation	1499.3
Max Flood Control/ESRD/Top of Spillway Gates	1546.8

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US Army Corps
of Engineers ®

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3.4.6 Presentation 2A-6: Reducing uncertainty in estimating rare flood events using paleoflood analyses: Insights from an investigation near Stillhouse Hollow Dam, TX

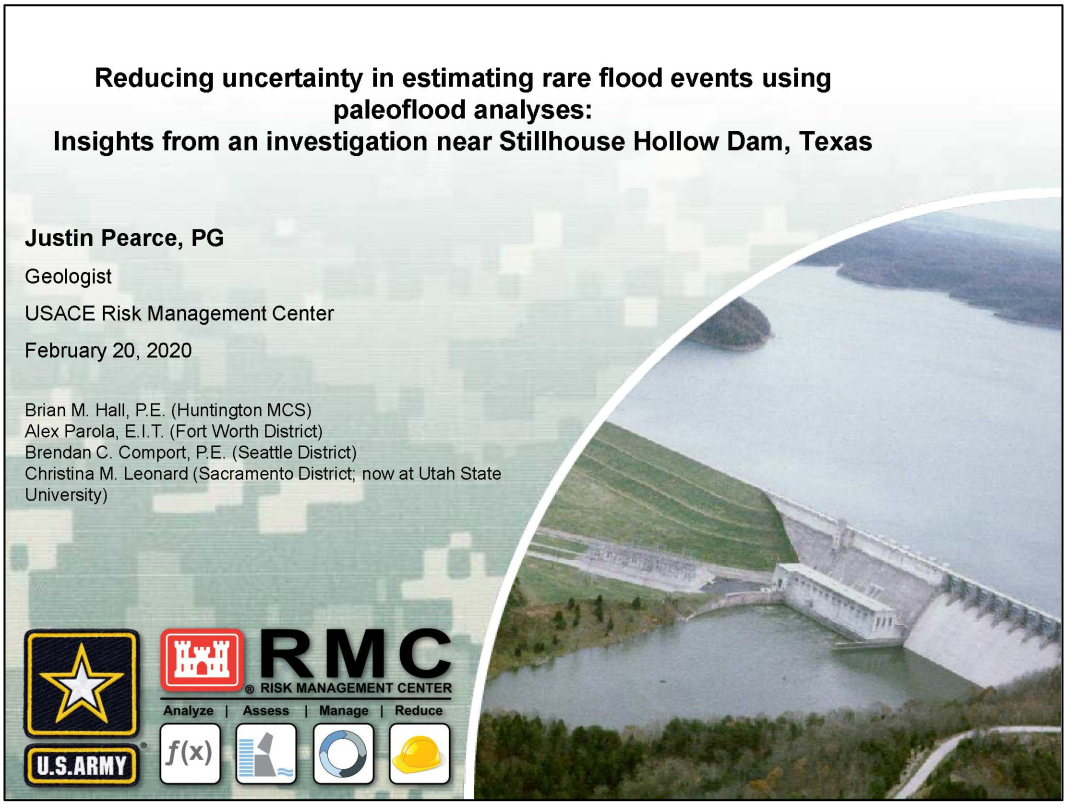
Authors: Justin Pearce, U.S. Army Corps of Engineers, Risk Management Center (USACE/RMC); Brian Hall, USACE Huntington District; Alessandro Parola, USACE, Fort Worth District; Brendan Comport, USACE, Seattle District; Christina Leonard, Utah State University

Speaker: Justin Pearce

3.4.6.1 Abstract

A reconnaissance-level paleoflood investigation was completed to support characterization and reduce uncertainties in large hydrologic loadings near Stillhouse Hollow Dam, Texas. Desktop analysis identified several remnant flights of Holocene terrace surfaces along the Lampasas River near Stillhouse Hollow Reservoir that were used as physical evidence of past large floods. Field geomorphic mapping, soil exposures, and analysis of aerial imagery demonstrated that lower terraces (Qt1, Qt2) were inundated during historic and modern peak flows. A higher terrace (Qt3), formed about 3,600 years ago, had soil profile characteristics suggestive of a non-exceedance boundary for large fluvial discharges. Two-dimensional hydraulic modeling, coupled with interdisciplinary collaboration, estimated that a minimum discharge of about 300,000 cfs would be needed to just inundate the Qt3 terrace, in an unregulated (non-dam) scenario. Historical large flood events (e.g., the 1873 and 1921 floods) were estimated and integrated with the systematic record using perception thresholds. This inclusion has the largest effect on the mean, standard deviation, and skew of the peak inflow frequency curve. Adding the paleodischarge non-exceedance bound estimation (Qt3 NEB) to the systematic-plus-historical record did not substantially change the mean and standard deviation of the peak inflow frequency curve as compared to the systematic-plus-historical record. However, addition of paleoflood NEB to the systematic-plus-historical record reduces uncertainty (measured as 90% confidence intervals) in the peak discharge estimates at the 1/10,000 AEP by about a factor of 1.5. Peak inflow volume-frequency analysis indicates that large discharges along the Lampasas River might occur more often than would be expected from analysis of systematic gage records alone; this information was used to support risk-informed assessments of the overtopping hazard.

3.4.6.2 Presentation (ADAMS Accession No. ML20080M209)



Reducing uncertainty in estimating rare flood events using paleoflood analyses: Insights from an investigation near Stillhouse Hollow Dam, Texas

Justin Pearce, PG

Geologist

USACE Risk Management Center

February 20, 2020

Brian M. Hall, P.E. (Huntington MCS)
Alex Parola, E.I.T. (Fort Worth District)
Brendan C. Comport, P.E. (Seattle District)
Christina M. Leonard (Sacramento District; now at Utah State University)

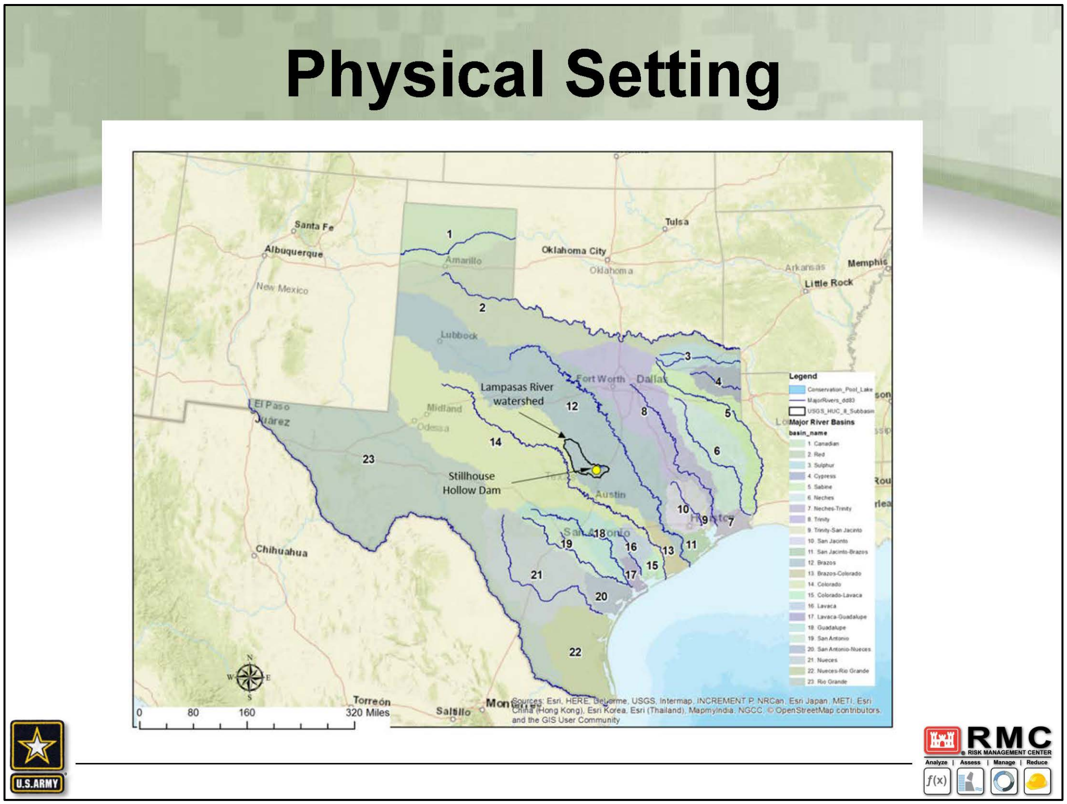
Introduction

A reconnaissance-level paleoflood investigation to **characterize rare hydrologic events** near Stillhouse Hollow Dam, Texas, to extend flood-frequency analyses beyond the systematic record.

The purpose was to provide paleoflood estimates in light of risk-informed dam safety decision making and uncertain hydrologic loadings.

Investigated several remnant flights of **Holocene riverine terrace surfaces** along the Lampasas River near Stillhouse Hollow Reservoir that were used as physical evidence of past large floods.

Outline
- Physical setting
- Riverine Terraces
- Field data: PSI and NEB
- Peak flow frequency analysis
- Summary.



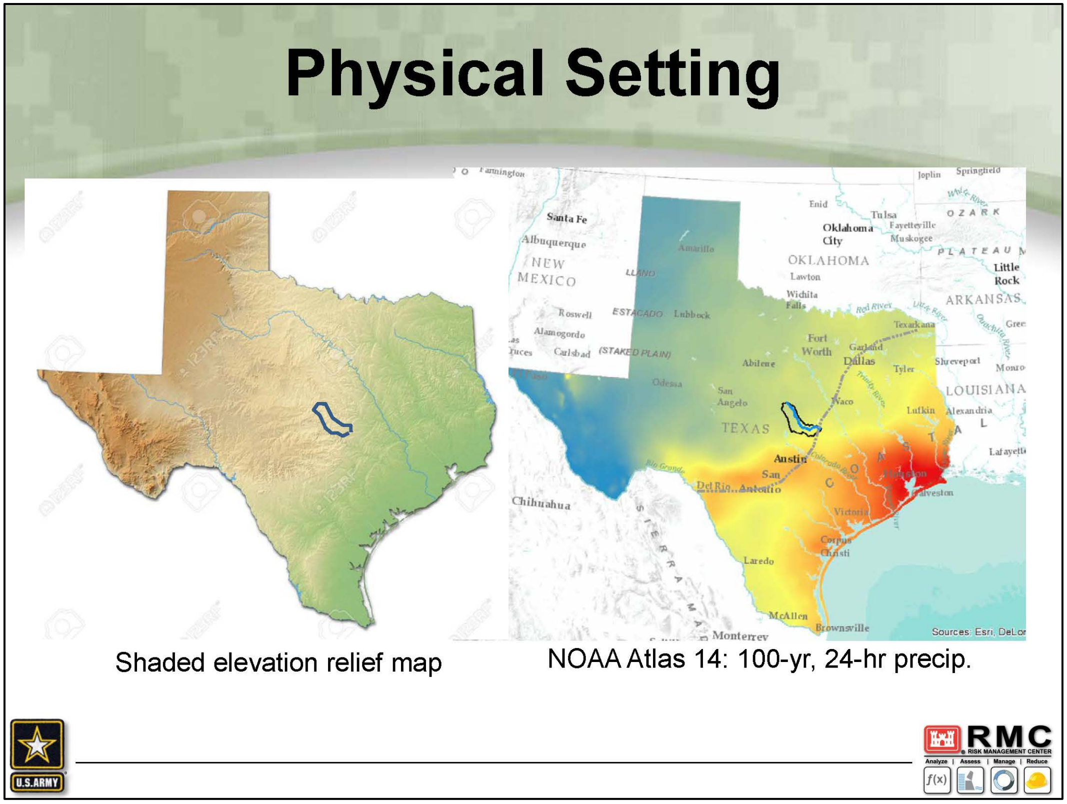
Physical Setting

Legend
- Conservation_Pool_Lake
- MajorRivers_dd83
- USGS_HUC_8_Subbasin

Major River Basins

basin_name
- 1. Canadian
- 2. Red
- 3. Sulphur
- 4. Cypress
- 5. Sabine
- 6. Neches
- 7. Neches-Trinity
- 8. Trinity
- 9. Trinity-San Jacinto
- 10. San Jacinto
- 11. San Jacinto-Brazos
- 12. Brazos
- 13. Brazos-Colorado
- 14. Colorado
- 15. Colorado-Lavaca
- 16. Lavaca
- 17. Lavaca-Guadalupe
- 18. Guadalupe
- 19. San Antonio
- 20. San Antonio-Nueces
- 21. Nueces
- 22. Nueces-Rio Grande
- 23. Rio Grande

Sources: Esri, HERE, DeLorme, USGS, Intermap, INCREMENT P, NRCan, Esri Japan, METI, Esri China (Hong Kong), Esri Korea, Esri (Thailand), MapmyIndia, NGCC, © OpenStreetMap contributors, and the GIS User Community

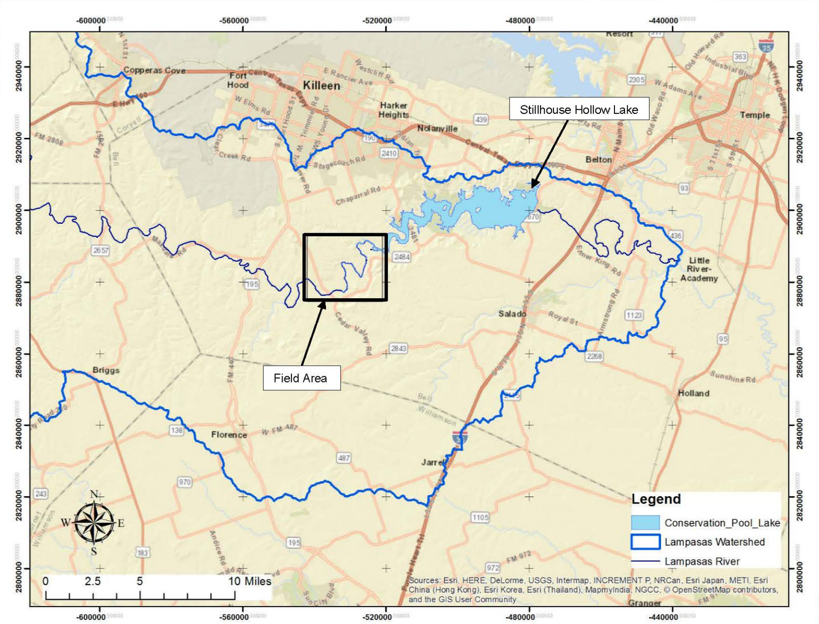


Physical Setting

Shaded elevation relief map

NOAA Atlas 14: 100-yr, 24-hr precip.

Physical Setting



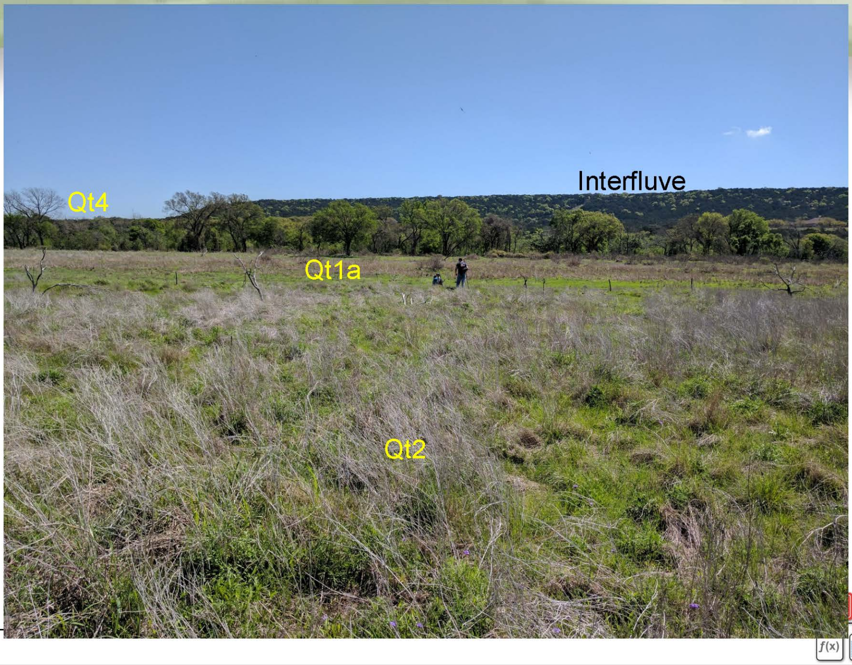
Legend
- 🟦 Conservation_Pool_Lake
- ▭ Lampasas Watershed
- — Lampasas River

Sources: Esri, HERE, DeLorme, USGS, Intermap, INCREMENT P, NRCan, Esri Japan, METI, Esri China (Hong Kong), Esri Korea, Esri (Thailand), MapmyIndia, NGCC, © OpenStreetMap contributors, and the GIS User Community

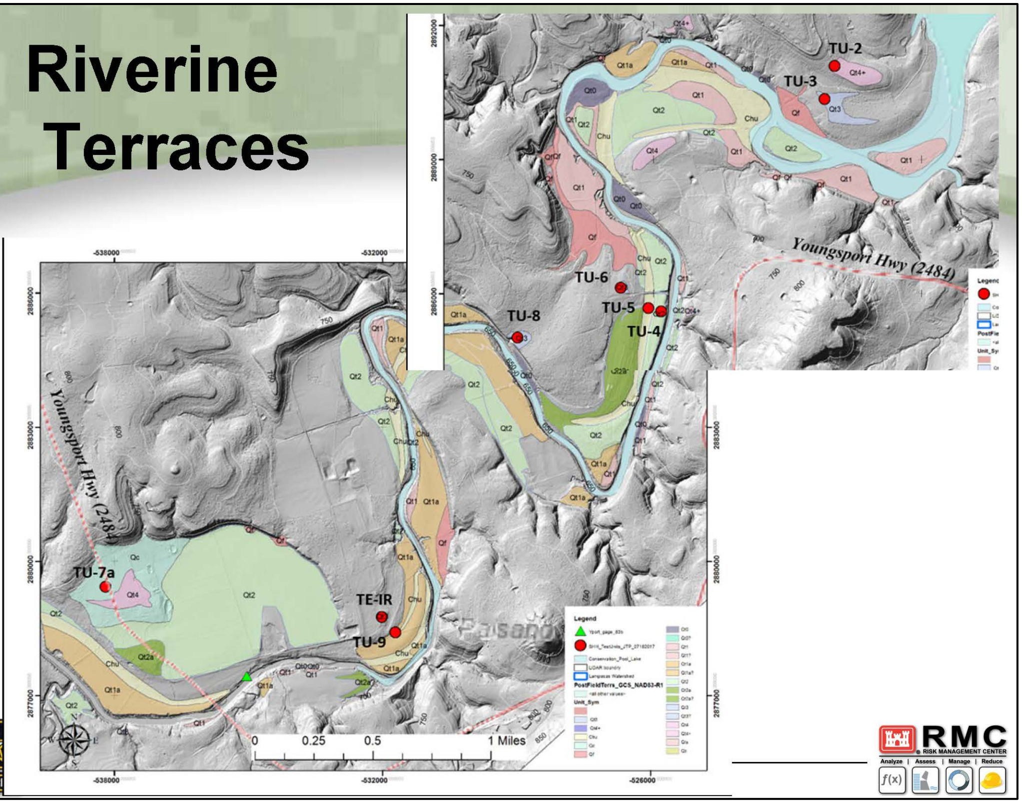
Physical Setting

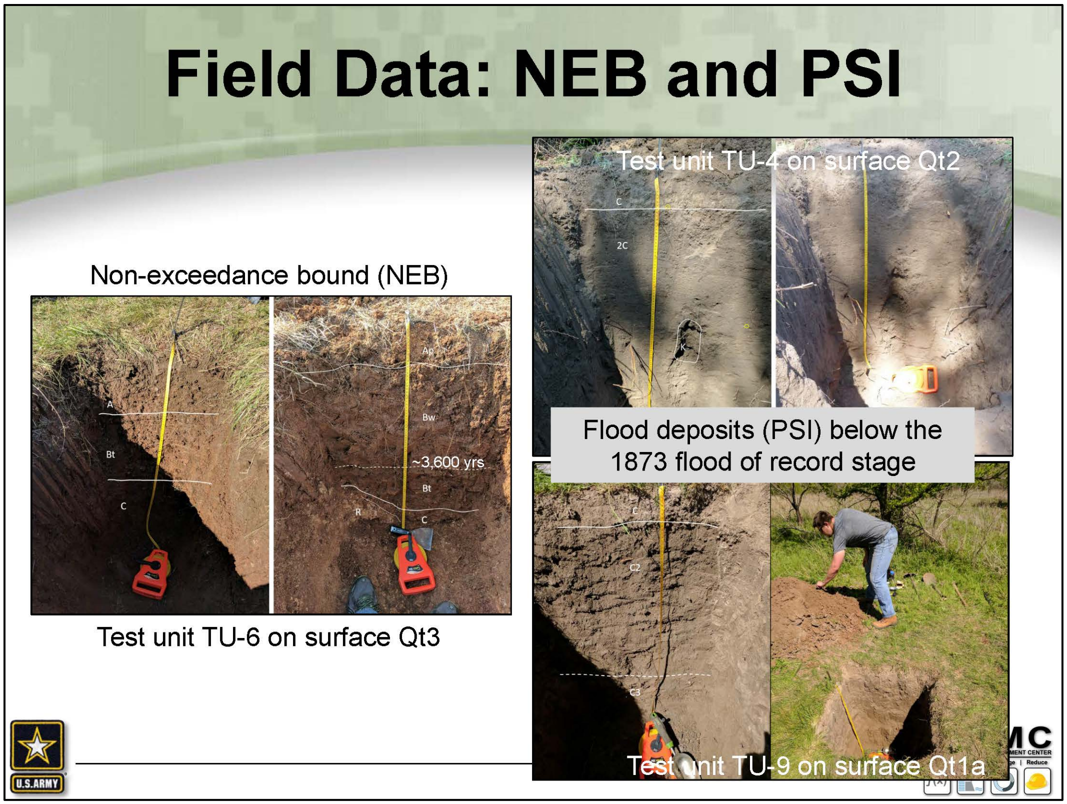
Glen Rose Formation outcrop

Riverine Terraces



Riverine Terraces





Field Data: NEB and PSI

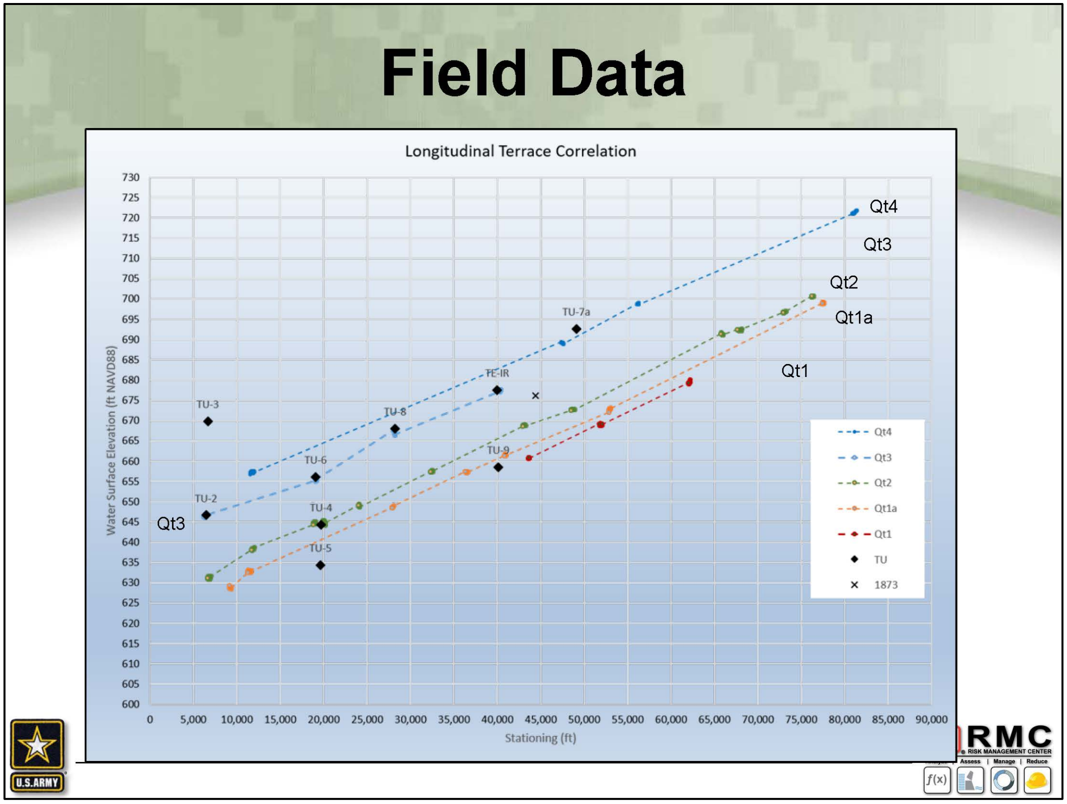
Non-exceedance bound (NEB)

Test unit TU-6 on surface Qt3

Test unit TU-4 on surface Qt2

Flood deposits (PSI) below the 1873 flood of record stage

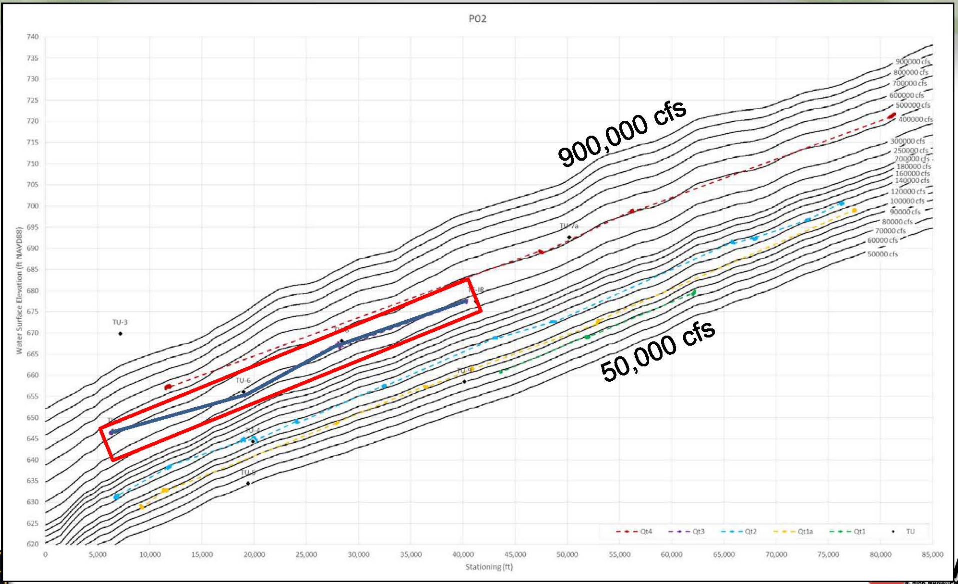
Test unit TU-9 on surface Qt1a



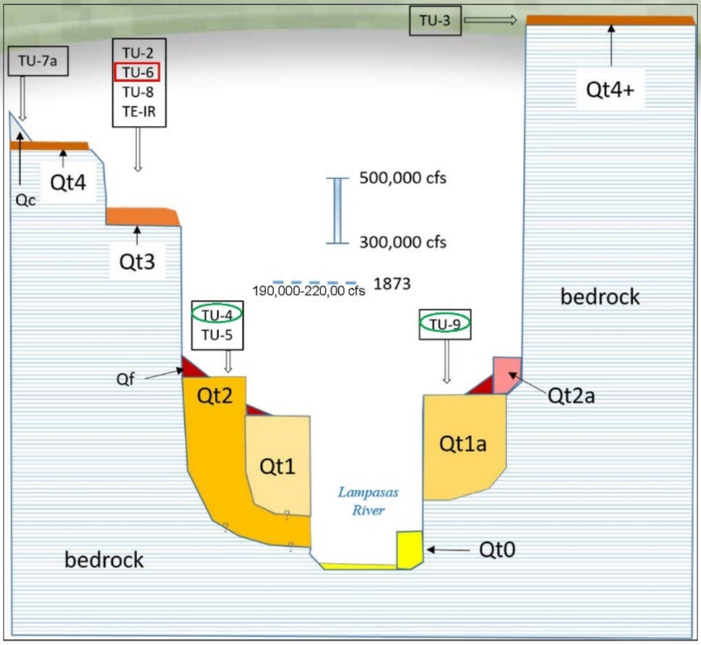
Field Data

Longitudinal Terrace Correlation

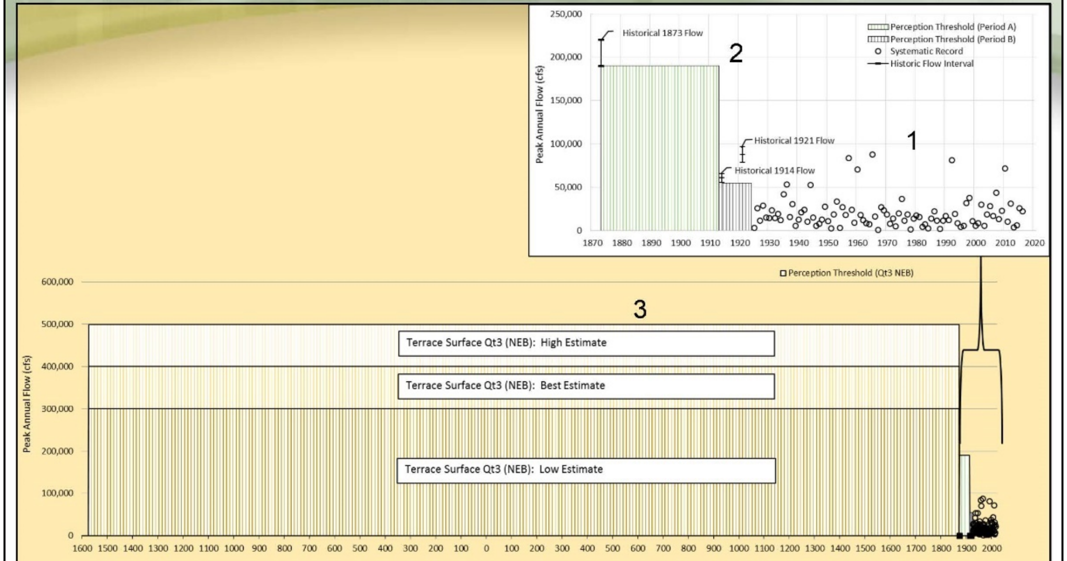
Paleodischarges



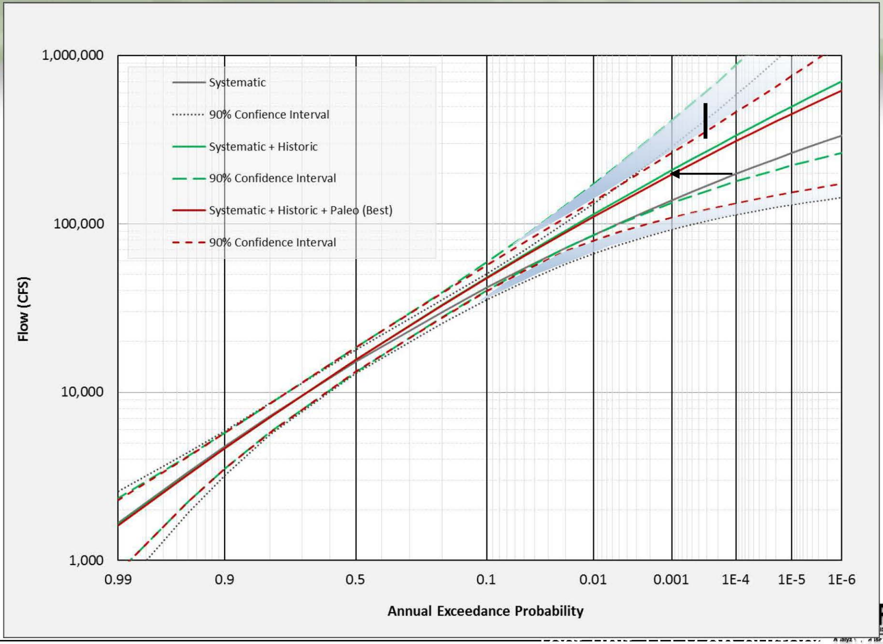
Geomorphic Model

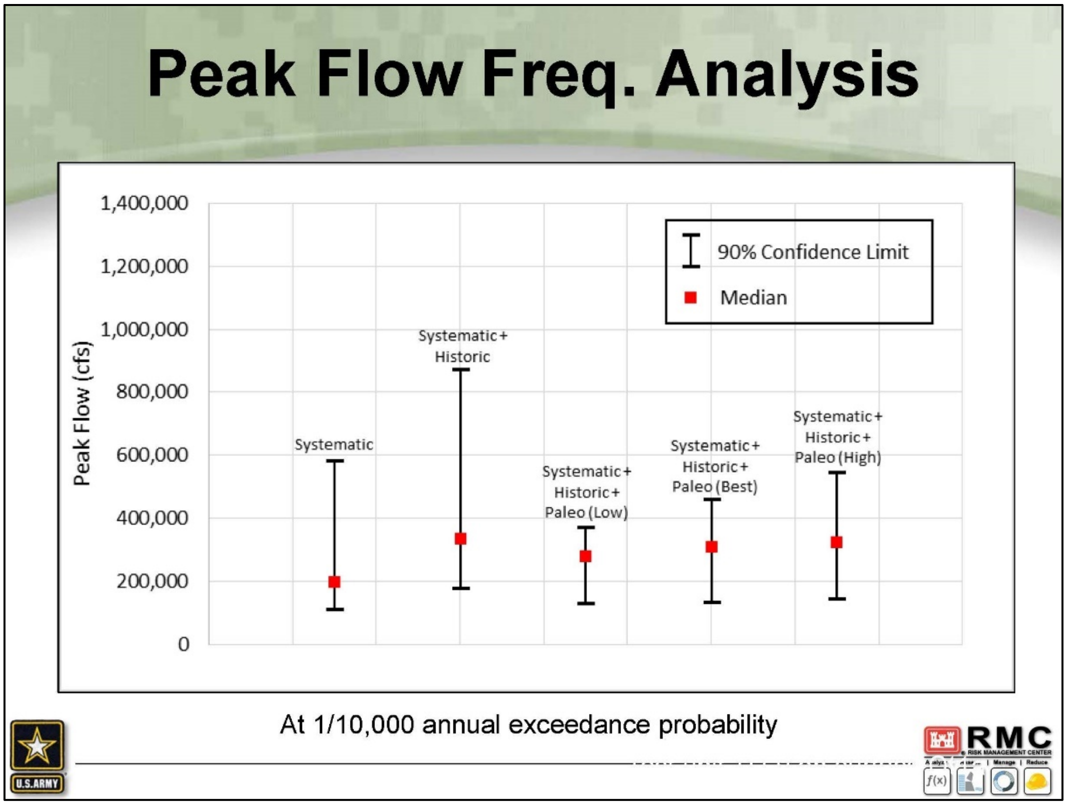


Perception Thresholds



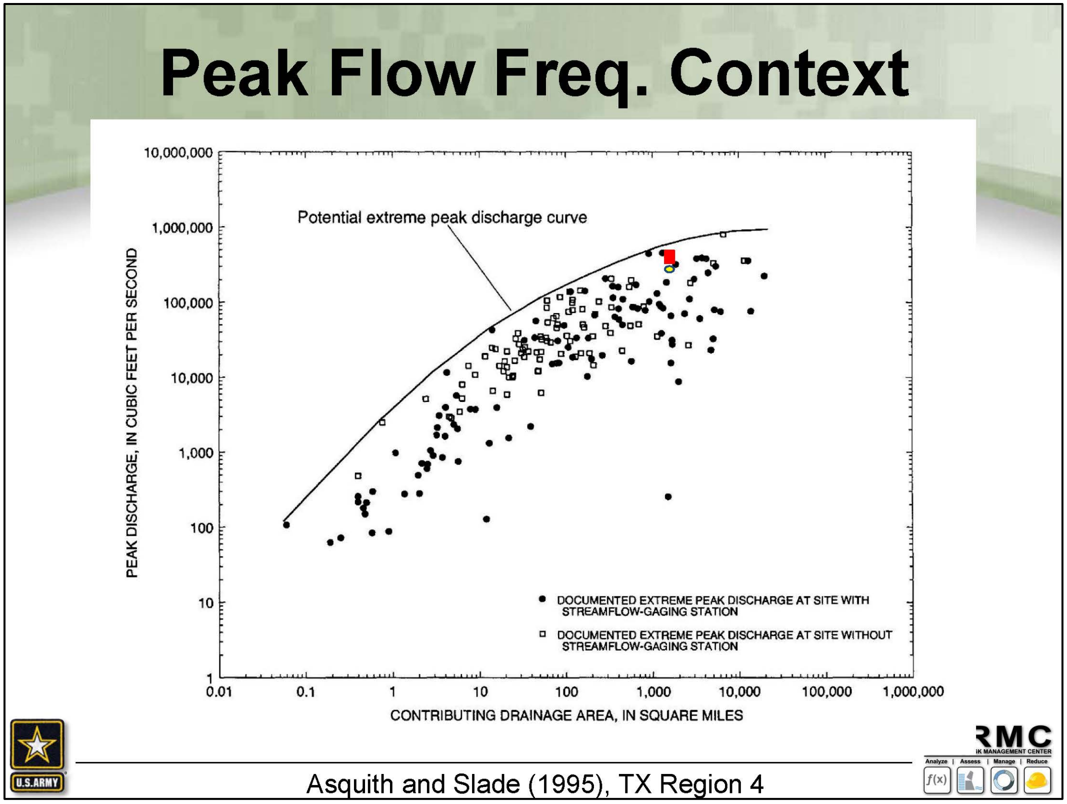
Peak Flow Freq. Analysis





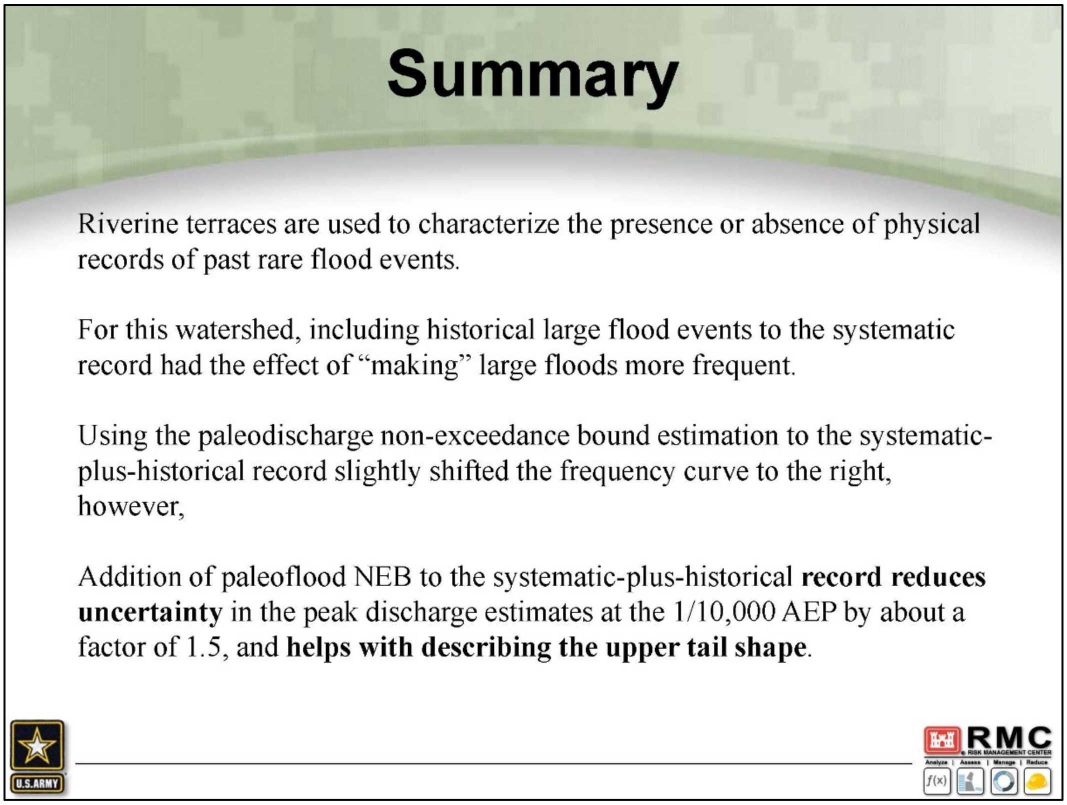
Peak Flow Freq. Analysis

At 1/10,000 annual exceedance probability



Peak Flow Freq. Context

Asquith and Slade (1995), TX Region 4



Summary

Riverine terraces are used to characterize the presence or absence of physical records of past rare flood events.

For this watershed, including historical large flood events to the systematic record had the effect of “making” large floods more frequent.

Using the paleodischarge non-exceedance bound estimation to the systematic-plus-historical record slightly shifted the frequency curve to the right, however,

Addition of paleoflood NEB to the systematic-plus-historical **record reduces uncertainty** in the peak discharge estimates at the 1/10,000 AEP by about a factor of 1.5, and **helps with describing the upper tail shape**.

3.4.7 Presentation 2A-7: Improving Flood Frequency Analysis with a Multi-Millennial Record of Extreme Floods on the Tennessee River near Chattanooga, TN

Authors: Tess Harden and Jim O’Connor, U.S. Geological Survey (USGS)

Speaker: Tess Harden

3.4.7.1 Abstract

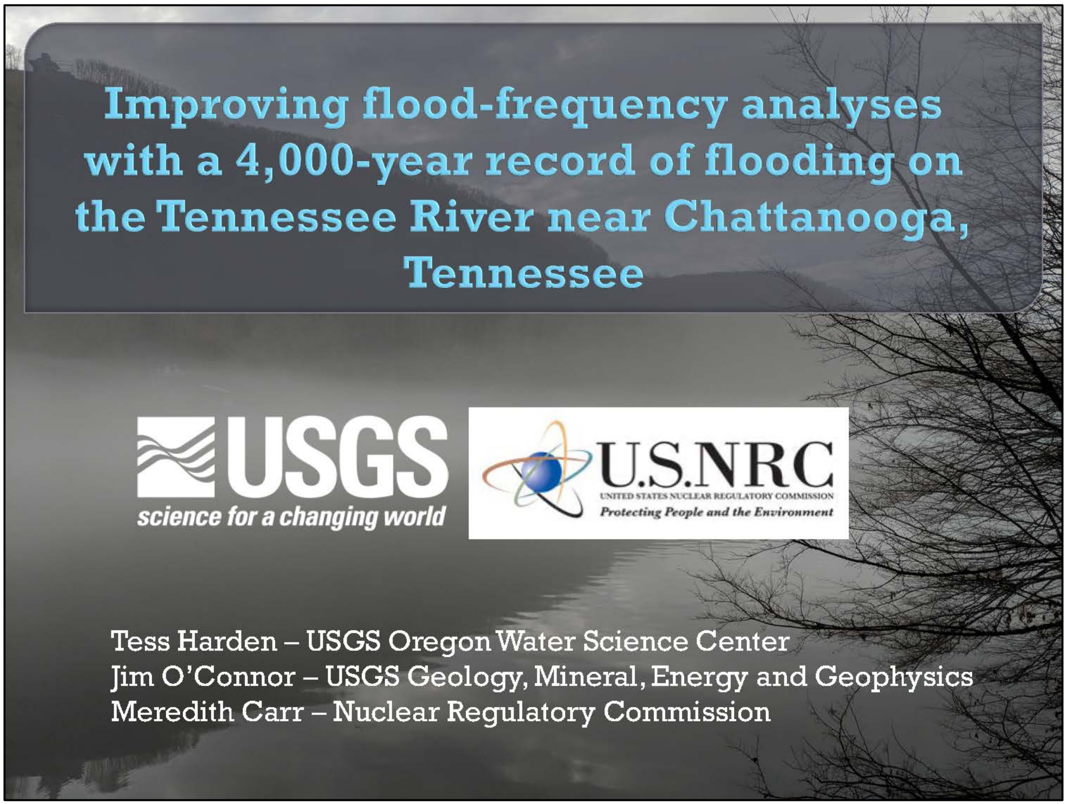
The primary purpose of this comprehensive field study was to use paleoflood hydrology methods to characterize the frequency of recurrence of low-probability floods and to inform and improve estimates of flood risk for the Tennessee River near Chattanooga, Tennessee. The main source of information used to improve flood-frequency estimates was stratigraphic records of large, previously unrecorded floods combined with modern streamflow records and historical flood accounts. The overall approach was to (1) develop a flood chronology for the Tennessee River near Chattanooga using stratigraphic analyses and geochronology from multiple sites at multiple elevations in the study area, (2) estimate peak flow magnitudes associated with elevations of flood evidence using a 1D hydraulic model, (3) combine the information developed for steps 1 and 2 to develop a history of timing and magnitude of large floods in the study reach, and (4) use all available information, including paleoflood, gaged, and historical records of flooding to estimate flood-frequency with a standardized statistical approach for flood frequency analysis.

The stratigraphy, geochronology, and hydraulic modelling results from all sites along the Tennessee River were distilled into an overall chronology of the number, timing, and magnitude of large unrecorded floods. In total, dozens of sites were identified and the stratigraphy of 17 of those sites were examined and described. Flood frequency analyses were performed using the USGS software program PeakFQ v7.2 that follows the Guidelines for Determining Flood Flow Frequency – Bulletin 17C.

Condensing all 17 sites into a single flood chronology for the Tennessee River near Chattanooga revealed eight unique floods in the last 3,500 - 4,000 years. Two of these floods had discharge magnitude of about 470,000 ft^3/s, slightly above the 1867 historical peak at the Chattanooga gage (459,000 ft^3/s). One was 1,100,000 ft^3/s, substantially larger than any other flood on the Tennessee River during the last ~4,000 years. This large flood likely occurred only a few hundred years ago, possibly in the mid-to-late-1600s. Two additional floods in the last 1,000 years had estimated magnitudes of about 420,000 ft^3/s and 400,000 ft^3/s. The remaining three unique floods identified in the stratigraphy were much smaller than the others–less than 240,000 ft^3/s.

Flood frequency analyses for all flood scenarios performed in this study indicate that the addition of paleoflood information markedly improves estimates of low probability floods – most clearly indicated by substantial narrowing of the 95-percent confidence limits. The 95 percent confidence interval for the 1,000-year quantile estimate derived from incorporating the four most recent paleofloods is about 480,000-620,000 ft^3/s, compared to about 380,000 – 610,000 ft^3/s from the gaged record alone (which includes the historical 1867 flood), a reduction of 38 percent. Similarly, uncertainty for all flood quantile estimates between 100-years and 10,000-years were reduced by 22-44 percent by adding the paleoflood record to the gaged and historical record in the flood frequency analyses. This reduction in uncertainty can lead to more reliable flood hazard assessments.

3.4.7.2 Presentation (ADAMS Accession No. ML20080M136)

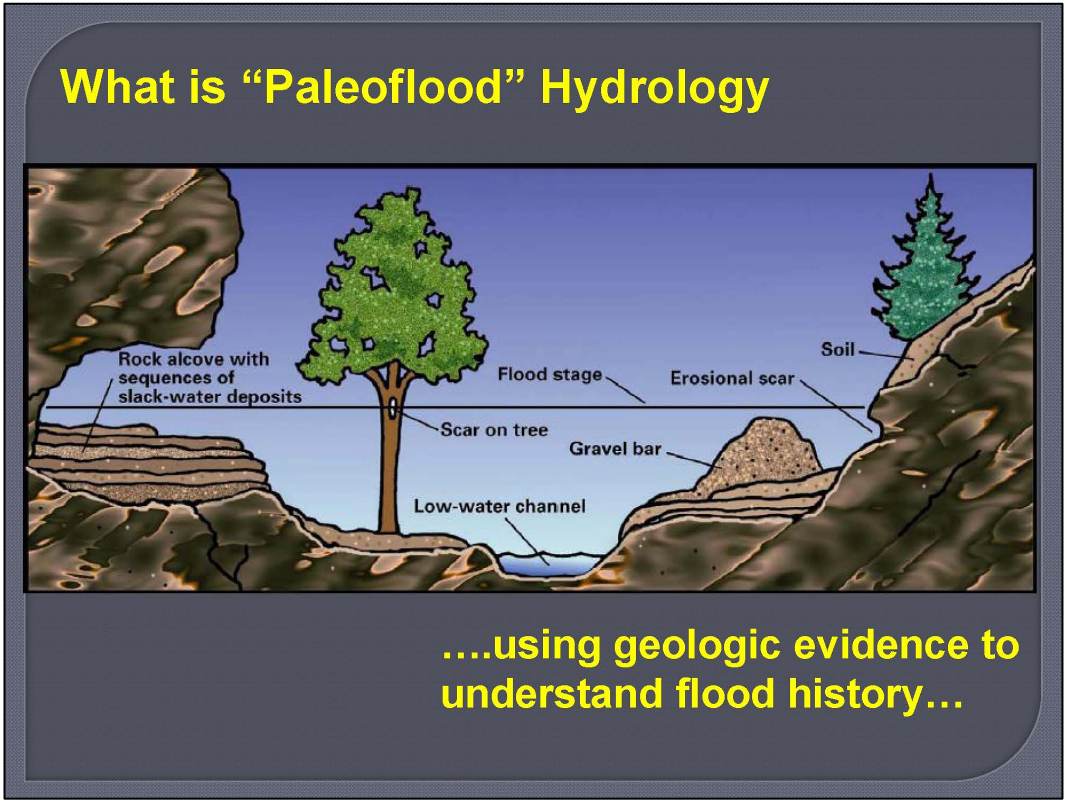


Improving flood-frequency analyses with a 4,000-year record of flooding on the Tennessee River near Chattanooga, Tennessee

USGS science for a changing world

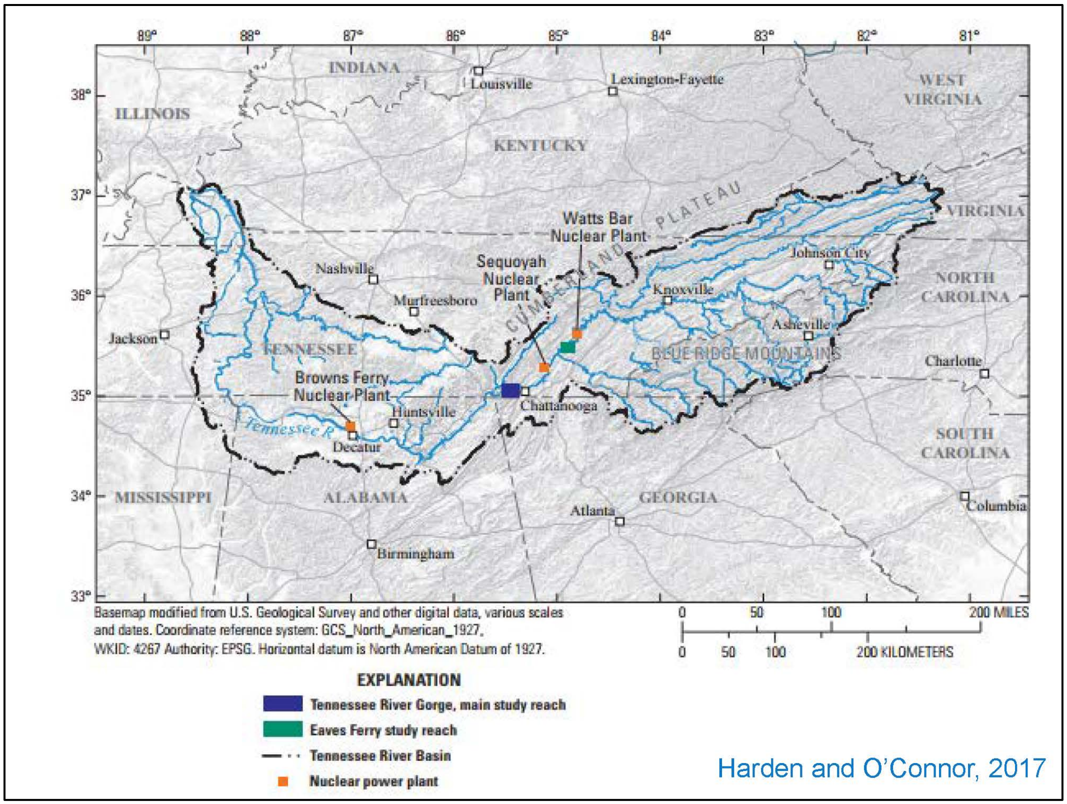
U.S.NRC UNITED STATES NUCLEAR REGULATORY COMMISSION Protecting People and the Environment

Tess Harden – USGS Oregon Water Science Center
Jim O'Connor – USGS Geology, Mineral, Energy and Geophysics
Meredith Carr – Nuclear Regulatory Commission



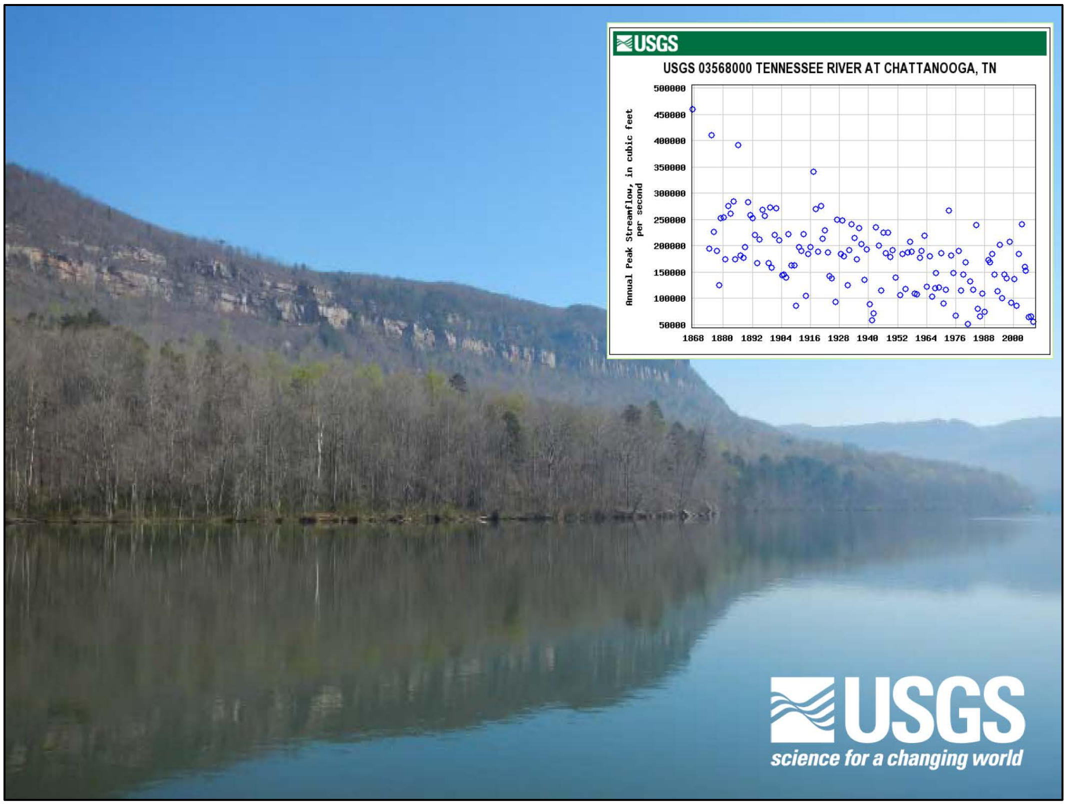
What is "Paleoflood" Hydrology

….using geologic evidence to understand flood history…

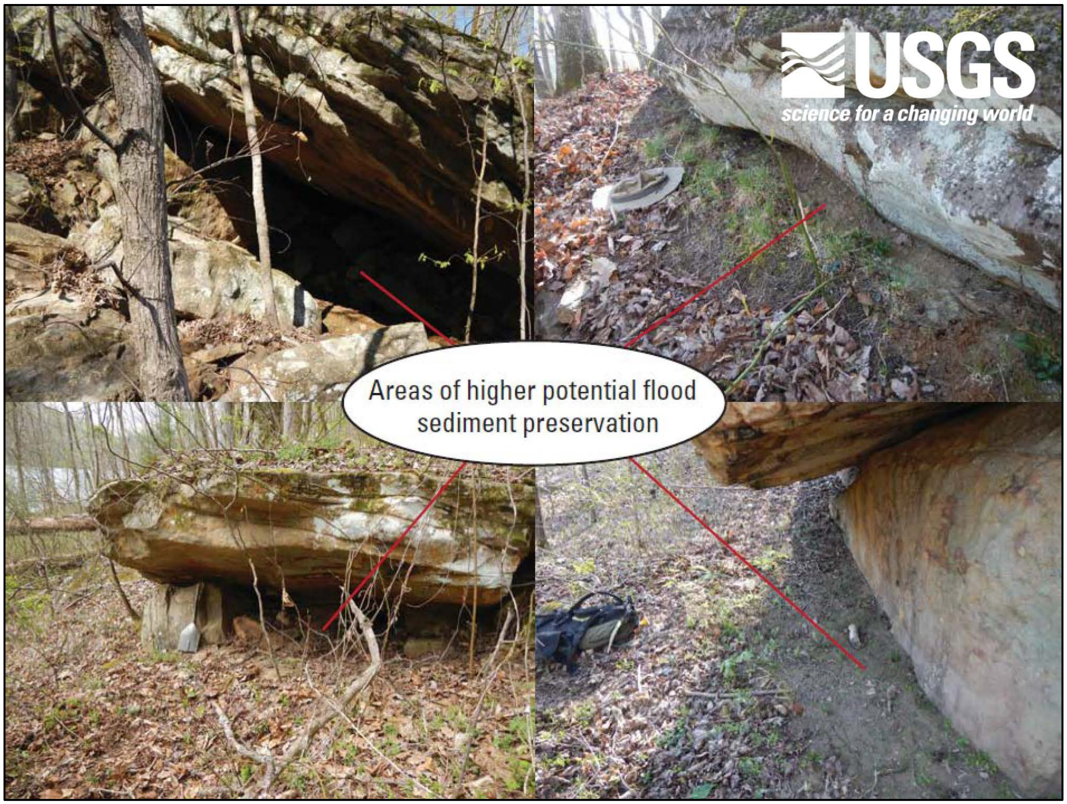


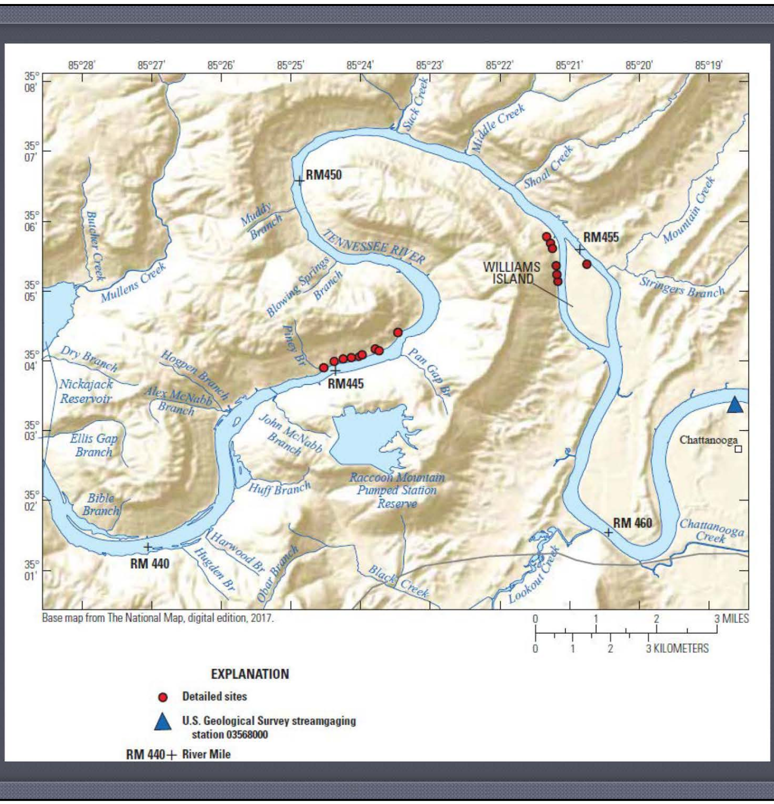
Basemap modified from U.S. Geological Survey and other digital data, various scales and dates. Coordinate reference system: GCS_North_American_1927. WKID: 4267 Authority: EPSG. Horizontal datum is North American Datum of 1927.

Harden and O'Connor, 2017

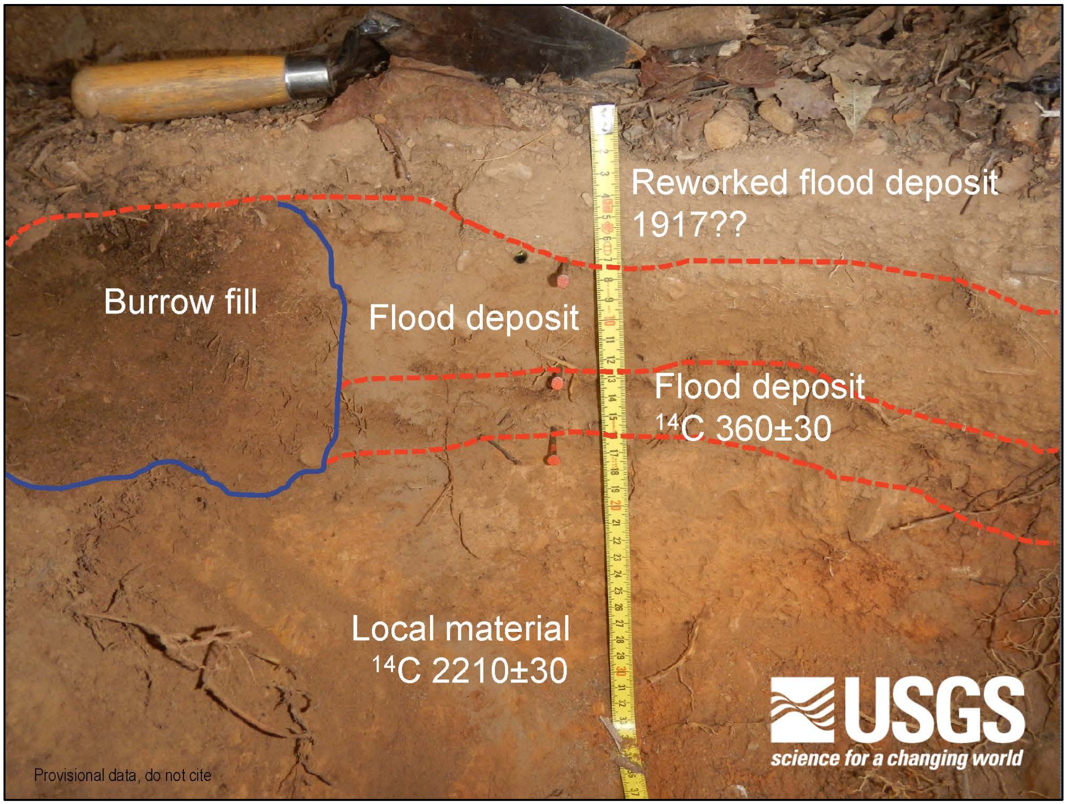

USGS
USGS 03568000 TENNESSEE RIVER AT CHATTANOOGA, TN
Annual Peak Streamflow, in cubic feet per second
500000
450000
400000
350000
300000
250000
200000
150000
100000
50000
1868
1880
1892
1904
1916
1928
1940
1952
1964
1976
1988
2000
USGS
science for a changing world


USGS
science for a changing world


Areas of higher potential flood sediment preservation



Base map from The National Map, digital edition, 2017.



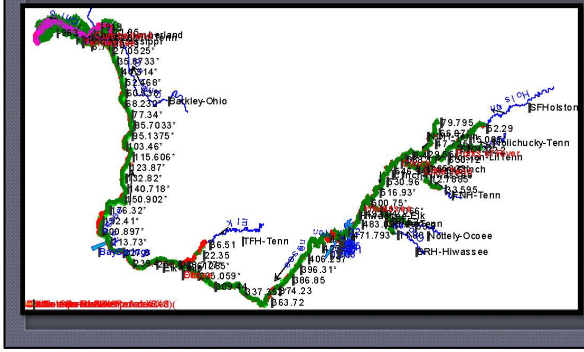
Provisional data, do not cite

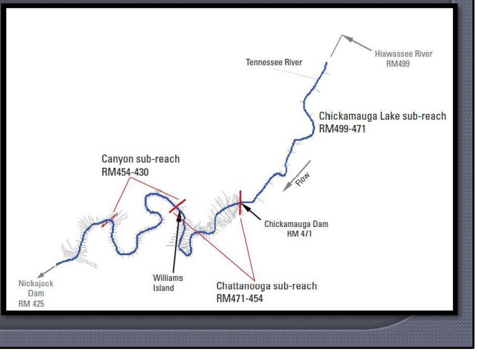
- Identified ~30 sites, fully described 17
- Focused on sites were preservation of sediment was most ideal
- Also targeted a full range of site elevations
- Radiocarbon dating and optically stimulated luminescence (OSL)

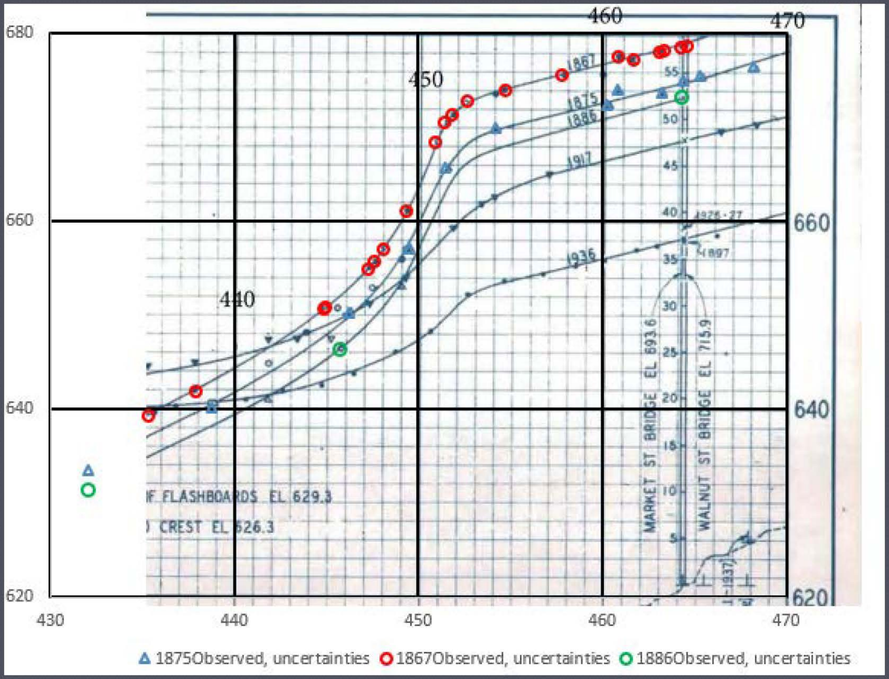
Hydraulic Model

Tennessee Valley Authority "Naturals" model in HEC-RAS shortened to provide sufficient length for boundary conditions.

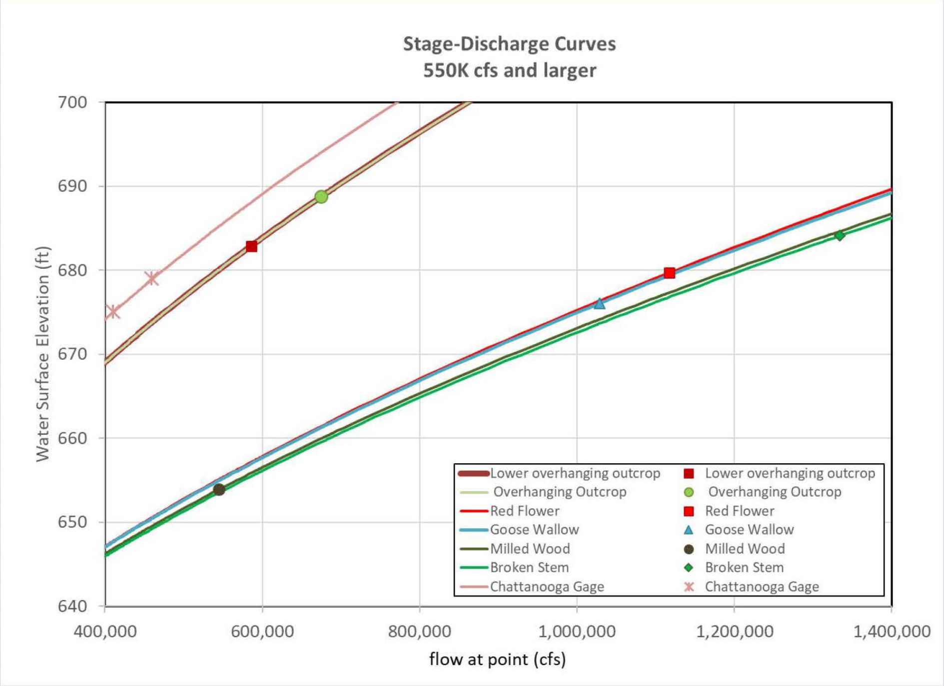
Calibrated to historical high water marks.

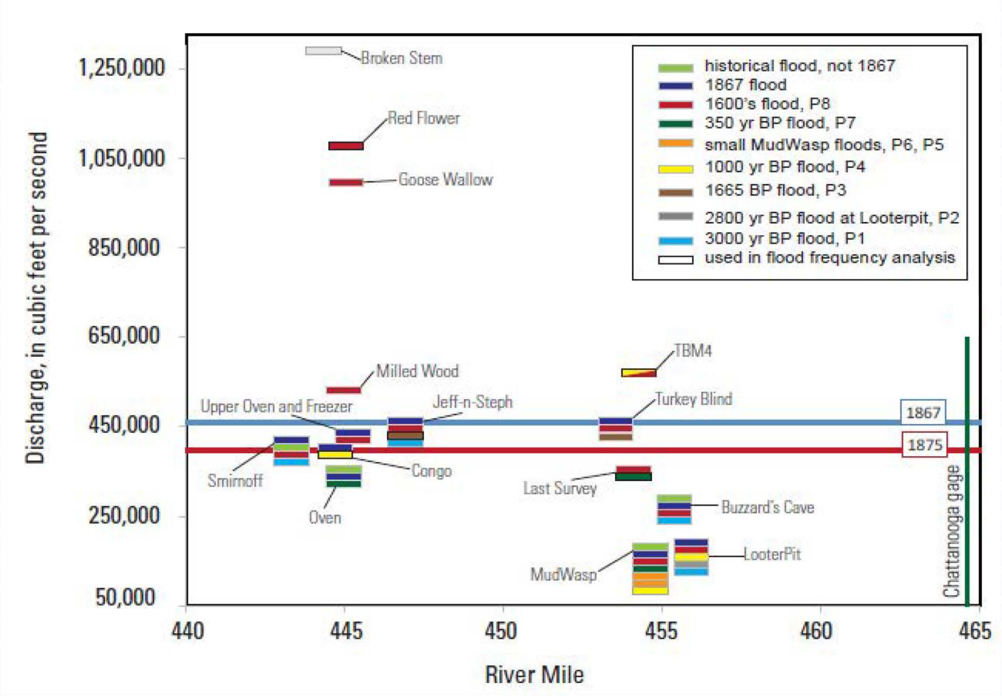






TVA, 1940

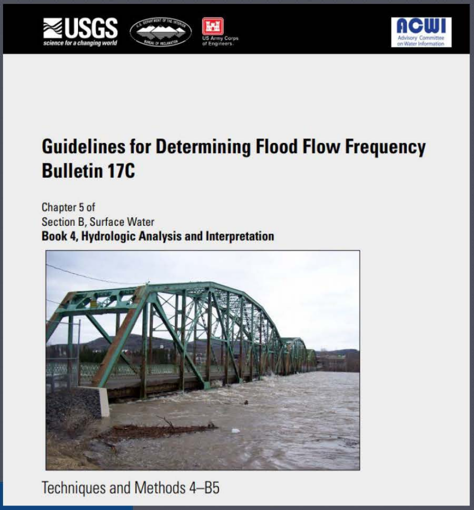




8 unique paleofloods in ~4,000 years

Flood-Frequency Analysis

- Bulletin 17C
- EMA
- LP3 distribution
- Discharge uncertainty and perception thresholds
- USGS PeakFQ



Guidelines for Determining Flood Flow Frequency Bulletin 17C

Chapter 5 of
Section B, Surface Water
Book 4, Hydrologic Analysis and Interpretation

Techniques and Methods 4–B5

England and others, 2019

Estimating Magnitude and Frequency of Floods Using the PeakFQ 7.0 Program

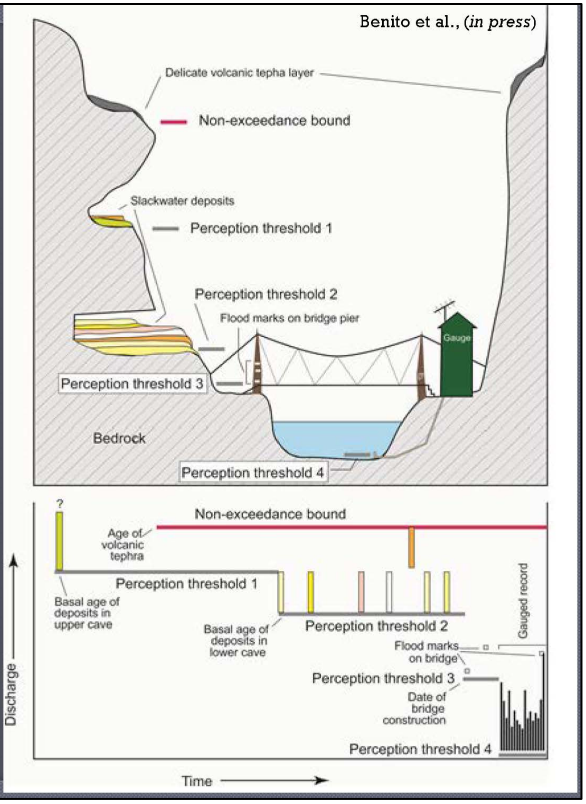
---

Benito et al., (*in press*)

Perception thresholds

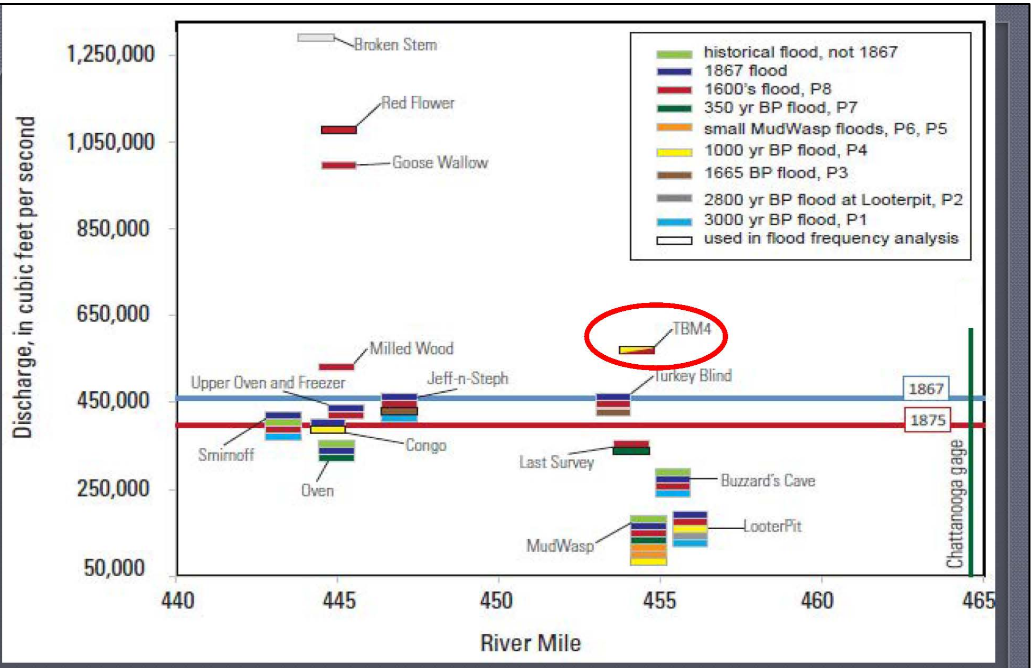
(17C; England et al., 2019):

- The stage or flow above which a source would provide information on the flood peak in any given year.
- Reflect the range of flows that would have been measured had they occurred

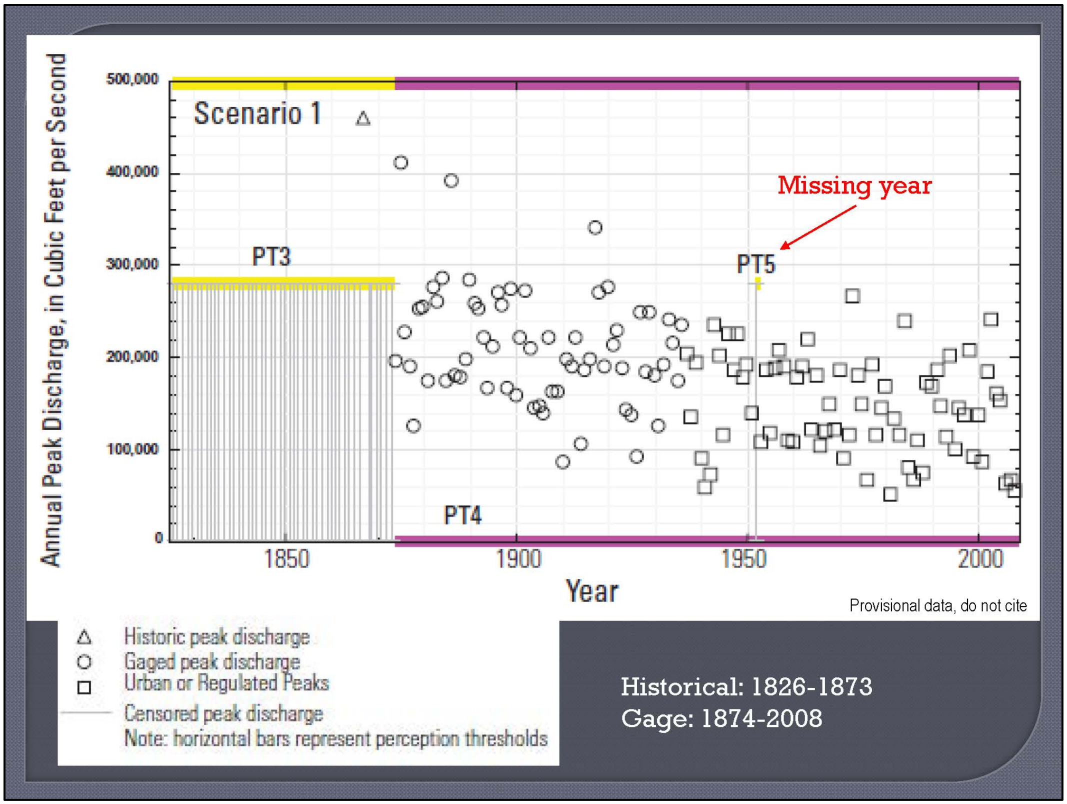


Flood-frequency analyses for 7 different scenarios:

- **Scenario 1:** Gaged plus historical record (1826-2008), 3 perception thresholds
- **Scenario 2-4:** 4 paleofloods (350,1000, 1500, 1650); 5 perception thresholds (variation to 1 paleo perception threshold)
- **Scenario 5-7:** 4 paleofloods (variation in age and magnitude); 5 perception thresholds

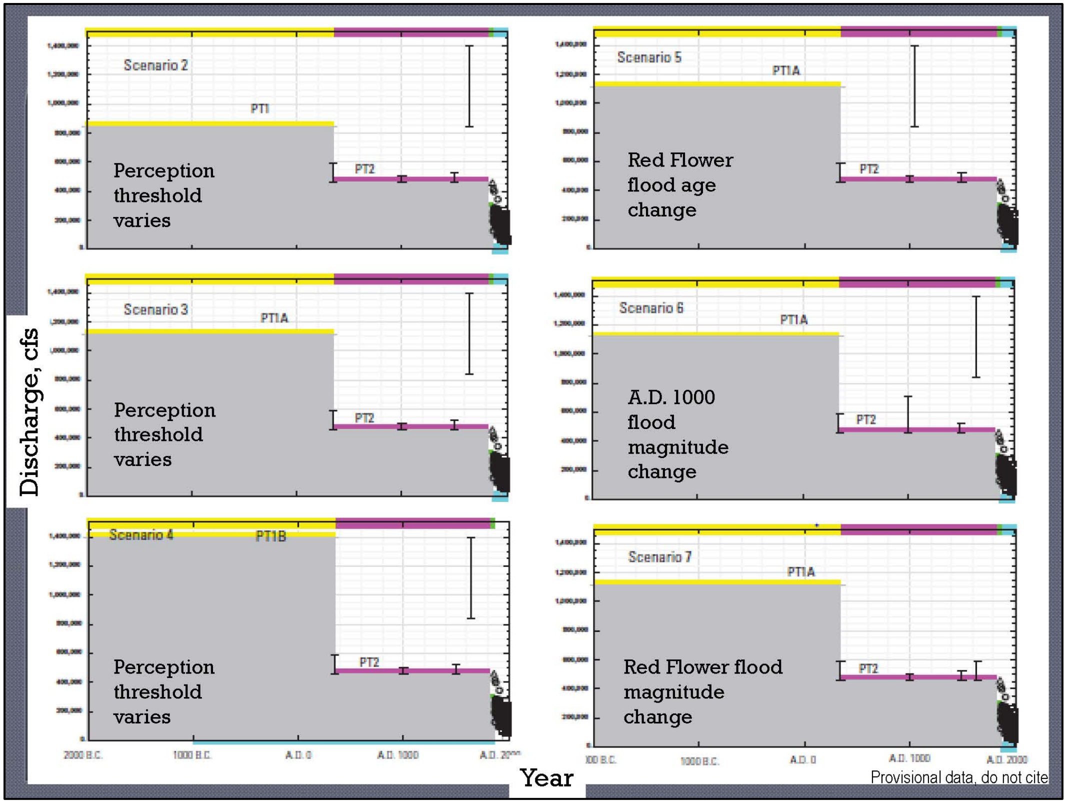


4 paleofloods used in the flood frequency analysis.
Age and magnitude was varied in some scenarios to account geochronologic and stratigraphic uncertainty.



Provisional data, do not cite

Historical: 1826-1873
Gage: 1874-2008



Perception threshold varies

Perception threshold varies

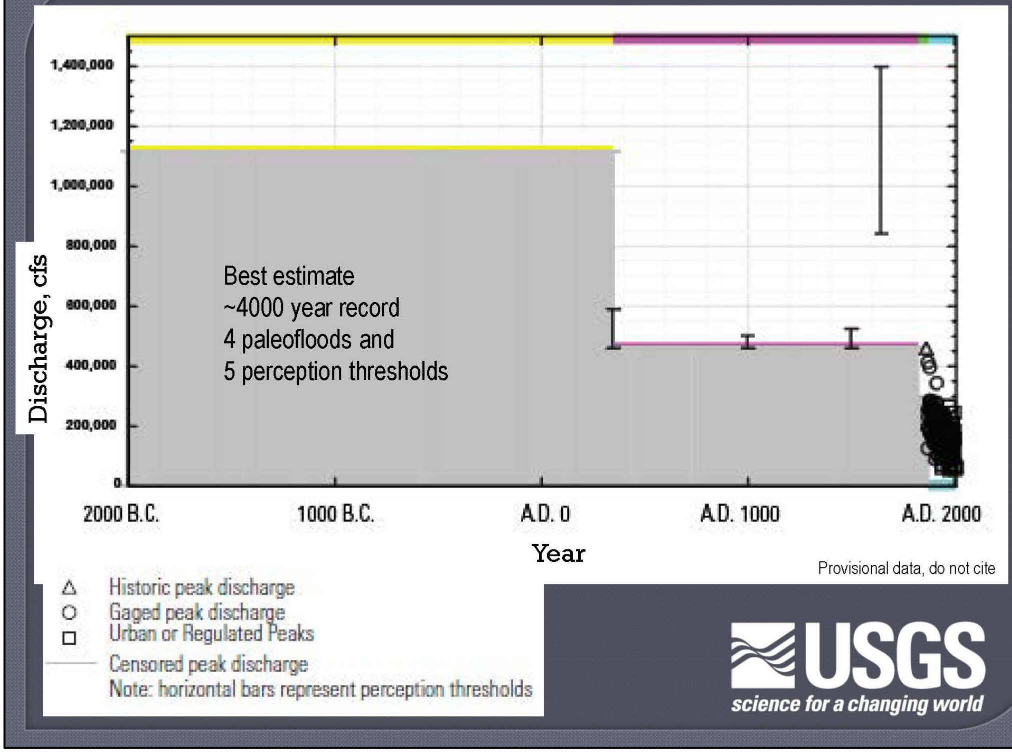
Perception threshold varies

Red Flower flood age change

A.D. 1000 flood magnitude change

Red Flower flood magnitude change

Provisional data, do not cite



Best estimate
~4000 year record
4 paleofloods and
5 perception thresholds

Provisional data, do not cite

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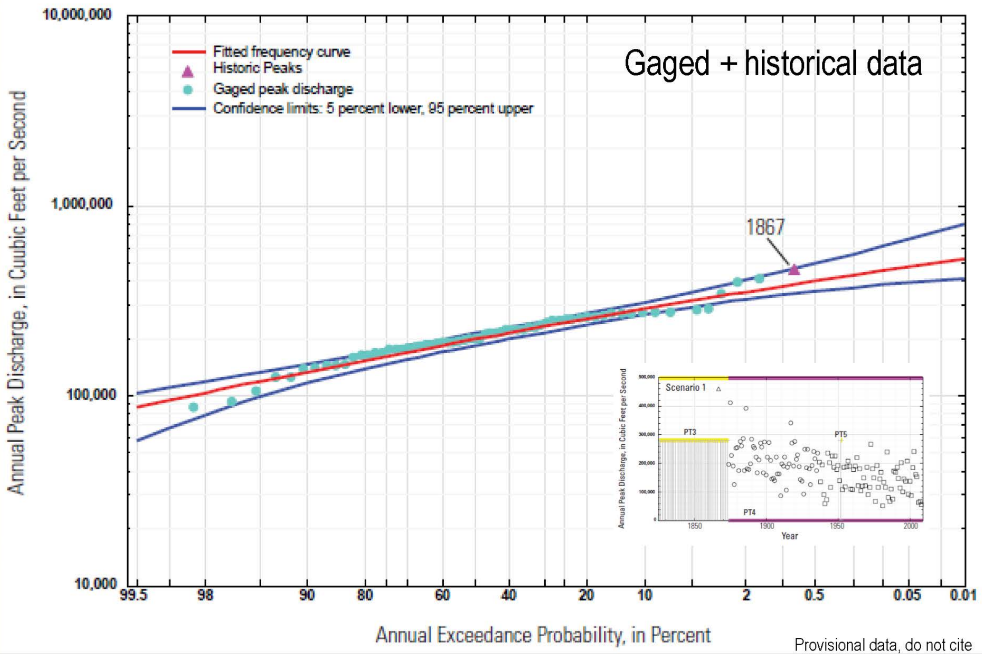
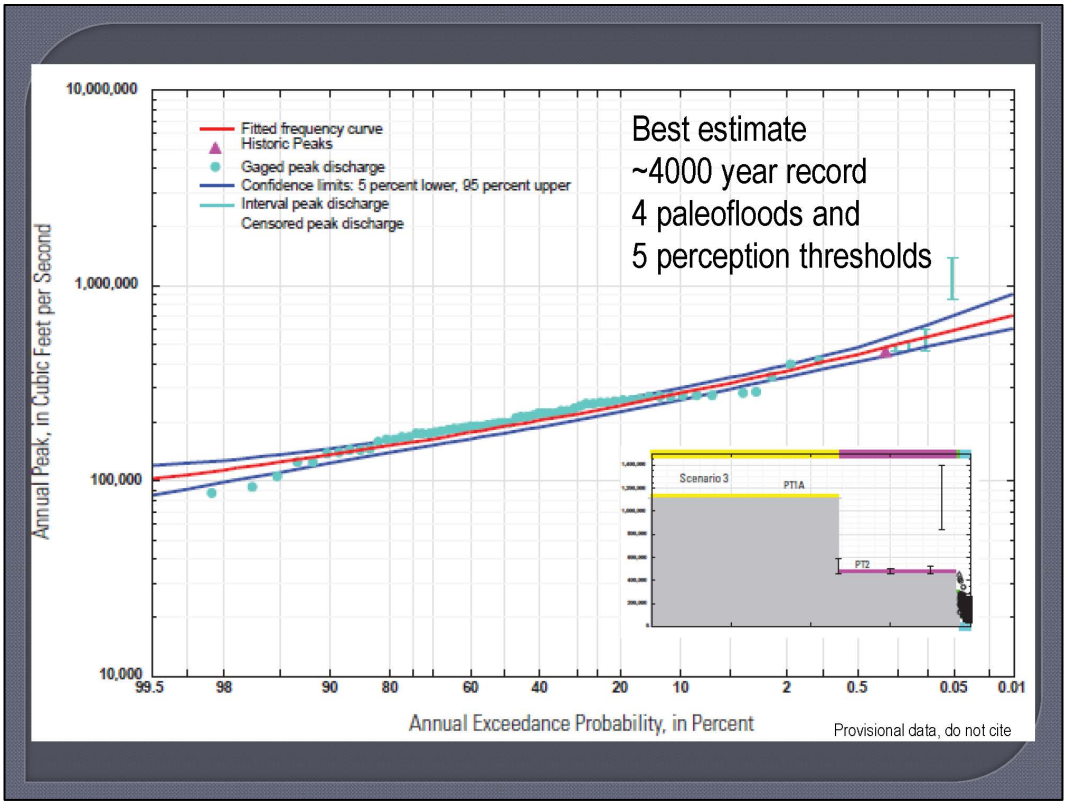


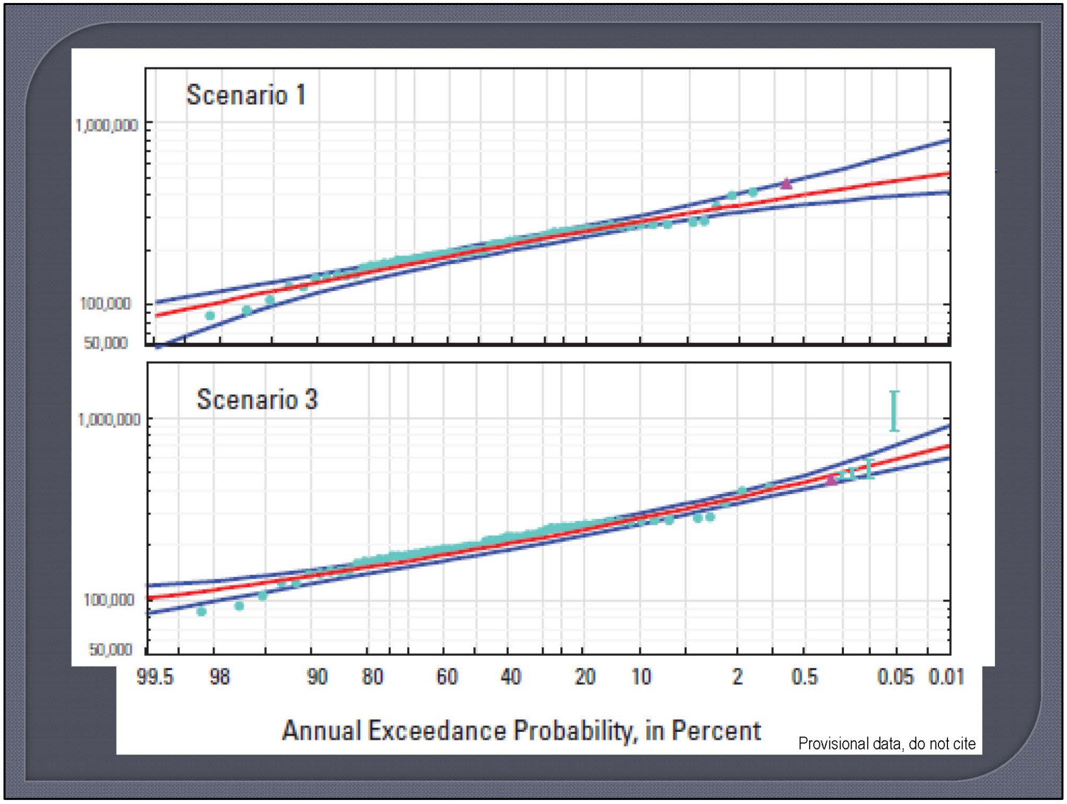
Gaged + historical data

Provisional data, do not cite

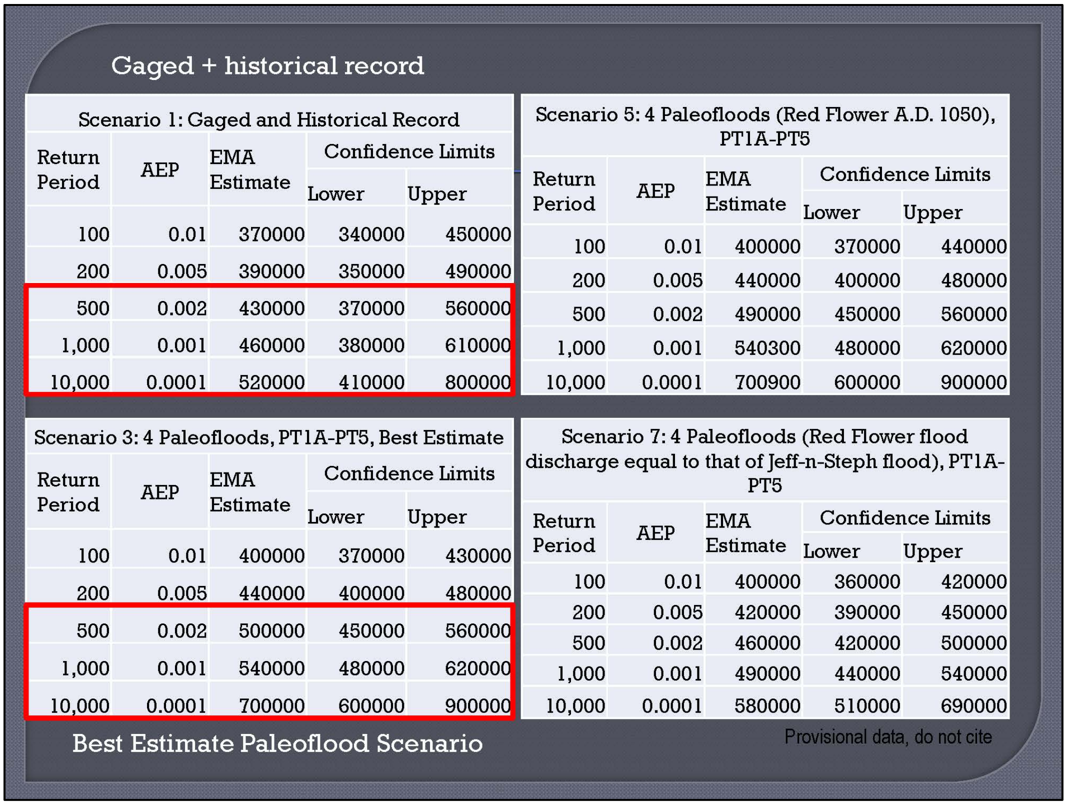


Best estimate
~4000 year record
4 paleofloods and
5 perception thresholds

Provisional data, do not cite



Provisional data, do not cite



Gaged + historical record

Scenario 1: Gaged and Historical Record

Return Period	AEP	EMA Estimate	Confidence Limits	
			Lower	Upper
100	0.01	370000	340000	450000
200	0.005	390000	350000	490000
500	0.002	430000	370000	560000
1,000	0.001	460000	380000	610000
10,000	0.0001	520000	410000	800000

Scenario 3: 4 Paleofloods, PT1A-PT5, Best Estimate

Return Period	AEP	EMA Estimate	Confidence Limits	
			Lower	Upper
100	0.01	400000	370000	430000
200	0.005	440000	400000	480000
500	0.002	500000	450000	560000
1,000	0.001	540000	480000	620000
10,000	0.0001	700000	600000	900000

Scenario 5: 4 Paleofloods (Red Flower A.D. 1050), PT1A-PT5

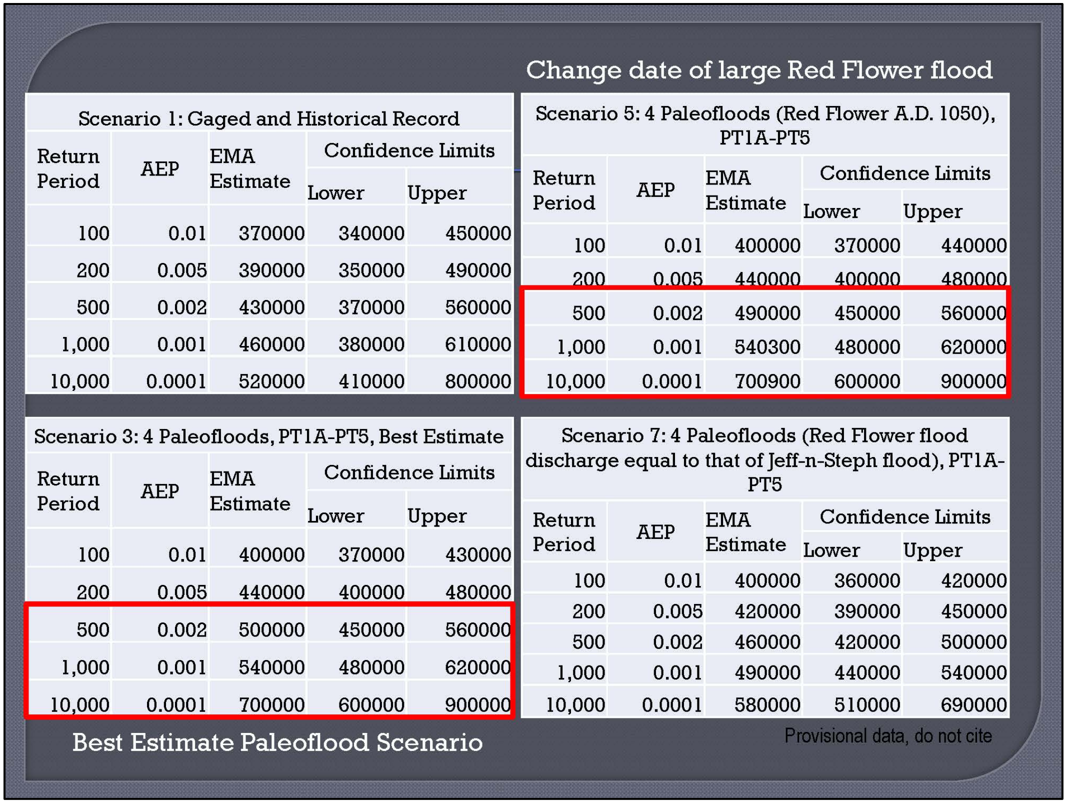
Return Period	AEP	EMA Estimate	Confidence Limits	
			Lower	Upper
100	0.01	400000	370000	440000
200	0.005	440000	400000	480000
500	0.002	490000	450000	560000
1,000	0.001	540300	480000	620000
10,000	0.0001	700900	600000	900000

Scenario 7: 4 Paleofloods (Red Flower flood discharge equal to that of Jeff-n-Steph flood), PT1A-PT5

Return Period	AEP	EMA Estimate	Confidence Limits	
			Lower	Upper
100	0.01	400000	360000	420000
200	0.005	420000	390000	450000
500	0.002	460000	420000	500000
1,000	0.001	490000	440000	540000
10,000	0.0001	580000	510000	690000

Best Estimate Paleoflood Scenario

Provisional data, do not cite



Change date of large Red Flower flood

Scenario 1: Gaged and Historical Record

Return Period	AEP	EMA Estimate	Confidence Limits	
			Lower	Upper
100	0.01	370000	340000	450000
200	0.005	390000	350000	490000
500	0.002	430000	370000	560000
1,000	0.001	460000	380000	610000
10,000	0.0001	520000	410000	800000

Scenario 3: 4 Paleofloods, PT1A-PT5, Best Estimate

Return Period	AEP	EMA Estimate	Confidence Limits	
			Lower	Upper
100	0.01	400000	370000	430000
200	0.005	440000	400000	480000
500	0.002	500000	450000	560000
1,000	0.001	540000	480000	620000
10,000	0.0001	700000	600000	900000

Scenario 5: 4 Paleofloods (Red Flower A.D. 1050), PT1A-PT5

Return Period	AEP	EMA Estimate	Confidence Limits	
			Lower	Upper
100	0.01	400000	370000	440000
200	0.005	440000	400000	480000
500	0.002	490000	450000	560000
1,000	0.001	540300	480000	620000
10,000	0.0001	700900	600000	900000

Scenario 7: 4 Paleofloods (Red Flower flood discharge equal to that of Jeff-n-Steph flood), PT1A-PT5

Return Period	AEP	EMA Estimate	Confidence Limits	
			Lower	Upper
100	0.01	400000	360000	420000
200	0.005	420000	390000	450000
500	0.002	460000	420000	500000
1,000	0.001	490000	440000	540000
10,000	0.0001	580000	510000	690000

Best Estimate Paleoflood Scenario

Provisional data, do not cite

Gaged plus historical record

Provisional data, do not cite

Scenario 1: Gaged and Historical Record

Return Period	AEP	EMA Estimate	Confidence Limits	
			Lower	Upper
100	0.01	370000	340000	450000
200	0.005	390000	350000	490000
500	0.002	430000	370000	560000
1,000	0.001	460000	380000	610000
10,000	0.0001	520000	410000	800000

Scenario 5: 4 Paleofloods (Red Flower A.D. 1050), PT1A-PT5

Return Period	AEP	EMA Estimate	Confidence Limits	
			Lower	Upper
100	0.01	400000	370000	440000
200	0.005	440000	400000	480000
500	0.002	490000	450000	560000
1,000	0.001	540300	480000	620000
10,000	0.0001	700900	600000	900000

Scenario 3: 4 Paleofloods, PT1A-PT5, Best Estimate

Return Period	AEP	EMA Estimate	Confidence Limits	
			Lower	Upper
100	0.01	400000	370000	430000
200	0.005	440000	400000	480000
500	0.002	500000	450000	560000
1,000	0.001	540000	480000	620000
10,000	0.0001	700000	600000	900000

Best Estimate Paleoflood Scenario

Scenario 7: 4 Paleofloods (Red Flower flood discharge equal to that of Jeff-n-Steph flood), PT1A-PT5

Return Period	AEP	EMA Estimate	Confidence Limits	
			Lower	Upper
100	0.01	400000	360000	420000
200	0.005	420000	390000	450000
500	0.002	460000	420000	500000
1,000	0.001	490000	440000	540000
10,000	0.0001	580000	510000	690000

Change magnitude of large Red Flower flood

Summary

- Adding 4000 years of paleoflood data reduces uncertainty of the very small AEP's by 22-44%
- Adding 4000 years of paleoflood data increases the magnitude of the very small AEP's.
- Record length has a strong influence on the curve.

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3.4.8 Presentation 2A-8: Estimating Design Floods with Specified Annual Exceedance Probabilities Using the Bayesian Estimation and Fitting Software (RMC-BestFit)

Speaker: Haden Smith, U.S. Army Corps of Engineers, Risk Management Center (USACE/RMC)

3.4.8.1 Abstract

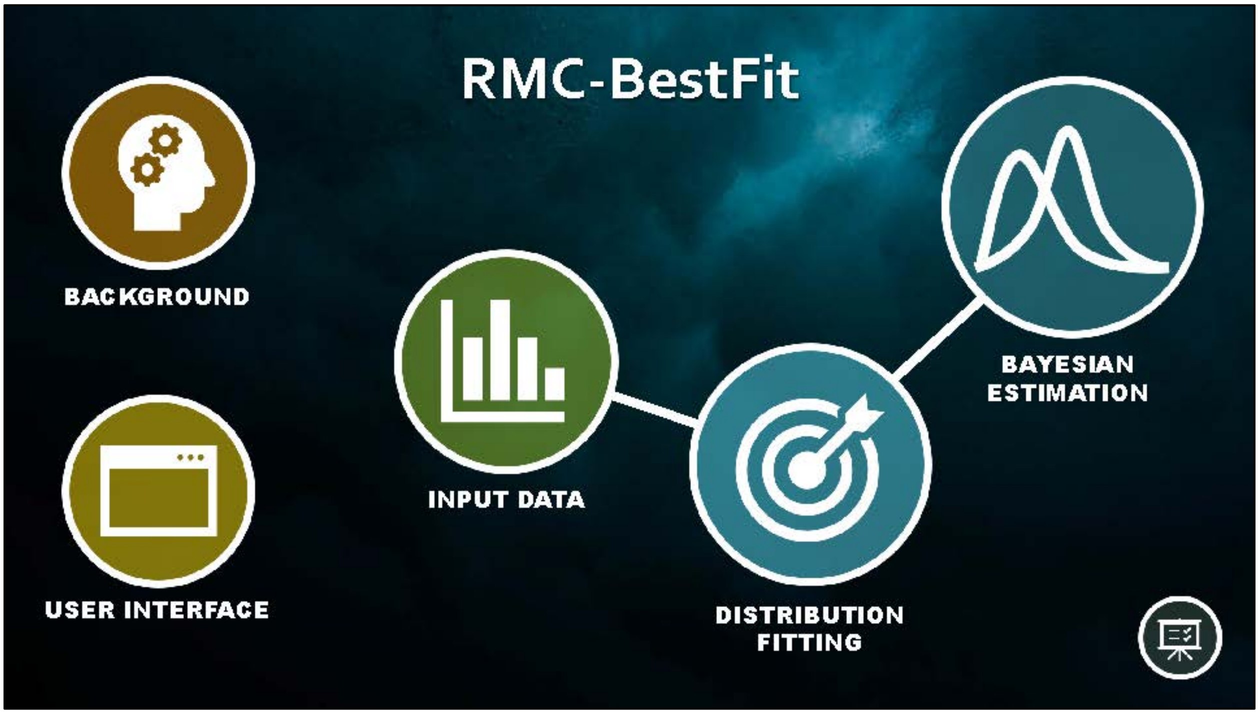
The U.S. Army Corps of Engineers (USACE) Risk Management Center (RMC), in collaboration with the Engineer Research and Development Center (ERDC) Coastal and Hydraulics Laboratory (CHL), developed the Bayesian estimation and fitting software RMC-BestFit to enhance and expedite flood hazard assessments within the Flood Risk Management, Planning, and Dam and Levee Safety communities of practice.

Design floods for most dams and levees typically have an annual exceedance probability (AEP) of 1:100 (1E-2) or less frequent. In the U.S., high hazard dams are designed to pass the Probable Maximum Flood (PMF), which typically has an AEP of 1:10,000 (1E-4) or less frequent. In order to reduce epistemic uncertainties in the estimated AEP for extreme floods, such as the PMF, it is important to incorporate as much hydrologic information into the frequency analysis as reasonably possible. This presentation demonstrates a Bayesian analysis framework, originally profiled by *Viglione et al.* (2013), for combining limited at-site flood data with temporal information on historic and paleofloods, spatial information on precipitation-frequency, and causal information on the flood processes. This framework is implemented in the RMC-BestFit software, which is used to evaluate the flood hazard for Lookout Point Dam, a high priority dam located in the Willamette River Basin, upstream of Portland, Oregon. Flood frequency results are compared with those from the Expected Moments Algorithm (EMA). Both analysis methods produce similar results for typical censored data, such as historical floods; however, unlike the Bayesian analysis framework, EMA is not capable of incorporating the causal rainfall-runoff information in a formal, probabilistic manner. Consequently, the Bayesian method considered herein provides higher confidence in the fitted flood frequency curves and resulting reservoir stage-frequency curves to be used in dam and levee safety risk assessments.

3.4.8.2 Presentation (ADAMS Accession No. ML20080M137)

RMC-BestFit

Bayesian Estimation and Fitting Software



RMC-BestFit

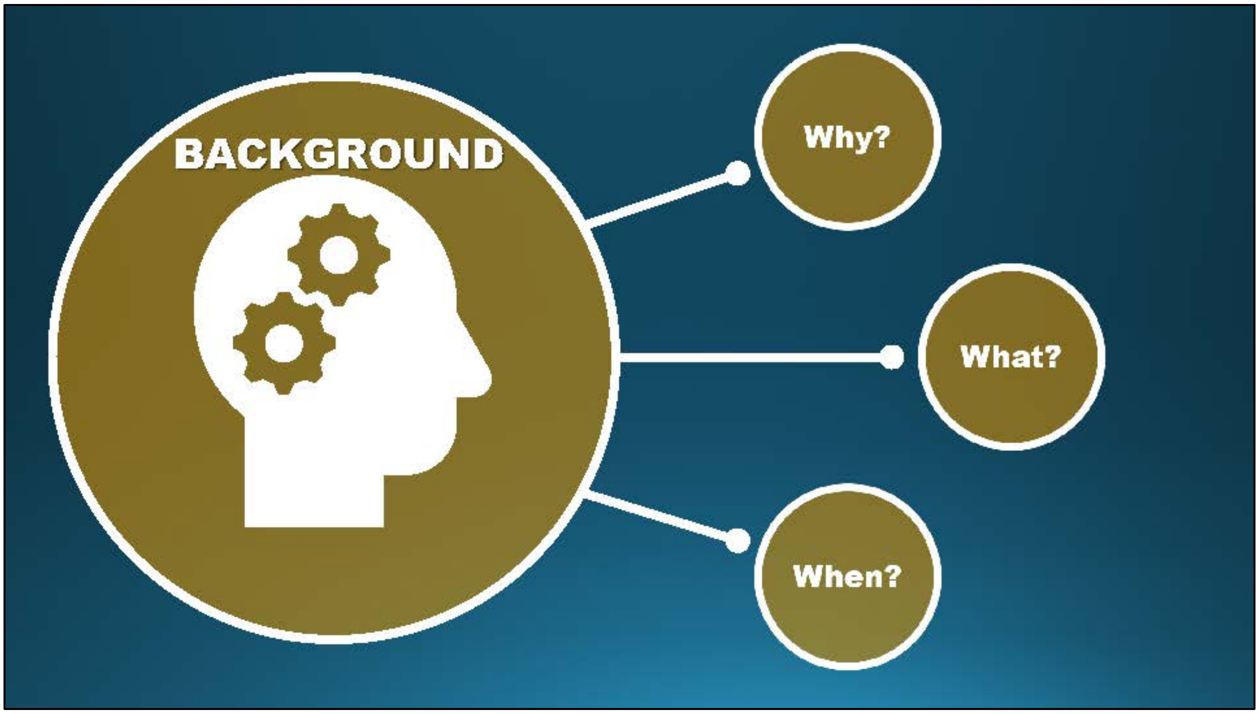
BACKGROUND

USER INTERFACE

INPUT DATA

DISTRIBUTION FITTING

BAYESIAN ESTIMATION



BACKGROUND

- Why?
- What?
- When?

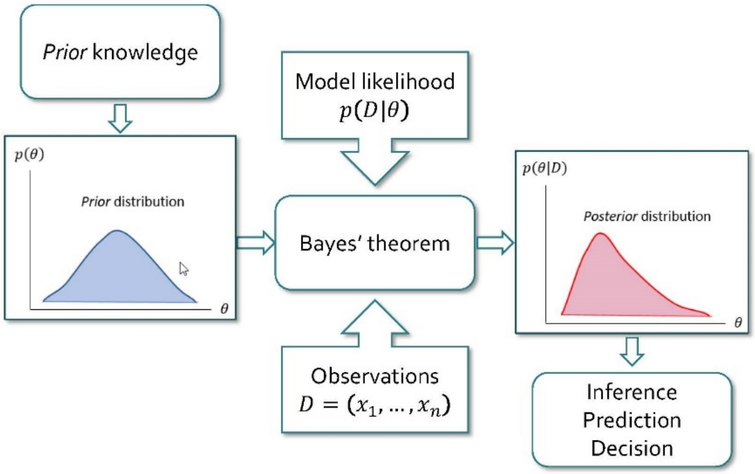
Why?

- **To enhance and expedite flood hazard assessments within the Flood Risk Management, Planning, and Dam and Levee Safety communities of practice**
  - The Bayesian method can incorporate all available sources of hydrologic information, such as paleofloods, regional rainfall-runoff results, and expert elicitation.
  - As such, it provides higher confidence in the fitted flood frequency curves and resulting reservoir stage-frequency curves
  - RMC-BestFit was developed by the RMC, in collaboration with ERDC–CHL

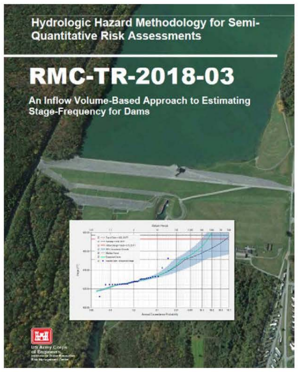
What?

Bayes' Theorem

$$P(\theta|\mathrm{D}) = \frac{P(D|\theta) \cdot P(\theta)}{\int P(D|\theta) \cdot P(\theta) \cdot d\theta}$$

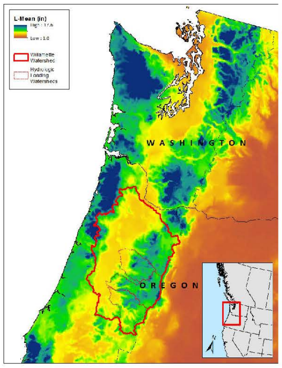


When?

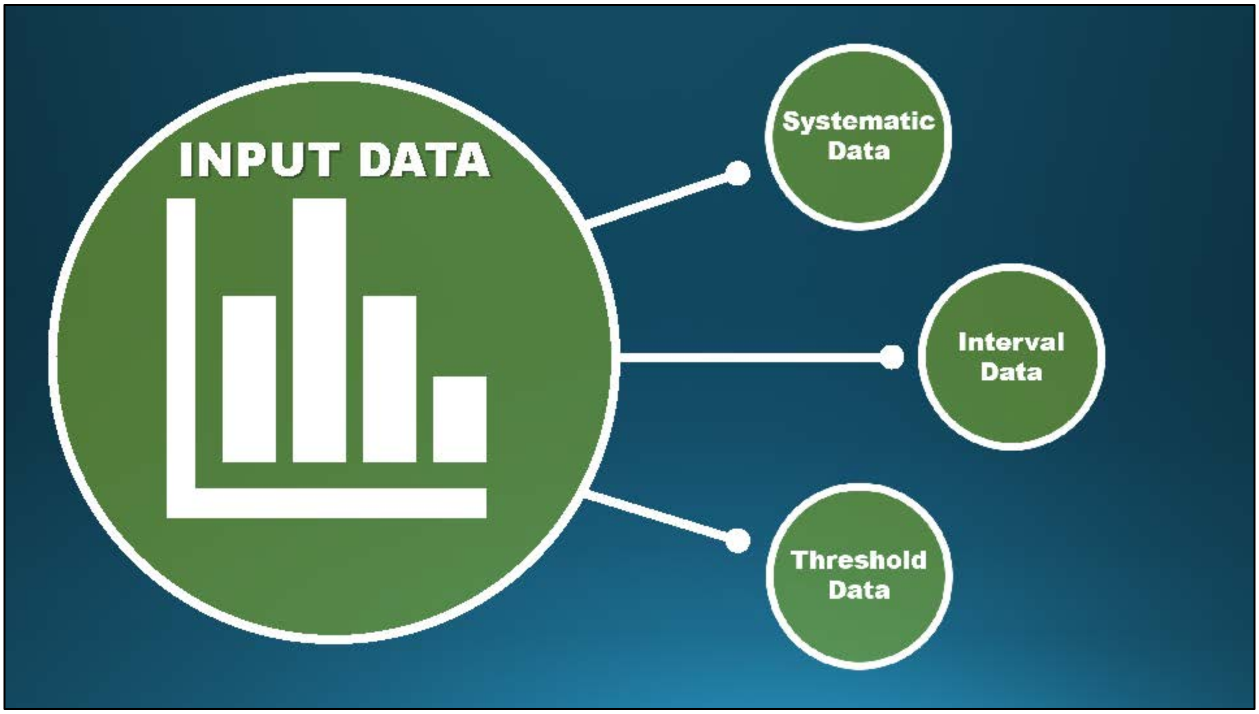

Hydrologic Hazard Methodology for Semi-Quantitative Risk Assessments

RMC-TR-2018-03

An Inflow Volume-Based Approach to Estimating Stage-Frequency for Dams



- Semi-Quantitative Risk or Hazard Assessments, or higher level of effort
- Most valuable when there are multiple sources of data
- Can be used in flood and/or seismic hazard assessments and reliability analysis



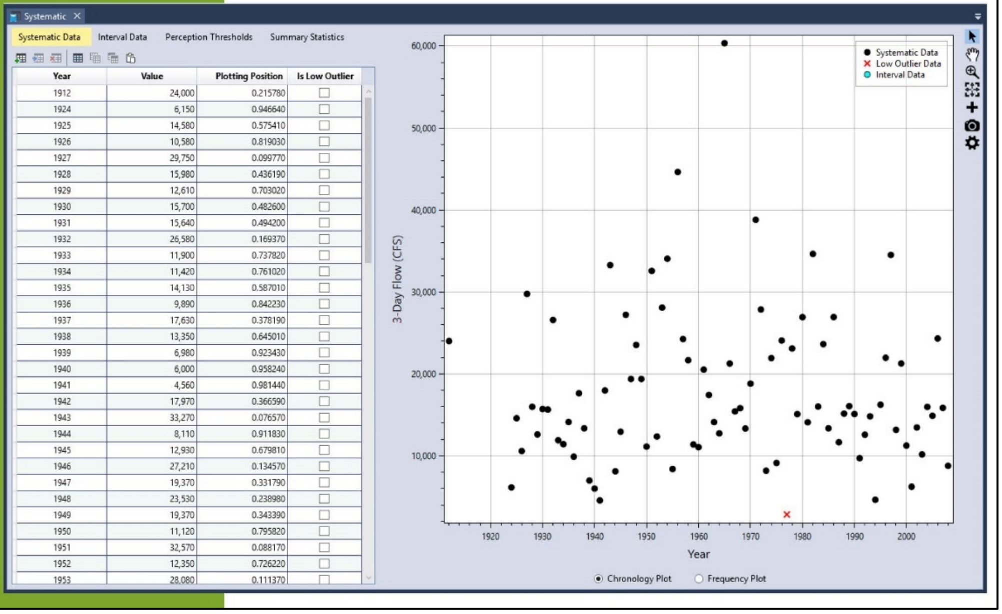
INPUT DATA

Systematic Data

Interval Data

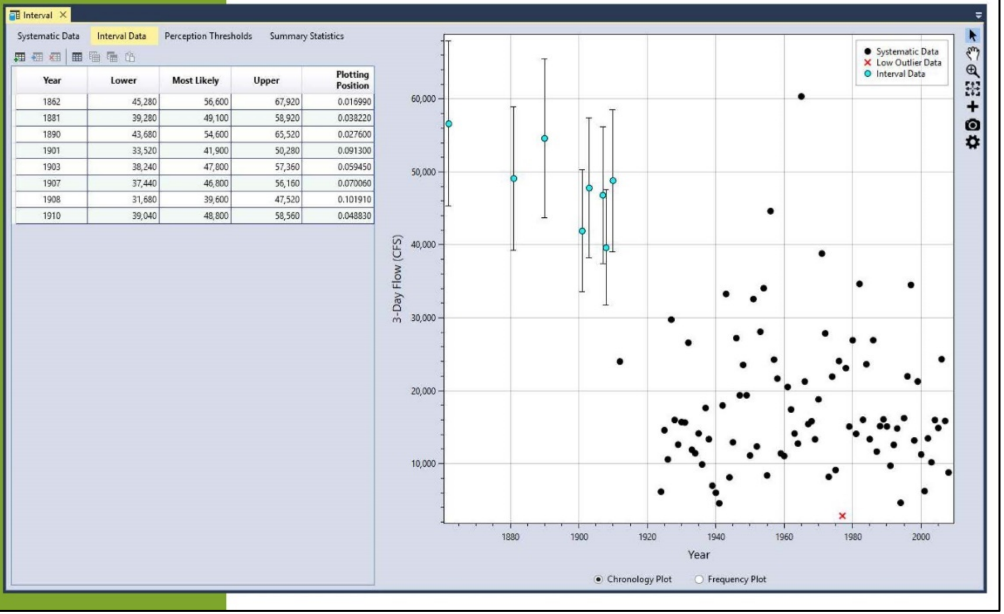
Threshold Data

Systematic Data



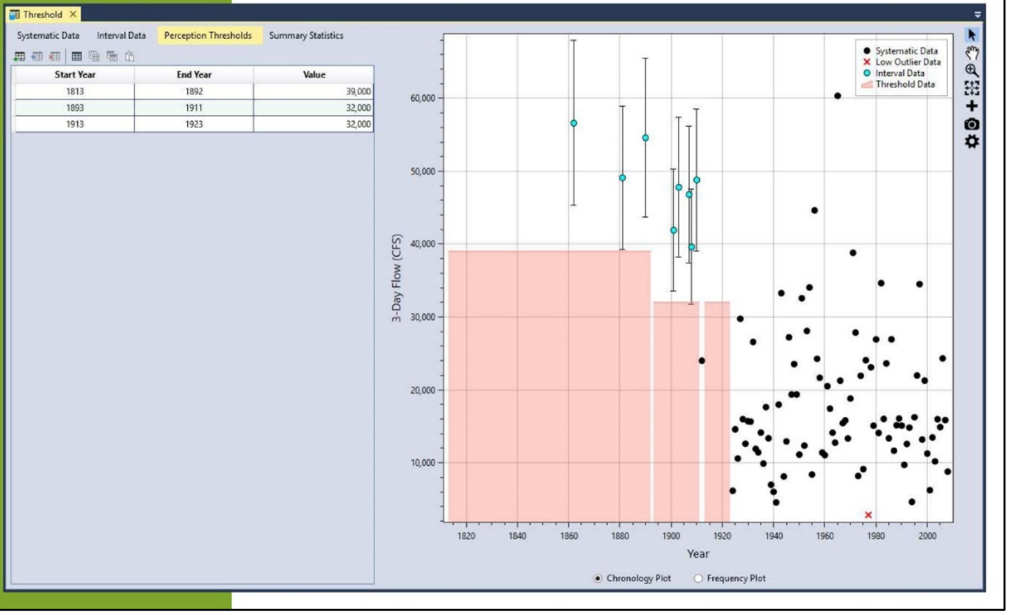
Year	Value	Plotting Position	Is Low Outlier
1912	24,000	0.215780	☐
1924	6,150	0.946640	☐
1925	14,580	0.575410	☐
1926	10,580	0.819030	☐
1927	29,750	0.099770	☐
1928	15,980	0.436190	☐
1929	12,610	0.703020	☐
1930	15,700	0.482600	☐
1931	15,640	0.494200	☐
1932	26,580	0.169370	☐
1933	11,900	0.737820	☐
1934	11,420	0.761020	☐
1935	14,130	0.587010	☐
1936	9,890	0.842230	☐
1937	17,630	0.378190	☐
1938	13,350	0.645010	☐
1939	6,980	0.923430	☐
1940	6,000	0.958240	☐
1941	4,560	0.981440	☐
1942	17,970	0.366590	☐
1943	33,270	0.076570	☐
1944	8,110	0.911830	☐
1945	12,930	0.679810	☐
1946	27,210	0.134570	☐
1947	19,370	0.331790	☐
1948	23,530	0.238980	☐
1949	19,370	0.343390	☐
1950	11,120	0.795820	☐
1951	32,570	0.088170	☐
1952	12,350	0.726220	☐
1953	28,080	0.111370	☐

Interval Data

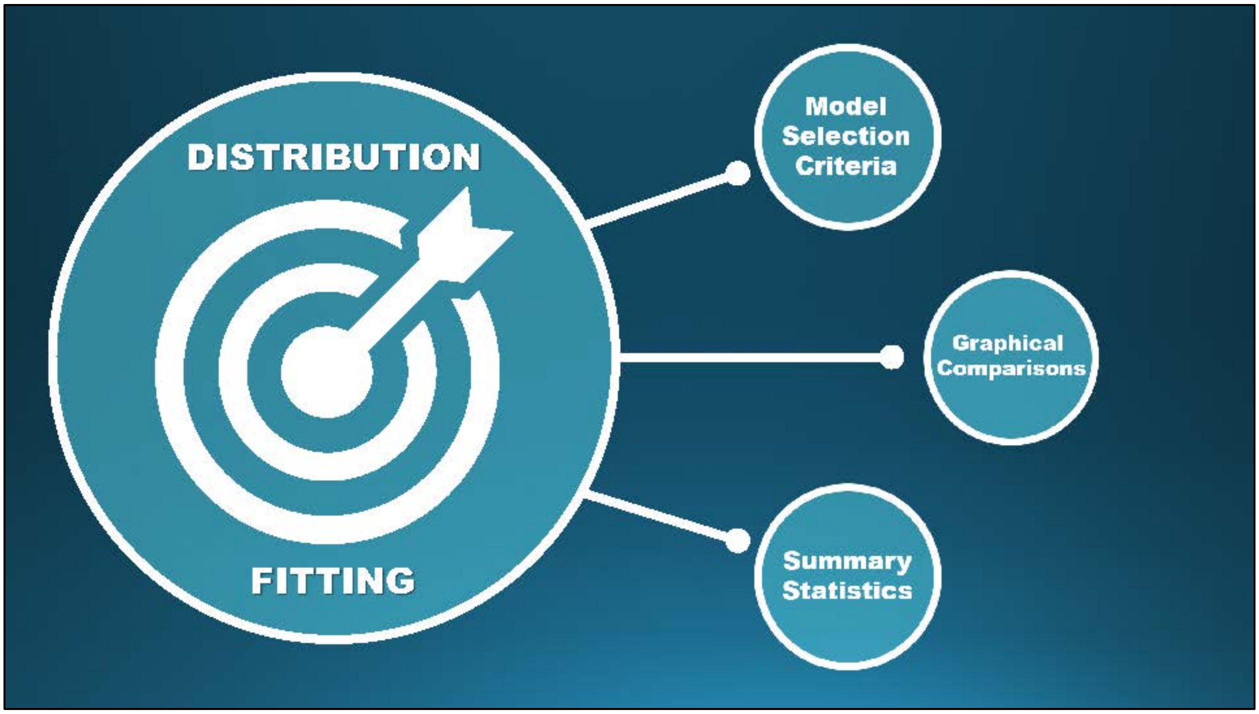


Year	Lower	Most Likely	Upper	Plotting Position
1862	45,280	56,600	67,920	0.016990
1881	39,280	49,100	58,920	0.038220
1890	43,680	54,600	65,520	0.027600
1901	33,520	41,900	50,280	0.091300
1903	38,240	47,800	57,360	0.059450
1907	37,440	46,800	56,160	0.070060
1908	31,680	39,600	47,520	0.101910
1910	39,040	48,800	58,560	0.048830

Threshold Data



Start Year	End Year	Value
1813	1892	39,000
1893	1911	32,000
1913	1923	32,000



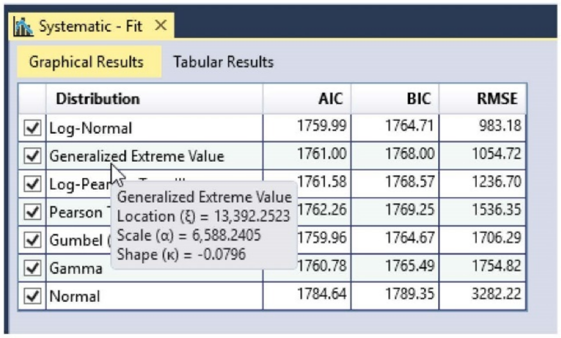
DISTRIBUTION FITTING

Model Selection Criteria

Graphical Comparisons

Summary Statistics

Model Selection Criteria

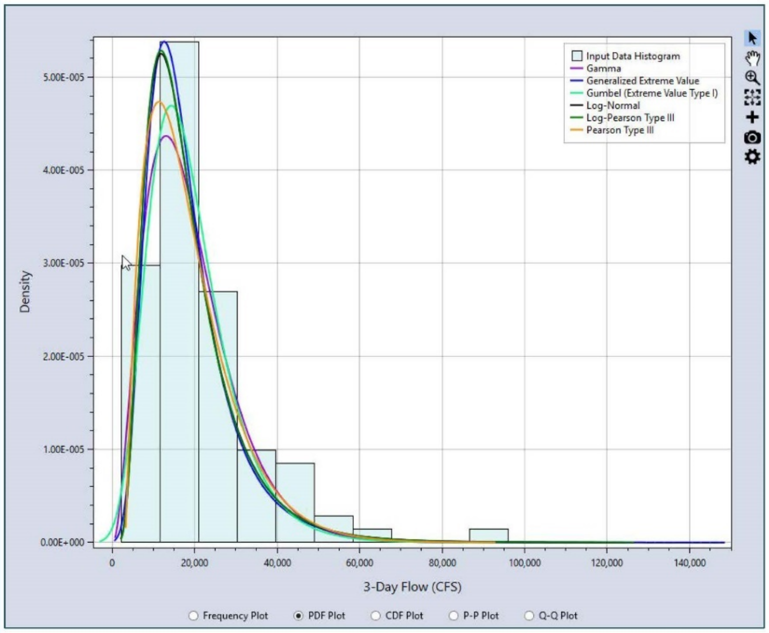


	Distribution	AIC	BIC	RMSE
☑	Log-Normal	1759.99	1764.71	983.18
☑	Generalized Extreme Value	1761.00	1768.00	1054.72
☑	Log-Pear	1761.58	1768.57	1236.70
☑	Pearson	1762.26	1769.25	1536.35
☑	Gumbel (	1759.96	1764.67	1706.29
☑	Gamma	1760.78	1765.49	1754.82
☑	Normal	1784.64	1789.35	3282.22

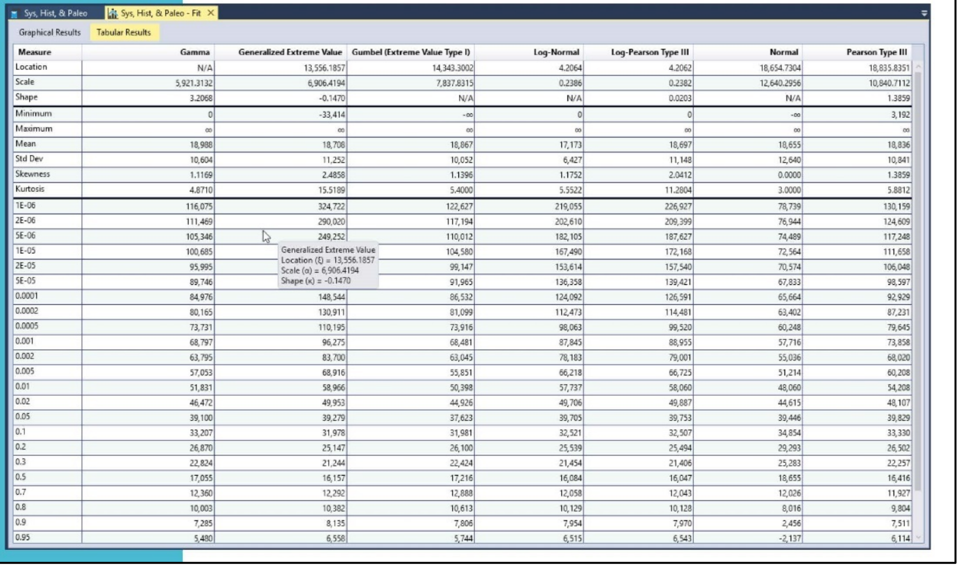
Generalized Extreme Value
Location (ξ) = 13,392.2523
Scale (α) = 6,588.2405
Shape (κ) = -0.0796

- Three “goodness-of-fit” measures to assist with model selection:
  - Akaike Information Criterion (AIC)
  - Bayesian Information Criterion (BIC)
  - Root Mean Square Error (RMSE)

Graphical Comparisons

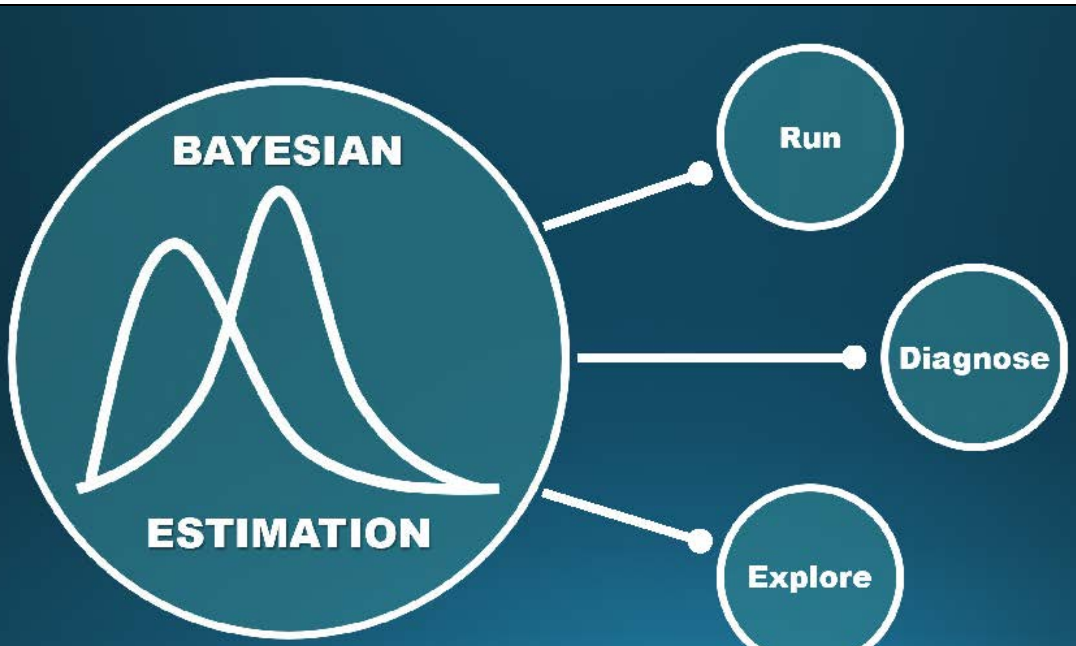


Summary Statistics



Measure	Gamma	Generalized Extreme Value	Gumbel (Extreme Value Type I)	Log-Normal	Log-Pearson Type III	Normal	Pearson Type III
Location	N/A	13,556.1857	14,343.3002	4.2064	4.2062	18,654.7304	18,835.8351
Scale	5,921.3132	6,906.4194	7,837.8315	0.2386	0.2382	12,640.2956	10,840.7112
Shape	3.2068	-0.1470	N/A	N/A	0.0203	N/A	1.3859
Minimum	0	-33,414	-∞	0	0	-∞	3,192
Maximum	∞	∞	∞	∞	∞	∞	∞
Mean	18,988	18,708	18,867	17,173	18,697	18,655	18,836
Std Dev	10,604	11,252	10,052	6,427	11,148	12,640	10,841
Skewness	1.1169	2.4858	1.1396	1.1752	2.0412	0.0000	1.3859
Kurtosis	4.8710	15.5189	5.4000	5.5522	11.2804	3.0000	5.8812
1E-06	116,075	324,722	122,627	219,055	226,927	78,739	130,159
2E-06	111,469	290,020	117,194	202,610	209,399	76,944	124,609
5E-06	105,346	249,252	110,012	182,105	187,627	74,489	117,248
1E-05	100,685	[illegible]	104,580	167,490	172,168	72,564	111,658
2E-05	95,995	[illegible]	99,147	153,614	157,540	70,574	106,048
5E-05	89,746	[illegible]	91,965	136,358	139,421	67,833	98,597
0.0001	84,976	148,544	86,532	124,092	126,591	65,664	92,929
0.0002	80,165	130,911	81,099	112,473	114,481	63,402	87,231
0.0005	73,731	110,195	73,916	98,063	99,520	60,248	79,645
0.001	68,797	96,275	68,481	87,845	88,955	57,716	73,858
0.002	63,795	83,700	63,045	78,183	79,001	55,036	68,020
0.005	57,053	68,916	55,851	66,218	66,725	51,214	60,208
0.01	51,831	58,966	50,398	57,737	58,060	48,060	54,208
0.02	46,472	49,953	44,926	49,706	49,887	44,615	48,107
0.05	39,100	39,279	37,623	39,705	39,753	39,446	39,829
0.1	33,207	31,978	31,981	32,521	32,507	34,854	33,330
0.2	26,870	25,147	26,100	25,539	25,494	29,293	26,502
0.3	22,824	21,244	22,424	21,454	21,406	25,283	22,257
0.5	17,055	16,157	17,216	16,084	16,047	18,655	16,416
0.7	12,360	12,292	12,888	12,058	12,043	12,026	11,927
0.8	10,003	10,382	10,613	10,129	10,128	8,016	9,804
0.9	7,285	8,135	7,806	7,954	7,970	2,456	7,511
0.95	5,480	6,558	5,744	6,515	6,543	-2,137	6,114

Generalized Extreme Value
Location (ξ) = 13,556.1857
Scale (α) = 6,906.4194
Shape (κ) = -0.1470



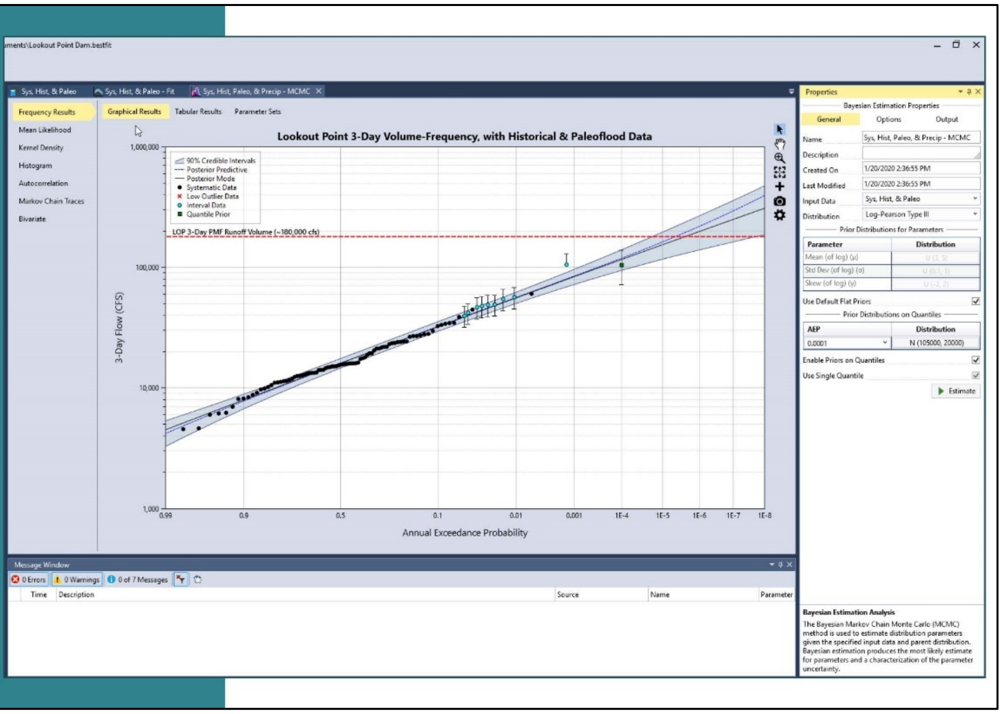
BAYESIAN ESTIMATION

Run

Diagnose

Explore

Run



Bayesian Estimation Properties

Name: Sys, Hist, Paleo, & Precip - MCMC
Description:
Created On: 1/20/2020 2:36:55 PM
Last Modified: 1/20/2020 2:36:55 PM
Input Data: Sys, Hist, & Paleo
Distribution: Log-Pearson Type III

Prior Distributions for Parameters

Parameter	Distribution
Mean (of log) (μ)	U (3, 5)
Std Dev (of log) (σ)	U (0.1, 1)
Skew (of log) (γ)	U (-2, 2)

Use Default Flat Priors ☑

Prior Distributions on Quantiles

AEP	Distribution
0.0001	N (105000, 20000)

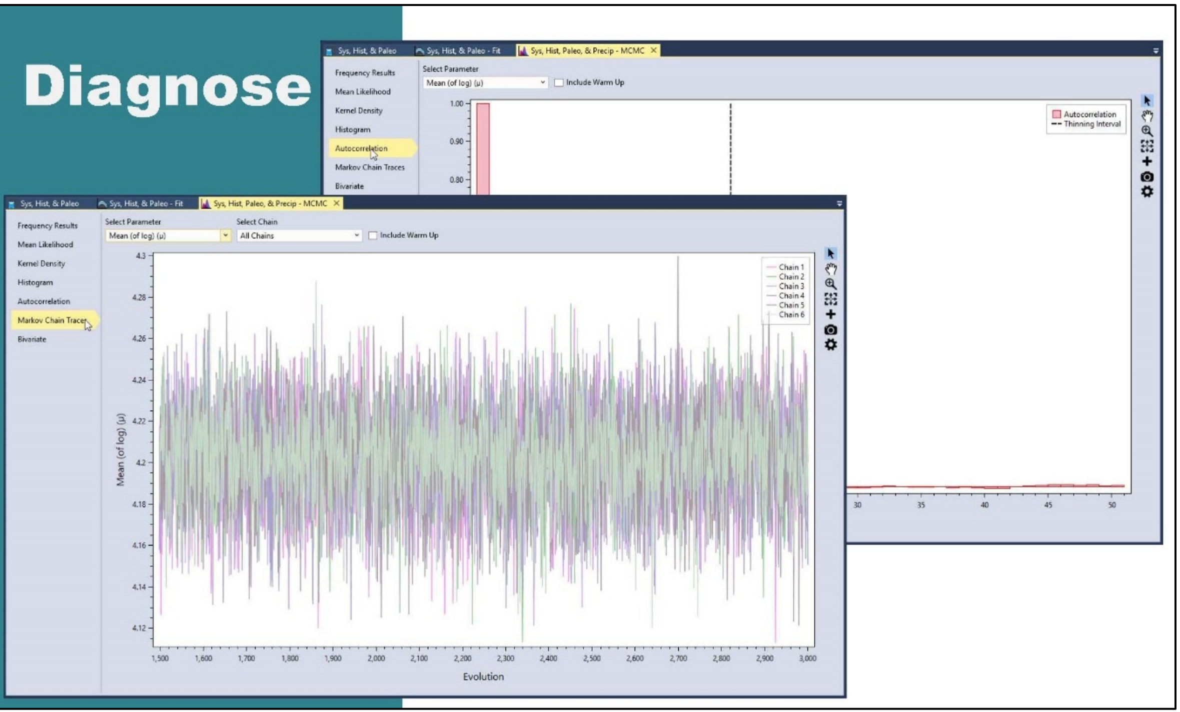
Enable Priors on Quantiles ☑

Use Single Quantile ☑

Bayesian Estimation Analysis

The Bayesian Markov Chain Monte Carlo (MCMC) method is used to estimate distribution parameters given the specified input data and parent distribution. Bayesian estimation produces the most likely estimate for parameters and a characterization of the parameter uncertainty.

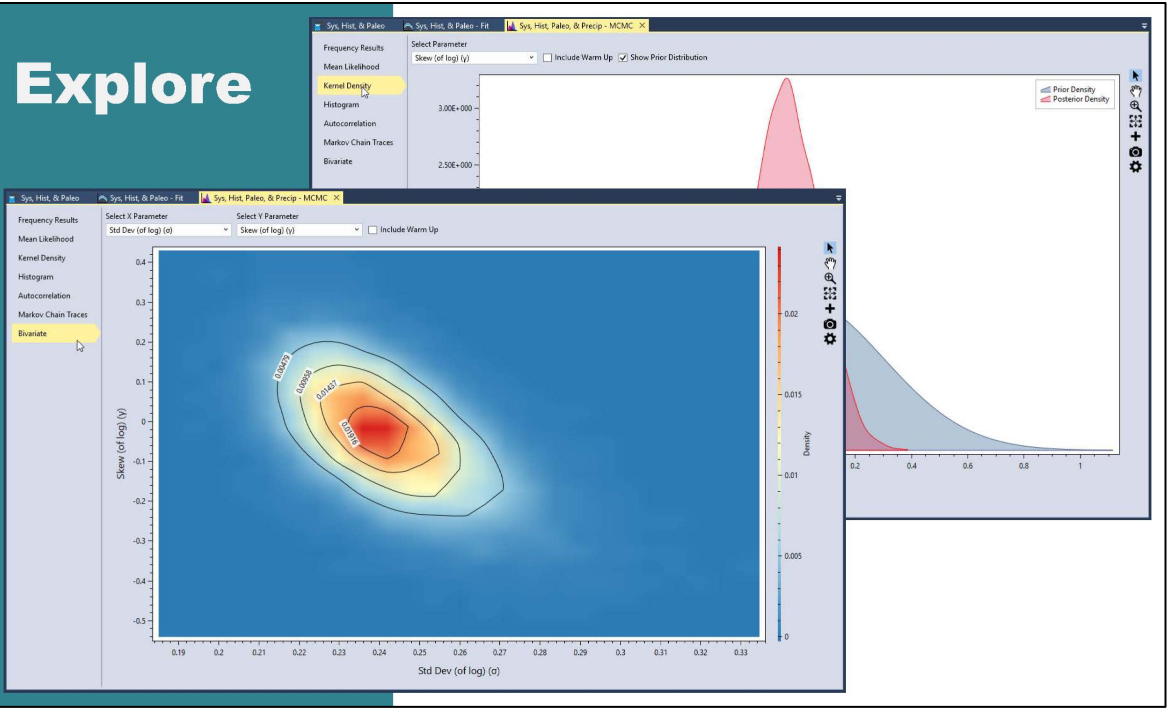
Diagnose



Select Parameter: Mean (of log) (μ) ☐ Include Warm Up

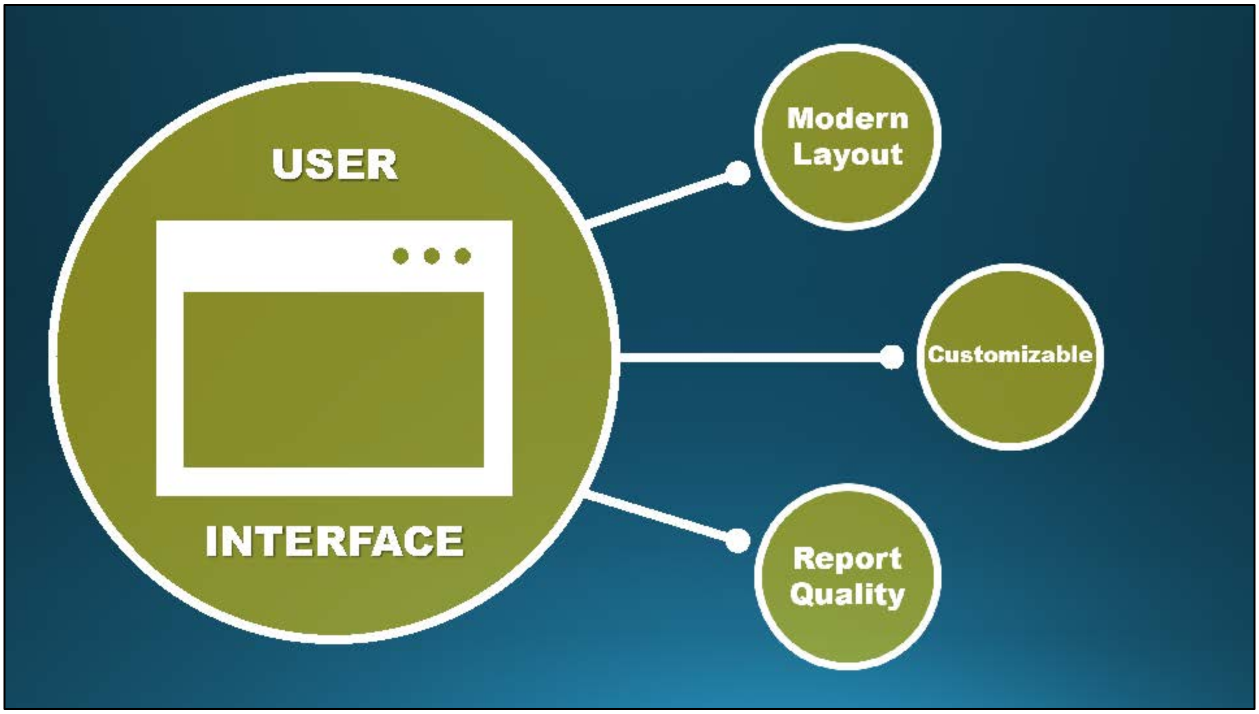
Select Parameter: Mean (of log) (μ) Select Chain: All Chains ☐ Include Warm Up

Explore



Select Parameter: Skew (of log) (γ) ☐ Include Warm Up ☑ Show Prior Distribution

Select X Parameter: Std Dev (of log) (σ) Select Y Parameter: Skew (of log) (γ) ☐ Include Warm Up



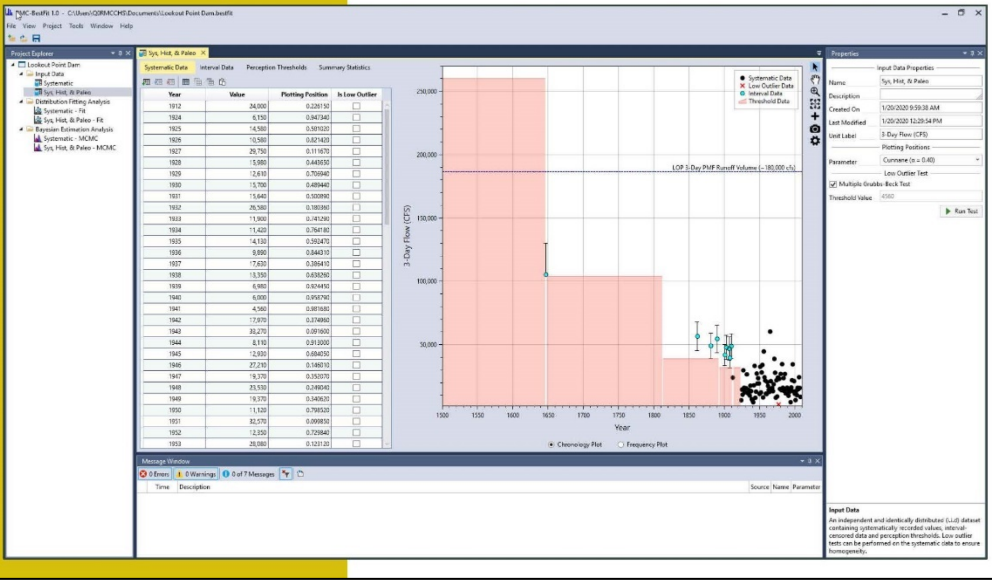
USER INTERFACE

Modern Layout

Customizable

Report Quality

Modern Layout



Year	Value	Plotting Position	Is Low Outlier
1912	24,000	0.226150	☐
1924	6,150	0.947340	☐
1925	14,580	0.581020	☐
1926	10,580	0.821420	☐
1927	29,750	0.111670	☐
1928	15,980	0.443650	☐
1929	12,610	0.706940	☐
1930	15,700	0.489440	☐
1931	15,640	0.500890	☐
1932	26,580	0.180360	☐
1933	11,900	0.741290	☐
1934	11,420	0.764180	☐
1935	14,130	0.592470	☐
1936	9,890	0.844310	☐
1937	17,630	0.386410	☐
1938	13,350	0.638260	☐
1939	6,980	0.924450	☐
1940	6,000	0.958790	☐
1941	4,560	0.981680	☐
1942	17,970	0.374960	☐
1943	33,270	0.091600	☐
1944	8,110	0.913000	☐
1945	12,930	0.684050	☐
1946	27,210	0.146010	☐
1947	19,370	0.352070	☐
1948	23,530	0.249040	☐
1949	19,370	0.340620	☐
1950	11,120	0.798520	☐
1951	32,570	0.099850	☐
1952	12,350	0.729840	☐
1953	28,080	0.123120	☐

Input Data Properties

Name: Sys, Hist, & Paleo

Description:

Created On: 1/20/2020 9:59:38 AM

Last Modified: 1/20/2020 12:29:54 PM

Unit Label: 3-Day Flow (CFS)

Plotting Positions

Parameter: Cunnane (α = 0.40)

Low Outlier Test

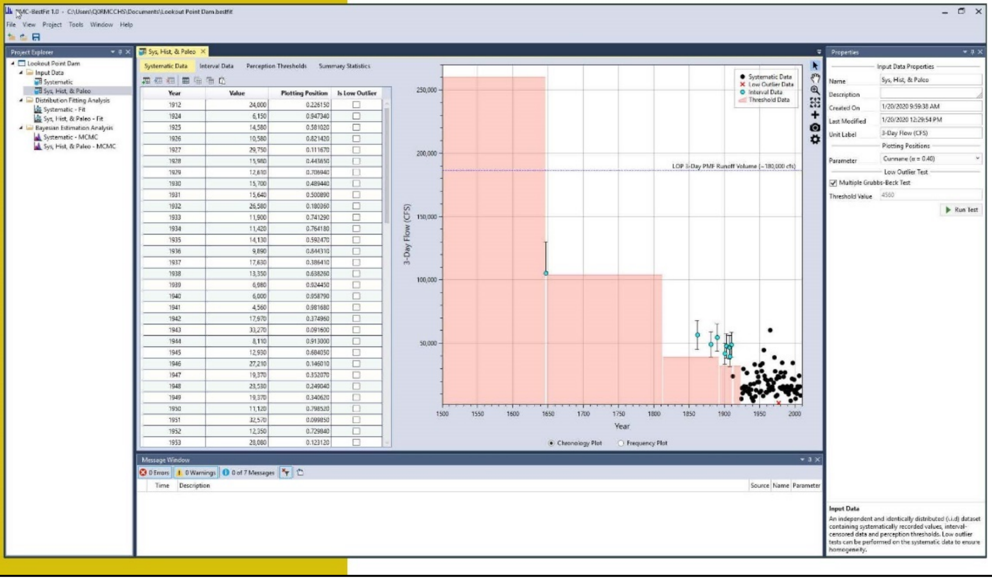
☑ Multiple Grubbs-Beck Test

Threshold Value: 4560

Input Data

An independent and identically distributed (i.i.d) dataset containing systematically recorded values, interval-censored data and perception thresholds. Low outlier tests can be performed on the systematic data to ensure homogeneity.

Customizable



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1931	15,640	0.500890	☐
1932	26,580	0.180360	☐
1933	11,900	0.741290	☐
1934	11,420	0.764180	☐
1935	14,130	0.592470	☐
1936	9,890	0.844310	☐
1937	17,630	0.386410	☐
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1939	6,980	0.924450	☐
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Input Data Properties

Name	Sys, Hist, & Paleo
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Created On	1/20/2020 9:59:38 AM
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Plotting Positions

Parameter: Cunnane (α = 0.40)

Low Outlier Test

☑ Multiple Grubbs-Beck Test

Threshold Value: 4560

Input Data

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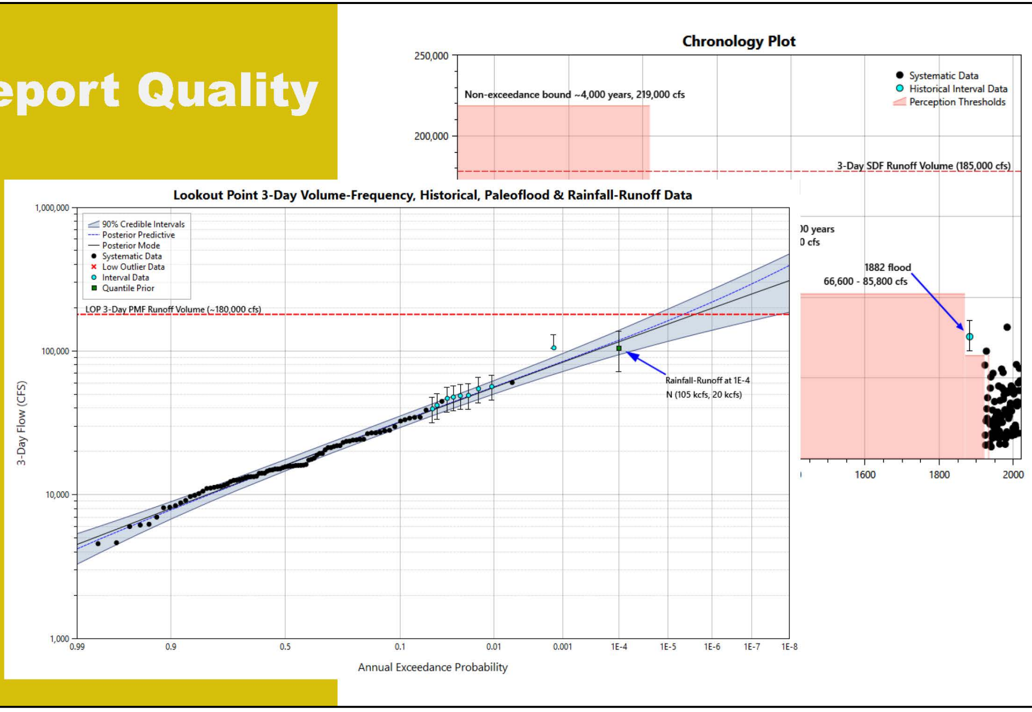
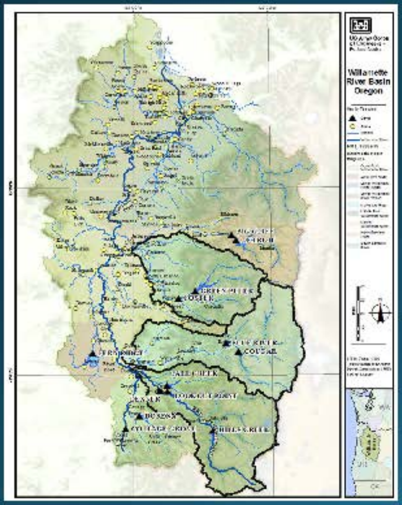
Report Quality

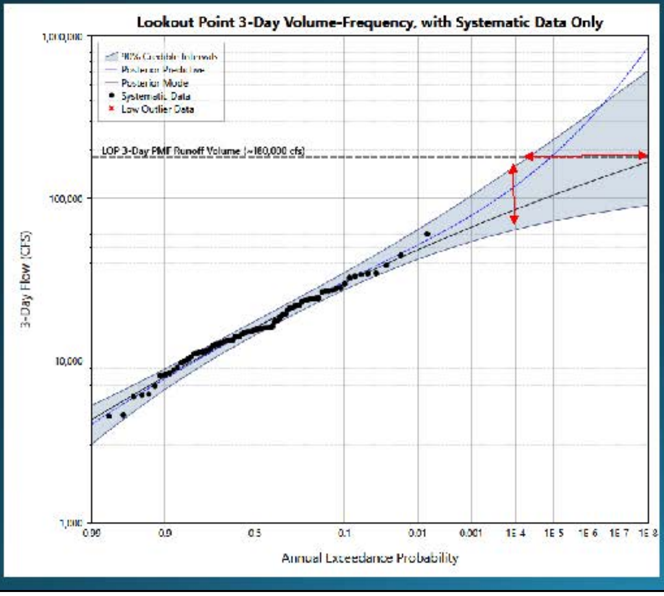


Case Study: Lookout Point Dam

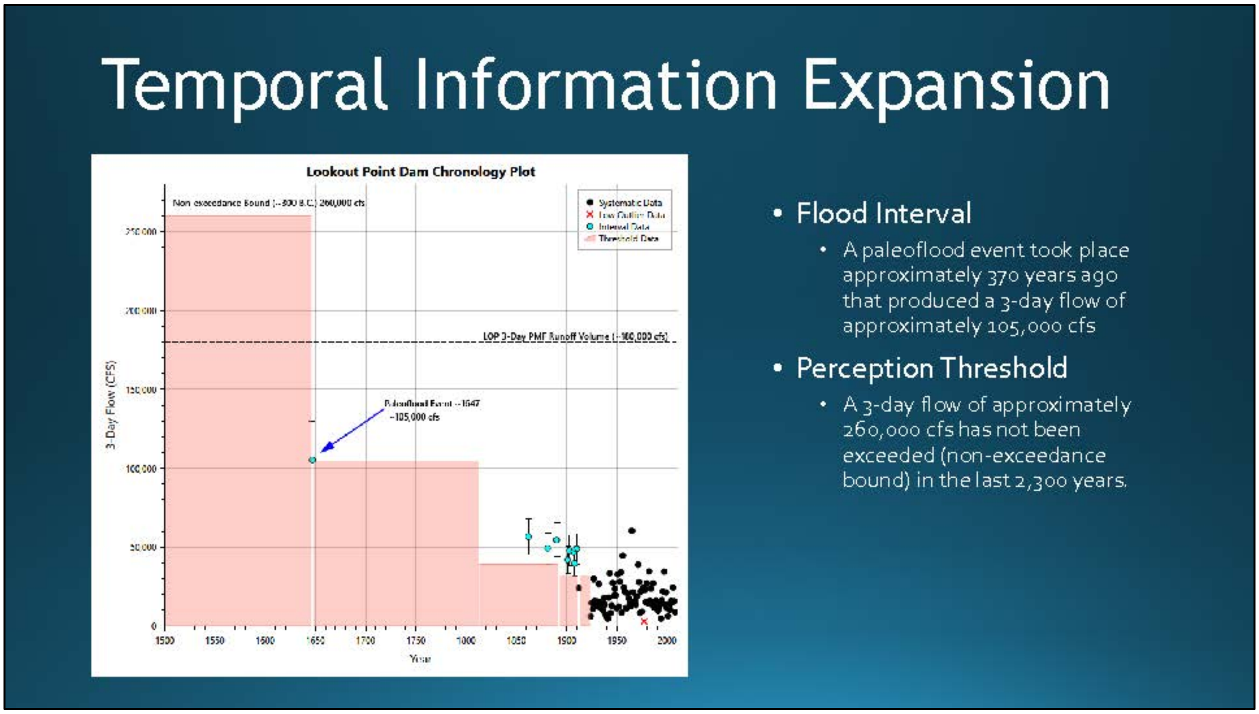


- Willamette River Basin (Oregon, USA)
  - 11,500 mi²
- Contains several high priority dams
  - Blue River
  - Cougar
  - Fall Creek
  - Foster
  - Green Peter
  - Hills Creek
  - **Lookout Point**
    - **996 mi²**
- Portland, OR downstream
- Dams operate as a complex system

Systematic Data

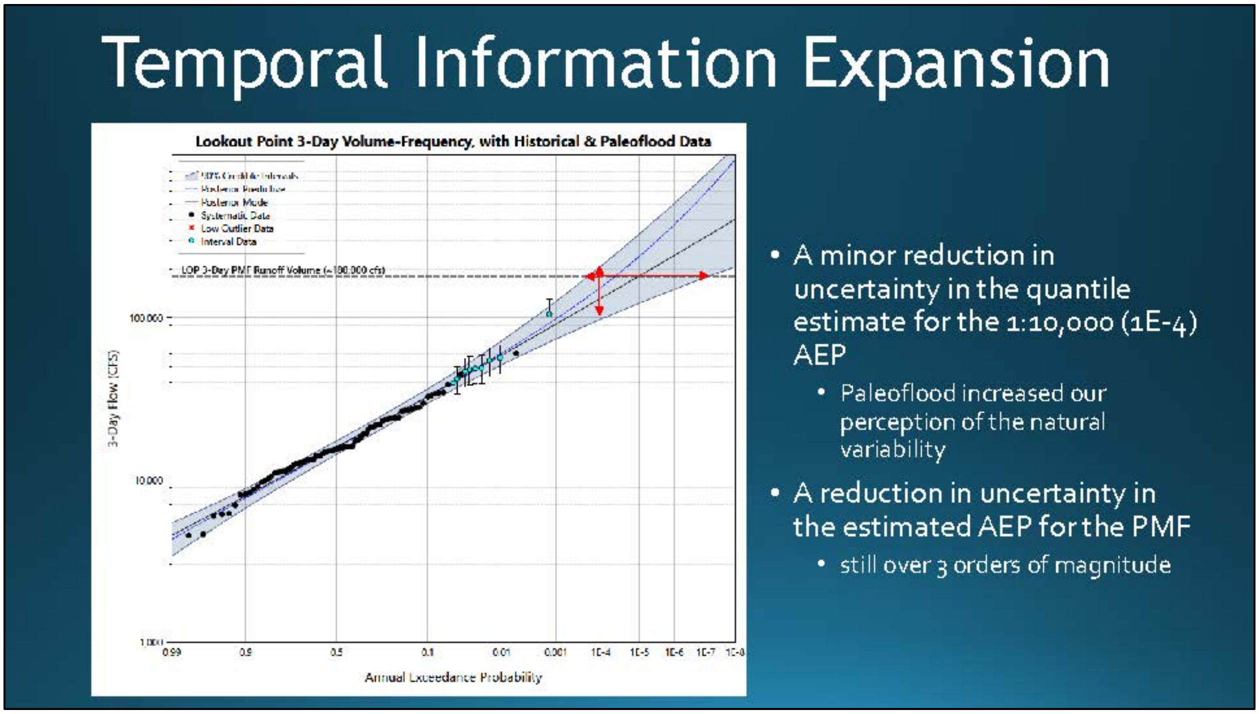


- Large uncertainty in the quantile estimate for the 1:10,000 (1E-4) AEP
- Very large uncertainty in the estimated AEP for the PMF
  - Well over 4 orders of magnitude of uncertainty



Temporal Information Expansion

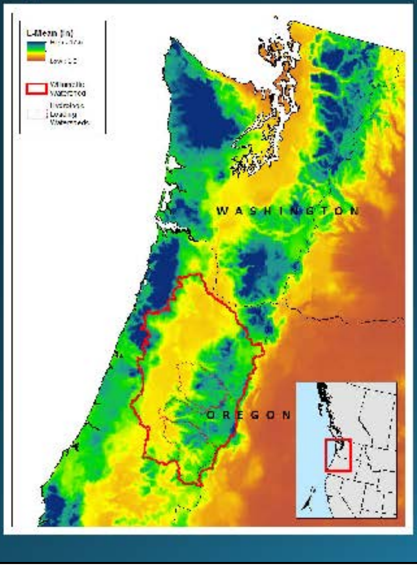
- Flood Interval
  - A paleoflood event took place approximately 370 years ago that produced a 3-day flow of approximately 105,000 cfs
- Perception Threshold
  - A 3-day flow of approximately 260,000 cfs has not been exceeded (non-exceedance bound) in the last 2,300 years.

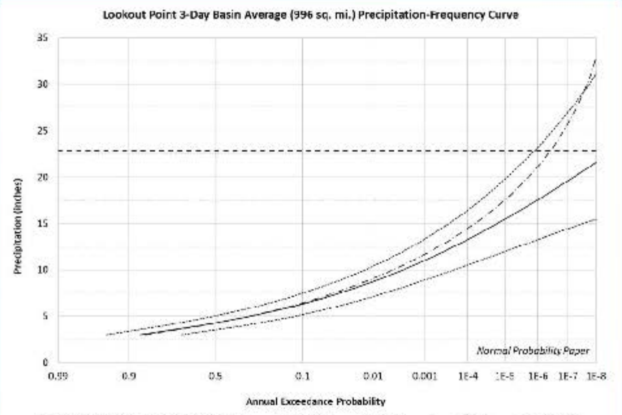


Temporal Information Expansion

- A minor reduction in uncertainty in the quantile estimate for the 1:10,000 (1E-4) AEP
  - Paleoflood increased our perception of the natural variability
- A reduction in uncertainty in the estimated AEP for the PMF
  - still over 3 orders of magnitude

Spatial & Causal Information Expansion





Spatial & Causal Information Expansion

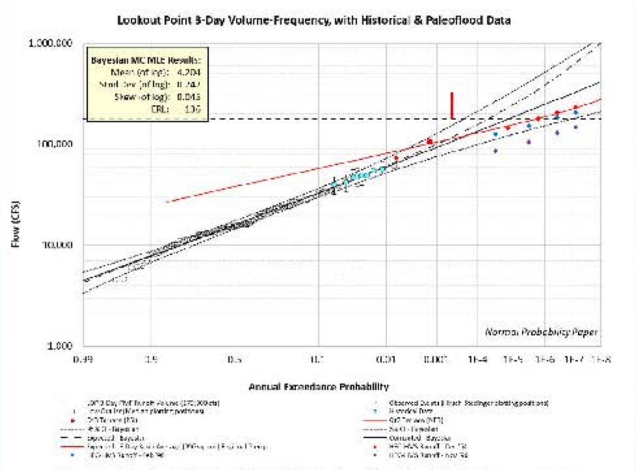
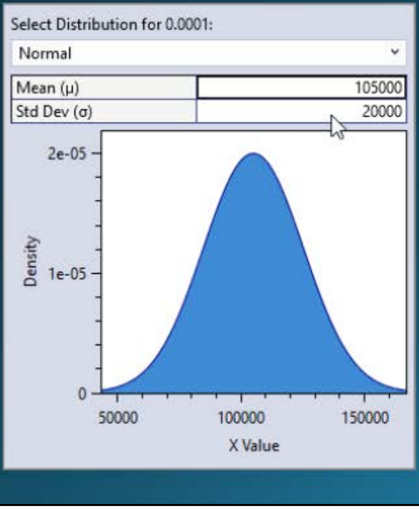


Figure 4-12. Lookout Point Dam HEC-HMS 3-Day Runoff from Precipitation-Frequency Events

- A regional rainfall-frequency analysis was performed
- Rainfall-frequency events were routed with HEC-HMS
- Results suggest much rarer AEPs for the PMF

Spatial & Causal Information Expansion



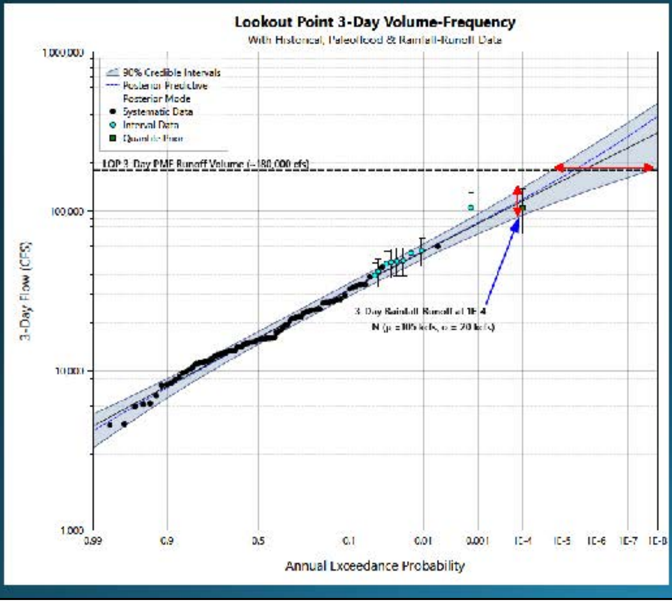
Select Distribution for 0.0001: Normal

Mean (μ) 105000

Std Dev (σ) 20000

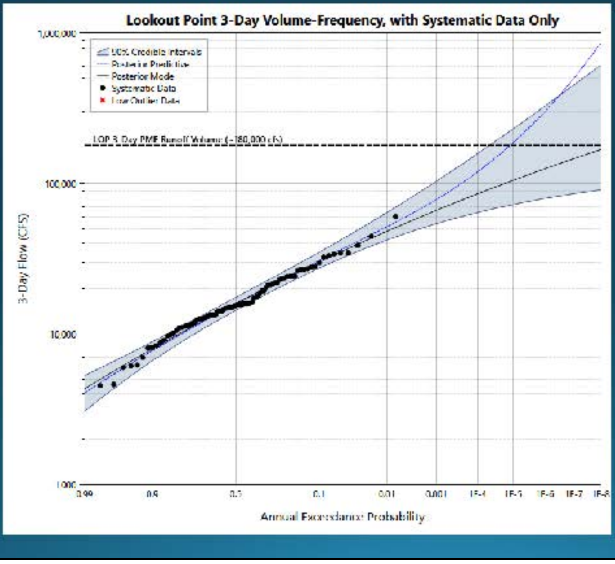
- Rainfall-Runoff at AEP of 1E-4
  - Normally distributed
  - Mean of 105,000 cfs
  - Standard Deviation of 20,000 cfs

Spatial & Causal Information Expansion

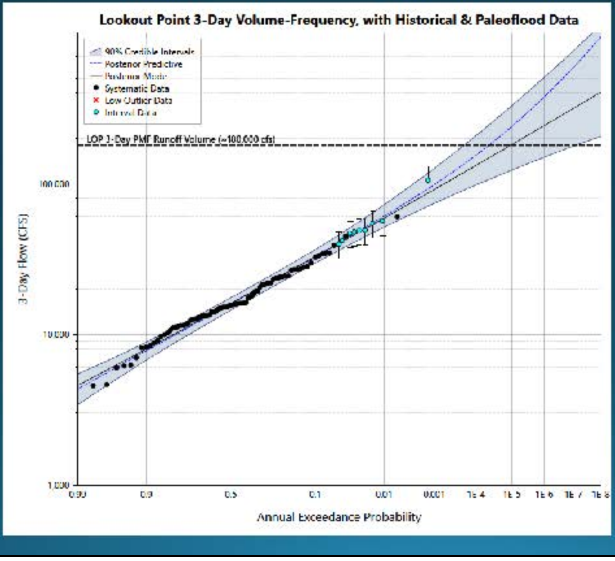


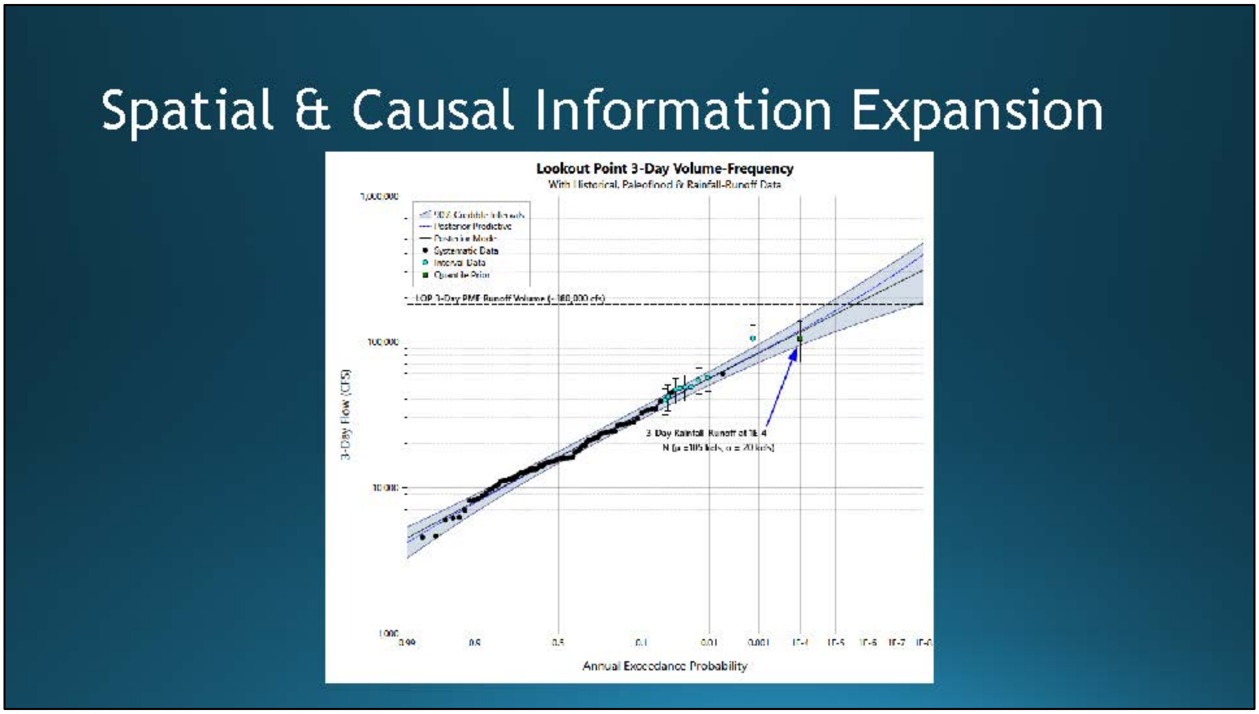
- A major reduction in uncertainty in the quantile estimate for the 1:10,000 (1E-4) AEP
- A sizeable reduction in uncertainty in the estimated AEP for the PMF
  - ~ 3 orders of magnitude
- The expected and most likely curves are much closer together

Systematic Data

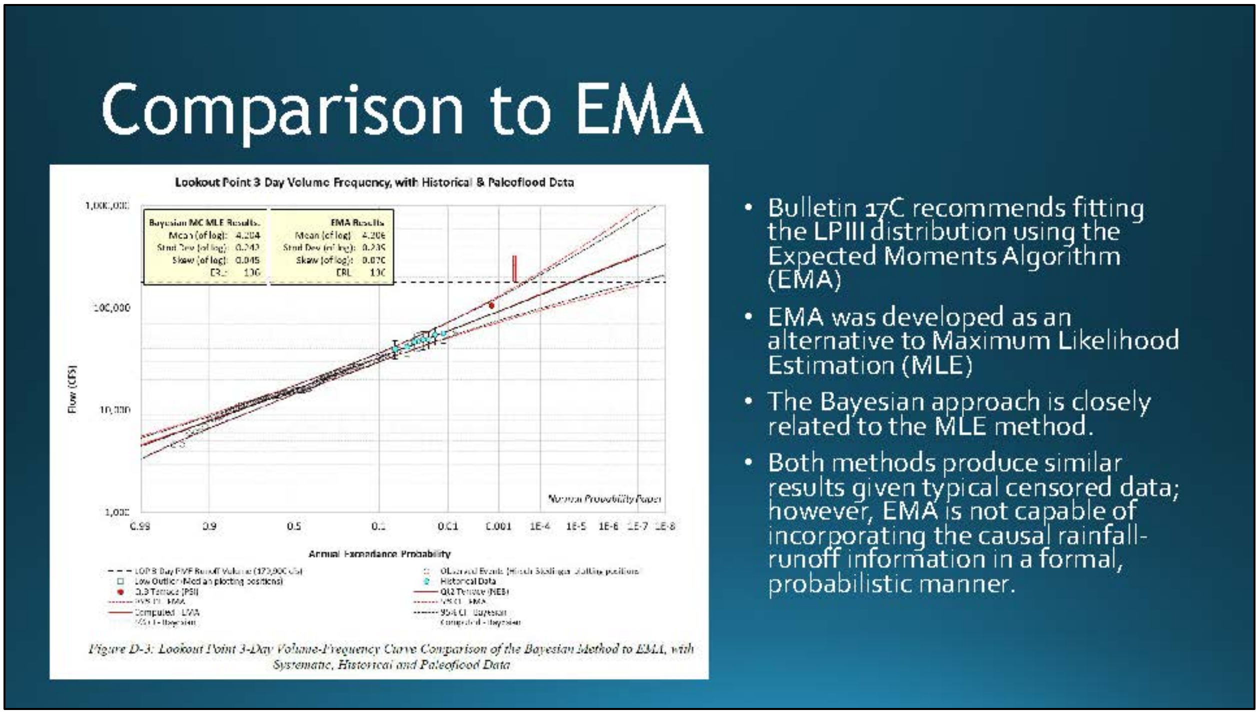


Temporal Information Expansion





Spatial & Causal Information Expansion



Comparison to EMA

Bayesian MC MLE Results		EMA Results	
Mean (of log):	4.204	Mean (of log):	4.206
Stnd Dev (of log):	0.242	Stnd Dev (of log):	0.235
Skew (of log):	0.045	Skew (of log):	0.070
ERL:	106	ERL:	106

Figure D-3: Lookout Point 3-Day Volume-Frequency Curve Comparison of the Bayesian Method to EMA, with Systematic, Historical and Paleoflood Data

- Bulletin 17C recommends fitting the LPIII distribution using the Expected Moments Algorithm (EMA)
- EMA was developed as an alternative to Maximum Likelihood Estimation (MLE)
- The Bayesian approach is closely related to the MLE method.
- Both methods produce similar results given typical censored data; however, EMA is not capable of incorporating the causal rainfall-runoff information in a formal, probabilistic manner.

Conclusions

- The Bayesian flood frequency approach can incorporate all available sources of hydrologic information, such as paleofloods, regional rainfall-runoff results, and expert elicitation.
- The ability of the Bayesian approach to use all pieces of information in conjunction is a major advantage over other methods, such as EMA, and provides much better estimates of design floods with specified AEPs.
- Complementing systematic flood data with temporal, spatial, and causal information should become the standard procedure for estimating exceedance probabilities for extreme floods.

RMC-BestFit

Bayesian Estimation and Fitting Software

3.5 Day 2: Session 2B – Coastal Flooding

Session Chair: Joseph Kanney, NRC/RES/DRA

3.5.1 Presentation 2B-1 (KEYNOTE): South Atlantic Coast Study: Coastal Hazards System

Authors: Norberto C. Nadal-Caraballo, Chris Massey, and Victor M. Gonzalez, U.S. Army Corps of Engineers, Engineer Research & Development Center, Coastal and Hydraulics Laboratory (USACE/ERDC/CHL); Kelly Legault, USACE Jacksonville District (Session 2B-1)

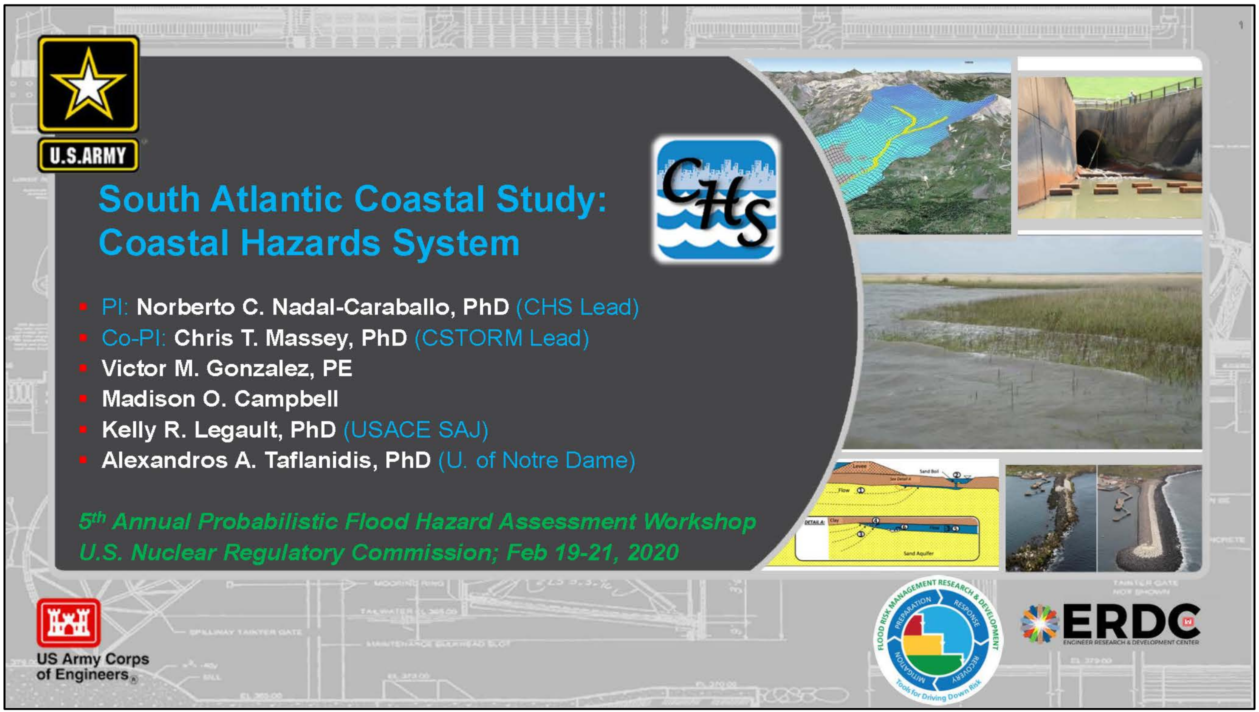
Speaker: Norberto C. Nadal-Caraballo

3.5.1.1 Abstract

Seven of the ten costliest U.S. tropical cyclones (TCs) have made landfall within the boundaries of the USACE South Atlantic Division (SAD) region. The devastation caused by recent TCs such as Hurricane Michael and Hurricane Maria have underscored the need for accurate quantification of coastal storm hazards. The South Atlantic Coast Study (SACS) is an on-going effort by SAD and the U.S. Army Engineer Research and Development Center's Coastal and Hydraulics Laboratory (ERDC-CHL) to expand the Coastal Hazards System (CHS) to cover the SAD domain. The CHS is a national program for the quantification of extreme coastal hazards that directly supports a wide range of coastal engineering and science activities within the federal government, private sector, and the academia. CHS includes a database, web-based data mining, and tools for the visualization of Probabilistic Coastal Hazards Analysis (PCHA) results.

The goal of the SACS-CHS is to quantify storm hazards under existing and future sea-level-change (SLC) conditions, in order to aid decision-making and employ modern engineering methods focused on reducing flooding risk and increasing resiliency. It encompasses three U.S. coastal regions: Phase 1, Puerto Rico and the U.S. Virgin Islands; Phase 2, North Carolina to South Florida; and Phase 3, South Florida to Mississippi. Conducting PCHA within these regions requires the development and simulation of synthetic TCs covering the practical physical-parameter and probability spaces. For the SACS-CHS, approximately 2,500 synthetic TCs are being simulated considering present-day conditions and future SLC scenarios, requiring over 250 million CPU-hours in a high-performance computing (HPC) environment. Coastal hazards to be computed include storm surge, wave climate, wind, and currents. SACS extends the coverage of the CHS to the entire U.S. hurricane-exposed coastline, with the exception of Southern California.

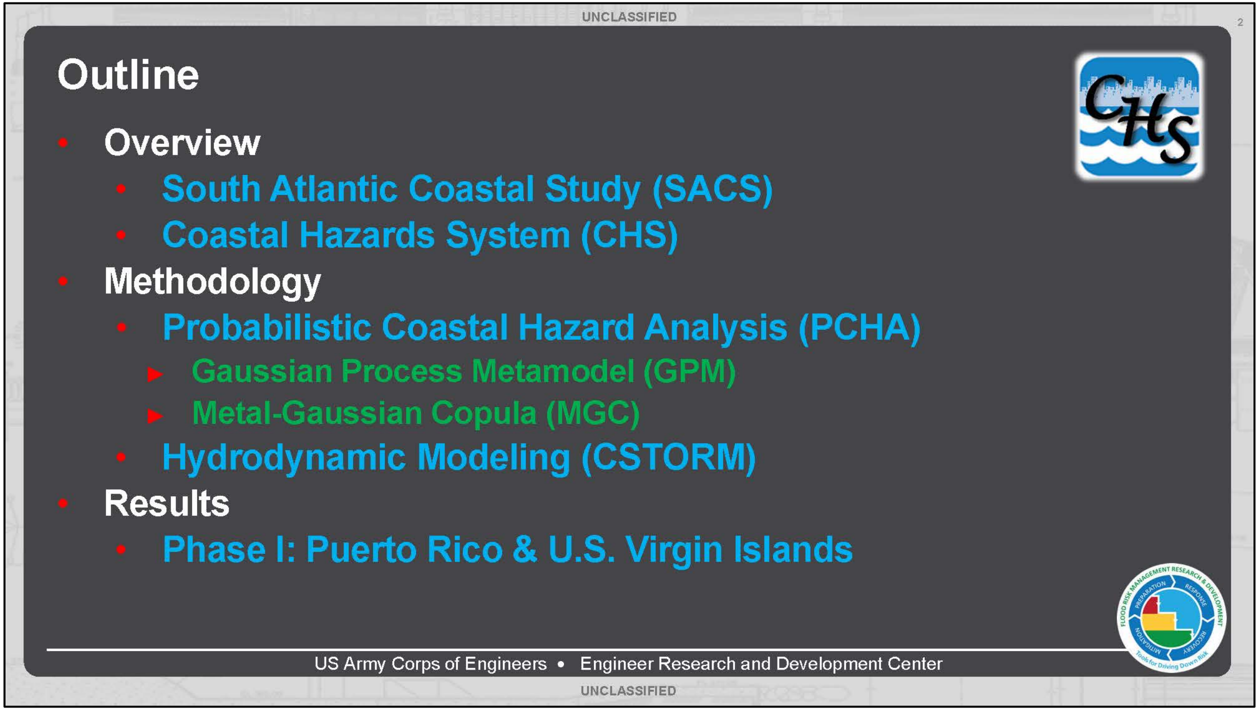
3.5.1.2 Presentation (ADAMS Accession No. ML20080M141)



South Atlantic Coastal Study: Coastal Hazards System

- PI: **Norberto C. Nadal-Caraballo, PhD** (CHS Lead)
- Co-PI: **Chris T. Massey, PhD** (CSTORM Lead)
- **Victor M. Gonzalez, PE**
- **Madison O. Campbell**
- **Kelly R. Legault, PhD** (USACE SAJ)
- **Alexandros A. Taflanidis, PhD** (U. of Notre Dame)

5th Annual Probabilistic Flood Hazard Assessment Workshop
U.S. Nuclear Regulatory Commission; Feb 19-21, 2020



Outline

- Overview
  - South Atlantic Coastal Study (SACS)
  - Coastal Hazards System (CHS)
- Methodology
  - Probabilistic Coastal Hazard Analysis (PCHA)
    - Gaussian Process Metamodel (GPM)
    - Metal-Gaussian Copula (MGC)
  - Hydrodynamic Modeling (CSTORM)
- Results
  - Phase I: Puerto Rico & U.S. Virgin Islands

Congressionally mandated regional study

Water Resources Development Act of 2016 (WRDA 2016)
Section 1204: South Atlantic Coastal Study (SACS)

Authorizes Secretary of the Army to conduct a comprehensive coastal study within the geographic boundaries of the South Atlantic Division (SAD) to

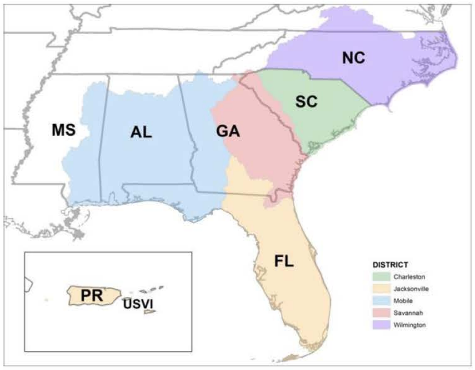
1. identify risks and vulnerabilities due to increased hurricane and storm damage as a result of sea level rise;
2. recommend measures to address the vulnerabilities; and
3. develop a long-term strategy
    - address increased storm damages from rising sea levels
    - identify opportunities to enhance resiliency and increase sustainability in high-risk areas

---

South Atlantic Coastal Study (SACS)

The geographic extent shall include the three distinct coastal regions within SAD's Area of Responsibility (AOR):

- Atlantic Coast
    - North Carolina to South Florida
- Gulf Coast
    - South Florida to Mississippi
- Caribbean
    - Puerto Rico and U.S. Virgin Islands



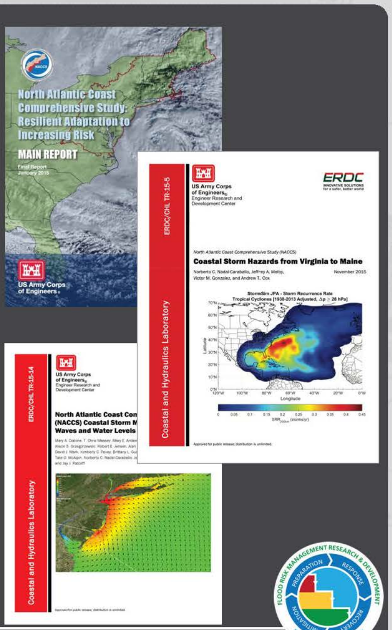
South Atlantic Coastal Study (SACS) Map
(Study extends from the coast inland to the extent of tidal influence)

Coastal AOR: from the coast to the extent of the tidal influence.

South Atlantic Coastal Study (SACS)

This comprehensive study shall be modeled after the North Atlantic Coast Comprehensive Study (NACCS)

- Leverage tools and processes where practicable and with applicable lessons learned applied.
- Data shall be evaluated consistent with the NACCS to the maximum extent practicable so that consistent standards can be applied between NAD and SAD.
- Coastal Hazards System (CHS)



South Atlantic Coastal Study (SACS)

Coastal Hazards System (CHS)

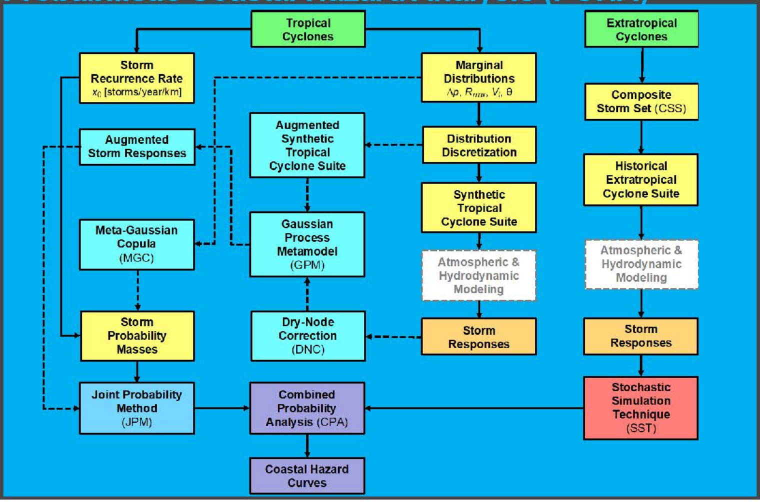
A national program with the primary goal of quantifying coastal hazards due to tropical, extratropical cyclones, and extreme storms. The CHS includes a database, web-based data mining, and visualization of PCHA results: storm surge, wave climate, currents, wind, and rainfall

Probabilistic Coastal Hazard Analysis (PCHA)

An innovative statistical and probabilistic framework for the comprehensive characterization of storm climatology, high-resolution numerical modeling, and advanced joint probability analysis of atmospheric forcing and primary storm responses, including associated aleatory and epistemic uncertainties.

Coastal Hazards System (CHS)

Probabilistic Coastal Hazard Analysis (PCHA)



PCHA Advancements

Filling historical TC data gaps

- Central pressure
- Radius of maximum winds

Gaussian Process Metamodel

- Dry-node correction
- Augmented TC suites

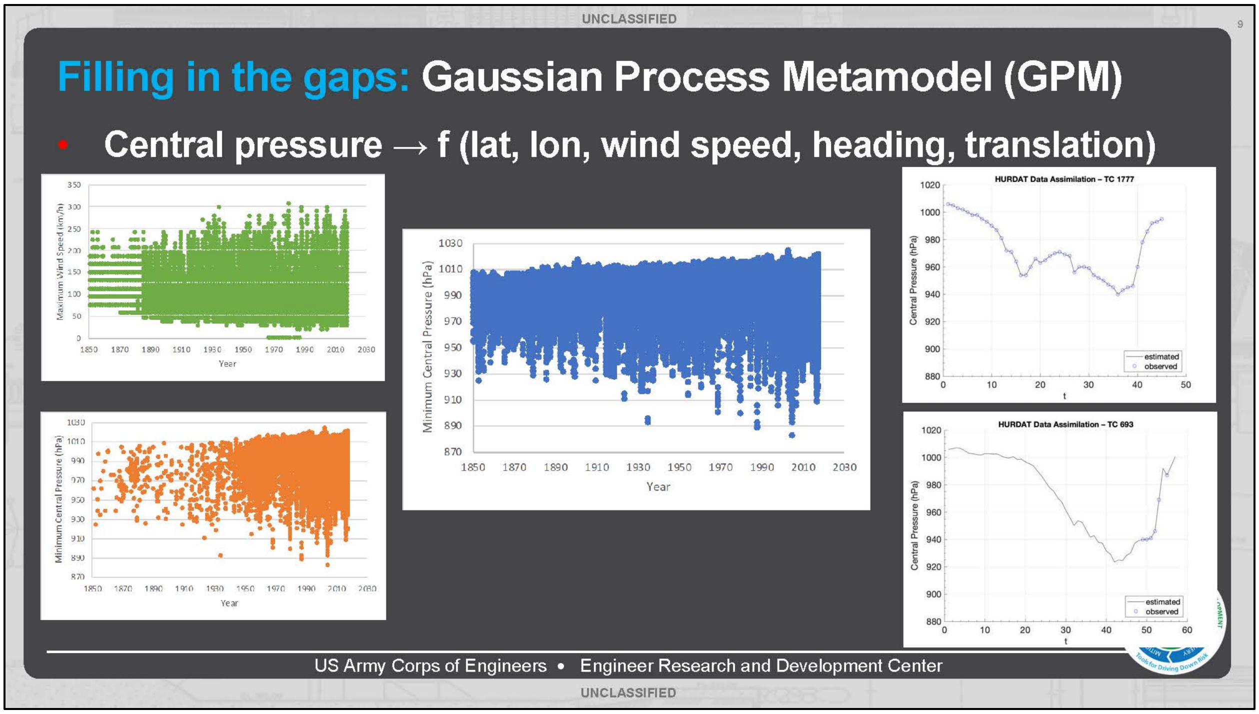
Meta-Gaussian Copula

- Correlation matrix
- Higher resolution in parameter & probability spaces

Coastal Hazards System (CHS)

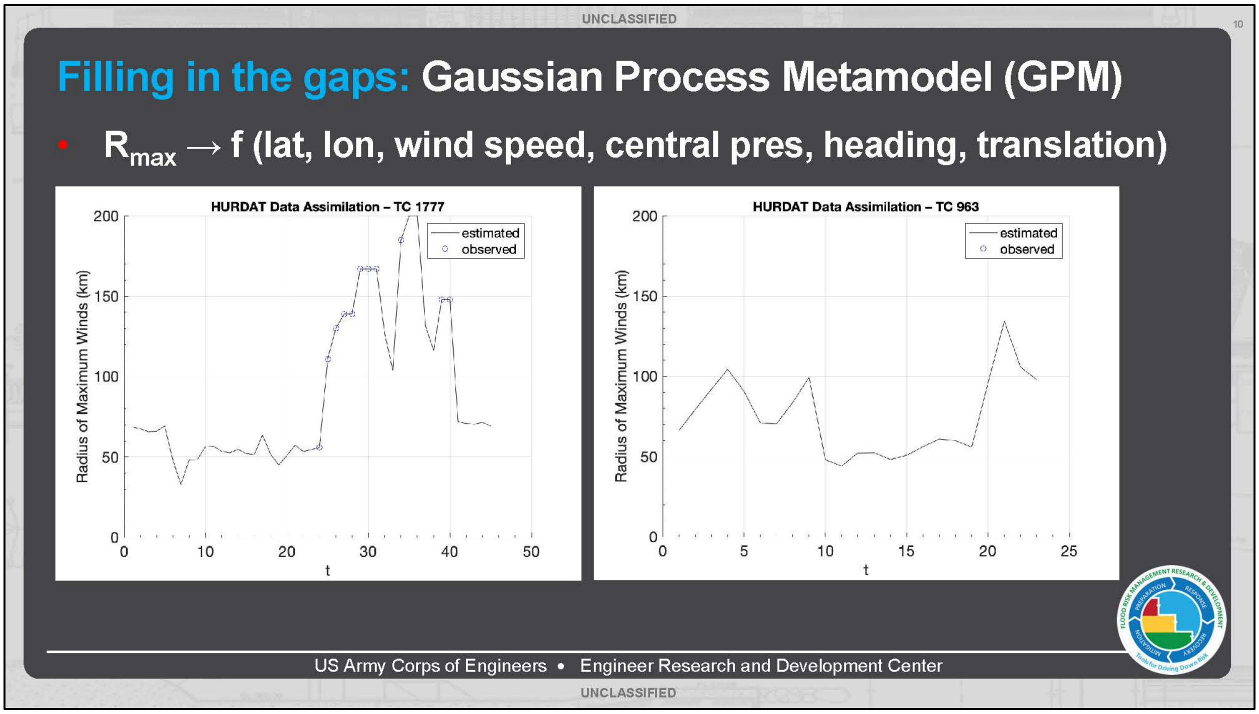
PCHA – Filling in the gaps

1. NHC HURricane DATa 2nd generation (HURDAT2)
   - TC parameters: max wind speed, central pressure, lat, lon
2. Automated Tropical Cyclone Forecast (ATCF)
   - Best track data: 2019
3. Colorado State (CSU) Extended Best Track (EBTRK)
   - R_{max} (1988 – 2018)
4. Gaussian Process Metamodel (GPM)
   - Fills in gaps in central pressure and estimates R_{max}
   - Period: 1851 – 2019



Filling in the gaps: Gaussian Process Metamodel (GPM)

- Central pressure → f (lat, lon, wind speed, heading, translation)

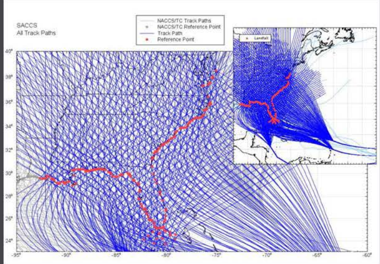


Filling in the gaps: Gaussian Process Metamodel (GPM)

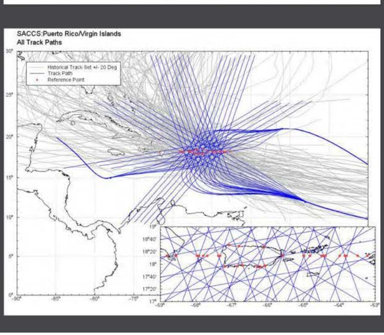
- R_{max} → f (lat, lon, wind speed, central pres, heading, translation)

SACS-CHS

- Phase I: Puerto Rico & USVI
  - TC suite: 300
  - Virtual gages: 14,891
- Phase II: Atlantic Coast
  - TC suite: 1,060
  - Virtual gages: 30,830
- Phase III: Gulf of Mexico
  - TC suite: 1,085
  - Virtual gages: 21,705



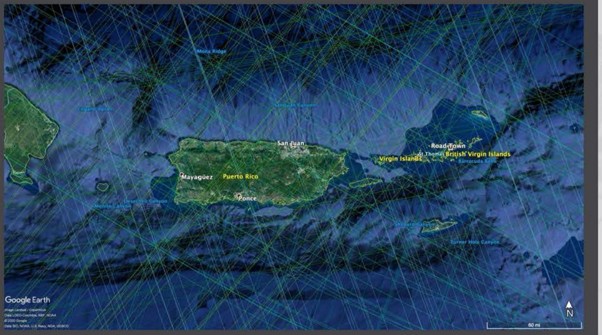
CONUS
1,700 TCs
70 XCs

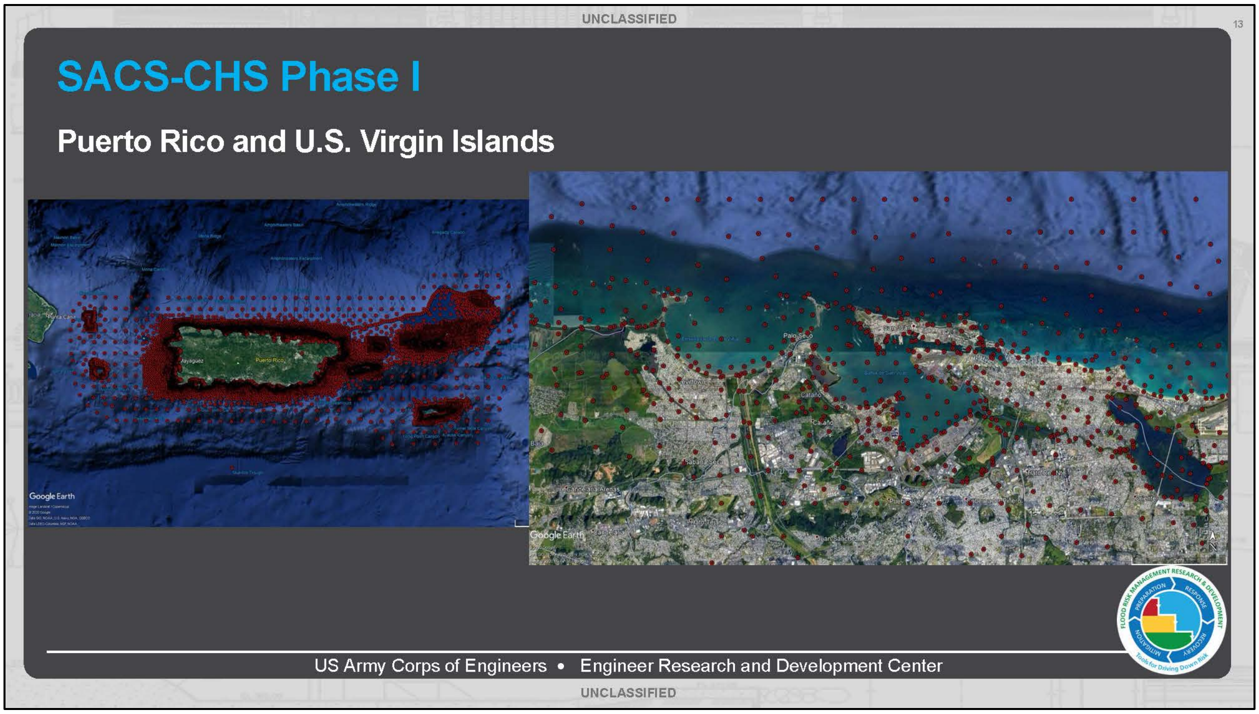


OCONUS
300 TCs

SACS-CHS Phase I

Puerto Rico and U.S. Virgin Islands





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SACS-CHS Phase I

Puerto Rico and U.S. Virgin Islands

US Army Corps of Engineers • Engineer Research and Development Center

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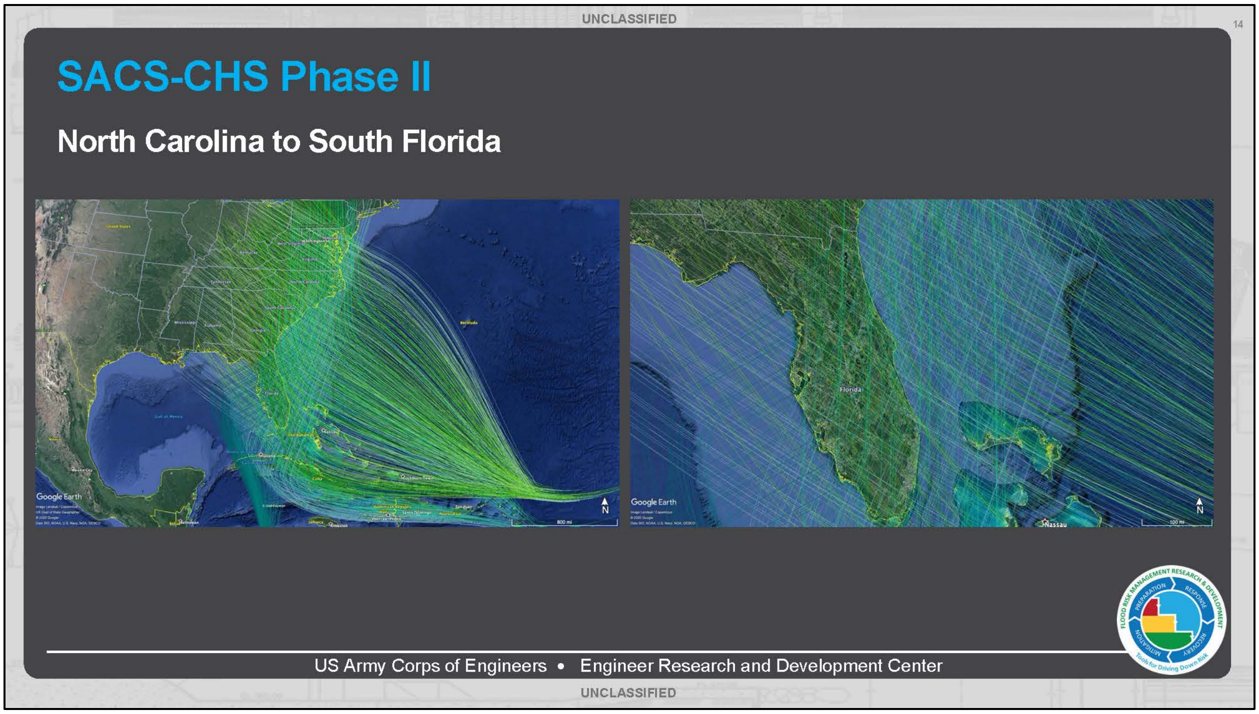

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SACS-CHS Phase II

North Carolina to South Florida

US Army Corps of Engineers • Engineer Research and Development Center

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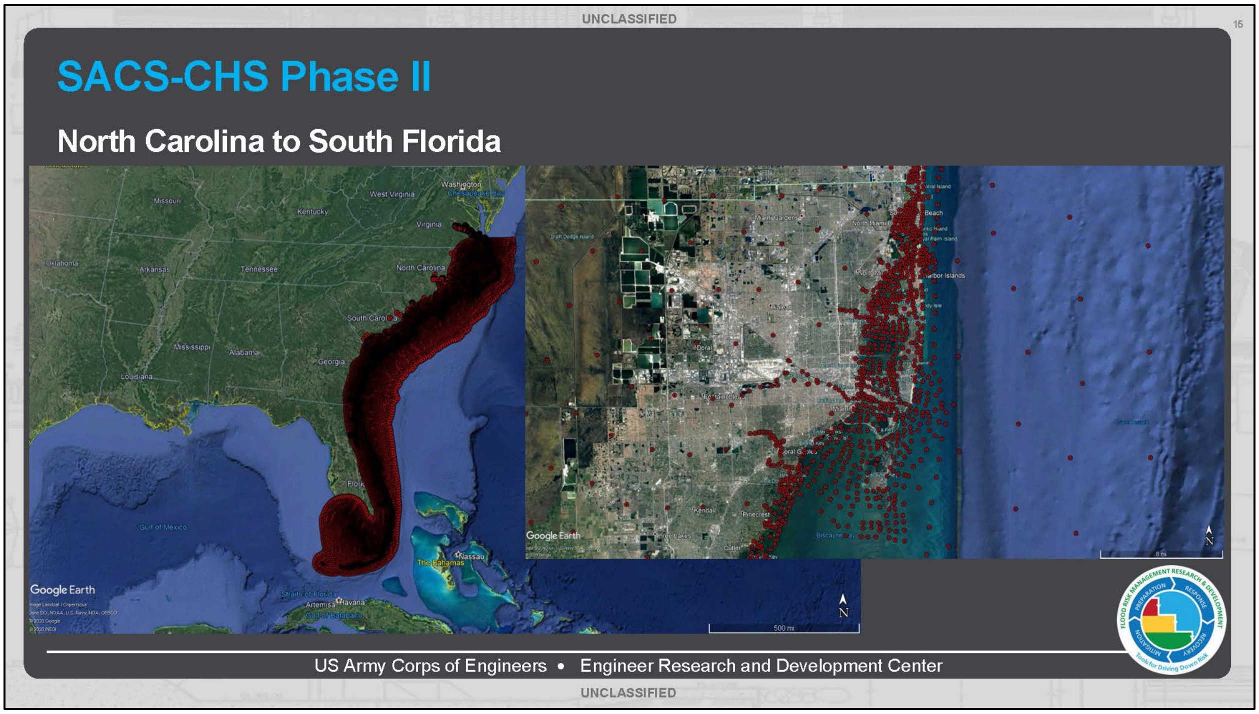
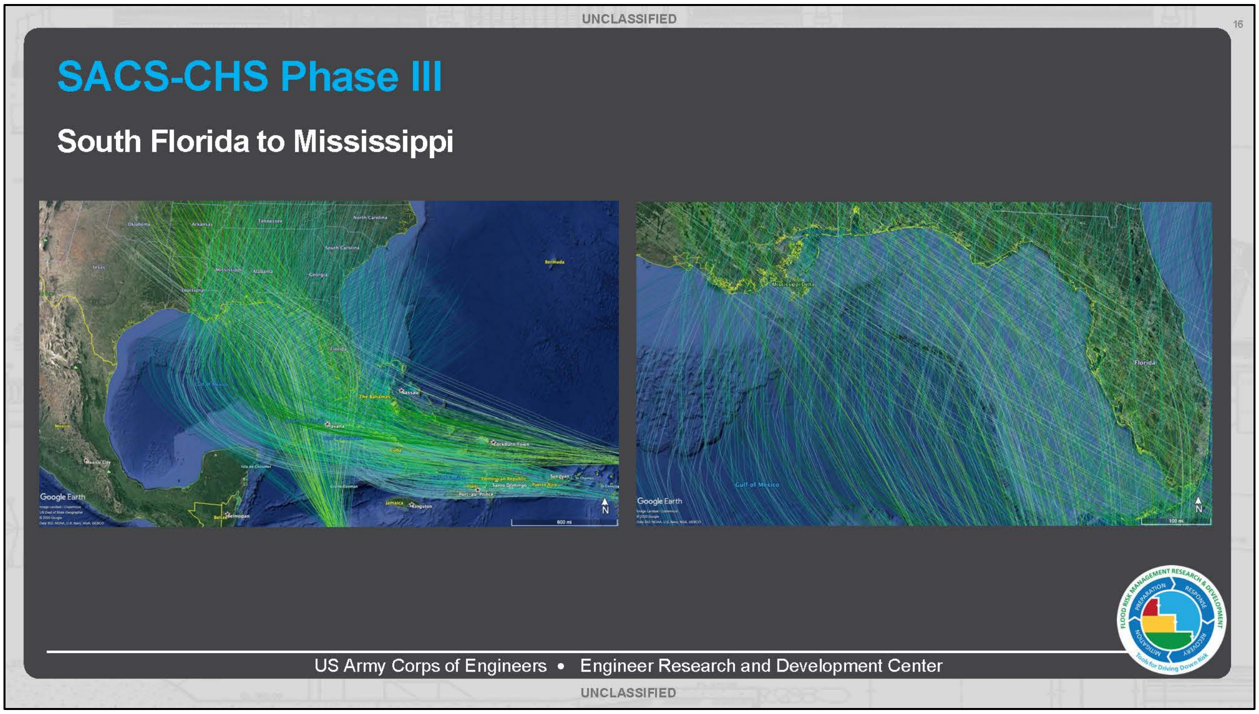


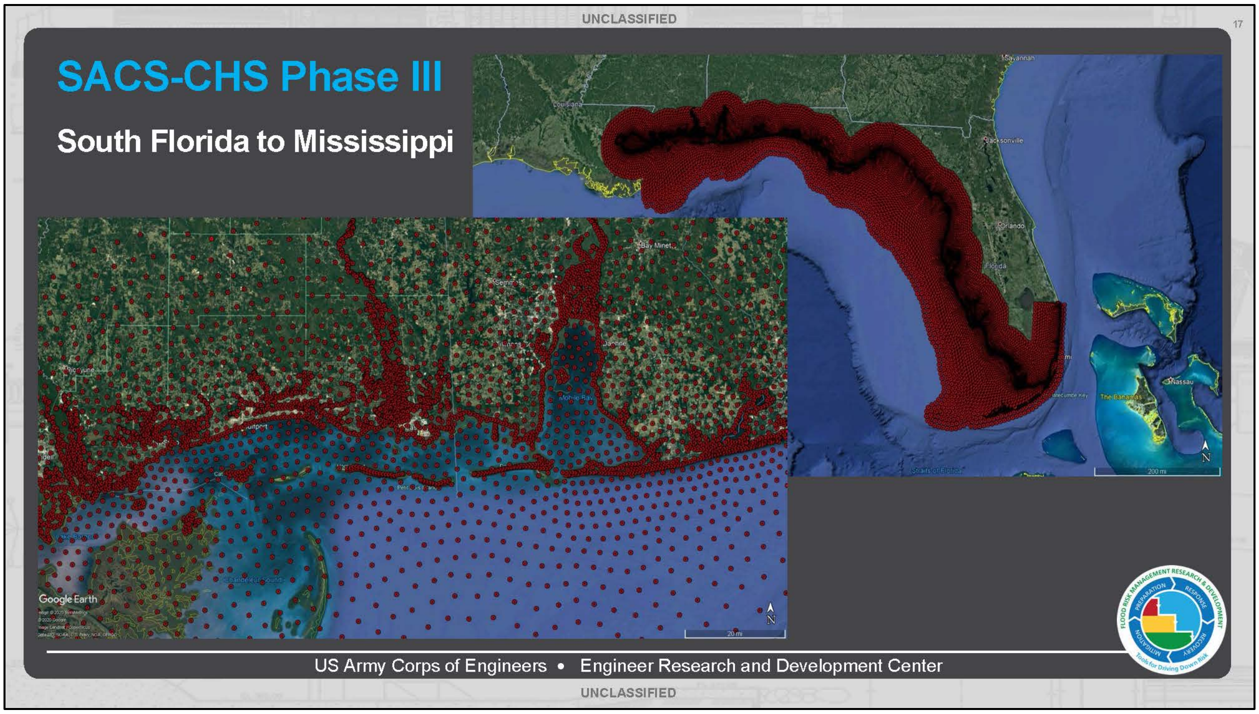
SACS-CHS Phase II

North Carolina to South Florida



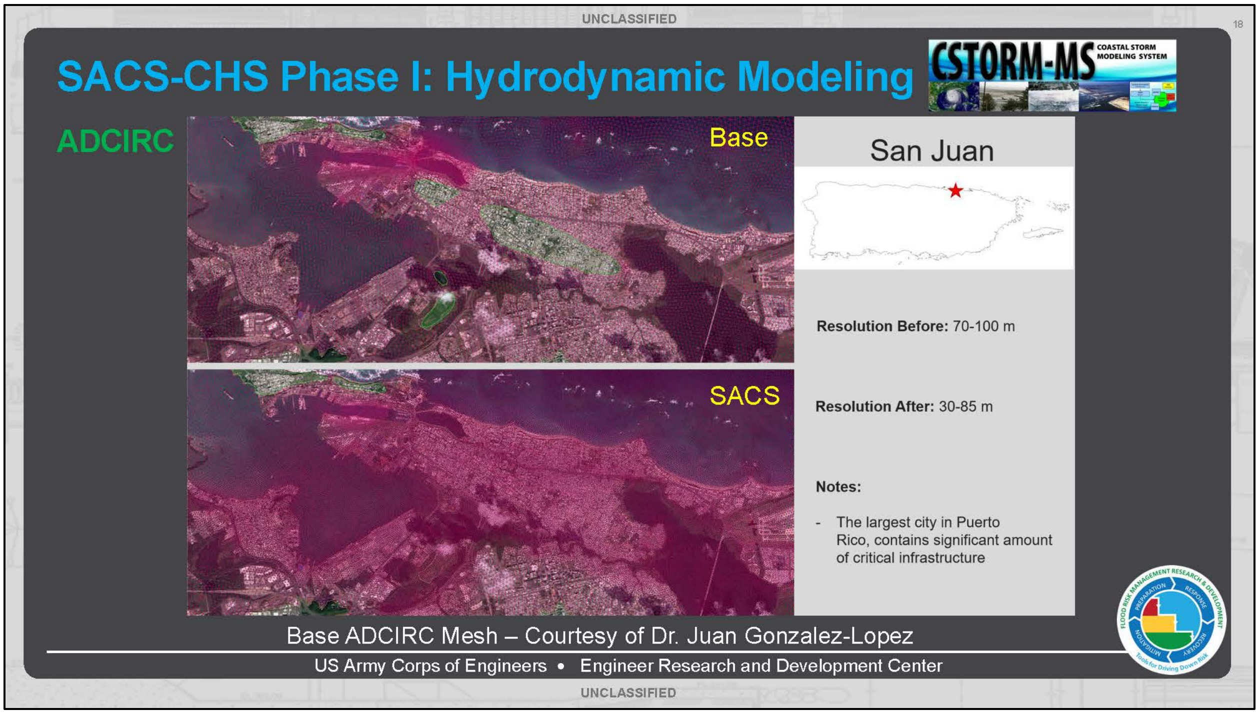
SACS-CHS Phase III

South Florida to Mississippi



SACS-CHS Phase III

South Florida to Mississippi



SACS-CHS Phase I: Hydrodynamic Modeling

San Juan

Resolution Before: 70-100 m

Resolution After: 30-85 m

Notes:

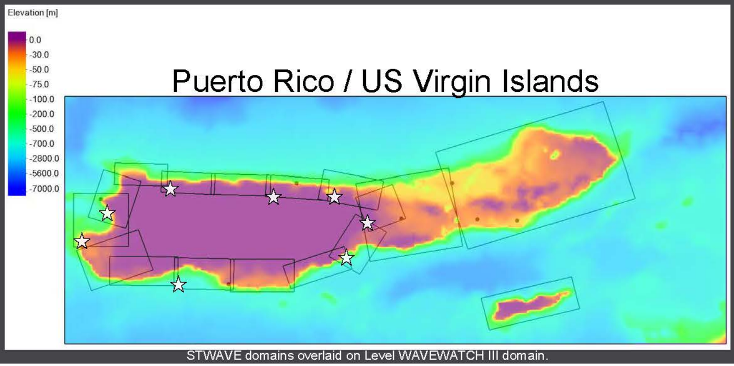
- The largest city in Puerto Rico, contains significant amount of critical infrastructure

Base ADCIRC Mesh – Courtesy of Dr. Juan Gonzalez-Lopez

SACS-CHS Phase I: Hydrodynamic Modeling

Waves

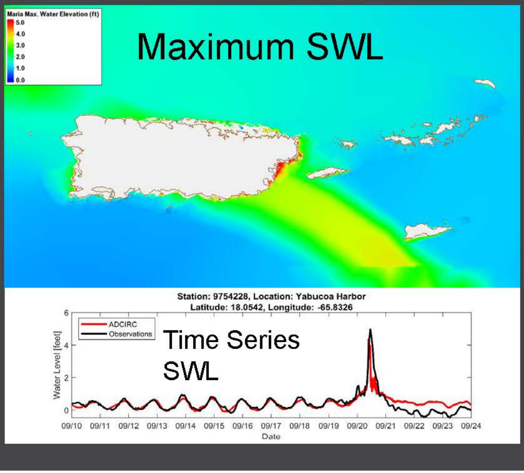
- Nearshore spectral wave model
- 17 STWAVE domains
  - starred domains are 150-m resolution, focused on PR population centers
  - others, including Vieques, Culebra, St. Croix, and the Virgin Islands, are 200-m
  - extended into deep water where possible for wave transformation over reefs/shallow water to be estimated by STWAVE model
- Black dots indicate location of buoys for validation

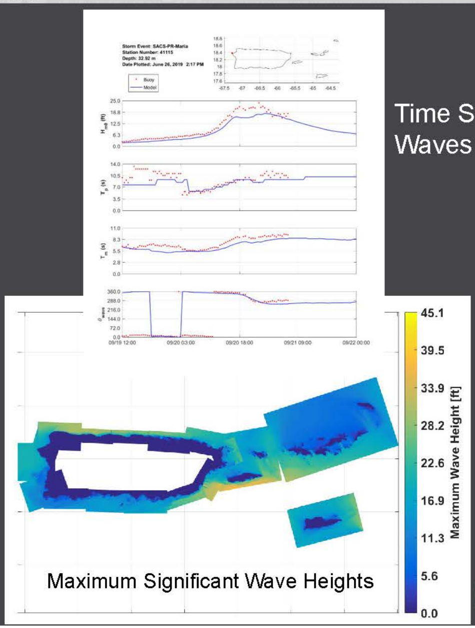


STWAVE domains overlaid on Level WAVEWATCH III domain.

SACS-CHS Phase I: Validation

Hurricane Maria

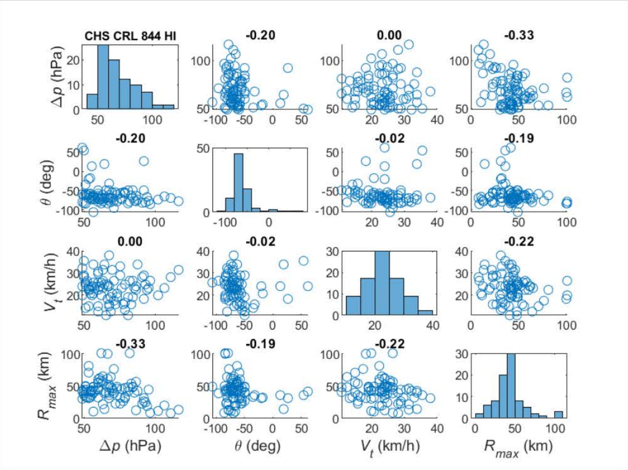


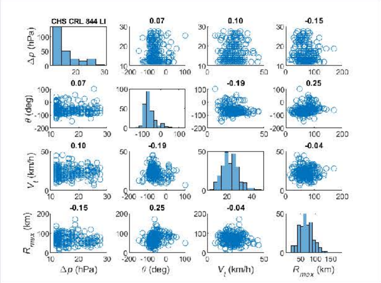


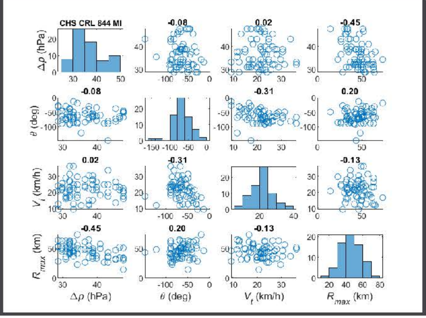
Time Series Waves

SACS-CHS Phase I: PCHA

Meta-Gaussian Copula: Correlation Matrix

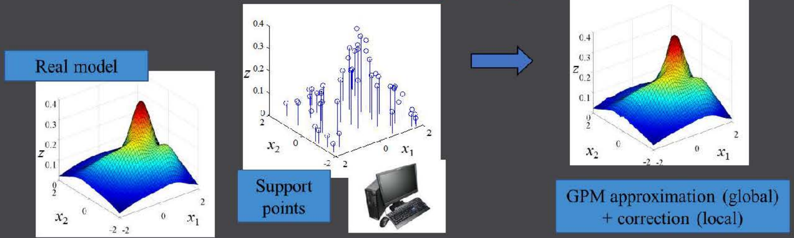




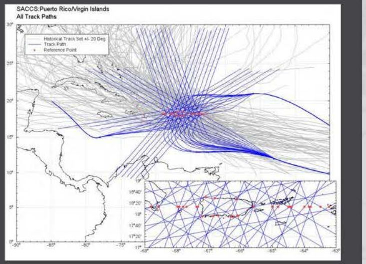


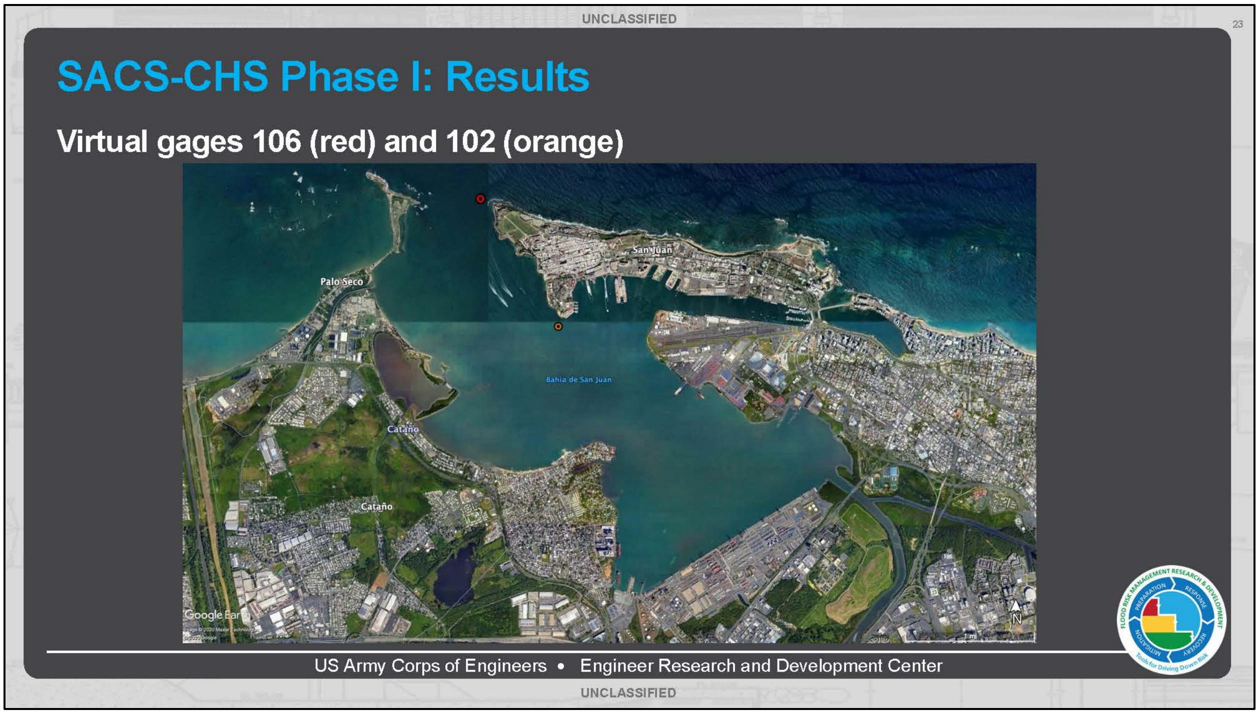
SACS-CHS Phase I: PCHA

Gaussian Process Metamodel (GPM)



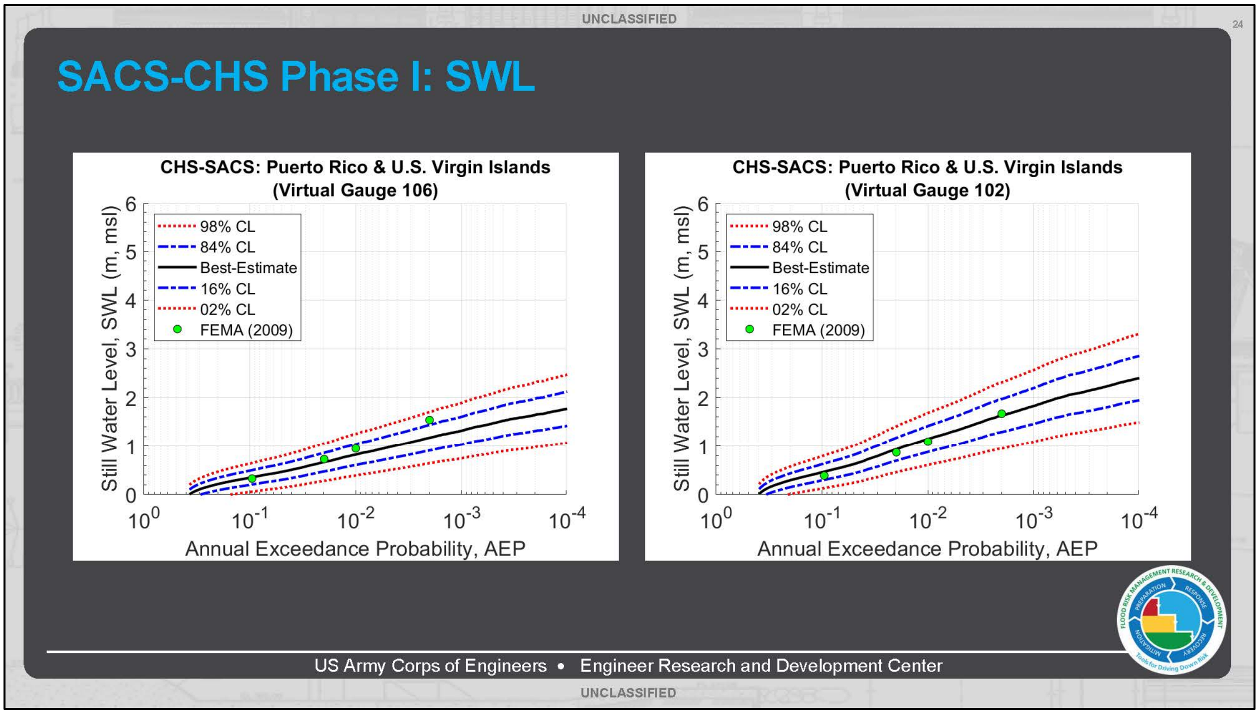
TC Parameter	Full Suite 300 TCs	Augmented Suite 348,000 TCs
θ (deg)	-60:20:60	-60:20:60
Δp (hPa)	8:10:148; 18:10:138	8:5:148
R_{max} (km)	8 to 143.6	10:5:155
V_f (km/h)	8 to 40	5:5:50



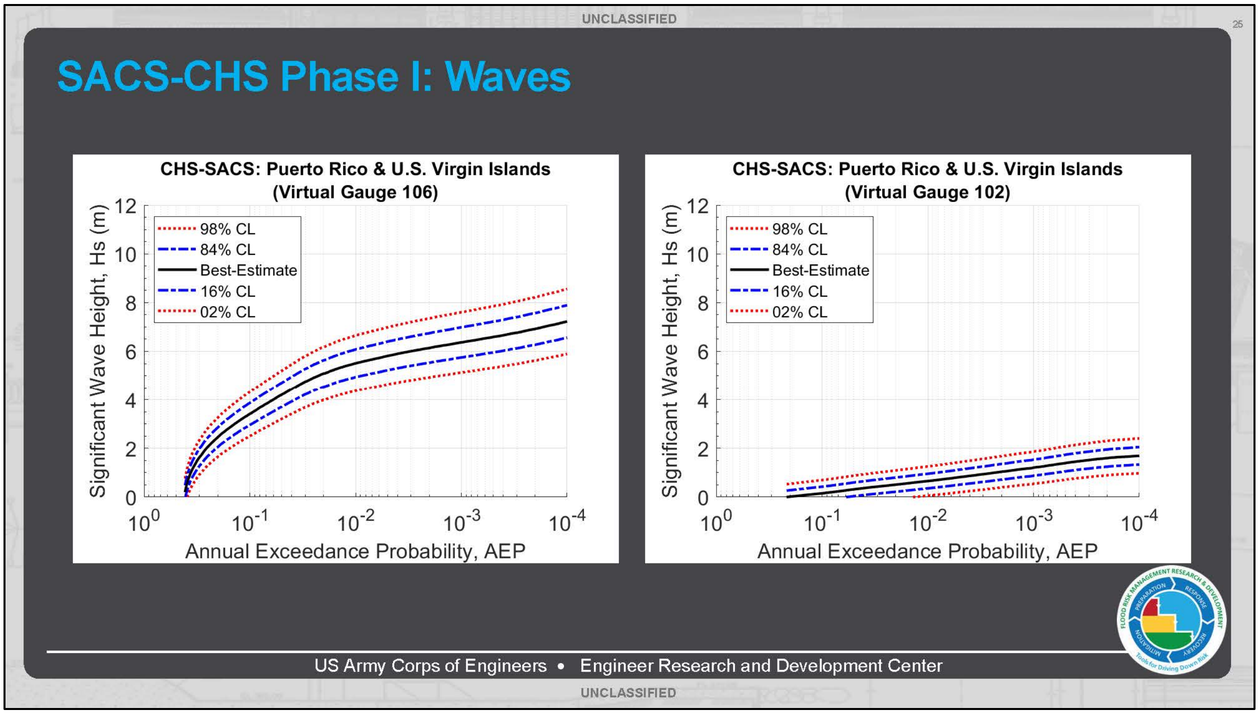


SACS-CHS Phase I: Results

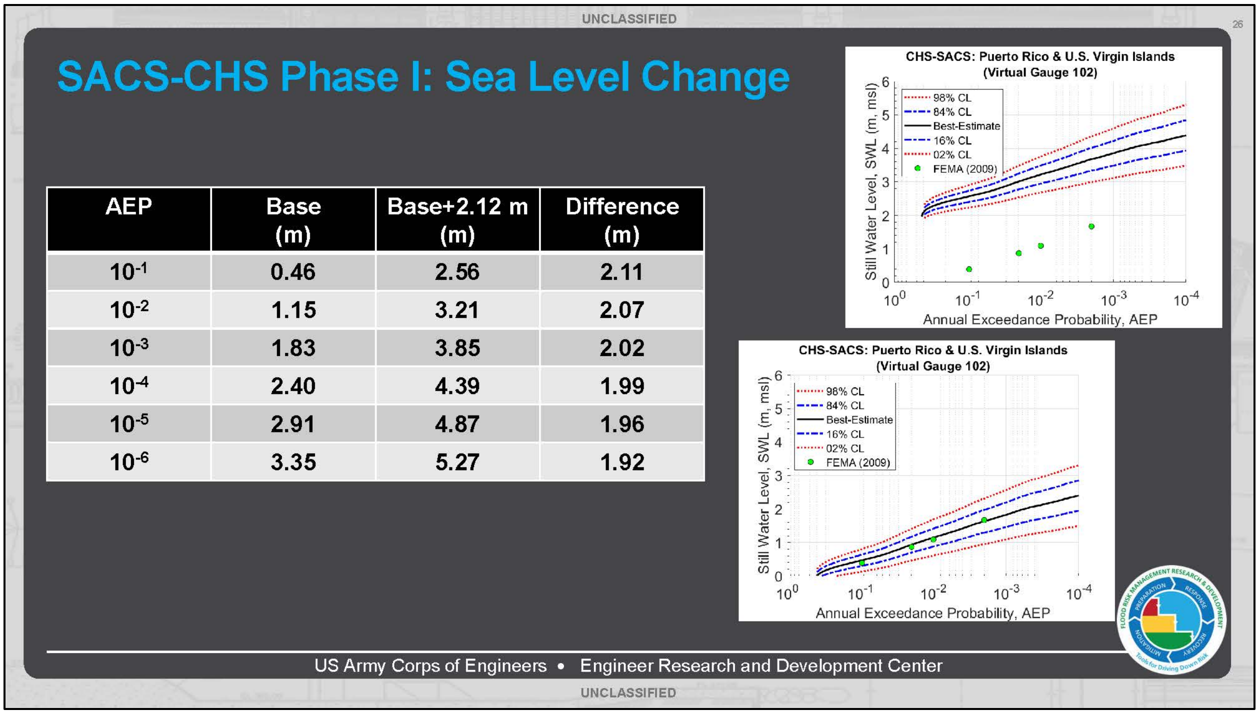
Virtual gages 106 (red) and 102 (orange)



SACS-CHS Phase I: SWL



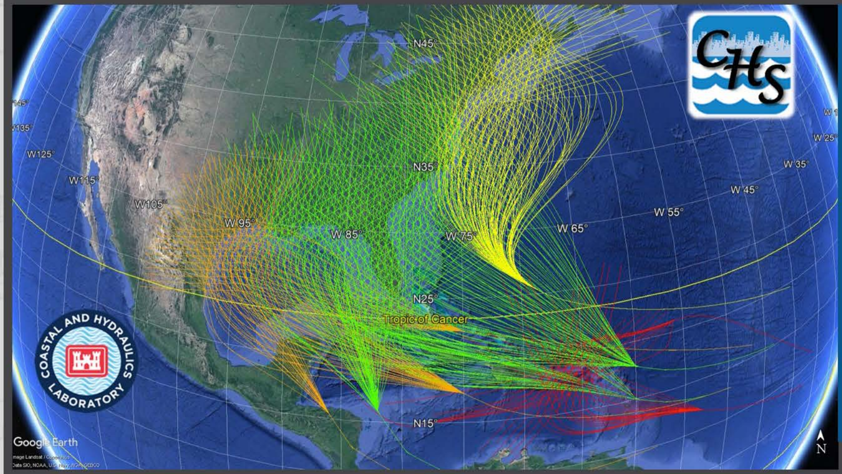
SACS-CHS Phase I: Waves



SACS-CHS Phase I: Sea Level Change

AEP	Base (m)	Base+2.12 m (m)	Difference (m)
10^{-1}	0.46	2.56	2.11
10^{-2}	1.15	3.21	2.07
10^{-3}	1.83	3.85	2.02
10^{-4}	2.40	4.39	1.99
10^{-5}	2.91	4.87	1.96
10^{-6}	3.35	5.27	1.92

CHS Synthetic Tropical Cyclone Suite: 4,356 TCs

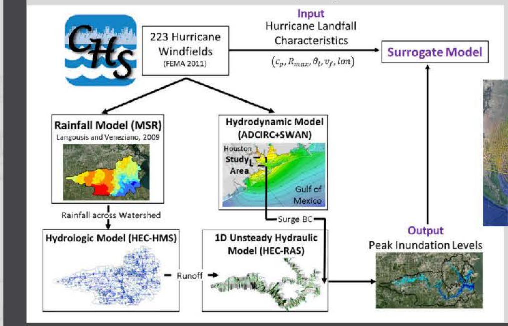


- North Atlantic Coast Comprehensive Study (NACCS)
  - 1,050 TCs (yellow tracks)
- Coastal Texas Protection and Restoration Feasibility Study (CTXS)
  - 660 TCs (orange tracks)
- South Atlantic Coastal Study (SACS): Puerto Rico & USVI
  - 300 TCs (red tracks)
- South Atlantic Coastal Study (SACS): OCONUS
  - 1,700 TCs (green tracks)
- Louisiana Coastal Protection and Restoration (LACPR)
  - 646 TCs (not shown)

Compound Coastal & Inland Hazards

PCHA + Physics-based Parametric TC Rainfall Model

Bass and Bedient (2018)



223 Hurricane Windfields (FEMA 2011)

Input
Hurricane Landfall Characteristics
$(c_p, R_{max}, \theta_l, v_f, lon)$

Surrogate Model

Rainfall Model (MSR)
Langousis and Veneziano, 2009

Hydrodynamic Model (ADCIRC+SWAN)

Rainfall across Watershed

Surge BC

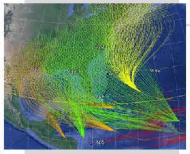
Hydrologic Model (HEC-HMS)

Runoff

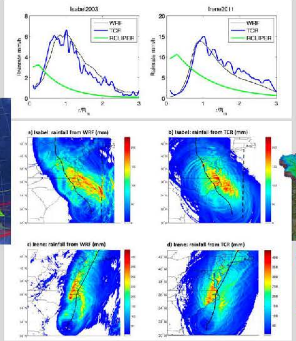
1D Unsteady Hydraulic Model (HEC-RAS)

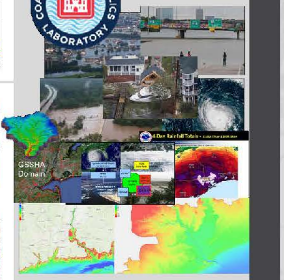
Output
Peak Inundation Levels

CHS
3,700+
Synthetic TCs



Lu et al. (2018)



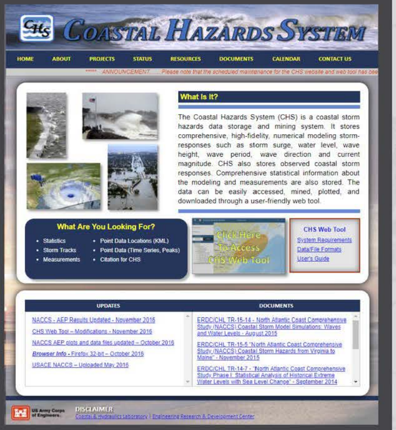


Conclusions

Coastal Hazards System (CHS)

The SACS-CHS will provide oceanographic and storm information to engineers, planners and managers across the South Atlantic and Northern Gulf of Mexico

- understand the likelihood and extent of present and future storm surge and storm waves
- design more reliable engineering projects and effective coastal storm damage solutions to reduce wave attack, provide flood protection, and create robust environments that can provide a buffer to coastal flooding
- allow communities to prepare for the future


COASTAL HAZARDS SYSTEM

***** ANNOUNCEMENT...... Please note that the scheduled maintenance for the CHS website and web tool has bee

What Is It?

The Coastal Hazards System (CHS) is a coastal storm hazards data storage and mining system. It stores comprehensive, high-fidelity, numerical modeling storm-responses such as storm surge, water level, wave height, wave period, wave direction and current magnitude. CHS also stores observed coastal storm responses. Comprehensive statistical information about the modeling and measurements are also stored. The data can be easily accessed, mined, plotted, and downloaded through a user-friendly web tool.

What Are You Looking For?

- Statistics
- Storm Tracks
- Measurements
- Point Data Locations (KML)
- Point Data (Time Series, Peaks)
- Citation for CHS

Click Here To Access CHS Web Tool

CHS Web Tool

System Requirements

Data/File Formats

User's Guide

UPDATES	DOCUMENTS
NACCS - AEP Results Updated - November 2016 CHS Web Tool – Modifications - November 2016 NACCS AEP plots and data files updated – October 2016 *Browser Info* - Firefox 32-bit – October 2016 USACE NACCS – Uploaded May 2016	ERDC/CHL TR-15-14 - North Atlantic Coast Comprehensive Study (NACCS) Coastal Storm Model Simulations: Waves and Water Levels - August 2015 ERDC/CHL TR-15-5 "North Atlantic Coast Comprehensive Study (NACCS) Coastal Storm Hazards from Virginia to Maine" - November 2015 ERDC/CHL TR-14-7 - "North Atlantic Coast Comprehensive Study Phase I: Statistical Analysis of Historical Extreme Water Levels with Sea Level Change" - September 2014

US Army Corps of Engineers

DISCLAIMER

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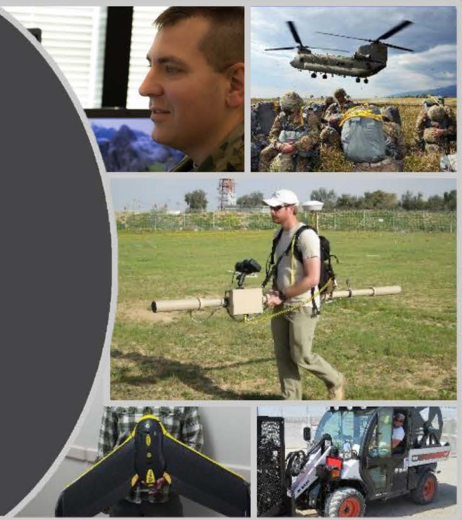
Questions?



Dr. Norberto C. Nadal-Caraballo

Leader, Coastal Hazards Group

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US Army Corps of Engineers

ERDC

ENGINEER RESEARCH & DEVELOPMENT CENTER

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3.5.2 Presentation 2B-2: Data, Models, Methods, and Uncertainty Quantification in Probabilistic Storm Surge Models.

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

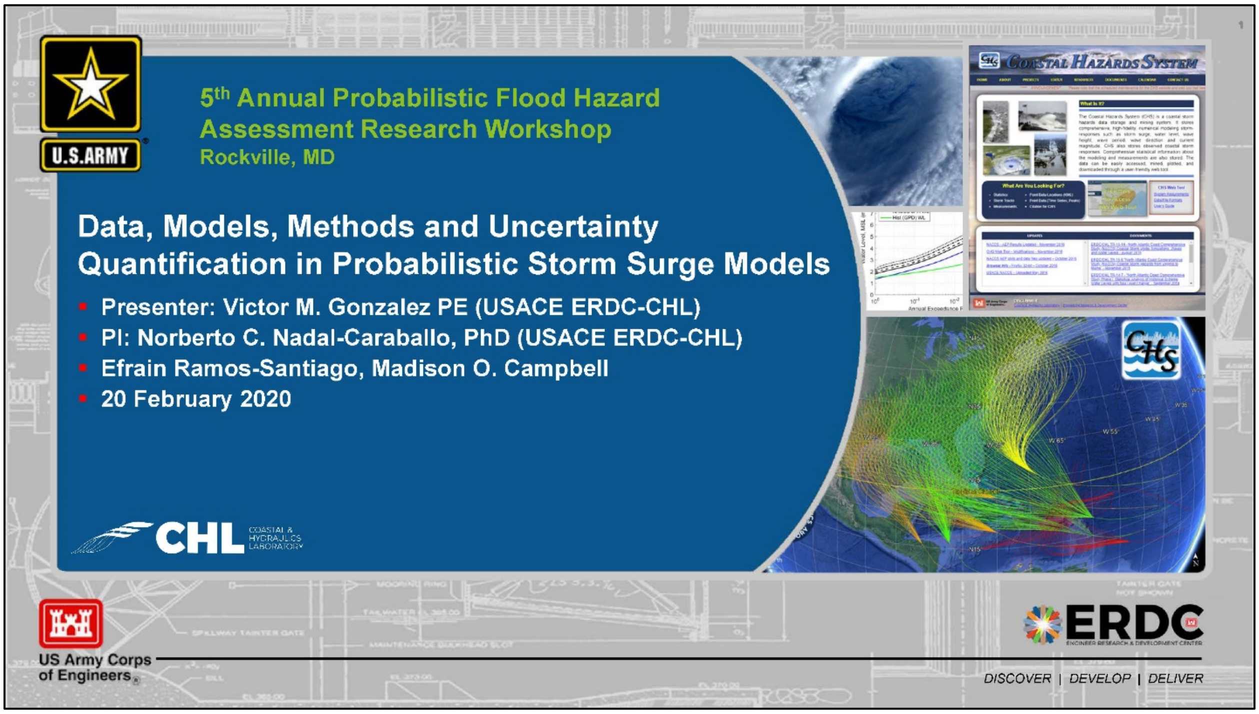
Speaker: Norberto C. Nadal-Caraballo

3.5.2.1 Abstract

Current approaches for probabilistic storm surge modeling rely on the joint probability analysis of tropical cyclone (TC) forcing and responses to overcome the temporal and spatial limitations of historical TC observations. Probabilistic coastal hazard analysis requires the quantification and propagation of uncertainties associated with the use of different data, models, and methods. This is of particular importance for critical infrastructure such as nuclear power plants where the quantification of storm surge hazard is sought for very small annual exceedance probabilities. The U.S. Army Engineer Research and Development Center, Coastal and Hydraulics Laboratory (ERDC-CHL) has performed a comprehensive assessment of uncertainties in probabilistic storm surge models in support of the U.S. Nuclear Regulatory Commission's (USNRC) efforts to develop a framework for probabilistic storm surge hazard assessment for nuclear power plants.

The examination of aleatory variability and epistemic uncertainty associated with the consideration of alternate technically defensible data, models, and methods was based on the application of the joint probability method (JPM). The JPM has become the standard probabilistic model used to assess coastal storm hazard in hurricane-prone U.S. coastal regions. This assessment also considered the use of methods not typically associated with the JPM such as Monte Carlo Simulation and surrogate modeling through the development of Gaussian process metamodels (GPMs). Specific topics that were examined include storm recurrence rate models, methods for defining joint probability of storm parameters, methods for generating synthetic storm simulation sets, and the integration of error terms in the development of hazard curves. The last topic included evaluating methods for calculating the error of the numerical storm surge model, distribution of the error, evaluation of Holland B as a JPM parameter, and characterization of the uncertainty in the integral. The approach followed was informed by USNRC guidance on probabilistic seismic hazard assessment (PSHA), in which uncertainty is propagated through the use of logic trees and quantified through the development of a family of hazard curves.

3.5.2.2 Presentation (ADAMS Accession No. ML20080M142)



5th Annual Probabilistic Flood Hazard Assessment Research Workshop
Rockville, MD

Data, Models, Methods and Uncertainty Quantification in Probabilistic Storm Surge Models

- Presenter: Victor M. Gonzalez PE (USACE ERDC-CHL)
- PI: Norberto C. Nadal-Caraballo, PhD (USACE ERDC-CHL)
- Efrain Ramos-Santiago, Madison O. Campbell
- 20 February 2020

CHL COASTAL & HYDRAULICS LABORATORY

US Army Corps of Engineers

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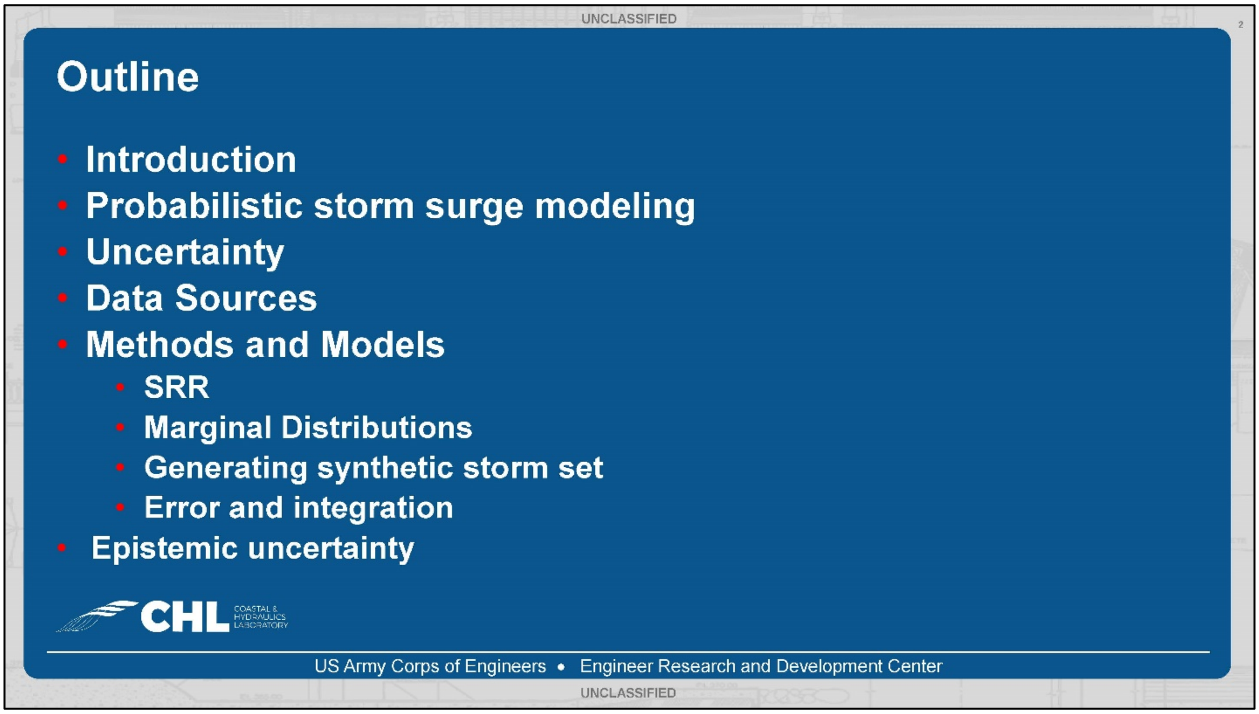

Outline

- Introduction
- Probabilistic storm surge modeling
- Uncertainty
- Data Sources
- Methods and Models
  - SRR
  - Marginal Distributions
  - Generating synthetic storm set
  - Error and integration
- Epistemic uncertainty

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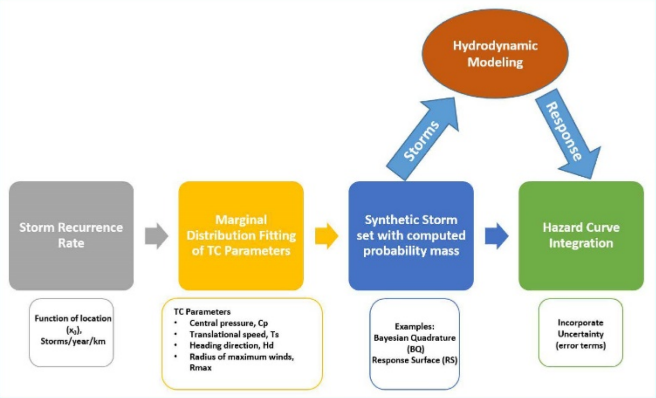
Introduction

- Project part of U.S. NRC's Probabilistic Flood Hazard Assessment (PFHA) research plan.
- Support risk-informed licensing and oversight activities.
- Develop hazard curves with uncertainty represented through confidence limit curves.
- Approach informed by USNRC guidance on probabilistic seismic hazard assessment (PSHA)
  - Evaluation of data, models, and methods used in probabilistic storm surge models.
  - Epistemic uncertainty is quantified and propagated through logic trees.
- Consider AEPs that go beyond traditional state-of-practice in non-nuclear facilities (e.g., 10^{-4} to 10^{-6}).

Probabilistic storm surge hazard modeling

- Based on the joint probability analysis of tropical cyclone (TC) forcing and responses.
- Basic elements:
  - SRR: Frequency of occurrence at location.
  - Development of Synthetic TCs and their probabilities.
  - Hydrodynamic Modeling: wind and pressure fields, circulation modeling (water levels), wave modeling.
  - Integration of response and uncertainty.



Uncertainty

JPM Integral

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

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

where:
$\lambda_{r(\hat{x})>r}$ = AEP 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 $\lambda\, p_i$, 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

- **Uncertainty:**
  - **Aleatory – natural randomness of a process, not reducible.**
  - **Epistemic – lack of knowledge about validity of models and data for the representation of real system.**

- **PSHA based approach:**
  - **Epistemic uncertainty based on the selection and application of alternative data, methods, and models.**
  - **Capture the center, body, and range of technically densible interpretations.**

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Data Sources

- **NOAA HURDAT2**
- **Extended Best Track Dataset - EBTRK (Demuth et al. 2006)**
- **GCM downscaling data**
- **Stochastic Track models**
- **Statistical models: e.g. R_{max} and Holland B**
- **Advance Tropical Cyclone Forecasting (ATCF) Data**
- **CHS Data (historical data reconstruction using metamodeling techniques)**

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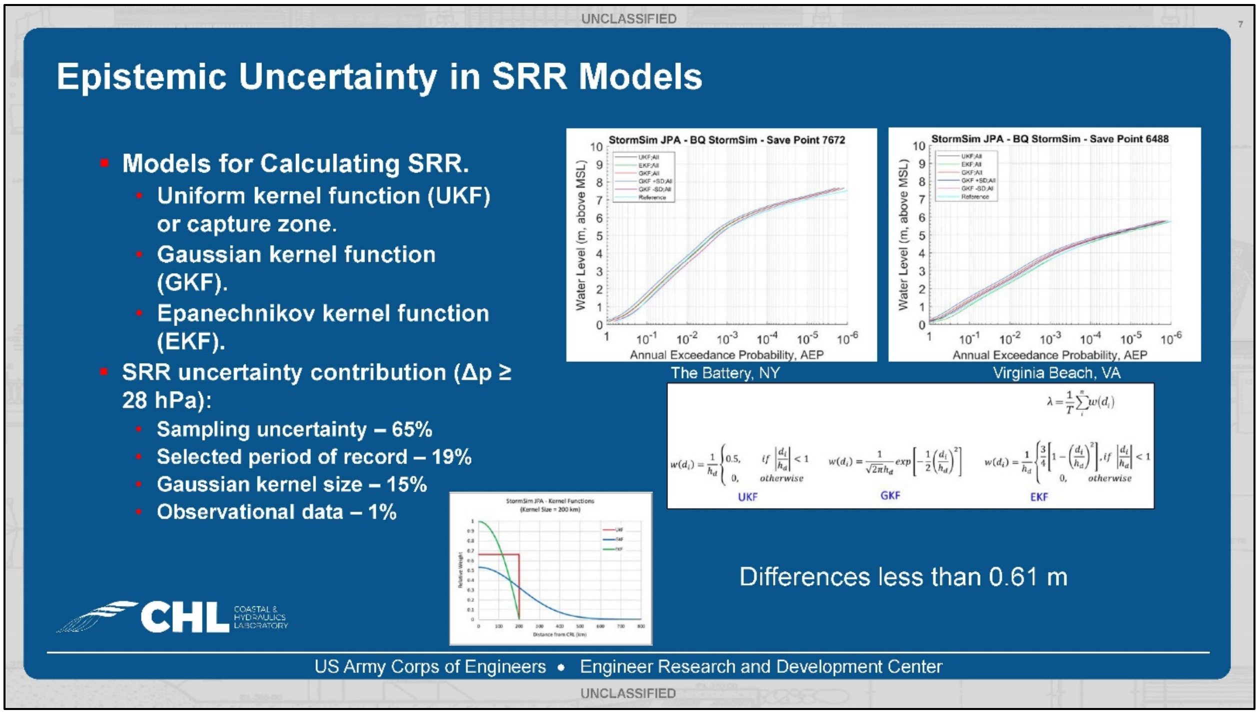


Epistemic Uncertainty in SRR Models

- **Models for Calculating SRR.**
  - **Uniform kernel function (UKF) or capture zone.**
  - **Gaussian kernel function (GKF).**
  - **Epanechnikov kernel function (EKF).**
- **SRR uncertainty contribution (Δp ≥ 28 hPa):**
  - **Sampling uncertainty – 65%**
  - **Selected period of record – 19%**
  - **Gaussian kernel size – 15%**
  - **Observational data – 1%**

The Battery, NY

Virginia Beach, VA

$$\lambda = \frac{1}{T}\sum_{i}^{n} w(d_i)$$

$$w(d_i) = \frac{1}{h_d}\begin{cases} 0.5, & if \left|\frac{d_i}{h_d}\right| < 1 \\ 0, & otherwise \end{cases}$$

UKF

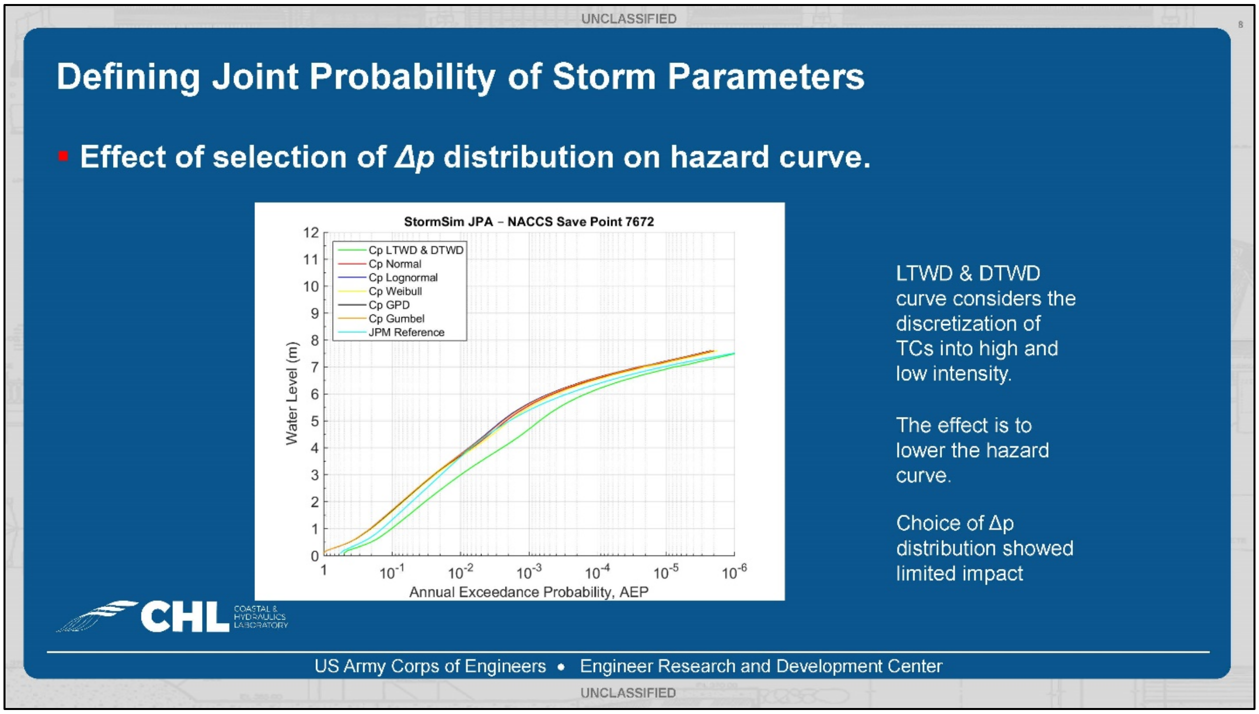
$$w(d_i) = \frac{1}{\sqrt{2\pi} h_d} exp\left[-\frac{1}{2}\left(\frac{d_i}{h_d}\right)^2\right]$$

GKF

$$w(d_i) = \frac{1}{h_d}\begin{cases} \frac{3}{4}\left[1-\left(\frac{d_i}{h_d}\right)^2\right], & if \left|\frac{d_i}{h_d}\right| < 1 \\ 0, & otherwise \end{cases}$$

EKF

Differences less than 0.61 m



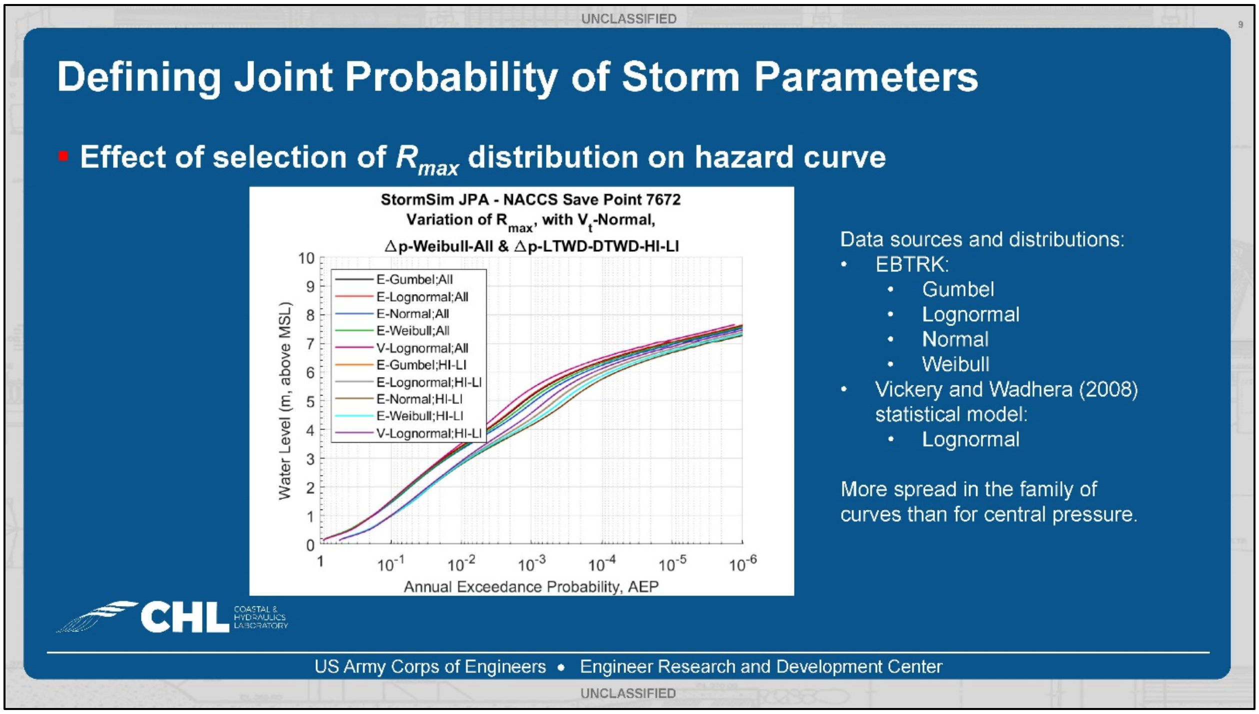
Defining Joint Probability of Storm Parameters

- **Effect of selection of *Δp* distribution on hazard curve.**

LTWD & DTWD curve considers the discretization of TCs into high and low intensity.

The effect is to lower the hazard curve.

Choice of Δp distribution showed limited impact



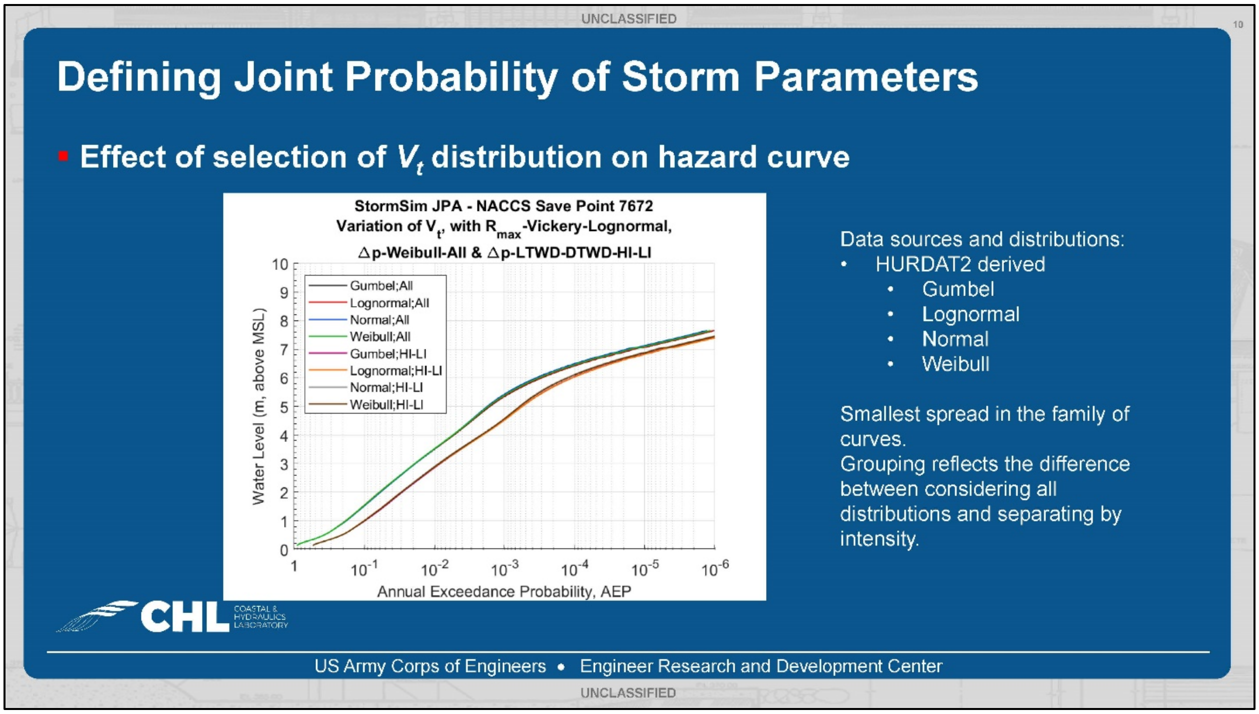
Defining Joint Probability of Storm Parameters

- **Effect of selection of R_{max} distribution on hazard curve**

StormSim JPA - NACCS Save Point 7672
Variation of R_{max}, with V_t-Normal,
Δp-Weibull-All & Δp-LTWD-DTWD-HI-LI

Data sources and distributions:
- EBTRK:
  - Gumbel
  - Lognormal
  - Normal
  - Weibull
- Vickery and Wadhera (2008) statistical model:
  - Lognormal

More spread in the family of curves than for central pressure.



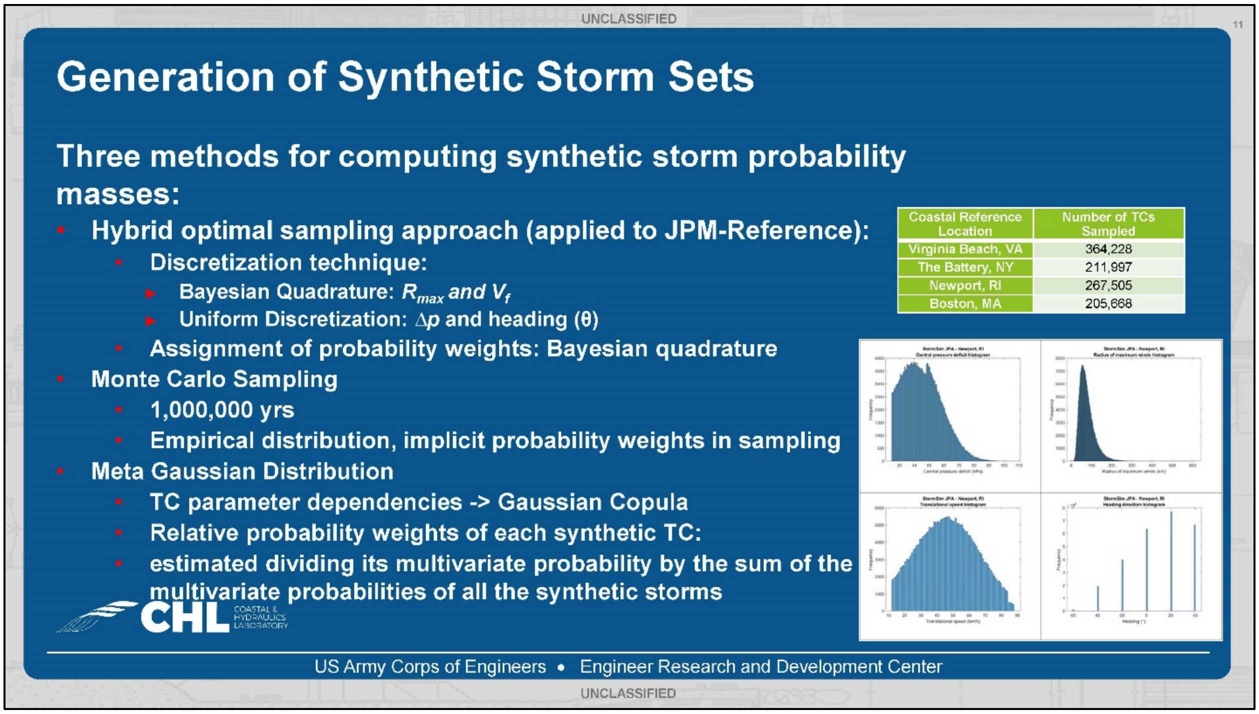
Defining Joint Probability of Storm Parameters

- **Effect of selection of V_t distribution on hazard curve**

StormSim JPA - NACCS Save Point 7672
Variation of V_t, with R_{max}-Vickery-Lognormal,
Δp-Weibull-All & Δp-LTWD-DTWD-HI-LI

Data sources and distributions:
- HURDAT2 derived
  - Gumbel
  - Lognormal
  - Normal
  - Weibull

Smallest spread in the family of curves.
Grouping reflects the difference between considering all distributions and separating by intensity.

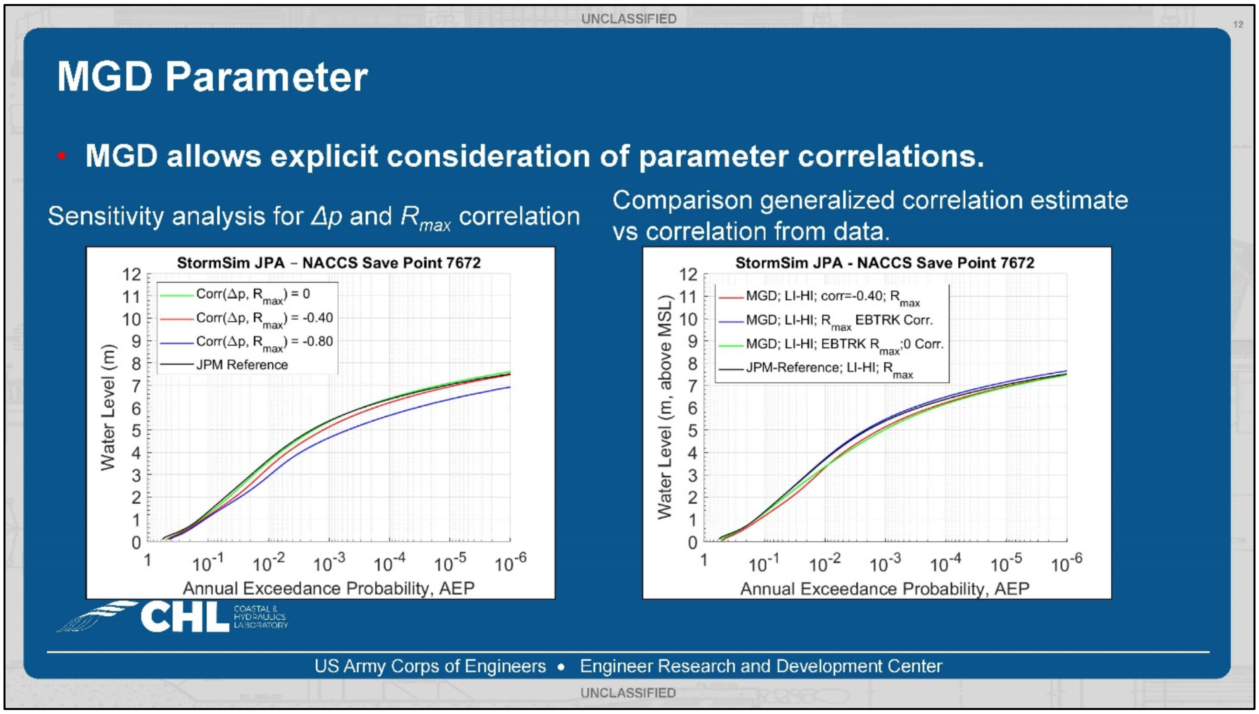


Generation of Synthetic Storm Sets

Three methods for computing synthetic storm probability masses:

- **Hybrid optimal sampling approach (applied to JPM-Reference):**
  - **Discretization technique:**
    - **Bayesian Quadrature: R_{max} and V_f**
    - **Uniform Discretization: Δp and heading (θ)**
  - **Assignment of probability weights: Bayesian quadrature**
- **Monte Carlo Sampling**
  - **1,000,000 yrs**
  - **Empirical distribution, implicit probability weights in sampling**
- **Meta Gaussian Distribution**
  - **TC parameter dependencies -> Gaussian Copula**
  - **Relative probability weights of each synthetic TC:**
  - **estimated dividing its multivariate probability by the sum of the multivariate probabilities of all the synthetic storms**

Coastal Reference Location	Number of TCs Sampled
Virginia Beach, VA	364,228
The Battery, NY	211,997
Newport, RI	267,505
Boston, MA	205,668

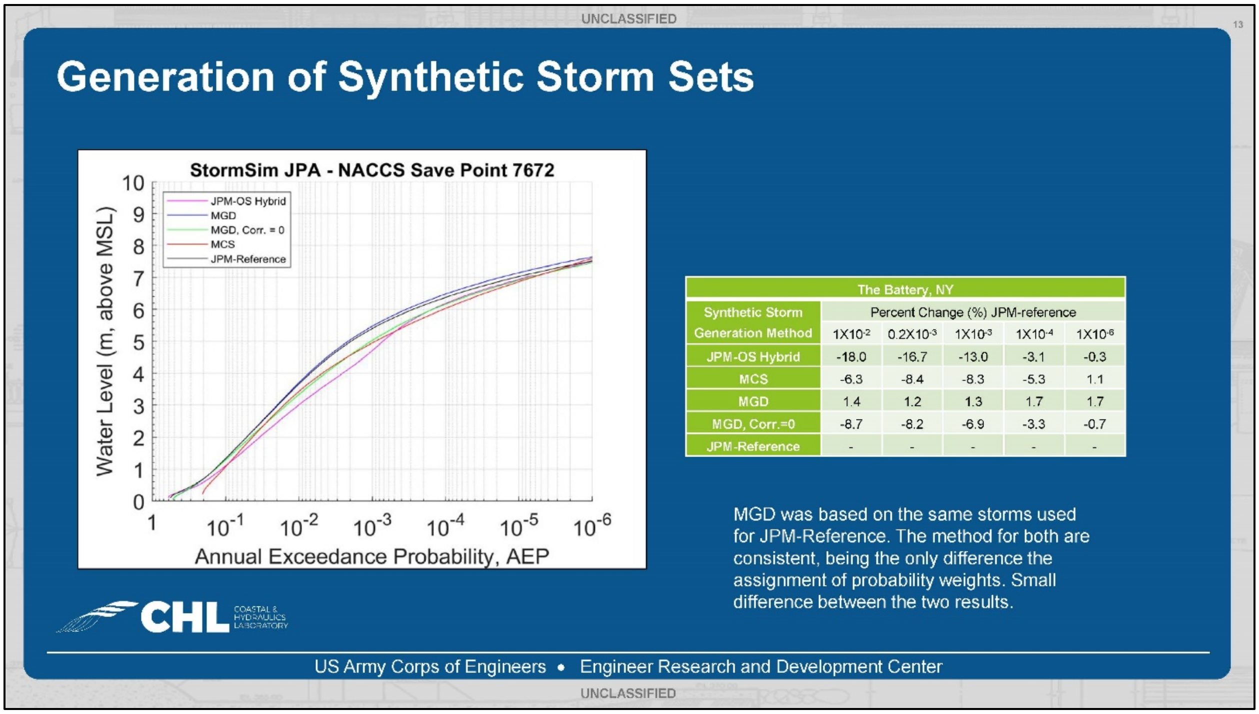


MGD Parameter

- **MGD allows explicit consideration of parameter correlations.**

Sensitivity analysis for Δp and R_{max} correlation

Comparison generalized correlation estimate vs correlation from data.

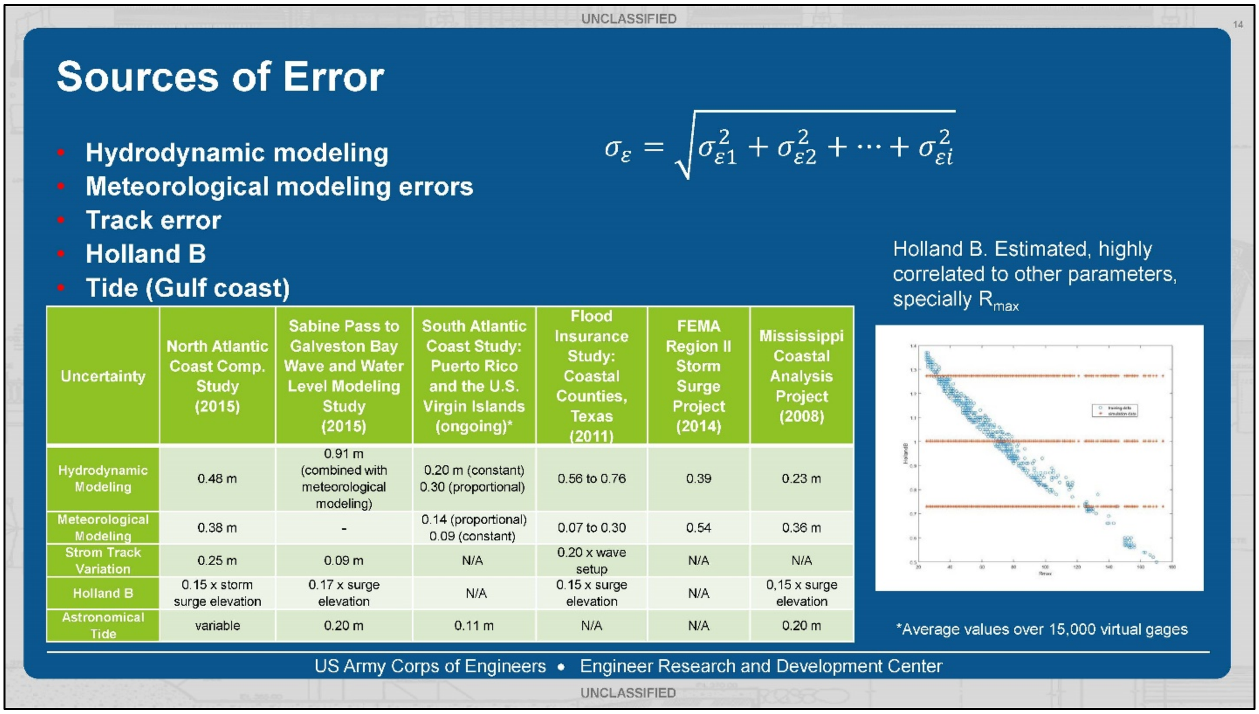


Generation of Synthetic Storm Sets

StormSim JPA - NACCS Save Point 7672

The Battery, NY					
Synthetic Storm Generation Method	Percent Change (%) JPM-reference				
	$1X10^{-2}$	$0.2X10^{-3}$	$1X10^{-3}$	$1X10^{-4}$	$1X10^{-6}$
JPM-OS Hybrid	-18.0	-16.7	-13.0	-3.1	-0.3
MCS	-6.3	-8.4	-8.3	-5.3	1.1
MGD	1.4	1.2	1.3	1.7	1.7
MGD, Corr.=0	-8.7	-8.2	-6.9	-3.3	-0.7
JPM-Reference	-	-	-	-	-

MGD was based on the same storms used for JPM-Reference. The method for both are consistent, being the only difference the assignment of probability weights. Small difference between the two results.



Sources of Error

- **Hydrodynamic modeling**
- **Meteorological modeling errors**
- **Track error**
- **Holland B**
- **Tide (Gulf coast)**

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

Uncertainty	North Atlantic Coast Comp. Study (2015)	Sabine Pass to Galveston Bay Wave and Water Level Modeling Study (2015)	South Atlantic Coast Study: Puerto Rico and the U.S. Virgin Islands (ongoing)*	Flood Insurance Study: Coastal Counties, Texas (2011)	FEMA Region II Storm Surge Project (2014)	Mississippi Coastal Analysis Project (2008)
Hydrodynamic Modeling	0.48 m	0.91 m (combined with meteorological modeling)	0.20 m (constant) 0.30 (proportional)	0.56 to 0.76	0.39	0.23 m
Meteorological Modeling	0.38 m	-	0.14 (proportional) 0.09 (constant)	0.07 to 0.30	0.54	0.36 m
Strom Track Variation	0.25 m	0.09 m	N/A	0.20 x wave setup	N/A	N/A
Holland B	0.15 x storm surge elevation	0.17 x surge elevation	N/A	0.15 x surge elevation	N/A	0,15 x surge elevation
Astronomical Tide	variable	0.20 m	0.11 m	N/A	N/A	0.20 m

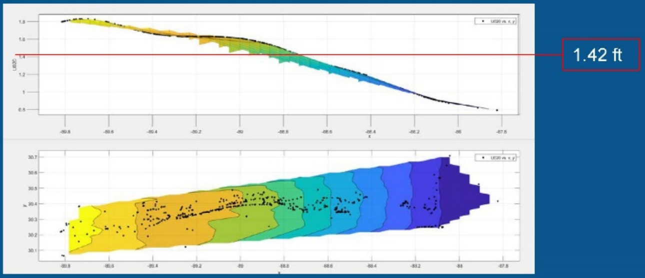
Holland B. Estimated, highly correlated to other parameters, specially R_{max}

*Average values over 15,000 virtual gages

Spatially-varying modeling error

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

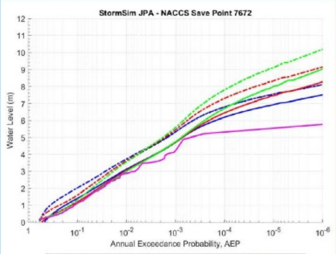
- **Global uncertainty: 1.42 ft.**
- **Spatially varying uncertainty:**

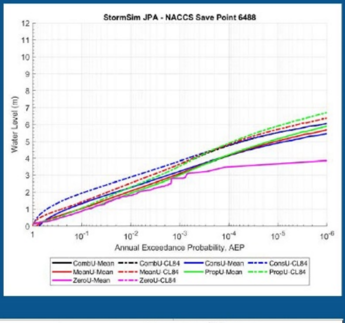

1.42 ft

Characterization of Uncertainty in JPM integral

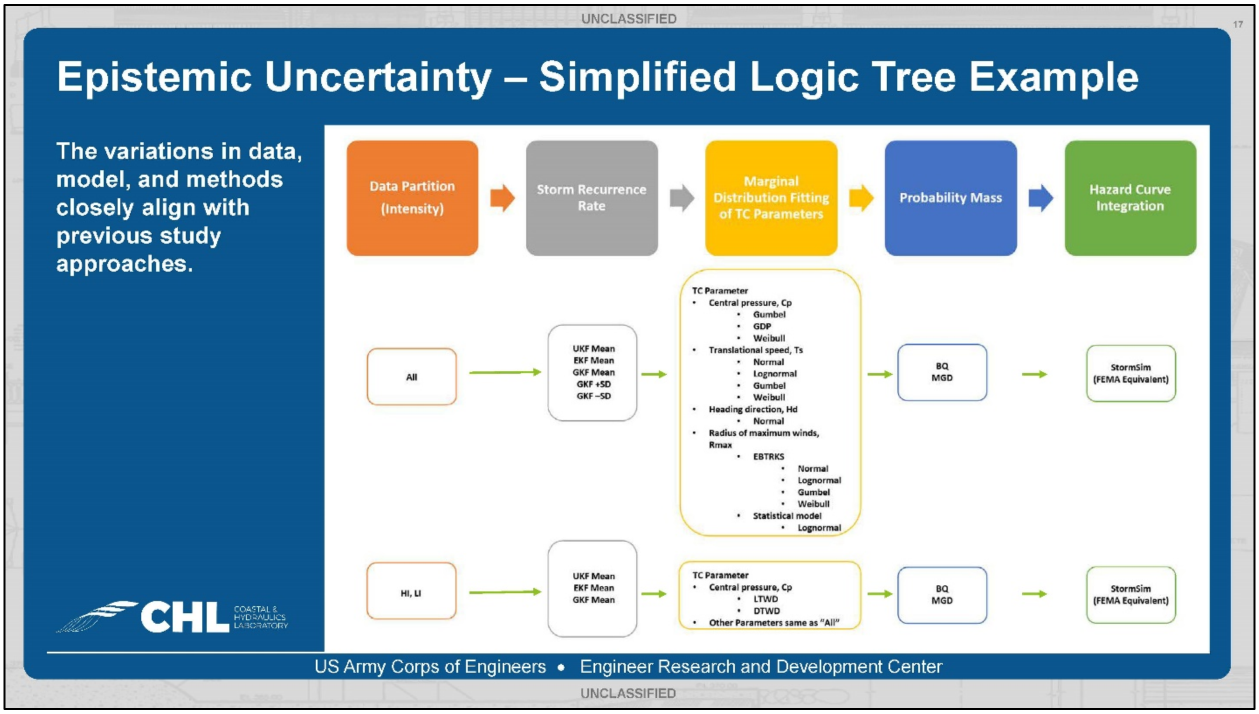
- **Methods:**
  - **Zero uncertainty, σ = 0**
  - **Constant uncertainty, σ = 0.61 m**
  - **Proportional uncertainty, σ = 0.2*WL**
  - **Constrained uncertainty, σ=min(σ_constant, σ_proportional)**
  - **Mean of constant and proportional, σ=mean (σ_constant, σ_proportional)**

$$WL_n = \mu + \sigma(Z^*)$$



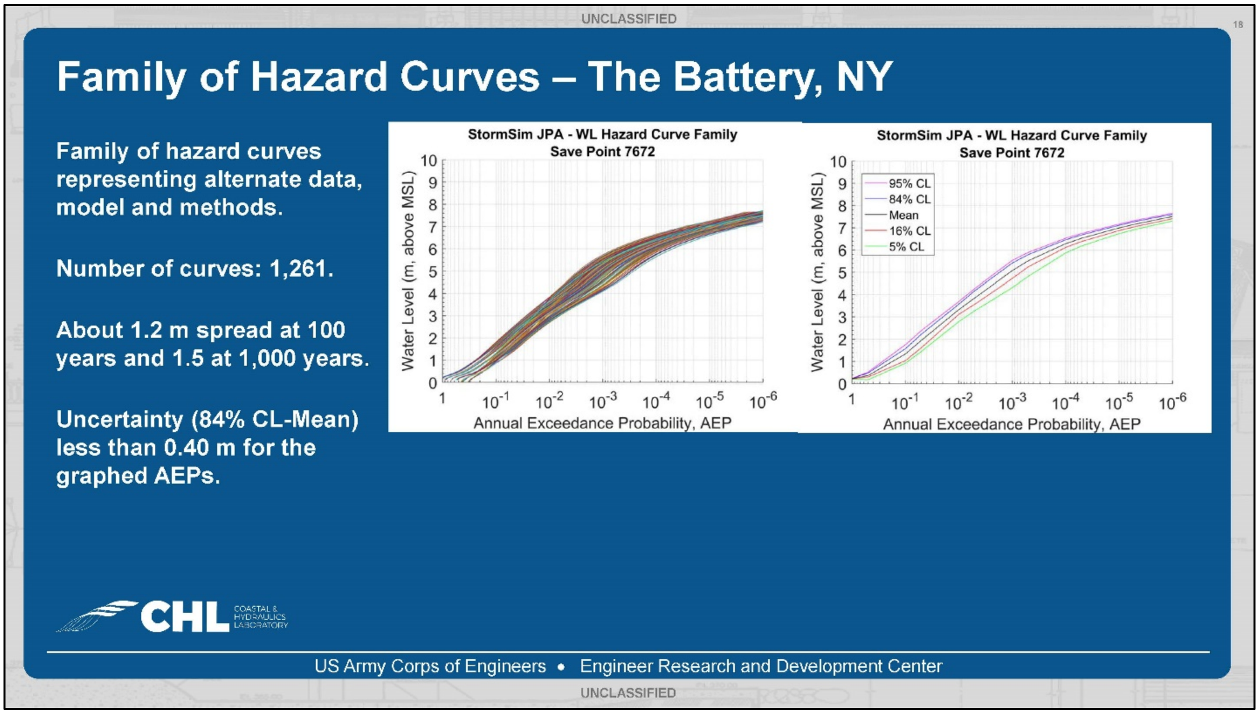


		Storm surge (m)					Percentage difference				
		AEP					AEP				
CRL	JPM-OS Uncertain	1E-02	1E-03	1E-04	1E-05	1E-06	1E-02	1E-03	1E-04	1E-05	1E-06
6488	Combined	1.9	3.0	4.2	4.9	5.5	-	-	-	-	-
	Constant	2.3	3.2	4.2	4.9	5.5	17	7	1	0	0
	Mean	2.1	3.1	4.2	5.0	5.7	7	3	1	2	4
	Proportion	1.9	3.0	4.2	5.2	5.9	0	0	1	5	8
	Zero	1.8	2.8	3.5	3.7	3.9	-6	-7	-16	-25	-29
7672	Combined	3.0	4.7	6.2	6.9	7.5	-	-	-	-	-
	Constant	3.1	4.7	6.2	6.9	7.5	4	0	0	0	0
	Mean	3.1	4.7	6.4	7.5	8.3	1	0	4	7	10
	Proportion	3.0	4.7	6.7	8.0	9.0	0	1	8	15	20
	Zero	2.9	4.2	5.3	5.5	5.8	-4	-11	-14	-20	-23



Epistemic Uncertainty – Simplified Logic Tree Example

The variations in data, model, and methods closely align with previous study approaches.



Family of Hazard Curves – The Battery, NY

Family of hazard curves representing alternate data, model and methods.

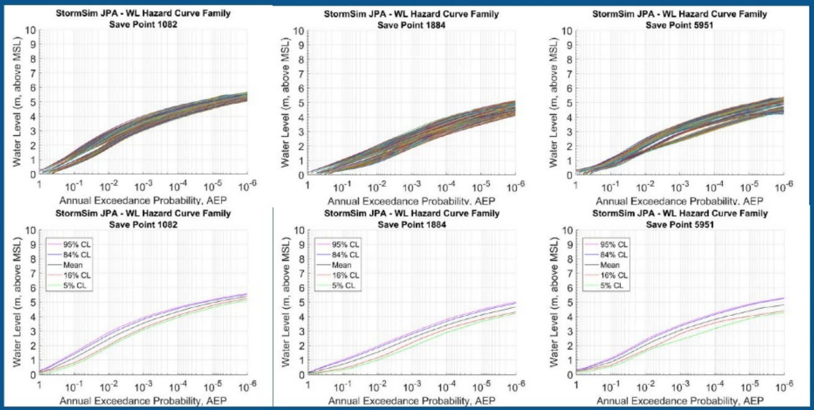
Number of curves: 1,261.

About 1.2 m spread at 100 years and 1.5 at 1,000 years.

Uncertainty (84% CL-Mean) less than 0.40 m for the graphed AEPs.

Family of Hazard Curves – Additional Locations

- **The uncertainty computed as the difference between the 84% confidence limit and the mean for the curves tops out at about 0.45 m for Chesapeake Bay.**
- **Curves cluster based on intensity grouping.**
- **Branches added based on method to characterize uncertainty would increase uncertainty.**



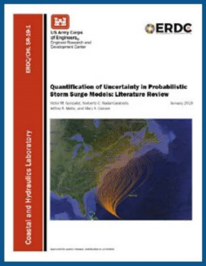
Newport, RI

Boston, MA

Chesapeake Bay, MD

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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- Chouinard, L., C. Liu, and C. Cooper. 1997. Model for Severity of Hurricanes in Gulf of Mexico. *Journal of Waterway, Port, Coastal, and Ocean Engineering* 123 (3): 120–129.
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Email: Joseph.Kanney@nrc.gov

3.5.3 Presentation 2B-3: Using Physical Insights in Spatial Decomposition Approaches to Surge Hazard Assessment

Authors: Jennifer Irish, Virginia Tech (VT); Donald T. Resio, University of North Florida; Michelle Bensi, University of Maryland; Taylor G. Asher, University of North Carolina; Yi Liu, VT, Environmental Science Associates; Jun-Whan Lee, VT

Speaker: Jennifer Irish

3.5.3.1 Abstract

The import of reliable probabilistic hurricane surge hazard assessment continues to grow as disasters emanating from these events become more prevalent. There have recently been a number of advances in hurricane surge hazard assessment, which consider a very large number of synthetic storms in order to produce a more statistically robust probabilistic assessment. Yet, application of these approaches remains constrained by the computational burden associated with high-fidelity storm surge simulation. Herein, we present a rapid storm surge predictive model that leverages physical insights along with spatial decomposition in order to reduce the dimensionality respectively in the storm parameter and the geographic spaces. In developing this hybrid predictive model, ease of use by being intuitive, transparent, and reproducible was favored over incremental improvements in surge prediction accuracy. Error and associated with this hybrid predictive model will also be presented

3.5.3.2 Presentation not available (pending journal manuscript publication)

3.5.4 Presentation 2B-4: Investigation of Surrogate Modeling Application in Storm Surge Assessment

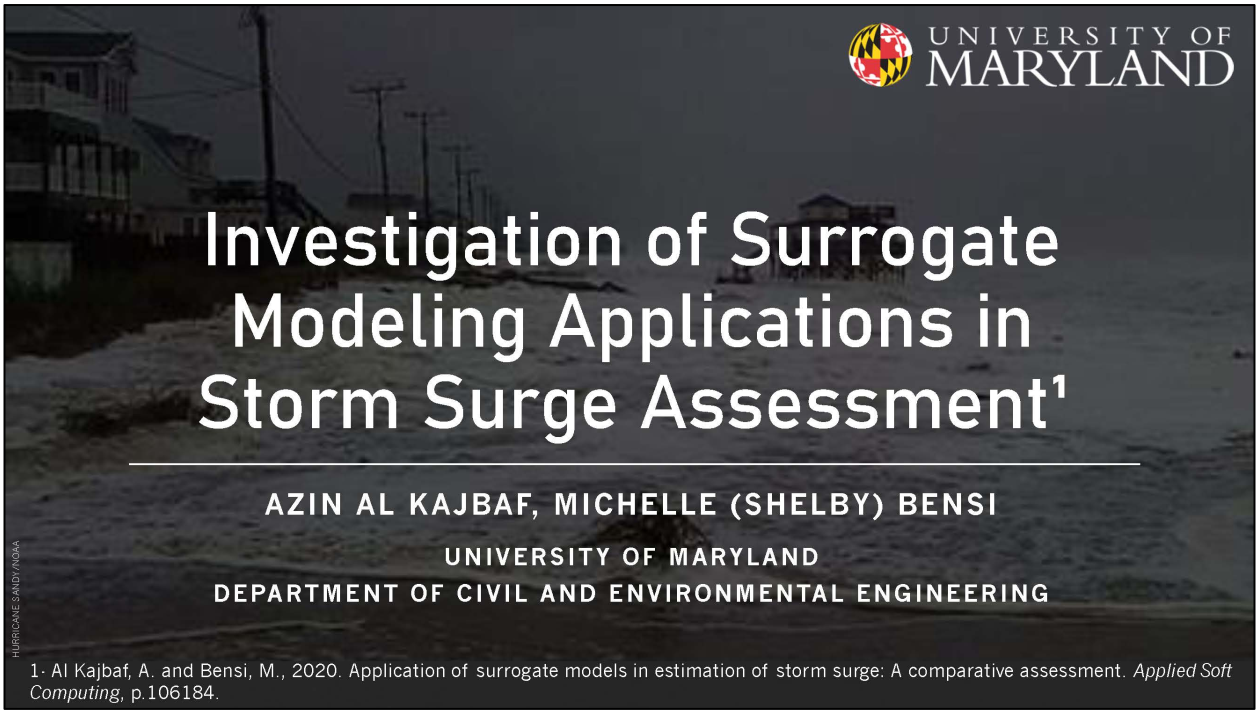
Authors: Azin Al Kajbaf and Michelle (Shelby) Bensi, University of Maryland

Speaker: Azin Al Kajbaf

3.5.4.1 Abstract

Major hurricane events in the past two decades have led to significant advancement in simulation models that can facilitate accurate and efficient storm surge estimation. Lack of numerical prediction models that can simultaneously provide high-fidelity results and real-time storm surge forecasts, has motivated the use of surrogate modeling methods (e.g. ANN, GPR) as an alternative approach that can balance efficiency and accuracy in storm surge prediction. With regards to recent efforts in exploring the operational application of surrogate modeling methods for surge prediction, there is a need for a comprehensive framework that thoroughly assesses and compares the performance of the method that are frequently used for storm surge prediction. These methods include Artificial Neural Network (ANN), Support Vector Regression (SVR), and Gaussian Process Regression (GPR; also known as Kriging models). One of the challenges with applying these methods in current state of practice is that their performance is usually assessed through aggregated error/loss metrics (e.g. R, RMSE) which might give incomplete information regarding performance. Furthermore, no study is available which compare all of these models together. In this study, the performance of the surrogate models of ANN, GPR and SVR for storm surge prediction is explored through a comprehensive framework that examines the stability of performance across training sample sizes, identifies systematic trends in errors, assesses performance in predicting large (i.e., risk-significant) surges, and characterizes the distribution of error.

3.5.4.2 Presentation (ADAMS Accession No. ML20080M143)



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Investigation of Surrogate Modeling Applications in Storm Surge Assessment[1]

AZIN AL KAJBAF, MICHELLE (SHELBY) BENSI

UNIVERSITY OF MARYLAND

DEPARTMENT OF CIVIL AND ENVIRONMENTAL ENGINEERING

HURRICANE SANDY/NOAA

1- Al Kajbaf, A. and Bensi, M., 2020. Application of surrogate models in estimation of storm surge: A comparative assessment. *Applied Soft Computing*, p.106184.

Necessity of Predicting Storm Surge

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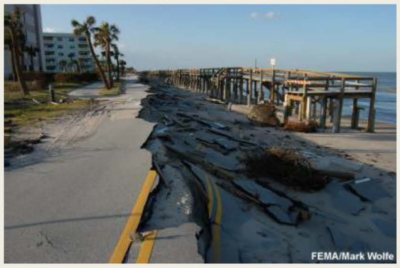
- Coastal storm surge hazard assessment has received increased attention due to major hurricane events in the last two decades.

- Robust hazard assessment requires accurate and efficient storm surge prediction models.

Hurricane Katrina/NOAA



Hurricane Jeanne /NOAA

Numerical models for Storm Surge Prediction

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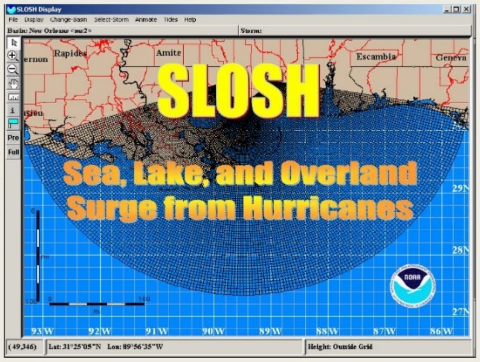
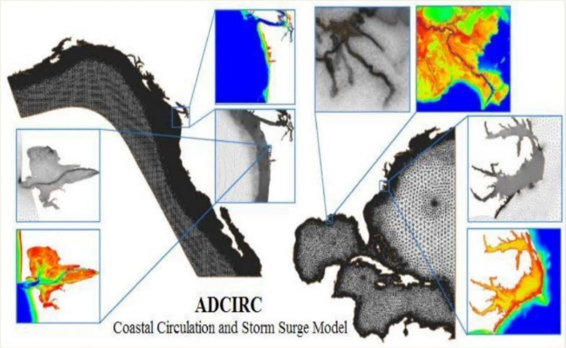
FEMA, U., 2003. USZ Army Corps of Engineers (2003)"SLOSH Display Training



Basin: New Orleans <ms2>
Storm:
(49,346) Lat: 31°25'05"N Lon: 89°56'35"W
Height: Outside Grid



US Army Engineer Research and development Center, USACE

✓ Computationally efficient and has been used for real-time storm surge forecasting.

× Accuracy - generally within ±20% of peak storm surge.

✓ High fidelity finite element hydrodynamic model that can be setup at a fine spatial resolution to perform accurate simulation.

× Computationally intensive to run.

Surrogate models for Storm Surge Prediction

- The computational expense associated with numerical models have encouraged the development of surrogate modeling methods.
- These methods provide a simplified functional relationship between input and response.
- The intent in utilizing these methods is to preserve the accuracy of the numerical model while providing a computational efficiency advantage.
- Surrogate modeling approaches that have been used for storm surge prediction include Artificial Neural Network (ANN), Support Vector Regression (SVR), and Gaussian Process Regression (GPR).

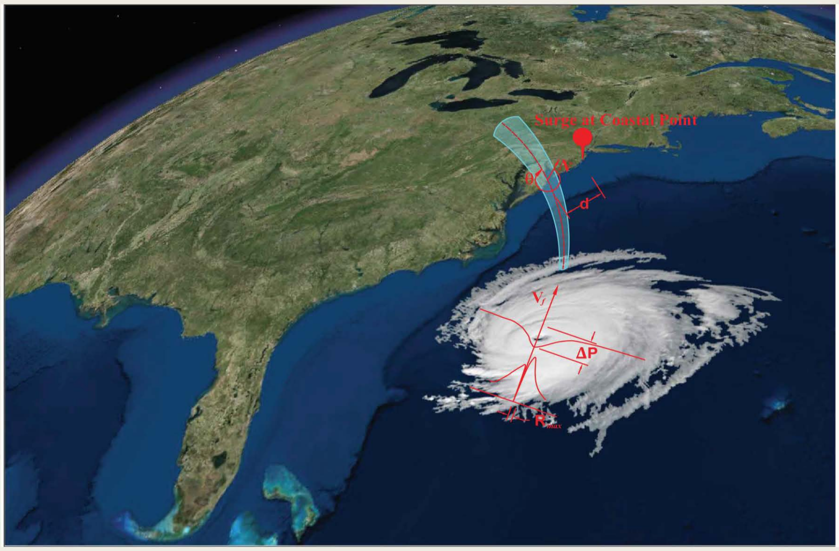
Gaps in Current State of Practice

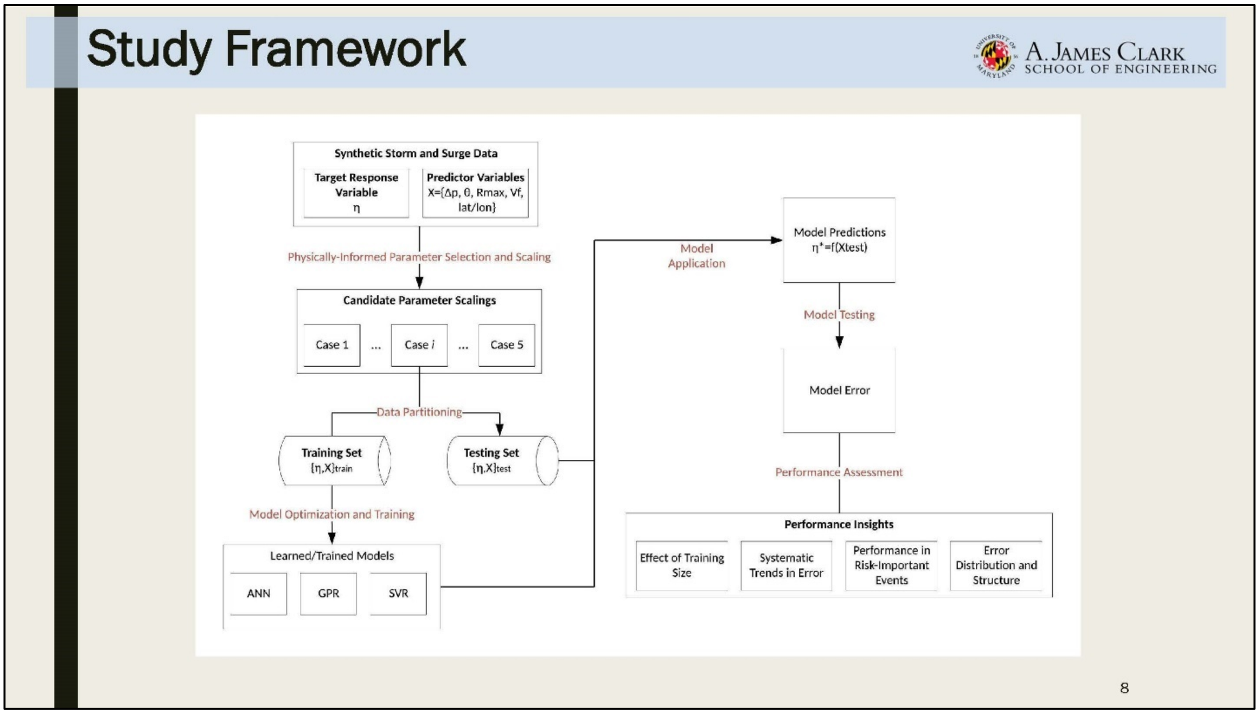
- Most studies have only explored one method at a time and no study has compared all three methods.
- These studies evaluate the performance of the modeling approaches through aggregated error metrics.
- These aggregated metrics give incomplete and potentially optimistic measures of the performance of surrogate models.
- Aggregated metrics do not yield information about the error structure and its relationship to model parameters.

Purpose of this Study

- Develop and compare ANN-, GPR-, and SVR-based surrogate models for predicting peak storm surge as a function of hurricane parameters using synthetic data.
- Providing a comprehensive framework for comparison and assessment of the performance of surrogate models through:
    - Investigating the stability of performance across training sample sizes.
    - Identifying systematic trends in errors.
    - Assessing performance in predicting large target response quantities.
    - Characterizing the distribution of error.

Storm parameterization from NACCS database





Study Framework

Synthetic Storm and Surge Data

Target Response Variable η

Predictor Variables X={Δp, θ, Rmax, Vf, lat/lon}

Physically-Informed Parameter Selection and Scaling

Candidate Parameter Scalings

Case 1 … Case *i* … Case 5

Data Partitioning

Training Set $\{\eta, X\}_{train}$

Testing Set $\{\eta, X\}_{test}$

Model Optimization and Training

Learned/Trained Models

ANN | GPR | SVR

Model Application

Model Predictions $\eta^* = f(X_{test})$

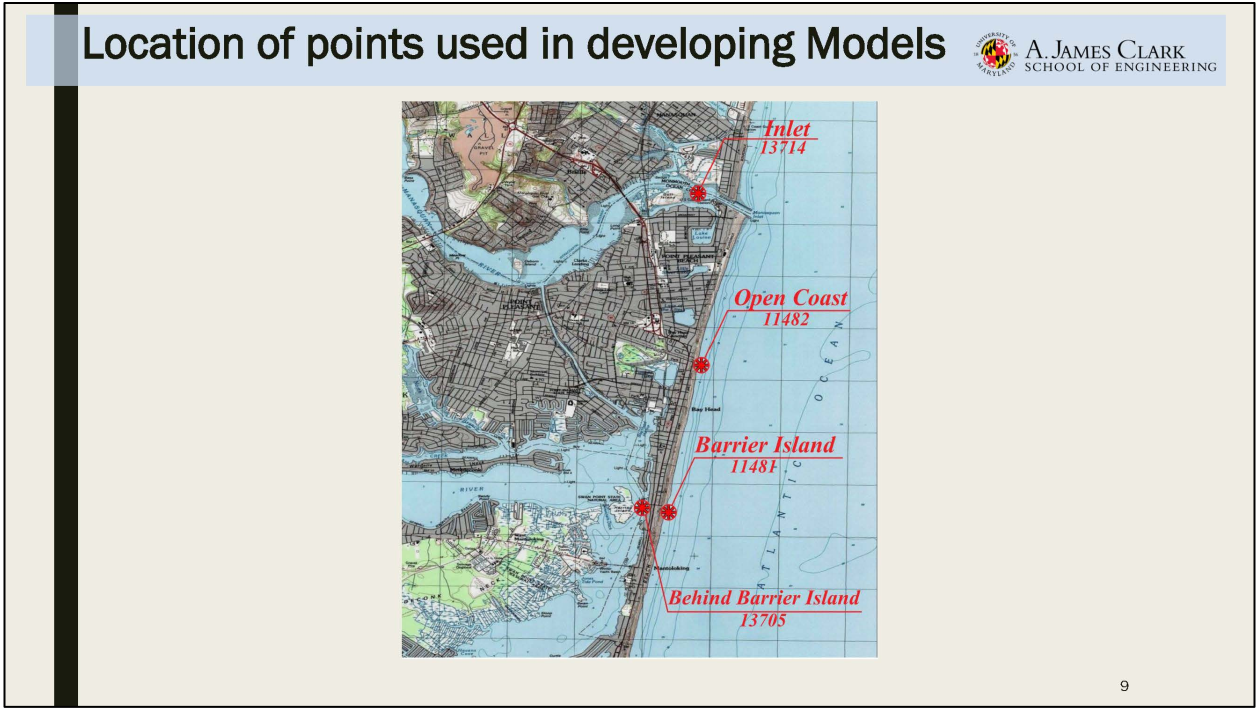
Model Testing

Model Error

Performance Assessment

Performance Insights

- Effect of Training Size
- Systematic Trends in Error
- Performance in Risk-Important Events
- Error Distribution and Structure



Location of points used in developing Models

Different Combinations of Input Parameters

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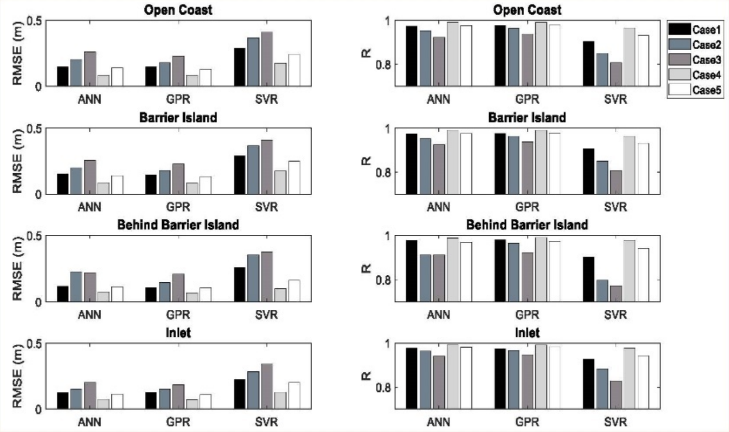
Case	Input Parameter	Target Response
1	$\Delta P, R_{max}, V_f, \theta,$ lat_{ref}, lon_{ref}	η_{NM}
2	$\Delta P, R_{max}, V_f, \theta, d$	η_{NM}
3*	$\Delta P, d/R_{max}, V_f, \theta$	η_{NM}
4*	$R_{max}, V_f, \theta,\ lat_{ref}, lon_{ref}$	$\eta_{NM}/\Delta \mathrm{P}$
5*	$\dfrac{d}{R_{max}}, V_f, \theta$	$\eta_{NM}/\Delta \mathrm{P}$



* J.L. Irish, D.T. Resio, M.A. Cialone, A surge response function approach to coastal hazard assessment. Part 2: Quantification of spatial attributes of response functions, Natural Hazards. 51 (2009) 183–205.

Error of Prediction and Surge Height vs. Storm Index Number

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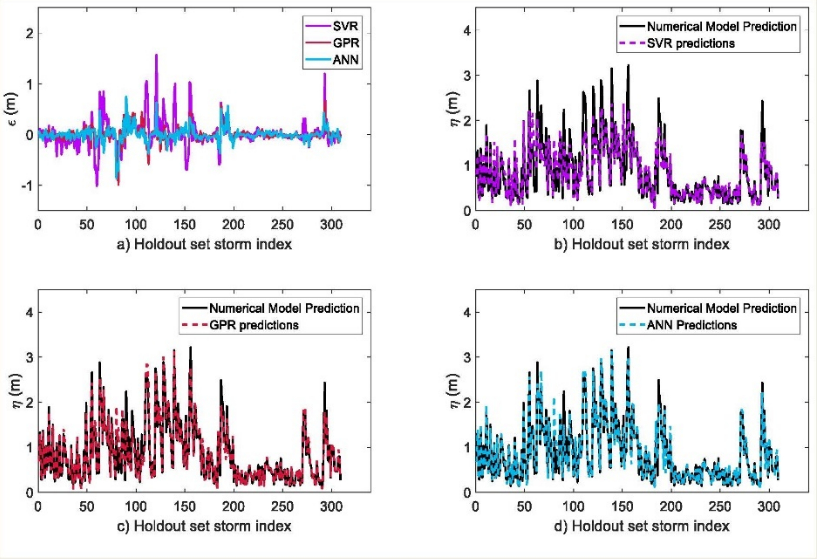

Effects of Training/Testing Size on Model Performance

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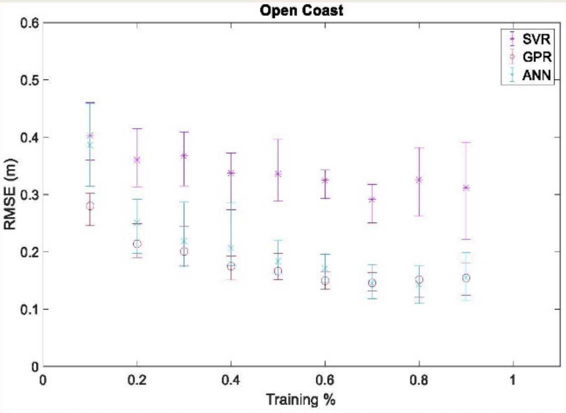

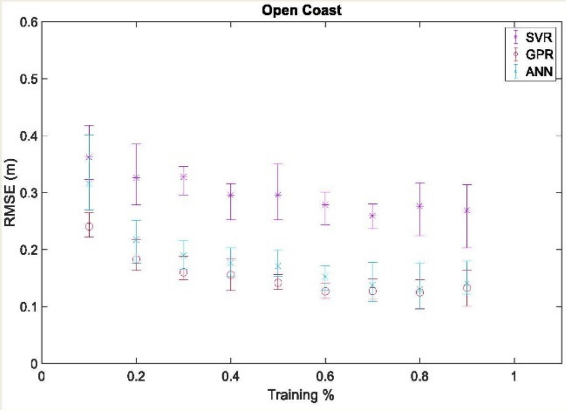

Case 1

Case 4

Systematic Trends in Error

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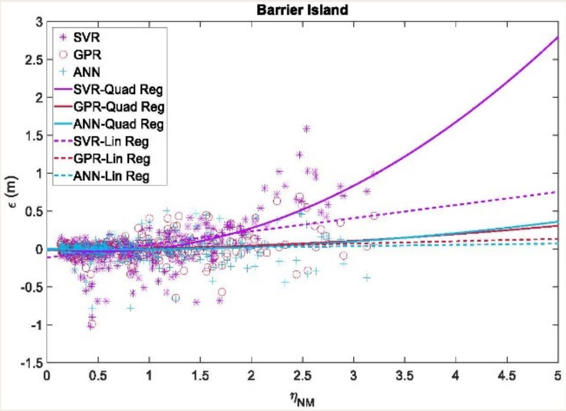
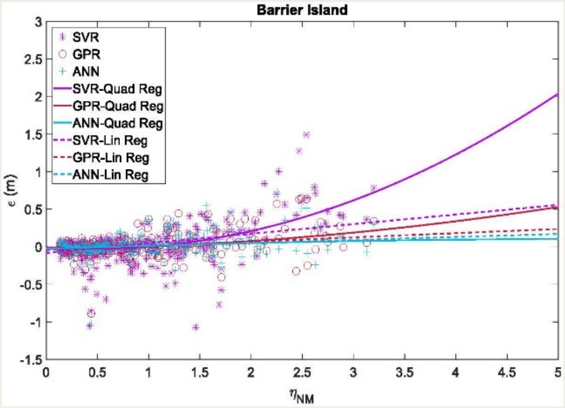
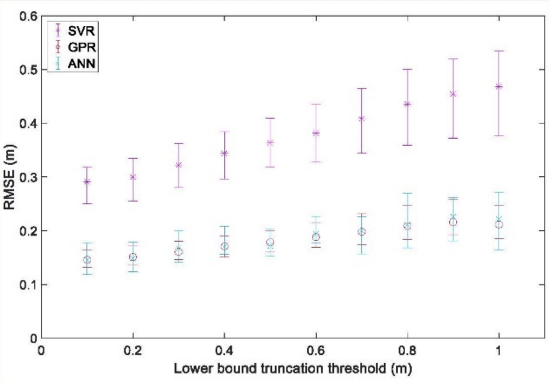




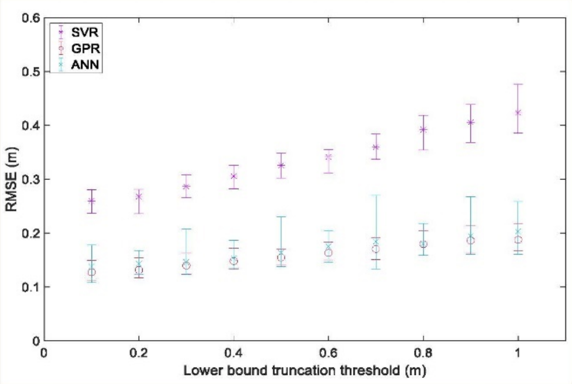
Case 1

Case 4

Truncation before Testing

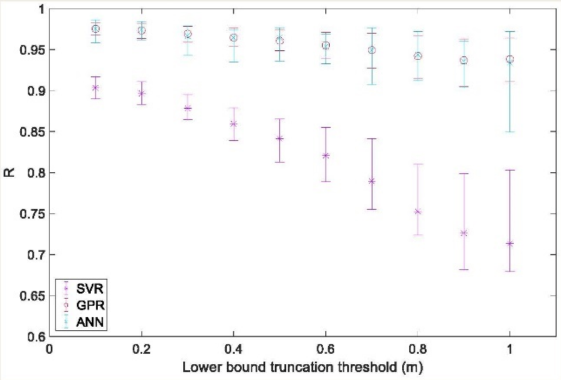


Case 1

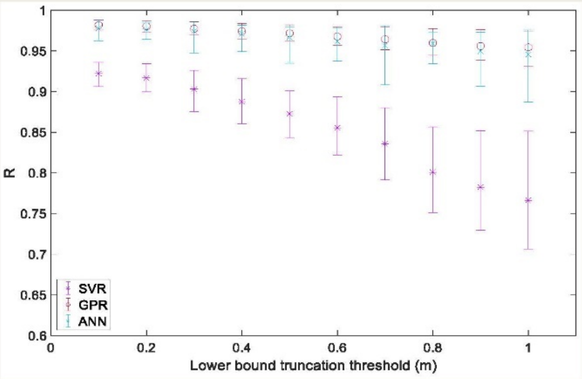


Case 4

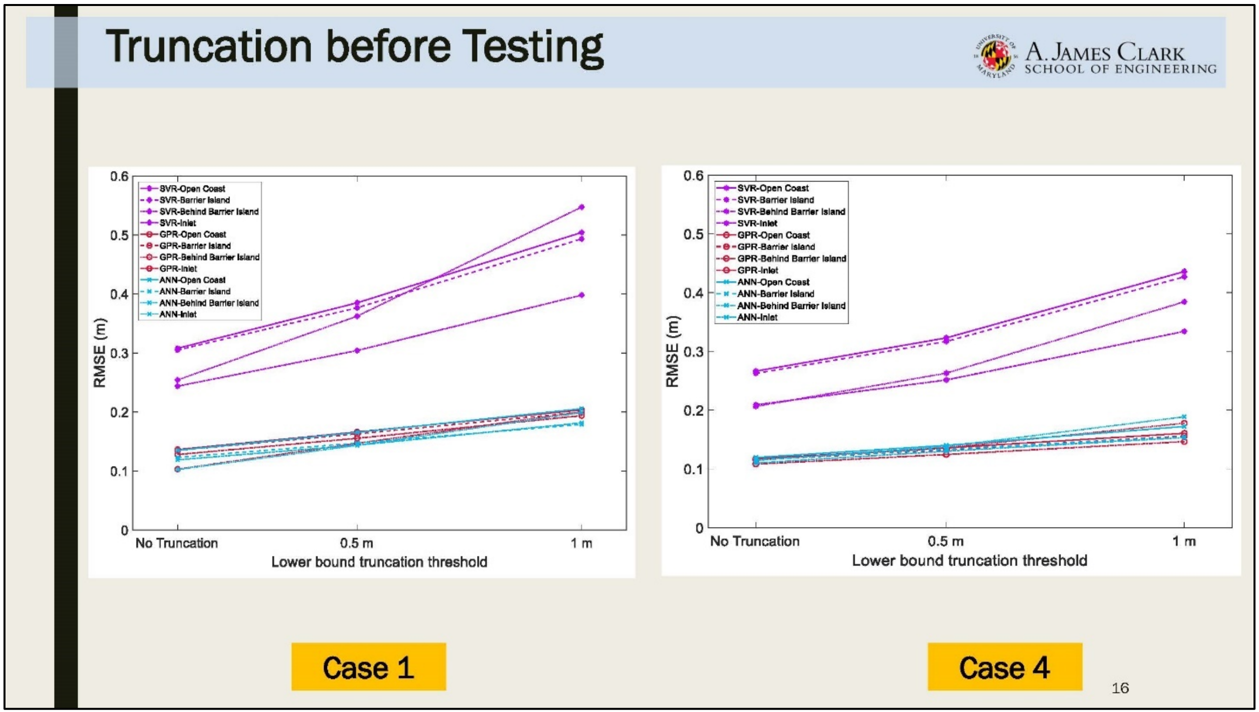
Truncation before Testing



Case 1



Case 4



Truncation before Testing

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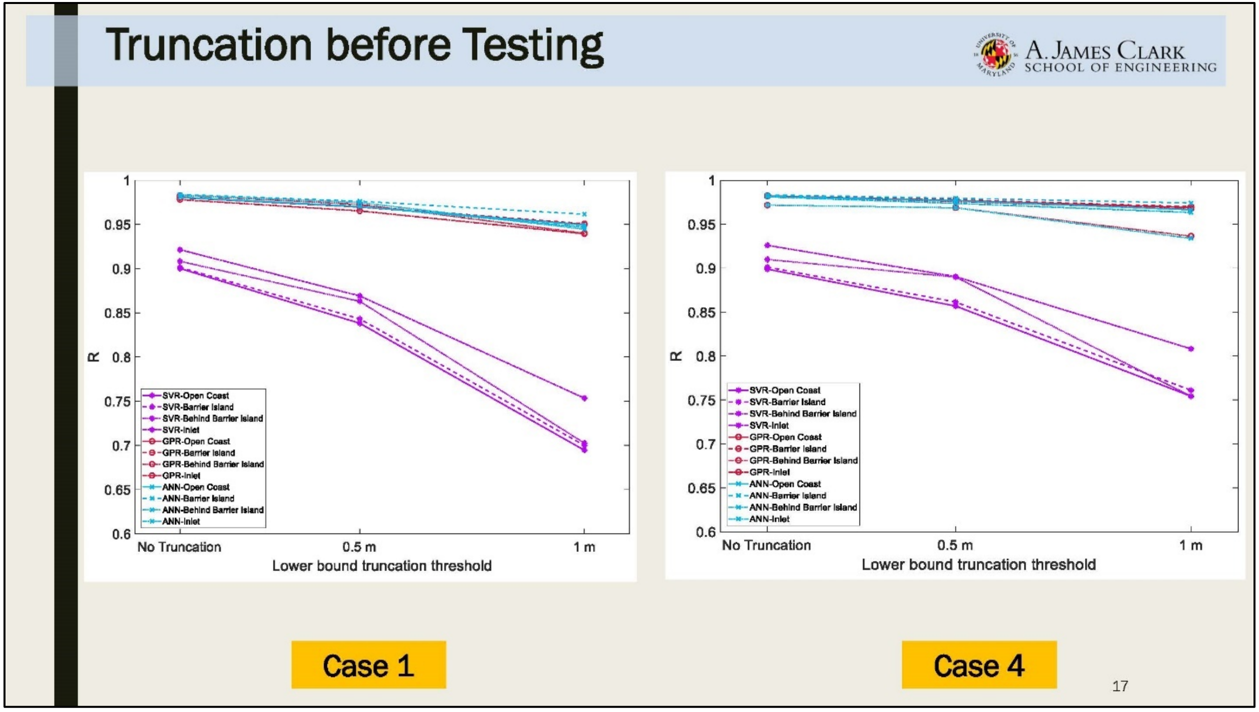
Case 1

Case 4

16



Truncation before Testing

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Case 1

Case 4

17

Truncation before Training

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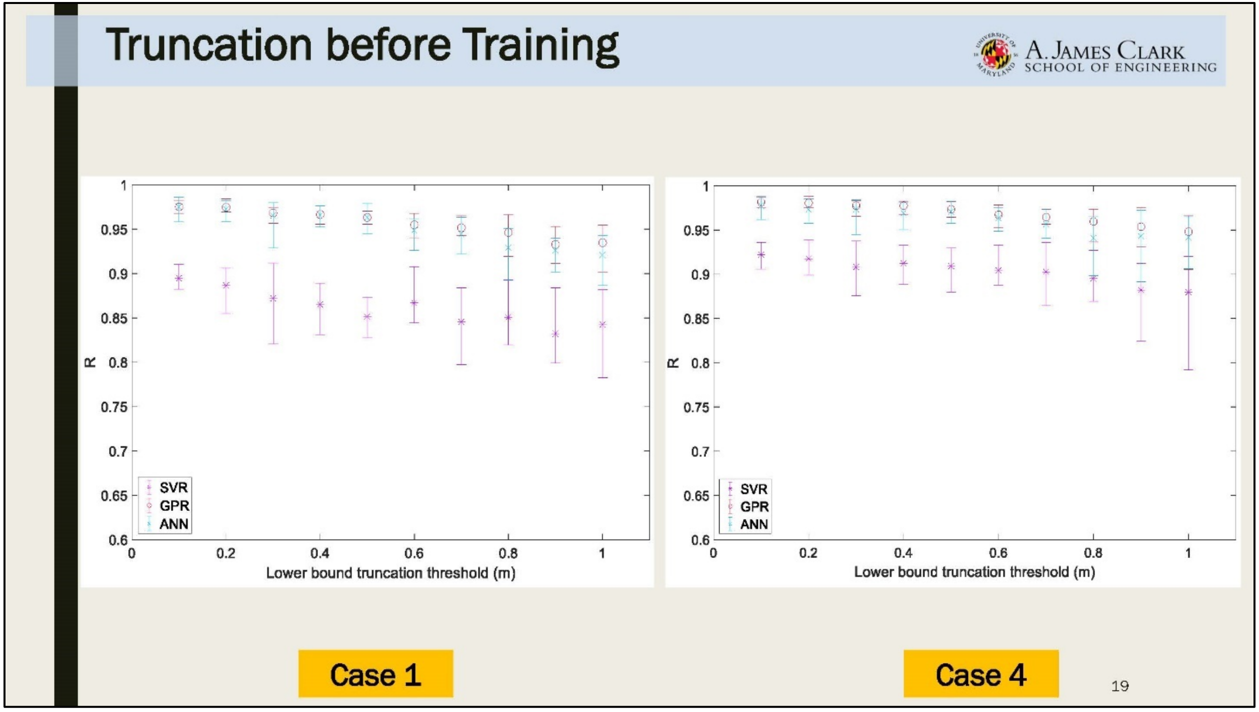
Case 1

Case 4



Truncation before Training

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Case 1

Case 4

Predicting Surge at Unseen Storm Parameters

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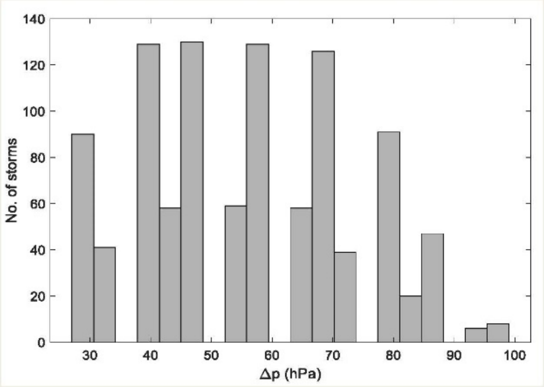

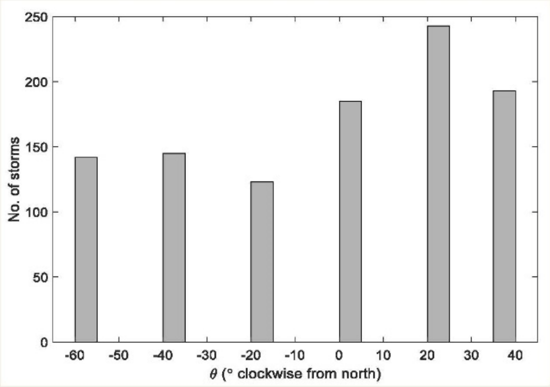

Predicting Surge at Unseen Storm Parameters

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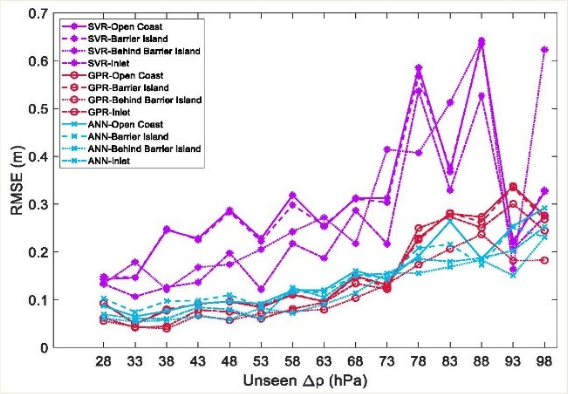

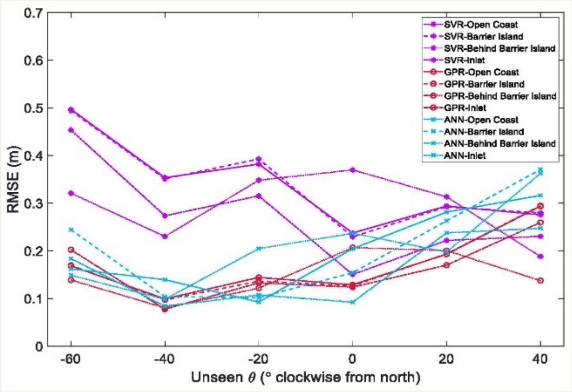

Predicting Surge at Unseen Storm Parameters

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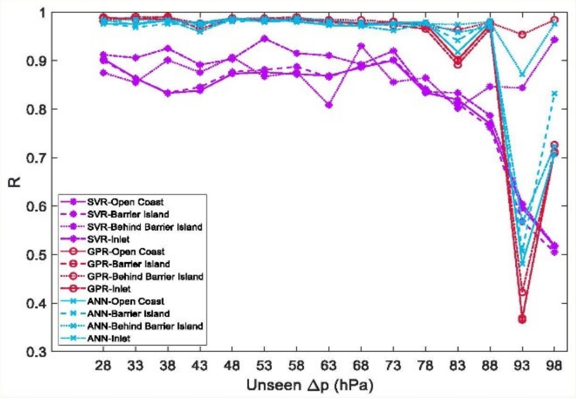

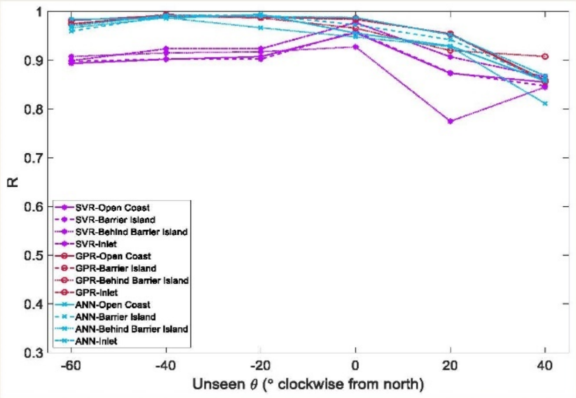

Distribution of Error

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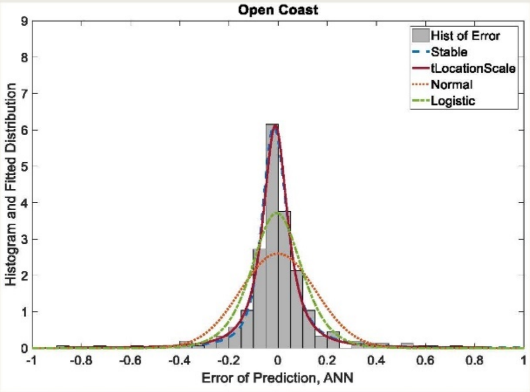
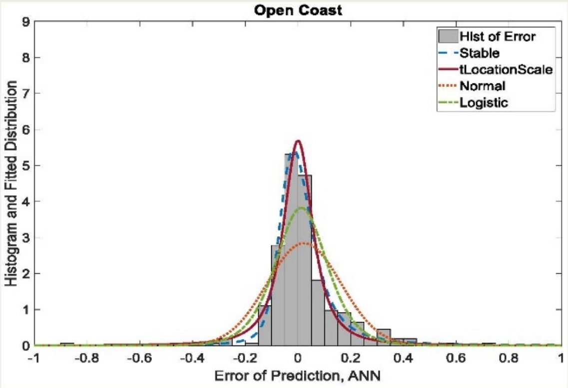


Case 1



Case 4

Results Summary

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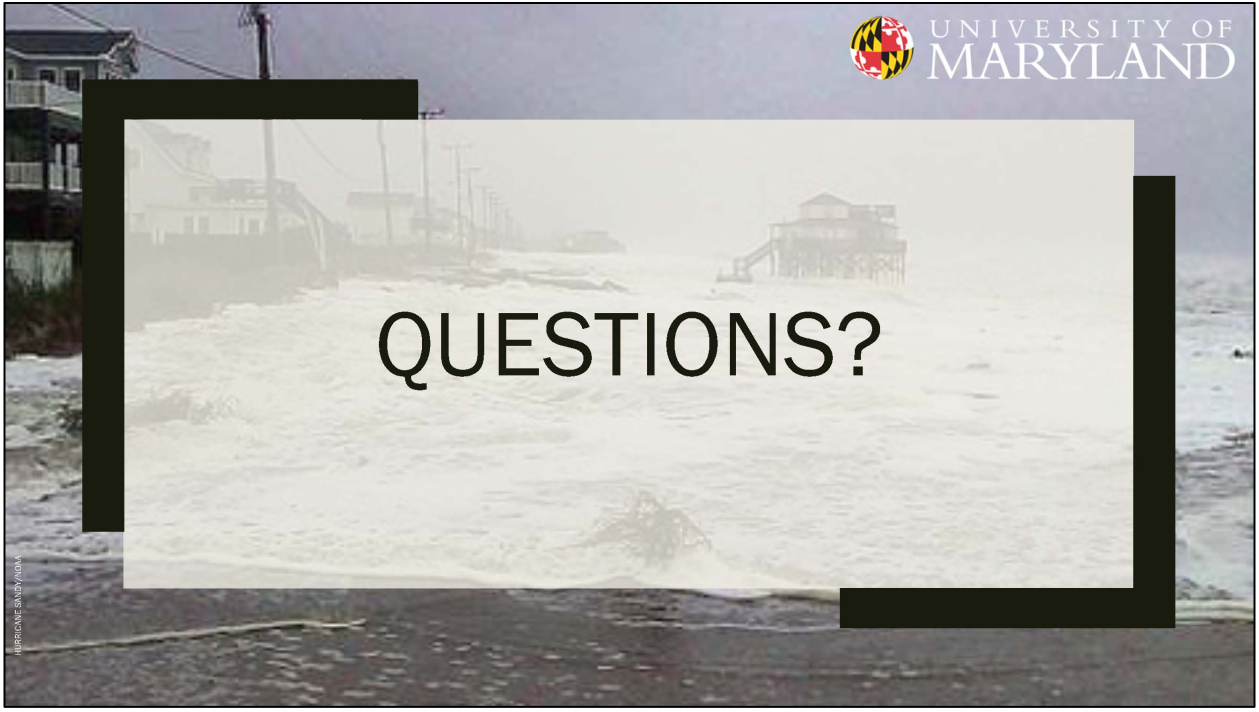
- Improvements to surrogate model performance may be achieved through physically informed scaling of certain quantities.
- The accuracy of the tested surrogate models may be significantly affected by the target surge height.
- The size of the dataset available for training affects performance differently across the modeling methods considered.
- Results suggest that the inclusion of many surge heights close to zero brings down the aggregated error metrics and may give an optimistic perspective regarding performance of surrogate models.
- The distribution of error is not necessarily Normal and needs to be fully characterized to have a more completed understanding of errors that can be used in hazard curve development and risk mitigation studies.



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QUESTIONS?

HURRICANE SANDY/NOAA

3.6 Day 2: Session 2C – Poster Session

Session Chair: Thomas Aird, NRC/RES/DRA

NOTE: Only poster abstracts are included in these proceedings.

3.6.1 Poster 2C-1: Flood Barrier Testing Strategies

Authors: Zhegang Ma and Sai Zhang, Idaho National Laboratory (INL); Chad L. Pope, Ben Farley, and Kean Martinic, Idaho State University; Curtis L. Smith, INL

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-related 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 issue. Domestic and international operational experience (OEs) 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. Preliminary results from this research including:

(1) Review summaries of the reports related to flood barriers employed at U.S. NPPs from the following sources: previous NRC research; nuclear industry activities conducted by the Nuclear Energy Institute (NEI), the Electric Power Research Institute (EPRI), etc.; NPP decommissioning activities; information from other government agencies such as the U.S. Army Corps of Engineers (USACE) and the Federal Emergency Management Agency (FEMA); international practices and guidance from the Nuclear Energy Agency (NEA)/Committee on the Safety of Nuclear Installations (CSNI).

(2) An overview of on-site permanent flood barriers (such as penetration seals and water-tight doors) and temporary flood barriers incorporated into the plant. Off-site flood barriers such as levees, berms, and sandbags fall outside the scope of this research.

(3) A review of potential flood barrier testing facilities including operating and decommissioning NPPs, Idaho State University (ISU) flood testing facility and Framatome Laboratory flood testing facility were reviewed.

(4) The questions and considerations pertaining to flood barrier testing strategies that could be utilized in testing strategy development. Several examples of previously conducted flood barrier tests are introduced and compared in regard to multiple aspects, including flood barrier type, testing location, facility type, testing type, test variables, test measurements, test termination rules, and numerical test outputs. These could be

served as the basis for developing new testing strategies in connection with future research.

3.6.2 Poster 2C-2: Component Flood Testing, Fragility Model Development, and Informed Flooding Simulation

Authors: C. L. Pope, A. Wells, and K. Martinic, Idaho State University

Abstract:

Idaho State University is engaged in the design, development, construction, and operation of component flood testing capabilities. Current capabilities center on the Portal Evaluation Tank (PET), which allows for the testing of non-contaminated components that can fit within an 8 ft by 8 ft opening. The PET can produce water flow rates up to 4500 gpm and a zero-flow head of 20 ft. Component testing experiments capabilities include measurement of flow rates, water depths, leakage rates, and pressures for simulated hydrostatic head. Experiments involving component destruction are also conducted in the PET.

Data collected during the experiments are being used to develop multi-parameter Bayesian component fragility models. The component fragility models are then being integrated into smoothed particle hydrodynamic (SPH) flooding simulation models. The overarching intent is to better inform plant flooding response and the corresponding risk analysis.

3.6.3 Poster 2C-3: Regional Flood Risk Projections from Future Climate

Author: Alfonso Mejia, Pennsylvania State University

Abstract:

Floods pose major risks to people and property. These risks are expected to rise in the future due to environmental and demographic changes. It is important to quantify and effectively communicate flood risks to inform the design and implementation of flood risk management strategies. One key challenge faced by decision-makers and researchers is that flood-risk projections are deeply uncertain. Uncertainties in flood risk projections arise from multiple sources such as the choice of model structures and forcing scenarios. Here we develop an integrated modeling framework to assess riverine flood risks for current and projected climate conditions. The framework samples future climate forcing scenarios and climate models to force a hydrologic model and generate discharge projections. Together with a statistical and hydraulic model, the projected discharges are then used to map the uncertainty of flood inundation projections for extreme flood events. The integrated framework accounts for the relative uncertainty contributions from (i) general circulation models, (ii) hydrologic model parameters, (iii) nonstationary extreme value distributions, and (iv) hydraulic model structure.

3.6.4 Poster 2C-4: Flood Nonstationarity across the United States, Detection, Attribution and Adjustment.

Authors: Karen R. Ryberg, Jory S. Hecht, Nancy A. Barth, Stacey A. Archfield, Annalise G. Blum, Katherine J. Chase, Robert W. Dudley, Angela E. Gregory, Glenn A. Hodgkins, Steven K. Sando, and Roy Sando, U. S. Geological Survey

Abstract:

As a statistical method, flood-frequency analysis has fundamental underlying assumptions, including an assumption that floods are generated by stationary processes (constant mean within a window of variance). As our understanding of nature, our effect on nature, and statistical principles has improved, standard flood-frequency analysis methods have become increasingly questionable for some sites or time periods. Yet, flood-frequency analysis remains critical for the appropriate sizing and construction of culverts, bridges, and other flood-control infrastructure and for informing decisions related to the safety of homes and businesses and to ecosystem management. Our goals, to date, for a multi-year project funded by the U.S. Federal Highway Administration have been to document trends and change points (nonstationarities that are violations of the assumptions of flood-frequency analysis) in annual peak streamflow across the conterminous United States and attribute these changes, where possible, to anthropogenic and environmental factors for which there are data. Once the anthropogenic or environmental changes causing these nonstationarities are better understood, analysts can then begin to make choices about the best methods for adjusting flood-frequency analyses. Our current goal is to take what we have learned about nonstationarities and their attributions and test potential methods for adjusting flood-frequency estimates. This poster demonstrates a framework for synchronizing efforts to detect, attribute, and adjust for changes in flood regimes, utilizing knowledge from experts in hydrologically diverse regions in the conterminous United States.

3.6.5 Poster 2C-5: Probabilistic Flood Hazard Assessment Framework: Riverine Flooding HEC-WAT Pilot Project.

Author: William Lehman, U.S. Army Corps of Engineers, Institute for Water Resources, Hydrologic Engineering Center (USACE/IWR/HEC)

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 poster will illustrate progress to date on the NRC riverine pilot project.

3.6.6 Poster 2C-6: Investigating the Sources of Uncertainty in Precipitation Frequency Estimates: Comparative Study of At-Site and Regional Frequency Analysis

Authors: Azin Al Kajbaf and Michelle Bensi, Department of Civil and Environmental Engineering, University of Maryland

Abstract:

This study is motivated by the two recent heavy rainfall events and flash floods in Ellicott City in 2016 and 2018. Before 2016, floods were primarily due to tropical cyclone activity. However, severe thunderstorms in 2016 and 2018 caused locally intense rainfall for only a few hours, which inundated the upper watershed of the city. The exceedance probability analysis prepared by National Weather Service, based on NOAA Atlas 14 volume 2, suggests that the probability of exceedance for the 5 minutes to 3 hours duration rainfalls for the 2016 event are estimated to be 1 in 1000 or less. The last revision of this Atlas was published in 2006, which has used data through 2000 and therefore does not contain the precipitation events that happened since then. The estimates computed in NOAA Atlas 14 are intended to support regional assessments. They are also subject to epistemic uncertainty that emerges due to the limited quality and duration of high-quality precipitation data to support frequency analyses. This study investigates the effects of recent locally intense rainfall events on precipitation frequency analysis for the Ellicott City area considering 24-hour precipitation data. Furthermore, this study explores the potential impacts of sources of epistemic uncertainty that are not fully addressed by NOAA Atlas 14 method, such as record length, number of stations, distribution type, and parameter estimation method for both regional and at-site frequency analysis.

3.7 Day 3: Session 3A – Modeling Frameworks

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

3.7.1 Presentation 3A-1: Structured Hazard Assessment Committee Process for Flooding (SHAC-F) for Probabilistic Flood Hazard Assessment (PFHA)

Authors: Rajiv Prasad and Phillip Meyer, Pacific Northwest National Laboratory (PNNL); Kevin Coppersmith, Coppersmith Consulting; Norberto C. Nadal-Caraballo and Victor M. Gonzalez, U.S. Army Corps of Engineers, Engineer Research & Development Center, Coastal and Hydraulics Laboratory (USACE/ERDC/CHL)

Speaker: Rajiv Prasad

3.7.1.1 Abstract

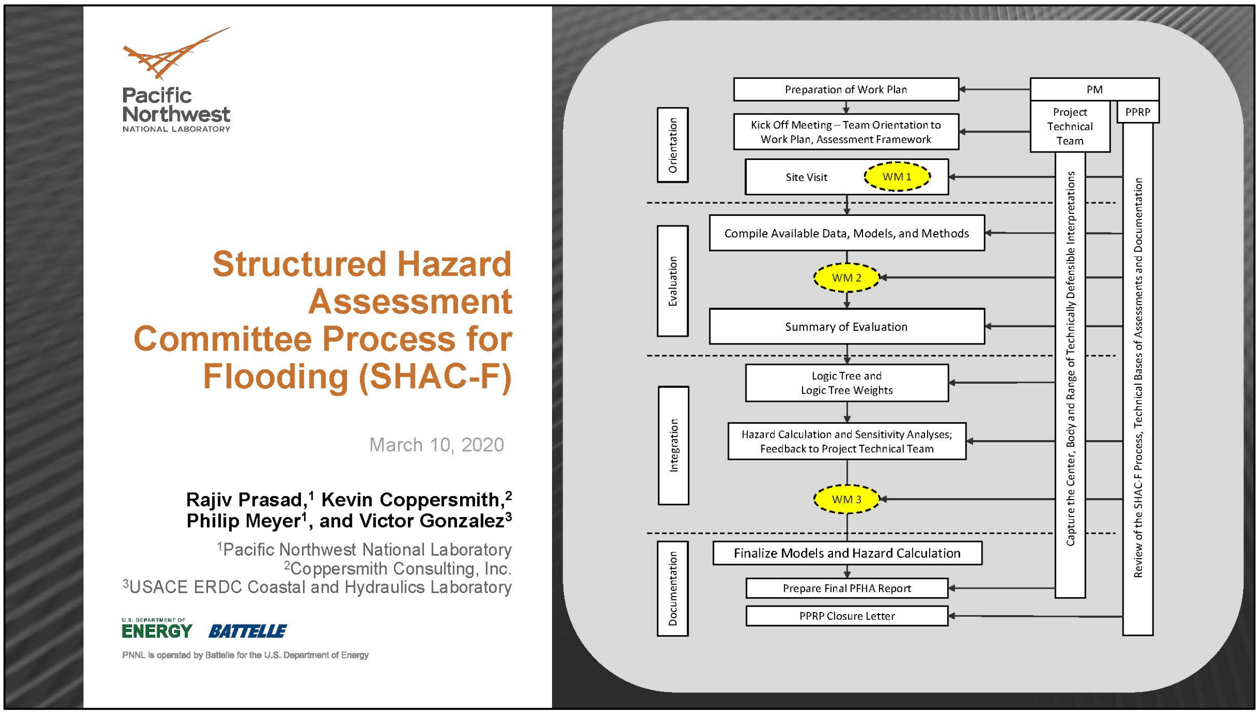
The Pacific Northwest National Laboratory (PNNL) led the development of the structured hazard assessment committee process for flooding (SHAC-F). One of the main goals of SHAC-F is to bring consistency to probabilistic flood hazard assessments (PFHAs). SHAC-F studies can be carried out at three levels, increasing in complexity and levels-of-effort from the lowest to the highest levels. Flood hazard assessments can support a variety of purposes for a nuclear power plant (NPP) permitting, licensing, and oversight activities. Therefore, SHAC-F study levels are structured to explicitly support these 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 (1) refine a Level 1 SHAC-F study that did not adequate resolve screening and binning of SSCs of interest or (2) update a Level 3 SHAC-F study considering availability of additional data, models, and methods. A Level 3 SHAC-F study is the most complex and used to support NPP permitting and licensing or probabilistic risk assessments involving plant-wide assessment of flood hazards and associated effects. Regardless of the level, SHAC-F studies must capture the range aleatory variability and the range of epistemic uncertainty reflected in the knowledge of the larger, technically informed flood hazard assessment community.

In a Level 1 SHAC-F study, a flood-frequency analysis using readily accessible hydrometeorological data combined with a relatively simple on-site hydraulic modeling may be performed by a small project technical team with expertise in statistical modeling, regional hydrometeorology, and site hydraulics. The participatory peer review panel (PPRP) may be structured similarly to the project technical team. In a Level 2 SHAC-F study to refine a previous Level 1 SHAC-F study, additional data collection and model refinement in consultation with experts may be performed. The project team could consist of Technical Integration (TI) teams and spend more time consulting with data and model experts. In a Level 2 SHAC-F study to update a previous Level 3 SHAC-F 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, the project technical team is the largest, consisting of meteorological and hydrological/hydraulic TI teams. The TI teams, led by a Project Technical Integrator, may need support for database and geographical information system management and specialty contractors for data collection or model simulations.

PNNL is working with the U.S. Army Corps of Engineers Coastal and Hydraulics Laboratory (CHL) to adapt the SHAC-F approach to coastal flooding from tropical cyclones. The Coastal SHAC-F levels are defined similarly to the three SHAC-F levels described above. In a Level 1 Coastal SHAC-F study, flood hazards may be estimated based on analyses of observed

extreme tide levels using statistical modeling and relatively simple site-scale hydraulic models. A Level 2 Coastal SHAC-F study could leverage existing probabilistic storm surge studies combined with site-scale hydraulic models. A Level 3 Coastal SHAC-F study would perform the full probabilistic storm surge analysis following the joint probability method and a detailed site-scale modeling to estimate site-wide flood hazards.

3.7.1.2 Presentation (ADAMS Accession No. ML20080M144)



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Structured Hazard Assessment Committee Process for Flooding (SHAC-F)

March 10, 2020

Rajiv Prasad,[1] Kevin Coppersmith,[2] Philip Meyer[1], and Victor Gonzalez[3]

[1]Pacific Northwest National Laboratory
[2]Coppersmith Consulting, Inc.
[3]USACE ERDC Coastal and Hydraulics Laboratory

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Orientation
Preparation of Work Plan
Kick Off Meeting – Team Orientation to Work Plan, Assessment Framework
Site Visit
WM 1

Evaluation
Compile Available Data, Models, and Methods
WM 2
Summary of Evaluation

Integration
Logic Tree and Logic Tree Weights
Hazard Calculation and Sensitivity Analyses; Feedback to Project Technical Team
WM 3

Documentation
Finalize Models and Hazard Calculation
Prepare Final PFHA Report
PPRP Closure Letter

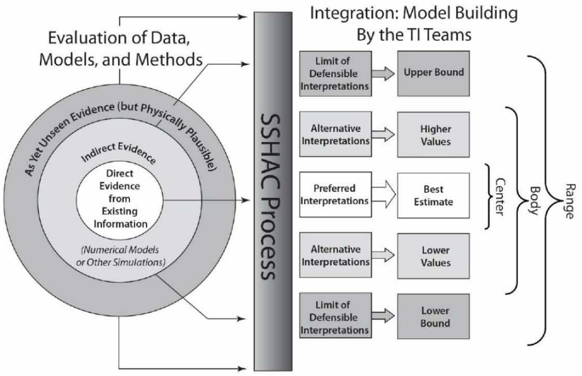
PM
Project Technical Team
PPRP
Capture the Center, Body and Range of Technically Defensible Interpretations
Review of the SHAC-F Process, Technical Bases of Assessments and Documentation

Motivation

- Flood frequency analysis (FFA) is well established
  - Suitable for at-site estimation of distribution of flood discharge or flood volumes
  - Bulletin 17B, 17C; Asquith et al. 2017
- NRC flood reviews need estimation of dynamic flood parameters and associated effects at very low exceedance probabilities
  - Complete flood hydrographs – temporal flood characteristics
  - Hydrostatic and hydrodynamic loadings – spatial flood characteristics
  - Inundation map – spatial flood characteristics
  - Inundation duration – temporal and spatial flood characteristics
- FFA needs to be supplemented with conceptual flood models
  - Watershed models, site-scale models
  - Introduction of additional uncertainties – epistemic and aleatory
- A structured process to account for all uncertainties is needed
  - Structured Hazard Assessment Committee Process for Flooding (SHAC-F)

SHAC-F Goals

- The fundamental goal of a SHAC-F process is to properly carry out and completely document the activities of evaluation and integration, defined as:
  - Evaluation: The consideration of the complete set of data, models, and methods proposed by the larger technical community that are relevant to flood hazard analysis.
  - Integration: Representing the center, body, and range of technically defensible interpretations in light of the evaluation process (i.e., informed by the assessment of existing data, models, and methods).



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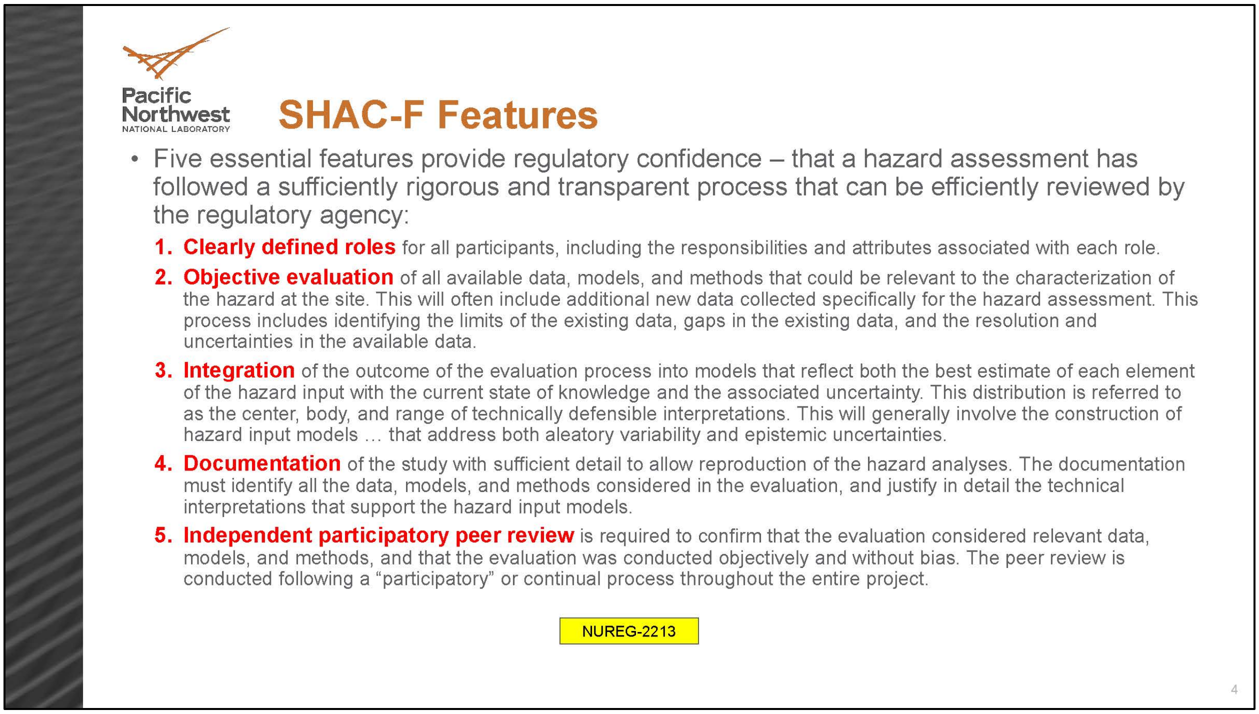

SHAC-F Features

- 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.

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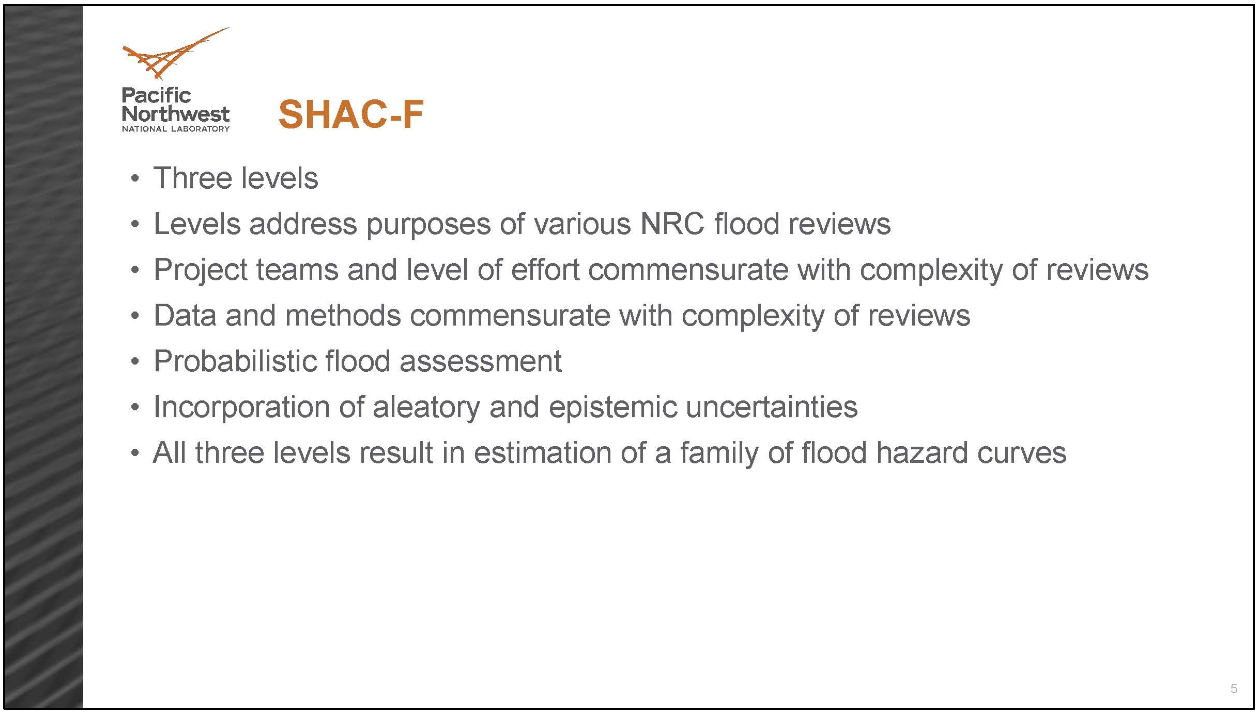
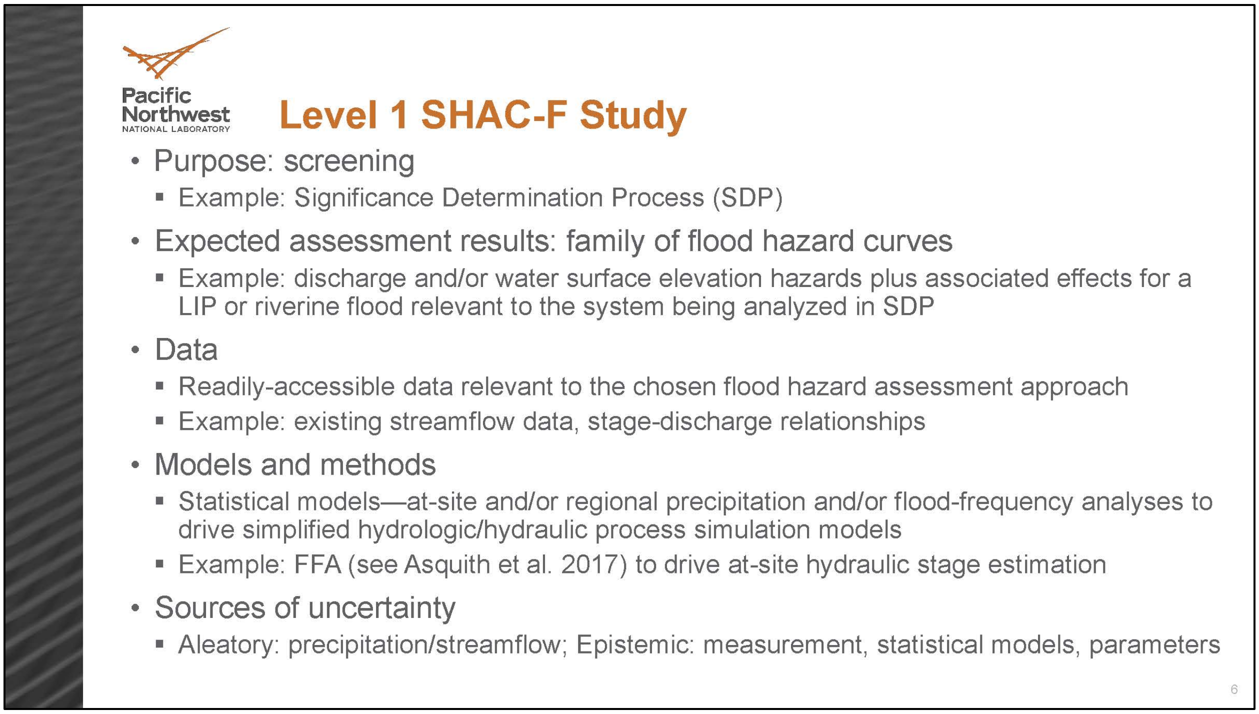


SHAC-F

- Three levels
- Levels address purposes of various NRC flood reviews
- Project teams and level of effort commensurate with complexity of reviews
- Data and methods 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



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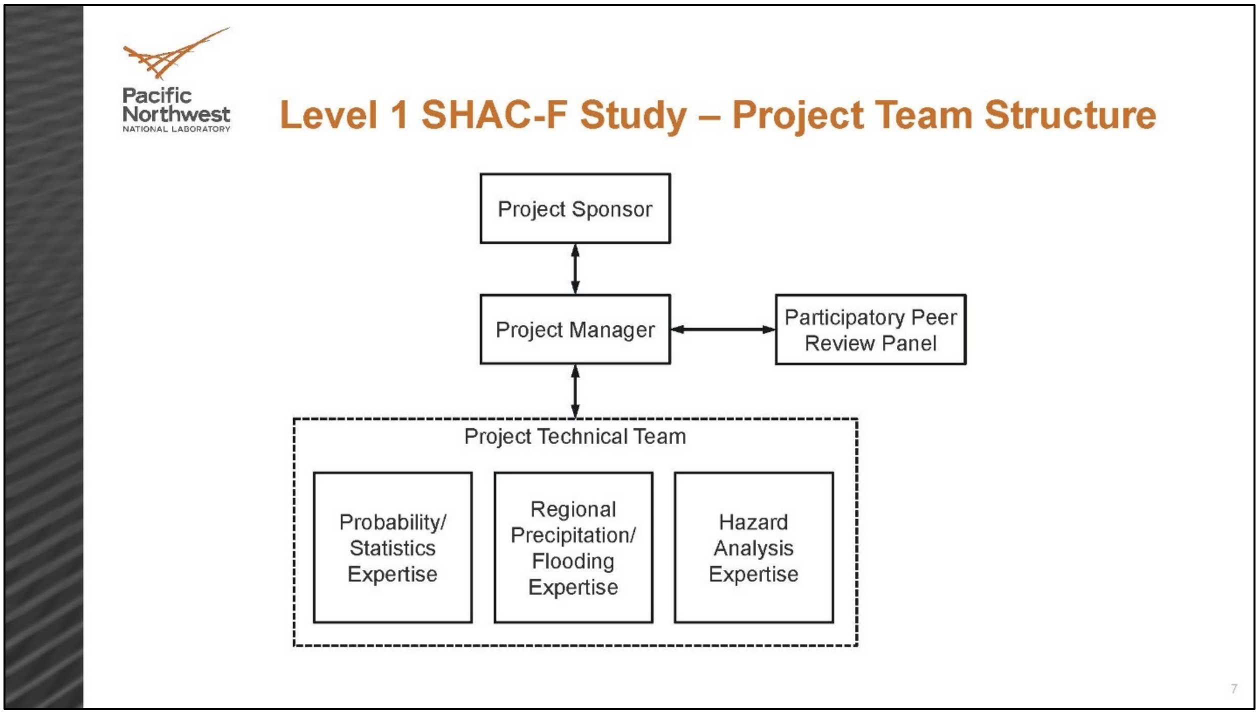
Level 1 SHAC-F Study

- Purpose: screening
  - Example: Significance Determination Process (SDP)
- Expected assessment results: family of flood hazard curves
  - Example: discharge and/or water surface elevation hazards plus associated effects for a LIP or riverine flood relevant to the system being analyzed in SDP
- Data
  - Readily-accessible data relevant to the chosen flood hazard assessment approach
  - Example: existing streamflow data, stage-discharge relationships
- Models and methods
  - Statistical models—at-site and/or regional precipitation and/or flood-frequency analyses to drive simplified hydrologic/hydraulic process simulation models
  - Example: FFA (see Asquith et al. 2017) to drive at-site hydraulic stage estimation
- Sources of uncertainty
  - Aleatory: precipitation/streamflow; Epistemic: measurement, statistical models, parameters



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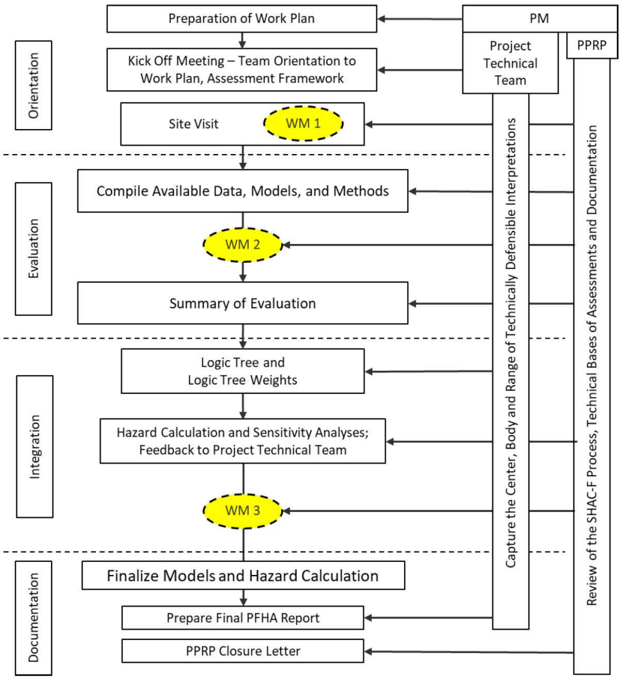
Level 1 SHAC-F Study – Project Team Structure

Level 1 SHAC-F Study: Workflow



Preparation of Work Plan

Kick Off Meeting – Team Orientation to Work Plan, Assessment Framework

Site Visit

WM 1

Compile Available Data, Models, and Methods

WM 2

Summary of Evaluation

Logic Tree and Logic Tree Weights

Hazard Calculation and Sensitivity Analyses; Feedback to Project Technical Team

WM 3

Finalize Models and Hazard Calculation

Prepare Final PFHA Report

PPRP Closure Letter

PM

Project Technical Team

PPRP

Orientation

Evaluation

Integration

Documentation

Capture the Center, Body and Range of Technically Defensible Interpretations

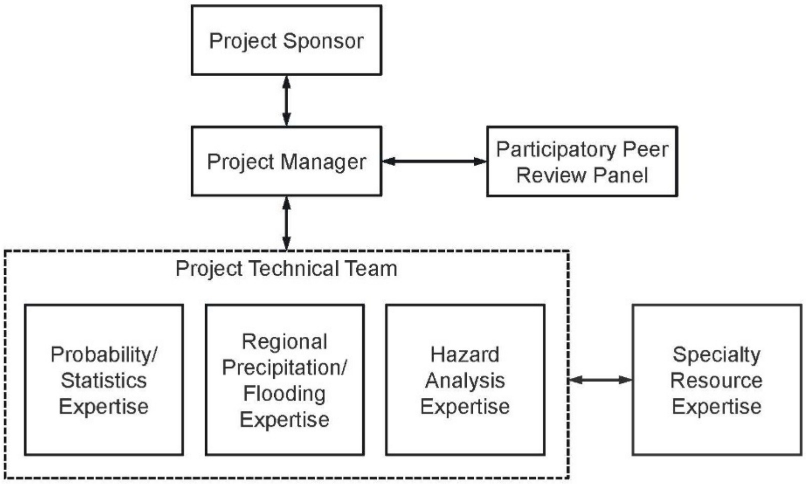
Review of the SHAC-F Process, Technical Bases of Assessments and Documentation

WM: Working Meeting

Level 2 SHAC-F Study

- Purpose: updating existing analyses or refining screening analyses
  - Example: support corrective actions, update or refine an existing Level 3 study, support License Amendment Requests, refine a Level 1 study
- Expected assessment results: family of flood hazard curves
  - Example: family of hazard curves plus associated effects for multiple systems/locations of interest for corrective actions or permitting/licensing
- Data
  - More extensive effort to assemble existing data, contact resource experts
  - Example: historical, non-public, reanalysis, available paleoflood, and synthetic data
- Models and methods
  - Statistical models, process-simulation models with spatial variations, consider nonstationarities
  - Example: frequency analysis incorporating additional data (see Asquith et al. 2017) to drive a watershed model
- Sources of uncertainty
  - Aleatory: streamflow, precipitation, initial conditions; Epistemic: discharge/precipitation/initial conditions measurement, alternative statistical/conceptual models, statistical/watershed model parameters

Level 2 SHAC-F Study – Project Team Structure for Refinement of a Level 1 Study


Project Sponsor

Project Manager

Participatory Peer Review Panel

Project Technical Team

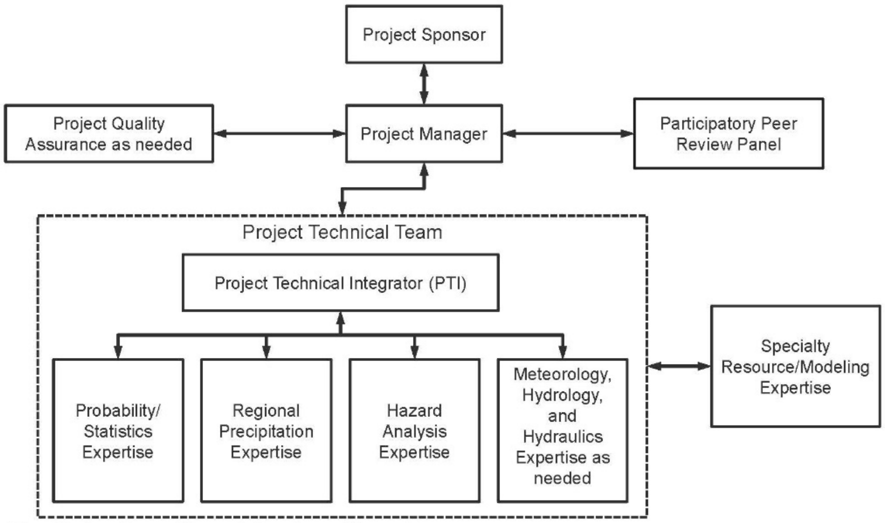
Probability/ Statistics Expertise

Regional Precipitation/ Flooding Expertise

Hazard Analysis Expertise

Specialty Resource Expertise

Level 2 SHAC-F Study – Project Team Structure for Update or Refinement of a Level 3 Study


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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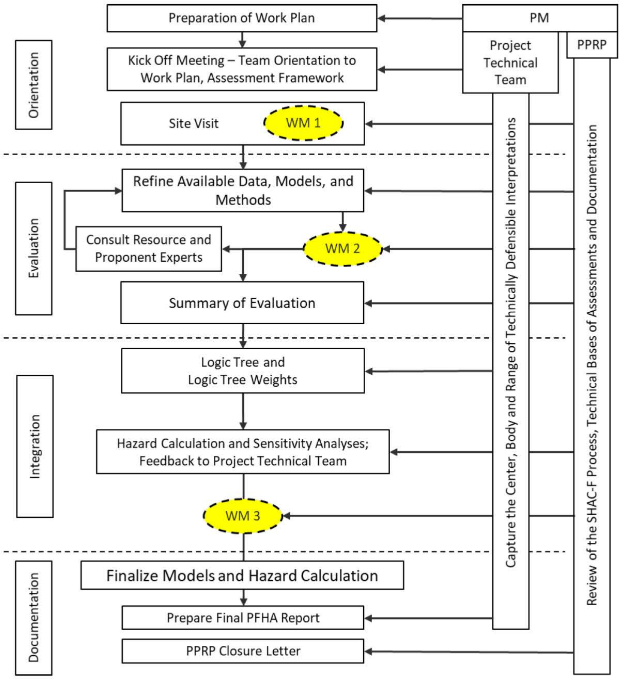
Level 2 SHAC-F Study: Workflow



WM: Working Meeting

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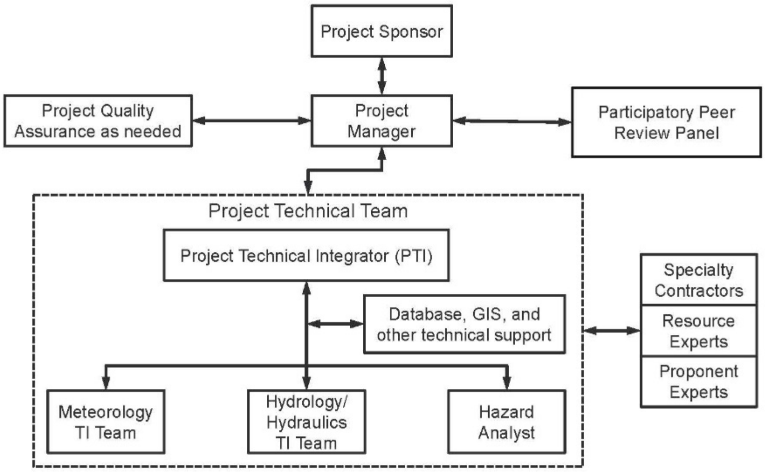
Level 3 SHAC-F Study

- Purpose: supporting design and/or providing inputs to a PRA
  - Example: support Combined License Application, support License Amendment Requests
- Expected assessment results: family of flood hazard curves
  - Example: family of hazard curves plus associated effects for site-wide hazards
- Data
  - Consider collecting new data
  - Example: paleoflood data, LiDAR surveys, remote sensing LULC data, bathymetric surveys
- Models and methods
  - Statistical and process-simulation models with spatiotemporal resolution to support PRA; consider nonstationarities
  - Example: FFA incorporating paleoflood data, site-specific watershed models driven with frequency inputs
- Sources of uncertainty
  - Aleatory: streamflow, precipitation, initial, and boundary conditions; Epistemic: discharge/precipitation/initial/boundary conditions measurement, alternative statistical models, statistical/watershed model parameters, alternative process representations in watershed models

Level 3 SHAC-F Study – Project Team Structure



Project Sponsor

Project Quality Assurance as needed

Project Manager

Participatory Peer Review Panel

Project Technical Team

Project Technical Integrator (PTI)

Database, GIS, and other technical support

Meteorology TI Team

Hydrology/ Hydraulics TI Team

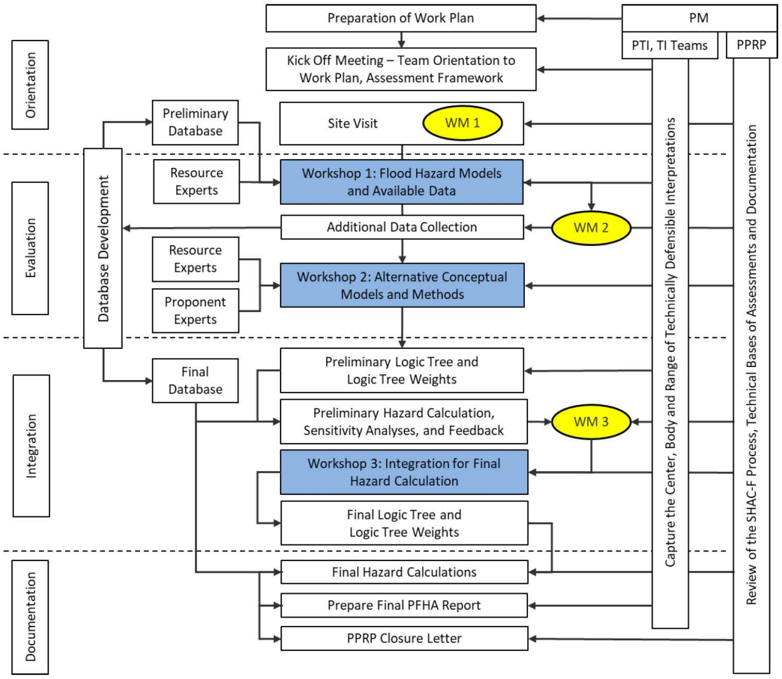
Hazard Analyst

Specialty Contractors

Resource Experts

Proponent Experts

Level 3 SHAC-F Study: Workflow



PM

PTI, TI Teams

PPRP

Orientation

Preparation of Work Plan

Kick Off Meeting – Team Orientation to Work Plan, Assessment Framework

Preliminary Database

Site Visit

WM 1

Evaluation

Database Development

Resource Experts

Workshop 1: Flood Hazard Models and Available Data

Additional Data Collection

WM 2

Resource Experts

Proponent Experts

Workshop 2: Alternative Conceptual Models and Methods

Integration

Final Database

Preliminary Logic Tree and Logic Tree Weights

Preliminary Hazard Calculation, Sensitivity Analyses, and Feedback

WM 3

Workshop 3: Integration for Final Hazard Calculation

Final Logic Tree and Logic Tree Weights

Documentation

Final Hazard Calculations

Prepare Final PFHA Report

PPRP Closure Letter

Capture the Center, Body and Range of Technically Defensible Interpretations

Review of the SHAC-F Process, Technical Bases of Assessments and Documentation

WM: Working Meeting

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SHAC-F for Coastal Flooding

- USACE Coastal and Hydraulics Laboratory and PNNL
- Series of conference calls starting Fall 2019
- Three Levels of coastal flooding SHAC-F studies
- Workshop scheduled for first week of March 2020

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Summary of Coastal SHAC-F Levels

Coastal Floods	SHAC-F Level 1	SHAC-F Level 2	SHAC-F Level 3
Purpose	Screening	Updating existing analyses or refining screening analyses	Supporting design and/or providing input to PRA
Expected Assessment Results	Limited family of water level and wave climate hazard curves.	Family of hazard curves	More complex family of hazard curves
Data	• Readily accessible data: e.g. Existing JPM data Gauge data.	• More extensive effort to find and assemble existing data: Historical data (HURDAT), reanalysis data (EBTRK). Previous JPM study data.	Extensive effort to find and assemble existing data: Topobathy data for new grid development or significant upgrade of existing grid.
Models and Methods	Extreme value analysis Response based approach: Monte Carlo TC sampling of existing JPM storm responses.	JPM • Storm recurrence rate models • Defining marginal distributions of TC parameters • Re-computing synthetic storm set probability weights. • JPM hazard curve integration Storm subsampling Incorporation of extratropical analysis in hazard. Limited grid modifications.	Full JPM • Synthetic storm track development. • Development of wind and pressure fields. • Validation of historical TCs • Computation of TC probability masses and generation of synthetic storm sets. • Statistical plus simulation • Soft coupling of process-simulation models
Principal Sources of aleatory variability	Water level (surge), wave data, and tides, TC frequency.	Water level (surge), wave data, and tides, TC frequency.	Water level (surge), wave data, and tides, TC frequency. Tides, SLC.
Principal sources of epistemic uncertainty	Measurement uncertainty in historical storm data, sampling variability, alternative statistical models, parameter uncertainty.	Measurement uncertainty in historical storm data, alternative data sources and statistical models and methods, parameter uncertainty in simulation model parameters, hydrodynamic modeling errors.	Measurement uncertainty in historical storm data, alternative statistical models, parameter uncertainty in simulation model parameters, alternative process representations in simulation models

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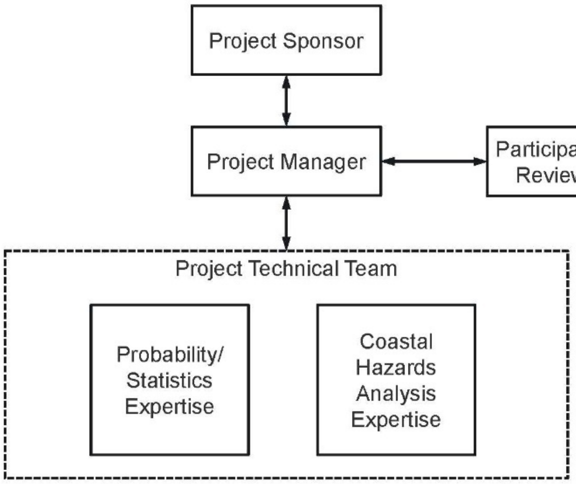
Level 1 SHAC-F Study – Project Team Structure


Project Sponsor

Project Manager

Participatory Peer Review Panel

Project Technical Team

Probability/ Statistics Expertise

Coastal Hazards Analysis Expertise

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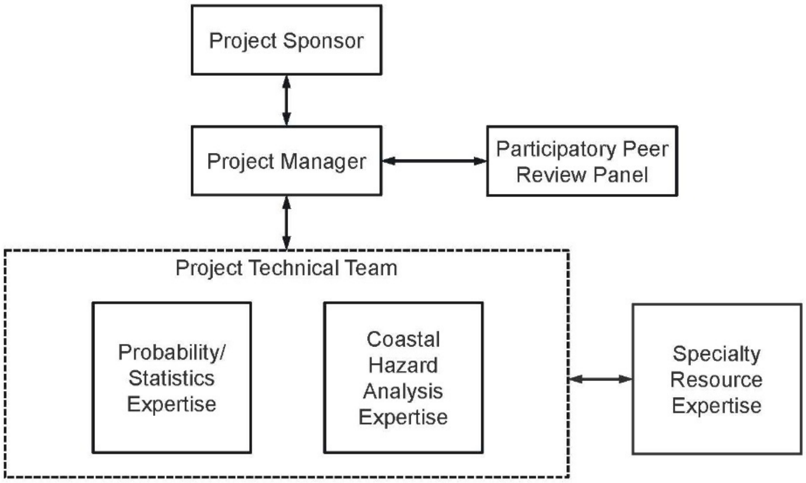
Level 2 SHAC-F Study – Project Team Structure for Refinement of a Level 1 Study


Project Sponsor

Project Manager

Participatory Peer Review Panel

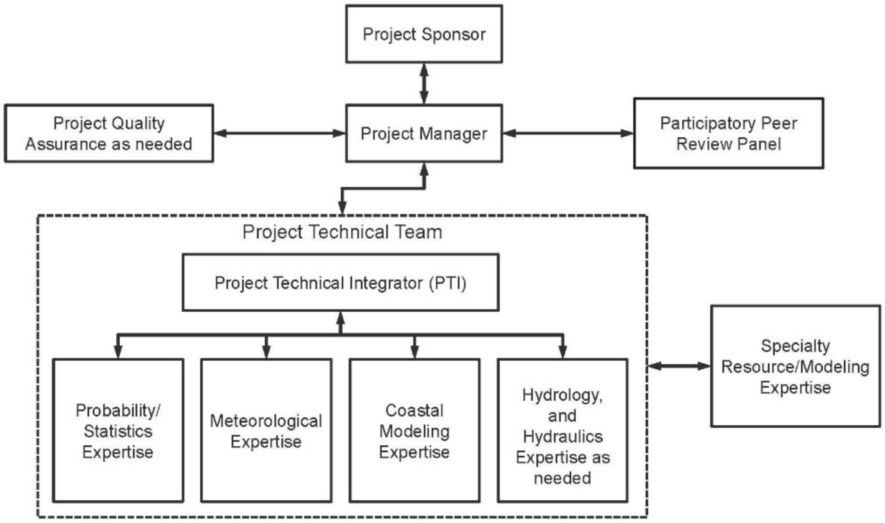
Project Technical Team

Probability/ Statistics Expertise

Coastal Hazard Analysis Expertise

Specialty Resource Expertise

Level 2 SHAC-F Study – Project Team Structure for Update of a Level 3 Study



Project Sponsor

Project Quality Assurance as needed

Project Manager

Participatory Peer Review Panel

Project Technical Team

Project Technical Integrator (PTI)

Probability/ Statistics Expertise

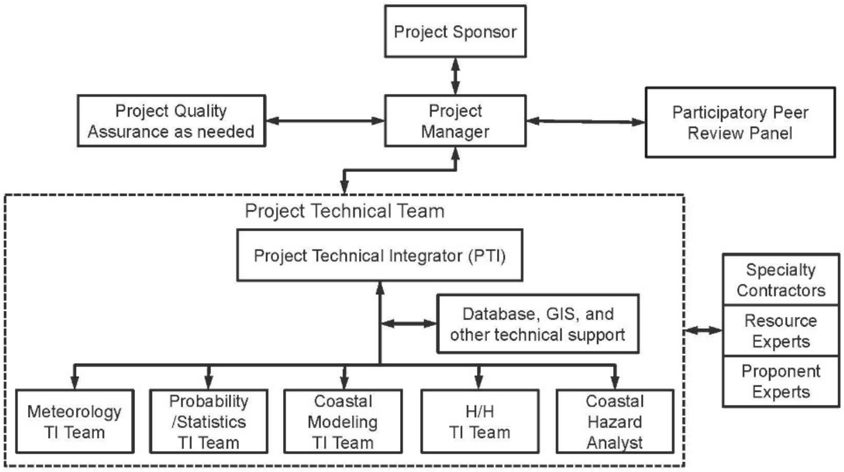
Meteorological Expertise

Coastal Modeling Expertise

Hydrology, and Hydraulics Expertise as needed

Specialty Resource/Modeling Expertise

Level 3 SHAC-F Study – Project Team Structure



Project Sponsor

Project Quality Assurance as needed

Project Manager

Participatory Peer Review Panel

Project Technical Team

Project Technical Integrator (PTI)

Database, GIS, and other technical support

Meteorology TI Team

Probability /Statistics TI Team

Coastal Modeling TI Team

H/H TI Team

Coastal Hazard Analyst

Specialty Contractors

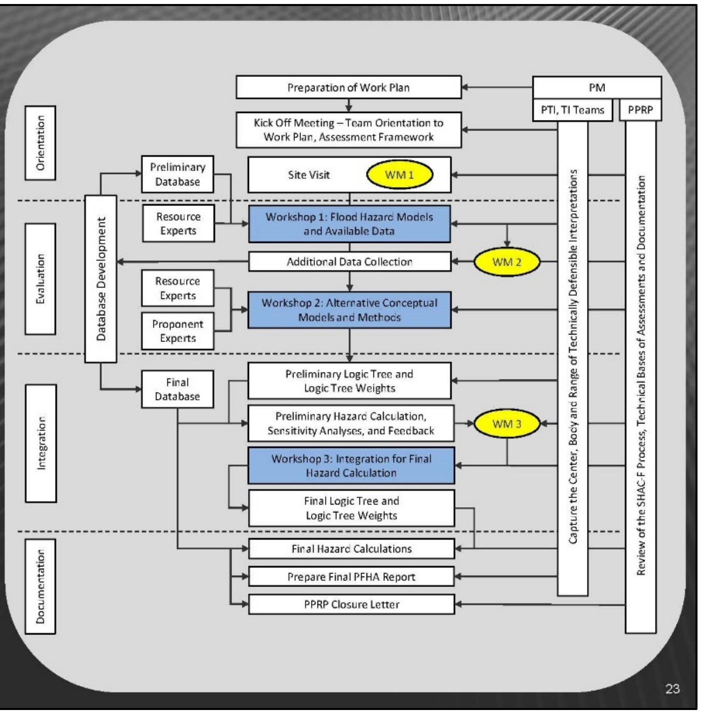
Resource Experts

Proponent Experts

Conclusions

- SHAC-F is tailored after the Senior Seismic Hazard Assessment Committee (SSHAC) process
  - Three levels address purposes of various NRC flood reviews
  - Project teams and levels of effort commensurate with complexity of reviews
- SHAC-F does not require specific models or methods to be used
- SHAC-F does require probabilistic flood assessment with incorporation of aleatory and epistemic uncertainties in estimation of a family of flood hazard curves
- SHAC-F does require documentation with sufficient detail to allow review, reproduction, and update to a PFHA

Thank you



3.7.2 Presentation 3A-2: Using HEC-WAT to Conduct a PFHA on a Medium Watershed

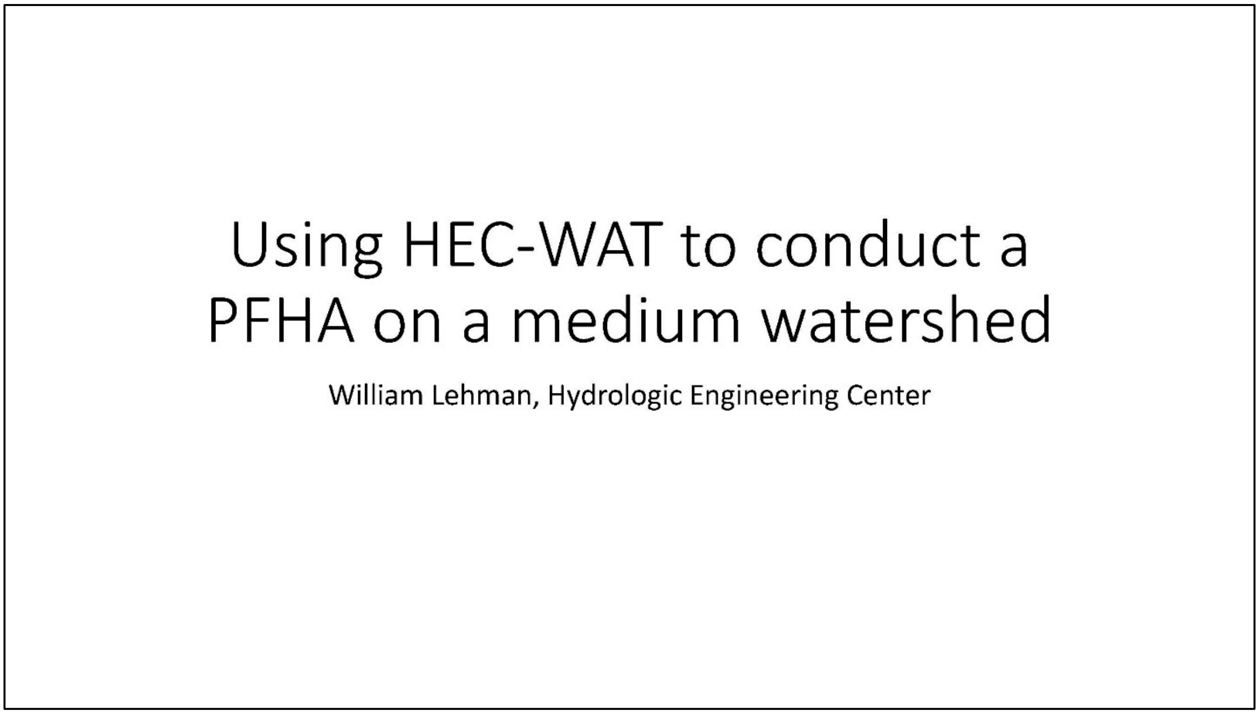
Authors: Will Lehman, Brennan Beam, Matthew Fleming, and Leila Ostadrahimi, U.S. Army Corps of Engineers, Institute for Water Resources, Hydrologic Engineering Center (USACE/IWR/HEC); Joseph Kanney and Meredith Carr, NRC Office of Nuclear Regulatory Research

Speaker: Will Lehman

3.7.2.1 Abstract

The Hydrologic Engineering Center's Watershed Analysis Tool (HEC-WAT) supports the evaluation of hydraulic hazards at sites throughout a floodplain. The example shows how to leverage HEC-HMS (hyrometerological processes), HEC-ResSim (reservoir operations), and HEC-RAS (river hydraulics and dam breaks) to work in concert to evaluate the impact of Aleatory and Epistemic uncertainties on the frequency of loading at a site in the floodplain. Within HEC-HMS, Markov Chain Monte Carlo was used to evaluate parameter sets in the HEC-HMS model, which is a strategy to improve model behavior during simulation. In HEC-ResSim, uncertainty distributions were used based on historic data for starting pool (treated as Aleatory for the IID events) to show the impact of that parameter on the hazard frequency curve. Epistemic uncertainty in precipitation frequency and dam failure (including comparisons with and without dam failure) impact the uncertainty bands around the hazard frequency curves and show how our limited knowledge impacts our ability to describe extreme events. The application required the use of distributed computing and stratified sampling to manage to report the Epistemic uncertainty associated with loading at the location out to 10e-6. This presentation will show how these complex software systems work together to describe a complex natural system to inform and improve our ability to make decisions in light of uncertainty.

3.7.2.2 Presentation (ADAMS Accession No. ML20080M148)

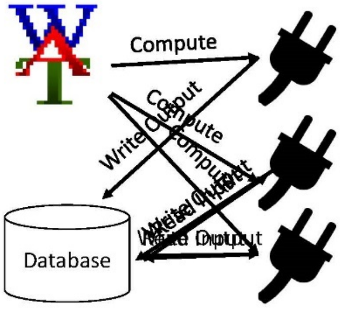


Using HEC-WAT to conduct a PFHA on a medium watershed

William Lehman, Hydrologic Engineering Center

Brief overview of HEC-WAT

- HEC-WAT Manages Watershed-wide System Based computes through plug-ins
- Plug-ins interact with each other through a centralized database



Repeat!

How do we capture a distribution of uncertainty in Output Metrics?

Nested Monte Carlo: *HEC-WAT/FRA*

A. Sample instances of natural variabilities as flood *events*, with enough events to capture the distribution of damage

B. Sample instances of knowledge uncertainties in model parameters to get their impact on the damage distribution

1 outer loop B = a realization

inner loop A varies natural variabilities, computes EAD

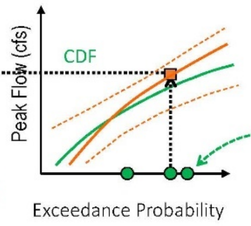
outer loop B varies knowledge uncertainty, computes EAD distribution

Sampling Variability and Uncertainty

Nested Monte Carlo Simulation

Reservoir Analysis
Channel Hydraulics
Levee Behavior
Spreading Model

hydrographs



sample new frequency curve (uncertainty)
and then sample events (variability)

Random choice of probability ~ $U_i[0,1]$ to "generate" event

One Event: sample member i

sample uncertain model parameters
sample variabilities

stage

Inundation Mapping
Structure Inventory
Damage to Structures

output

Output(i)

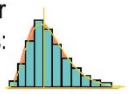
For each realization, get an output estimate

EV = 1/nSum(Output(i))

…still end with a sample of outputs

One Realization

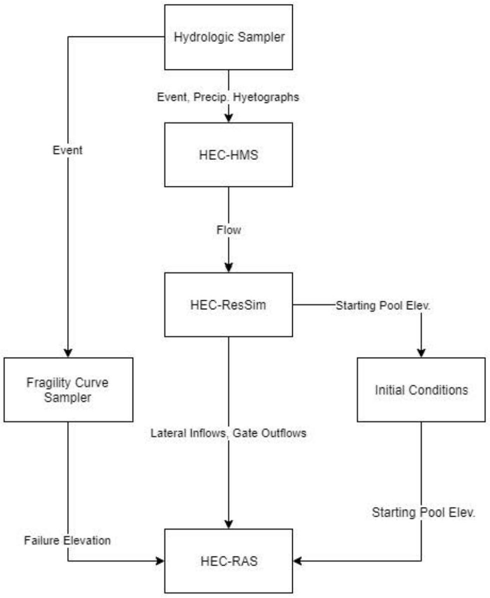
After repeating for many realizations:



Distribution of Output

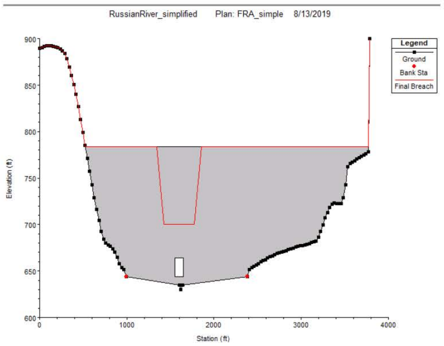
What is an "Event"?

- Precipitation Events
- Reservoir Regulation
- Dam Failure
- Hydraulic modeling

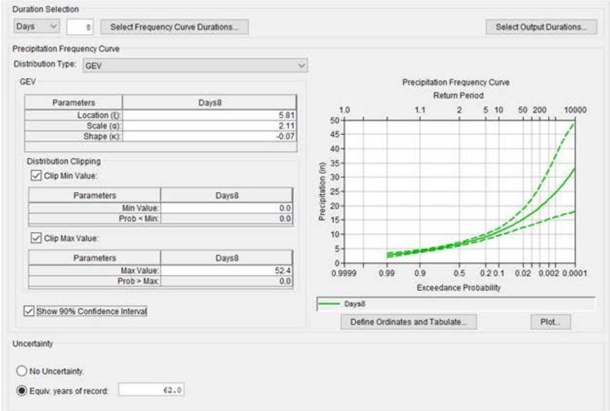


Watershed

- Russian River, Sonoma County California
- 1,485-square-mile watershed from the Coast Ranges in northern California
- Lake Mendocino, Coyote Valley Dam
- Outputs were stored at three downstream locations (in Red).



Precipitation Frequency



Duration Selection

Days 8

Precipitation Frequency Curve

Distribution Type: GEV

GEV

Parameters	Days8
Location (ξ):	5.81
Scale (α):	2.11
Shape (κ):	-0.07

Distribution Clipping

☑ Clip Min Value:

Parameters	Days8
Min Value:	0.0
Prob < Min:	0.0

☑ Clip Max Value:

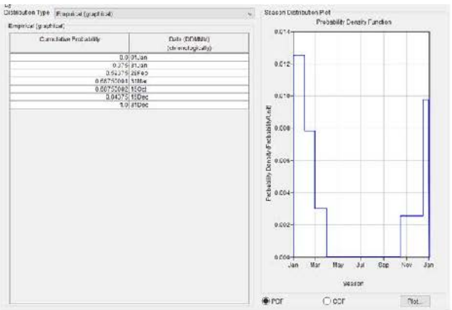
Parameters	Days8
Max Value:	52.4
Prob > Max:	0.0

☑ Show 90% Confidence Interval

Uncertainty

○ No Uncertainty.

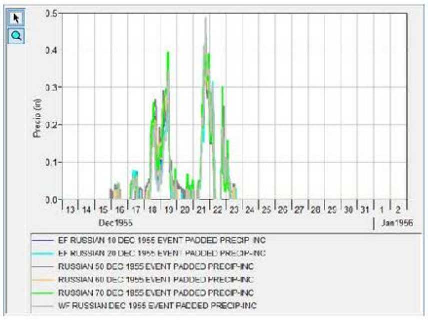
● Equiv. years of record: 62.0



Distribution Type: Empirical (graphical)

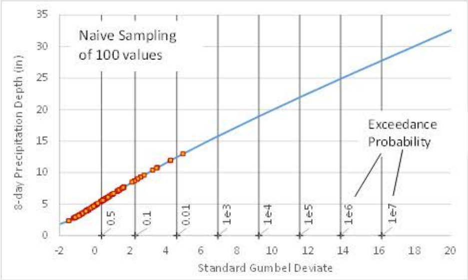
Empirical (graphical)

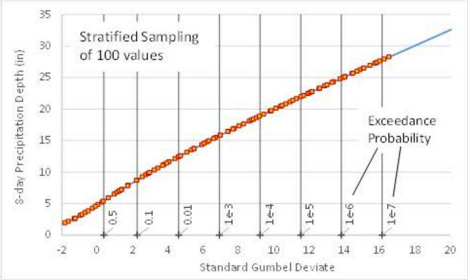
Cumulative Probability	Date (DDMMM) (chronologically)
0.0	01Jan
0.375	31Jan
[illegible]	28Feb
[illegible]	31Mar
[illegible]	15Oct
[illegible]	15Dec
1.0	31Dec



Stratification

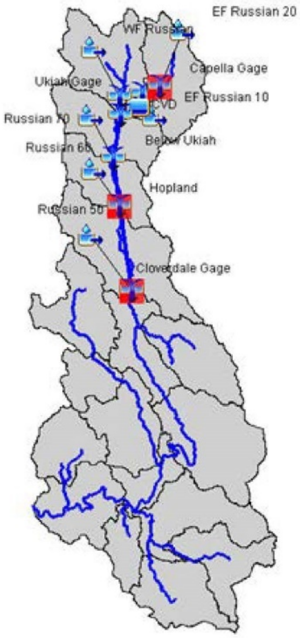
- In order to achieve sufficient modeling samples we stratified the Natural variability loop



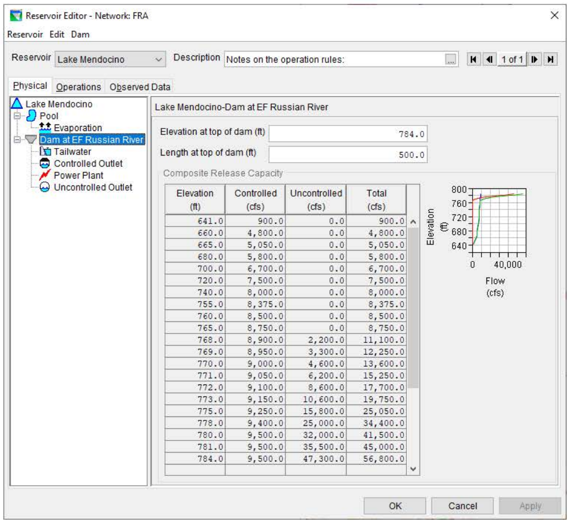


Rainfall Runoff

- Precipitation generated by the Hydrologic Sampler were provided to HEC-HMS
- Each basin receives a unique hyetograph for the shape set selected
- Basin outflows are mapped to HEC-RAS lateral inflows



Reservoir Operations



Reservoir: Lake Mendocino

Description: Notes on the operation rules:

1 of 1

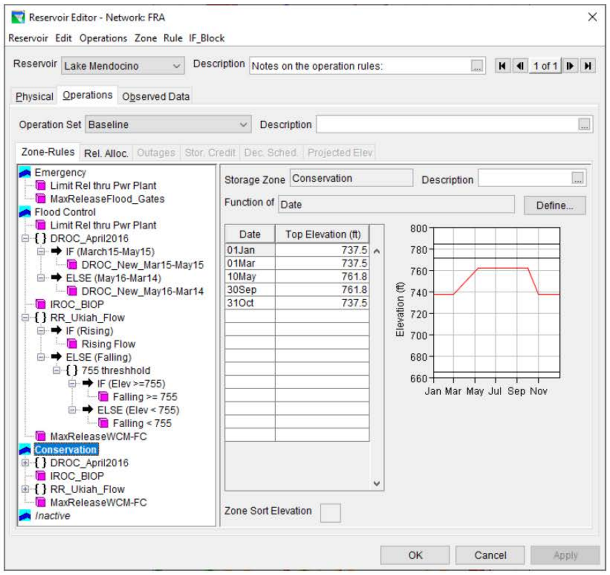
Lake Mendocino-Dam at EF Russian River

Elevation at top of dam (ft): 784.0

Length at top of dam (ft): 500.0

Composite Release Capacity

Elevation (ft)	Controlled (cfs)	Uncontrolled (cfs)	Total (cfs)
641.0	900.0	0.0	900.0
660.0	4,800.0	0.0	4,800.0
665.0	5,050.0	0.0	5,050.0
680.0	5,800.0	0.0	5,800.0
700.0	6,700.0	0.0	6,700.0
720.0	7,500.0	0.0	7,500.0
740.0	8,000.0	0.0	8,000.0
755.0	8,375.0	0.0	8,375.0
760.0	8,500.0	0.0	8,500.0
765.0	8,750.0	0.0	8,750.0
768.0	8,900.0	2,200.0	11,100.0
769.0	8,950.0	3,300.0	12,250.0
770.0	9,000.0	4,600.0	13,600.0
771.0	9,050.0	6,200.0	15,250.0
772.0	9,100.0	8,600.0	17,700.0
773.0	9,150.0	10,600.0	19,750.0
775.0	9,250.0	15,800.0	25,050.0
778.0	9,400.0	25,000.0	34,400.0
780.0	9,500.0	32,000.0	41,500.0
781.0	9,500.0	35,500.0	45,000.0
784.0	9,500.0	47,300.0	56,800.0



Reservoir: Lake Mendocino

Description: Notes on the operation rules:

1 of 1

Operation Set: Baseline

Description:

Storage Zone: Conservation

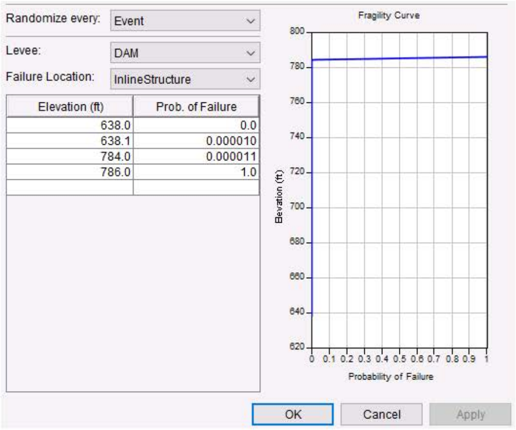
Description:

Function of: Date

Date	Top Elevation (ft)
01Jan	737.5
01Mar	737.5
10May	761.8
30Sep	761.8
31Oct	737.5

Zone Sort Elevation

Dam Failure

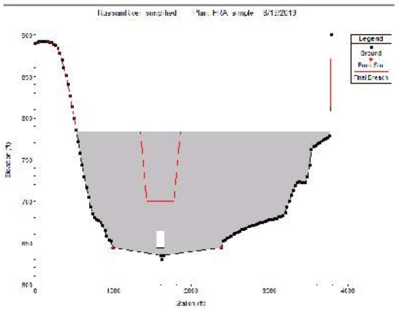


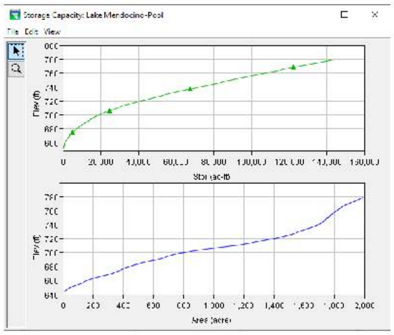
Randomize every: Event

Levee: DAM

Failure Location: InlineStructure

Elevation (ft)	Prob. of Failure
638.0	0.0
638.1	0.000010
784.0	0.000011
786.0	1.0

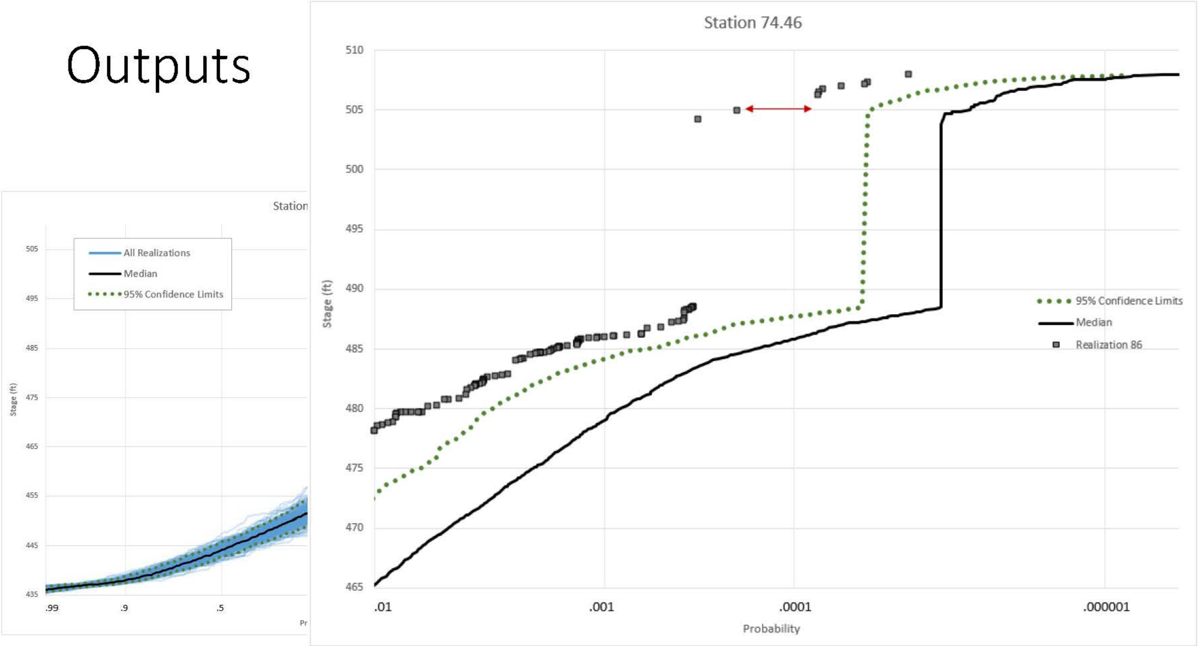


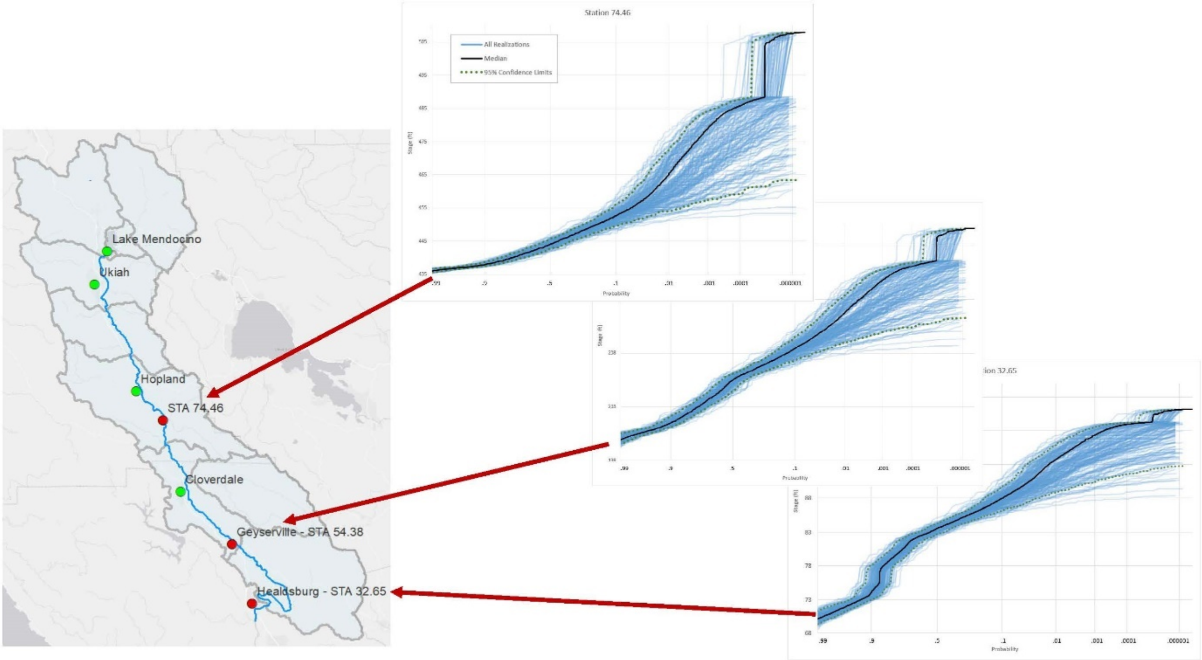


Hydraulic Modeling

- The Starting Pool Elevation for ResSim was used to set the initial pool for RAS
- Releases from the gate in the inline structure were set to be overridden by ResSim

Outputs





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.

3.7.3 Presentation 3A-3: Paleoflood Analyses for Probabilistic Flood Hazard Assessments— Approaches and Review Guidelines

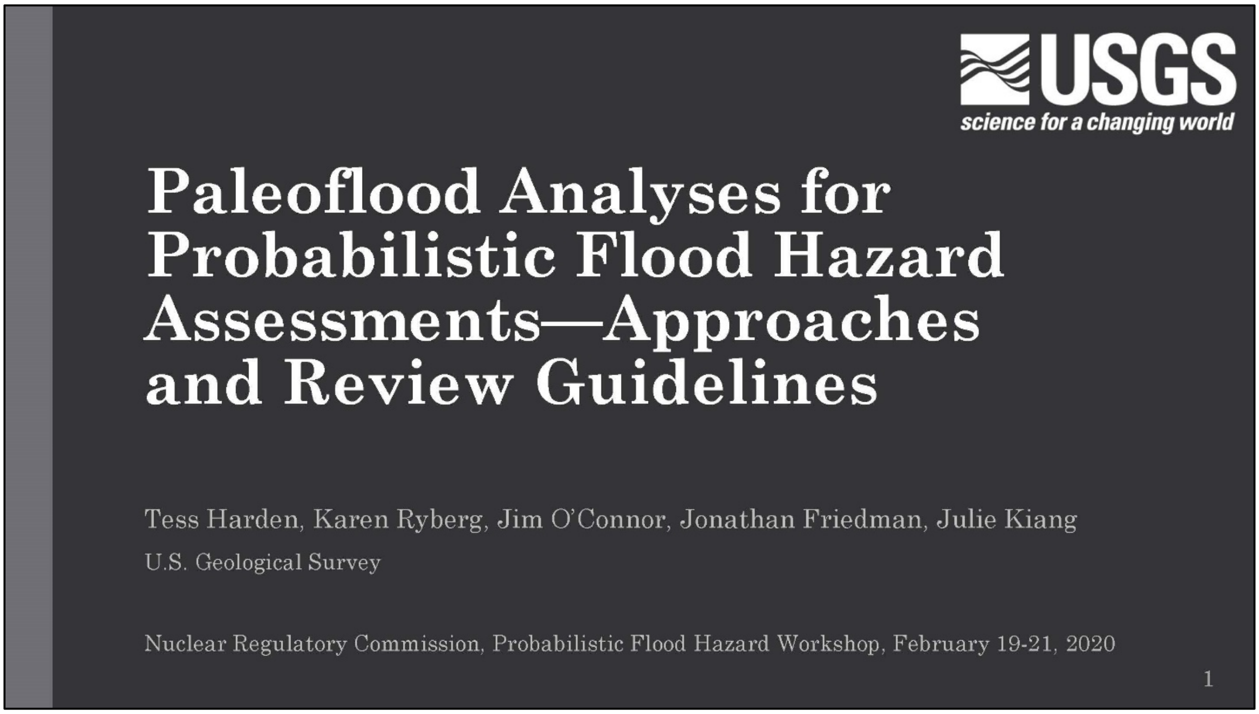
Authors: Tessa Harden, Karen Ryberg*, Jim E. O'Connor, Jonathan M. Friedman, and Julie E. Kiang, U.S. Geological Survey (USGS)

Speaker: Tessa Harden

3.7.3.1 Abstract

Paleoflood studies are an effective means of providing specific information on the recurrence and magnitude of rare and large floods, which can be combined with systematic flood measurements to improve the ability to accurately assess hydrologic risk to critical infrastructure. Paleoflood data also provides valuable information about the linkages among climate, land use, channel morphology and flood frequency. Standards of practice for conducting and reviewing such studies, however, are lacking, inhibiting their effective use in regulatory decision making. This presentation summarizes methods and techniques for preparation, collection, evaluation, and interpretation of paleoflood information, including uncertainties, especially with respect to new statistical approaches available to efficiently use such data in flood frequency analyses. Also presented will be guidance on the levels of study appropriate for specific questions or issues as well as appropriate corresponding levels of technical review.

3.7.3.2 Presentation (ADAMS Accession No. ML20080M150)



USGS
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Paleoflood Analyses for Probabilistic Flood Hazard Assessments—Approaches and Review Guidelines

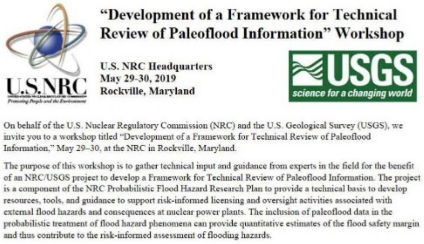
Tess Harden, Karen Ryberg, Jim O'Connor, Jonathan Friedman, Julie Kiang

U.S. Geological Survey

Nuclear Regulatory Commission, Probabilistic Flood Hazard Workshop, February 19-21, 2020

2019 Paleoflood Workshop

- USGS, NRC, USACE, Bureau of Reclamation, several universities
- Purpose of the workshop was to gather technical input and guidance from experts in the field for the benefit of a USGS Techniques and Methods Report.



"Development of a Framework for Technical Review of Paleoflood Information" Workshop

U.S. NRC Headquarters
May 29-30, 2019
Rockville, Maryland

On behalf of the U.S. Nuclear Regulatory Commission (NRC) and the U.S. Geological Survey (USGS), we invite you to a workshop titled "Development of a Framework for Technical Review of Paleoflood Information," May 29–30, at the NRC in Rockville, Maryland.

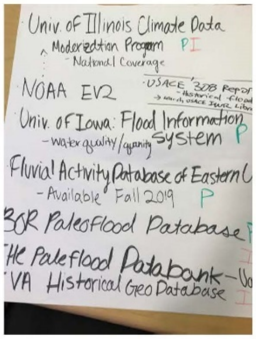
The purpose of this workshop is to gather technical input and guidance from experts in the field for the benefit of an NRC/USGS project to develop a Framework for Technical Review of Paleoflood Information. The project is a component of the NRC Probabilistic Flood Hazard Research Plan to provide a technical basis to develop resources, tools, and guidance to support risk-informed licensing and oversight activities associated with external flood hazards and consequences at nuclear power plants. The inclusion of paleoflood data in the probabilistic treatment of flood hazard phenomena can provide quantitative estimates of the flood safety margin and thus contribute to the risk-informed assessment of flooding hazards.

Workshop Motivation

- Paleoflood hydrology studies are an increasingly important 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.

Panel Discussions

- Uses of systematic, historical, and paleoflood data in PFHA—Probabilistic flood-hazard assessment
- Historical peak-flow data
- Determining floods from botanical evidence
- Sedimentological, stratigraphic, geochronological data
- Flow reconstruction
- Levels of review
- Databases



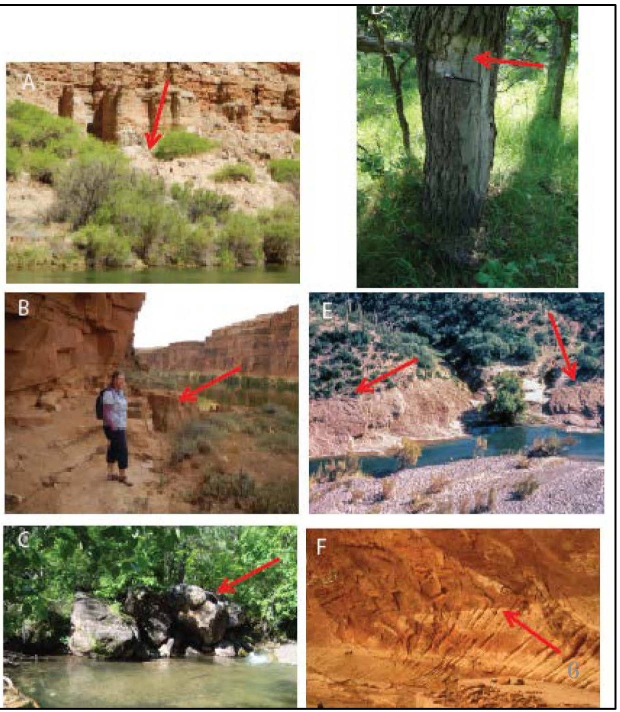
Univ. of Illinois Climate Data
Moderization Program P I
- National Coverage
NOAA EV2
USACE 308 Repor
- historical floo
→ search USACE IWR Libr
Univ. of Iowa: Flood Information System P
- water quality/quanity
Fluvial Activity Database of Eastern
- Available Fall 2019 P
BOR Paleoflood Database
HE Paleflood Databank –Vo
VA Historical Geo Database I

Paleoflood Analysis and Review Guidelines Document

- Document summarizes methods and techniques for preparation, gathering, evaluation, and interpretation of paleoflood information, including uncertainties, especially with respect to new statistical approaches available to efficiently use such data.
- Also provided is guidance on the levels of study appropriate for specific questions or issues as well as appropriate corresponding levels of technical review.

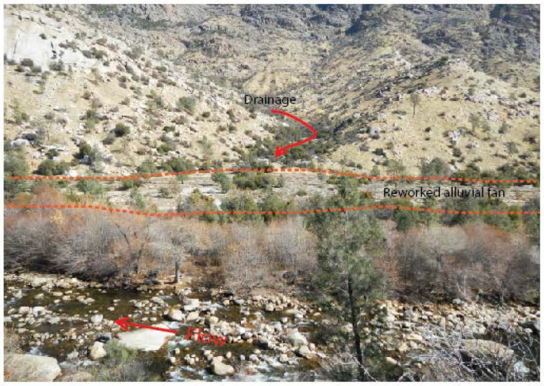
Included in analysis and review guidelines:

- Paleostage Indicators (PSI) and High water marks
  - Slack-water deposits
  - Site selection and stratigraphy
  - Age determination
    - Radiocarbon
    - Optically Stimulated Luminescence
    - Dendrochronology
    - Cesium-137
    - Lichenometry
    - Others
  - Overall Flood Chronology



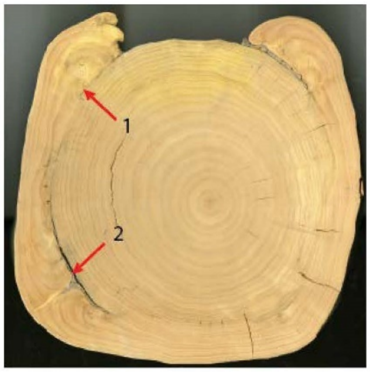
Included in analysis and review guidelines:

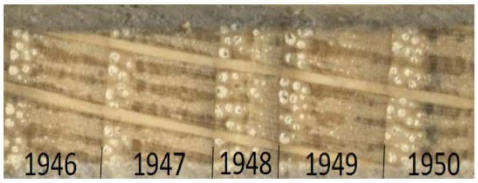
- Terrace and Floodplain deposits
  - Site selection and identification
  - Terraces as non-exceedance bounds
- Lake and Wetland Deposits
  - Site selection and identification of flood sequences
  - Stratigraphic analysis and age determination
- Uncertainties associated with paleostage indicators
- Stratigraphic uncertainties



Dendrochronology

- Date and elevation of flood scars
- Death date of flooded trees
- Alteration of tree-ring anatomy by flooding and burial
- Flood-related anomaly in ring width
- Establishment of seedlings or vegetative sprouts following flood disturbance





Hydraulic Analysis

- **Common techniques for paleohydraulic calculation**
  - Manning's Equation
  - Critical Flow
  - Gradually Varied Flow
- **Channel geometry and roughness**
- **Flow directly from sedimentary deposits**
  - Based on thickness and grain size
  - Can be developed where the elevation of flood deposits is not likely to closely represent maximum flood stage.

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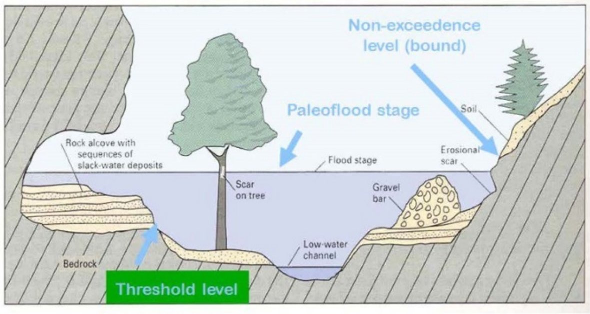
Flood-frequency Analysis

- Incorporating historical and paleoflood information into flood-frequency analysis
- Bulletin 17C
- Identification of perception thresholds and non-exceedance bounds



Paleoflood Analysis and Review Levels

- Three levels of paleoflood analyses and review for PFHAs.
- Boundaries are vague, and the scope and intensity of individual studies will vary depending on agency goals, guidelines, and objectives.
- This categorization helps organize discussion of levels of effort involved in conducting paleoflood studies as well as the degree of appropriate technical review.

Level 1

- Considered scoping level studies and are typically the first step in almost all paleoflood analyses.
- Purpose varies but typically level 1 studies:
  - 1) provide an initial screening of a local flood hazard issue,
  - 2) support nearby study or supply correlative information,
  - 3) serve as a feasibility assessment for a possible higher-level analysis,
  - 4) collect information for a regional flood assessment,
  - 5) or serve as a periodic review or update for site-specific flood hazard information
- If regional paleoflood information is available, Level 1 studies may not require a site visit.
- Uncertainty analyses are limited, and results may be preliminary.

Level 1 Review

- Preliminary scoping and project guidance may be solely determined by the project lead in accordance with the project purpose.
- Independent technical review of studies may be minimal, typically conducted by a subject matter expert or experts external to the project.
- A field review may not be required for this level.
- Commonly serve as feasibility studies to test the applicability of methods for a larger more comprehensive Level 2 or Level 3 study.

Level 2

- Improve flood frequency and magnitude estimates for a specific location, site hazard assessments and/or hydroclimate analysis.
- Involve a multidisciplinary team and one or more field campaigns to investigate paleoflood evidence at multiple sites on a single reach or multiple reaches of a river.
- Flood chronologies are supported by numeric dating methods.
- Step-backwater or 2D hydraulic modeling using high resolution topographic data support discharge estimates associated with flood evidence or non-exceedance bounds.
- Hydraulic modelling provides estimates of uncertainty through sensitivity to model uncertainties such as roughness, boundary conditions, etc.
- Flood–frequency analyses using gaged, historical and paleoflood information, including flow intervals, identification of perception thresholds, and non-exceedance bounds.

Level 2 Review

- May be guided by a technical steering committee composed of subject matter experts and stakeholders who can assist with project scoping and offer guidance in the initial planning stages of the paleoflood study.
- In-progress review may be overseen by a technical steering committee.
- In-field review of benchmark sites and accompanying interpretations.
- Technical review of the final report and conclusions typically involves a team of independent experts, including scientists and engineers with knowledge of all study components (for example, stratigraphy, dendrochronology, hydraulics, flood frequency analysis).
- Comprehensive record keeping, including field notes, photographs, and laboratory analyses will aid technical review.

Level 3

- Most comprehensive.
- Support regional and site-specific flood frequency and magnitude estimates to address broad flood hazard or hydroclimate issues.
- May support siting, design, or retrofits of critical infrastructure such as dams, levees and nuclear power plants.

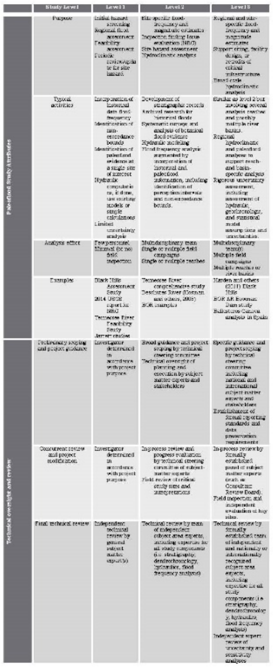
Level 3 cont.

- Project components include those associated with a Level 2 analysis— rigorous development of stratigraphic records, systematic surveys and analysis of botanical flood evidence, historical flood research, hydraulic modeling, and frequency analysis involving all available information including perception thresholds and non-exceedance bounds.
- Level 3 studies, however, generally involve multiple river reaches and possibly multiple river basins.
- May also be supported by regional hydroclimate and paleoflood analyses to confirm reach- and basin-specific conclusions.
- Include rigorous uncertainty assessments encompassing all aspects (hydraulic, geochronologic, and statistical model analyses) and underlying assumptions.
- Conducted by multidisciplinary teams of researchers over the course of multiple field campaigns and for multiple reaches of the river or even multiple river basins.

Level 3 Review

- More intensive than the other 2 levels of study, especially for studies assessing hazards to critical facilities.
- A technical steering committee composed of national and/or international subject matter experts and stakeholders may be assembled during the initial planning stages of the project.
- Such a technical steering committee can offer specific guidance and help with project scoping and determination of formal reporting standards and data preservation requirements.
- The technical steering committee may also conduct in-process reviews and field inspections at benchmark sites.
- Final technical review may be conducted by an established and independent team of experts for all study components (stratigraphy, dendrochronology, hydraulics, flood frequency analysis).

Analysis and Review table for all three levels



	Study Level	Level 1	Level 2	Level 3
Paleoflood Study Attributes	Purpose	Initial hazard screening Regional flood assessment Feasibility assessment Periodic review/update to the site hazard.	Site specific flood-frequency and magnitude estimates Inspection finding issue evaluation (NRC) Site hazard assessment Hydroclimatic analysis	Regional and site-specific flood-frequency and magnitude estimates Support siting, facility design, or retrofits of critical infrastructure Broad scale hydroclimatic analysis
	Typical activities	Incorporation of historical data flood-frequency Identification of non-exceedance bounds Identification of paleoflood evidence at a single site of interest Hydraulic computations, if done, use existing models or simple calculations Limited uncertainty analysis	Development of stratigraphic records Archival research for historical floods Systematic surveys and analysis of botanical flood evidence Hydraulic modeling Flood frequency analysis augmented by incorporation of historical and paleoflood information, including identification of perception intervals and non-exceedance bounds.	Similar as level 2 but involving several analysis reaches and possibly multiple river basins. Regional hydroclimatic and paleoflood analyses to support reach- and basin-specific analysis Rigorous uncertainty assessment, including assessment of hydraulic, geochronologic, and statistical model assumptions and uncertainties.
	Analysis effort	Few personnel Minimal (or no) field inspection	Multidisciplinary team Single or multiple field campaigns Single or multiple reaches	Multidisciplinary team(s) Multiple field campaigns Multiple reaches or river basins
	Examples	Black Hills Assessment Study 2014 USGS report for NRC Tennessee River Feasibility Study Jarrett studies	Tennessee River comprehensive study Deschutes River (Hosman and others, 2003) BOR examples	Harden and others (2011) Black Hills BOR AR Bowman Dam study Ballesteros Canovas analysis in Spain
Technical oversight and review	Preliminary scoping and project guidance	Investigator determined in accordance with project purpose	Broad guidance and project scoping by technical steering committee Technical oversight of planning and execution by subject matter experts and stakeholders	Specific guidance and project scoping by technical steering committee including national and international subject matter experts and stakeholders Establishment of formal reporting standards and data preservation requirements
	Concurrent review and project modification	Investigator determined in accordance with project purpose	In-process review and progress evaluation by technical steering committee of subject-matter experts Field review of critical study sites and interpretations	In-process review by formally established panel of subject matter experts (such as Consultant Review Board). Field inspection and independent evaluation of key sites.
	Final technical review	Independent technical review by general subject matter expert(s)	Technical review by team of independent subject area experts, including expertise for all study components (i.e. stratigraphy, dendrochronology, hydraulics, flood frequency analysis)	Technical review by formally established team of independent and nationally or internationally recognized subject area experts, including expertise for all study components (i.e. stratigraphy, dendrochronology, hydraulics, flood frequency analysis) Independent expert review of uncertainty and sensitivity analyses

	Study Level	**Level 1**	**Level 2**	**Level 3**
Paleoflood Study Attributes	Purpose	Initial hazard screening Regional flood assessment Feasibility assessment Periodic review/update for site hazard	Site specific flood-frequency and magnitude estimates Inspection finding Issue evaluation (NRC) Site hazard assessment Hydroclimatic analysis	Regional and site-specific flood-frequency and magnitude estimates Support siting, facility design, or retrofits of critical infrastructure. Broad-scale hydroclimatic analysis
	Typical activities	Incorporation of historical data flood-frequency Identification of non-exceedance bounds Identification of paleoflood evidence at a single site of interest Hydraulic computations, if done, use existing models or simple calculations Limited uncertainty analysis	Development of stratigraphic records Archival research for historical floods Systematic surveys and analysis of botanical flood evidence Hydraulic modeling Flood frequency analysis augmented by incorporation of historical and paleoflood information, including identification of perception intervals and non-exceedance bounds.	Similar as level 2 but involving several analysis reaches and possibly multiple river basins. Regional hydroclimatic and paleoflood analyses to support reach- and basin-specific analysis Rigorous uncertainty assessment, including assessment of hydraulic, geochronologic, and statistical model assumptions and uncertainties.
	Analysis effort	Few personnel Minimal (or no) field inspection	Multidisciplinary team Single or multiple field campaigns Single or multiple reaches	Multidisciplinary team(s) Multiple field campaigns Multiple reaches or river basins
	Examples	O'Connor et al., 2014 Harden and O'Connor, 2017	Tennessee River comprehensive study Deschutes River (Hosman and others, 2003)	Harden et al. (2011) Black Hills BOR AR Bowman Dam study

		Level 1	Level 2	Level 3
Technical oversight and review	Preliminary scoping and project guidance	Investigator determined in accordance with project purpose	Broad guidance and project scoping by technical steering committee Technical oversight of planning and execution by subject matter experts and stakeholders	Specific guidance and project scoping by technical steering committee including national and international subject-matter experts and stakeholders Establishment of formal reporting standards and data preservation requirements
	Concurrent review and project modification	Investigator determined in accordance with project purpose	In-process review and progress evaluation by technical steering committee of subject-matter experts Field review of critical study sites and interpretations	In-process review by formally established panel of subject matter experts (such as Consultant Review Board). Field inspection and independent evaluation of key sites.
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Reporting requirements

- Similar regardless of the level of study.
- Documenting all site and stratigraphic or botanic information, analysis steps, laboratory analyses and results, modeling approaches and associated uncertainty, and assumptions allows for study transparency and more thorough and objective review.
- Documentation should be sufficient to reproduce the flood frequency results.

Paleoflood Analyses for Probabilistic Flood Hazard Assessments—Approaches and Review Guidelines

Tess Harden, Karen Ryberg, Jim O'Connor, Jonathan Friedman, Julie Kiang
U.S. Geological Survey

Nuclear Regulatory Commission, Probabilistic Flood Hazard Workshop, February 19-21, 2020

3.7.4 Presentation 3A-4: Probabilistic Assessment of Flood Hazards Due to Combinations of Flooding Mechanisms: Study Progress and Next Steps.

Authors: Michelle (Shelby) Bensi and Somayeh Mohammadi, University of Maryland (UMD); Shih-Chieh Kao and Scott DeNeale, Oak Ridge National Laboratory (ORNL)

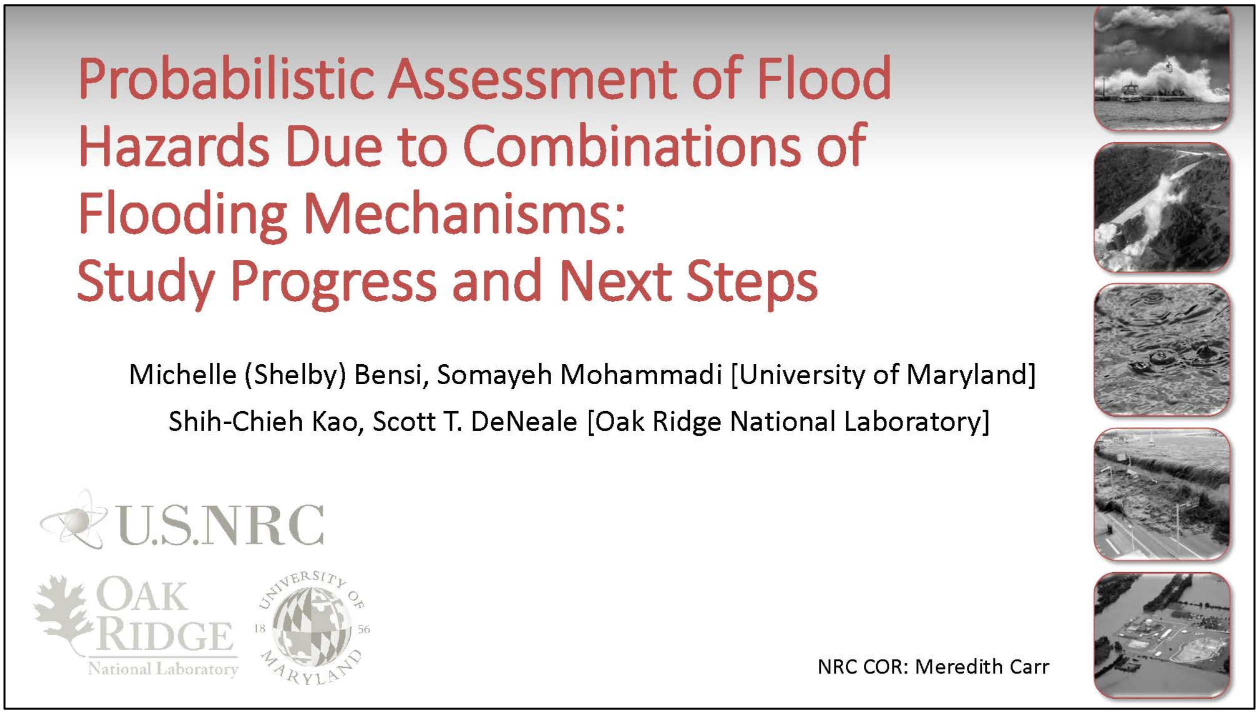
Speaker: Michelle (Shelby) Bensi

3.7.4.1 Abstract

Flooding of nuclear power plants (NPPs) and other infrastructure can occur as a result of events involving one or multiple coincident or correlated flood mechanisms. Existing approaches for probabilistic flood hazard assessment (PFHA) focus primarily on the occurrence of a single flood hazard mechanism. However, multi-mechanism flood (MMF) events may result in flooding with severity, duration, characteristics, and extent of impacts that differ from the effects of floods involving a single mechanism. Moreover, the estimated frequency of occurrence of flood severity metrics (e.g., flood elevation or depth) may change (increase) when considering the enhanced impacts of MMF events. Thus, to have a comprehensive estimate of flood hazards for our critical infrastructures, it is important to consider events involving both single and multiple flood mechanisms.

To extend the state-of-practice of multi-mechanism flood analysis, this study focuses on the identification of existing research and development of new methods to probabilistically assess hazards associated with MMF events. This research project is funded by the U.S. Nuclear Regulatory Commission PFHA Research Program with an intent to support the development of future guidance on PFHA. This presentation provides an overview of project research activities focusing on identification of existing approaches for probabilistically assessing MMF events and provides a critique and gap assessment of the current state of practice. It further discusses options for leveraging and extending approaches that show promise (with or without modifications) to support probabilistic assessment of MMF hazards associated with the range of return periods of relevance to NPPs and other critical infrastructure

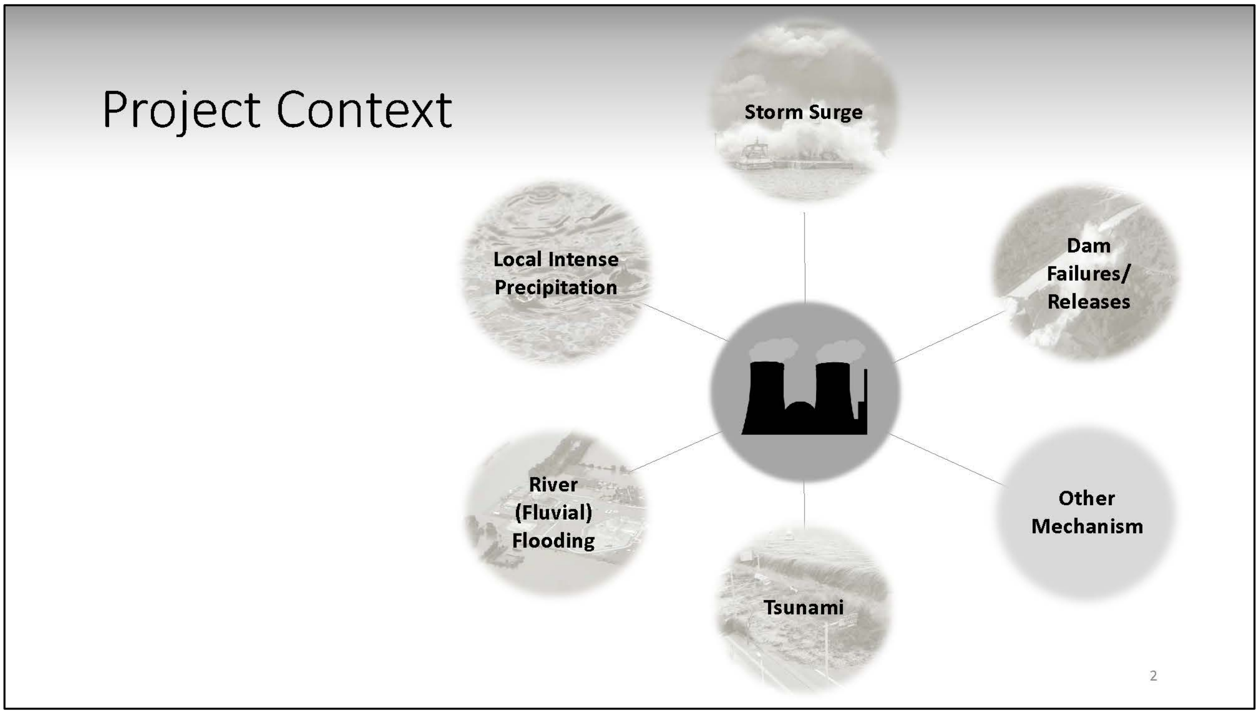
3.7.4.2 Presentation (ADAMS Accession No. ML20080M152)



Probabilistic Assessment of Flood Hazards Due to Combinations of Flooding Mechanisms: Study Progress and Next Steps

Michelle (Shelby) Bensi, Somayeh Mohammadi [University of Maryland]
Shih-Chieh Kao, Scott T. DeNeale [Oak Ridge National Laboratory]

NRC COR: Meredith Carr



Project Context

Storm Surge

Dam Failures/ Releases

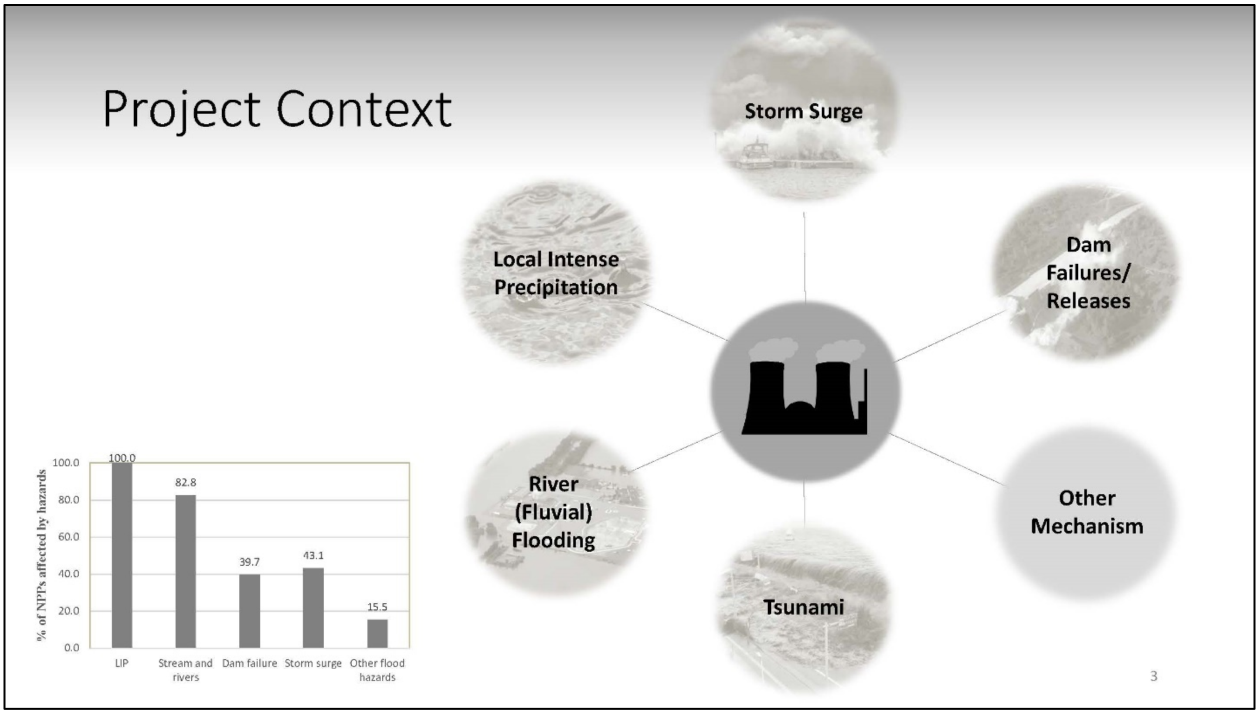
Other Mechanism

Tsunami

River (Fluvial) Flooding

Local Intense Precipitation

2



Project Context

Storm Surge

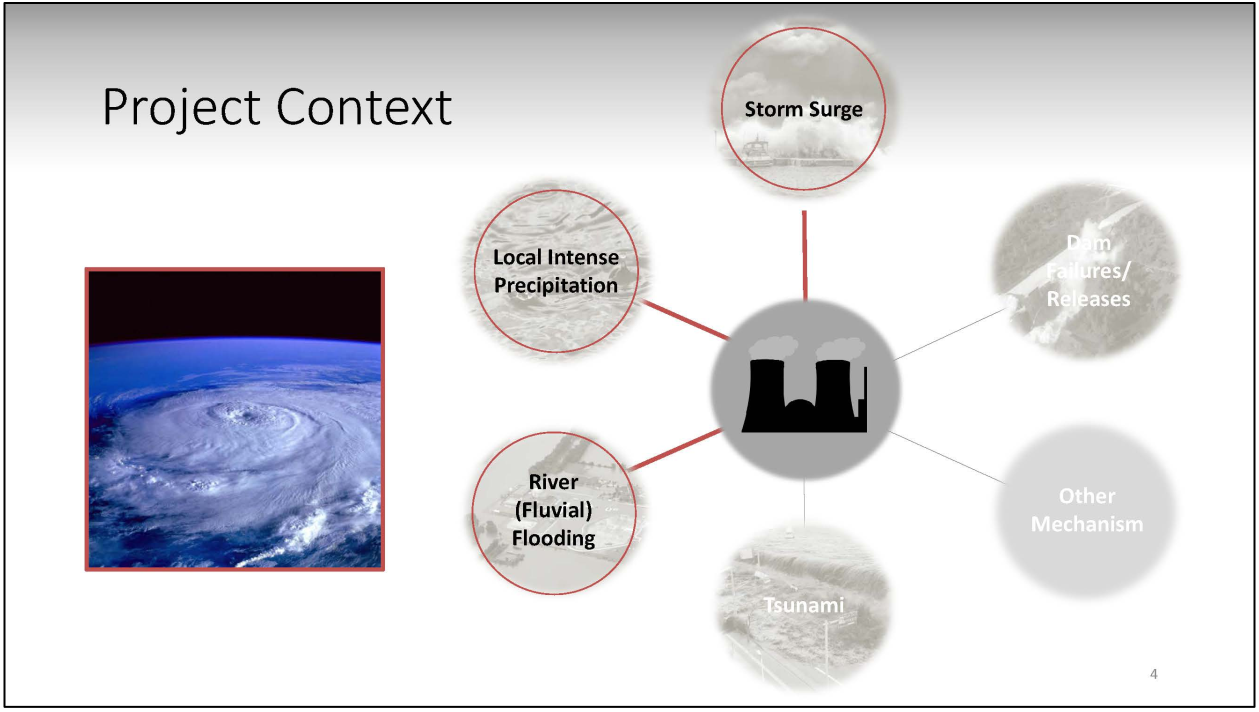
Local Intense Precipitation

Dam Failures/ Releases

River (Fluvial) Flooding

Other Mechanism

Tsunami



Project Context

Storm Surge

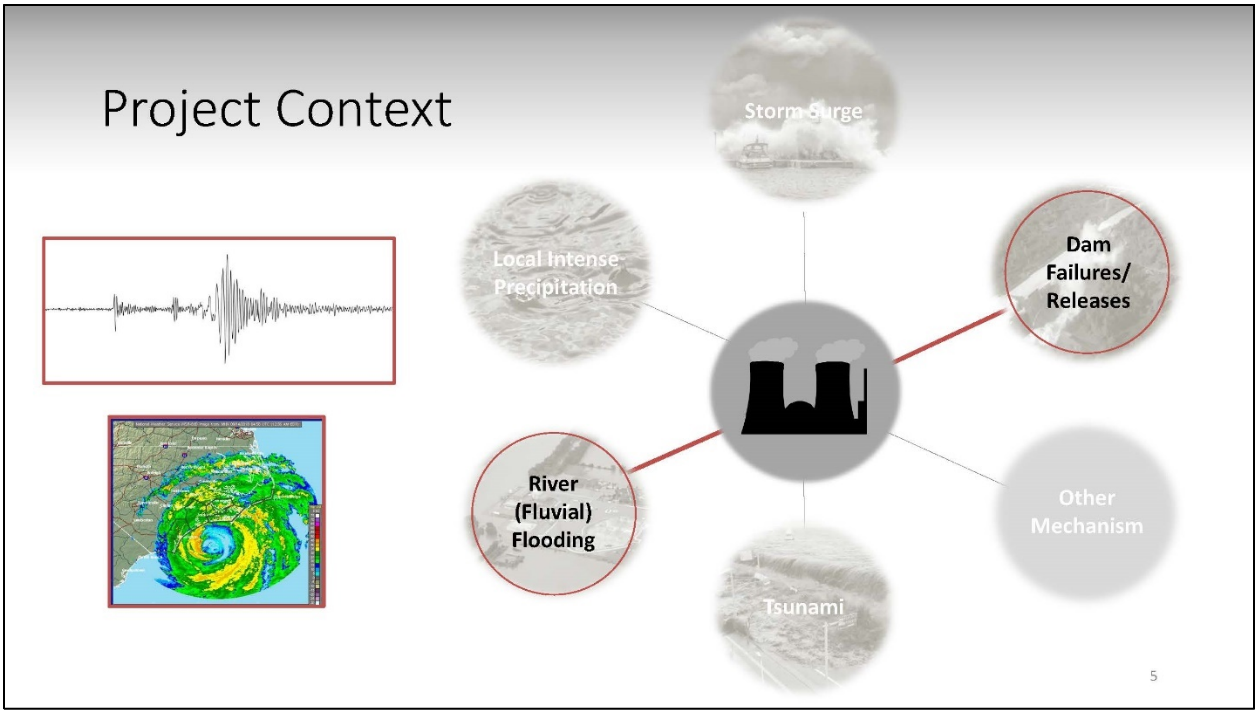
Local Intense Precipitation

Dam Failures/ Releases

River (Fluvial) Flooding

Other Mechanism

Tsunami



Project Context

Storm Surge

Dam Failures/ Releases

Local Intense Precipitation

River (Fluvial) Flooding

Other Mechanism

Tsunami

Project Overview

NRC Sponsored Project Title:

Methods for Estimating Joint Probabilities of Coincident and Correlated Flooding Mechanisms for Nuclear Power Plant Flood Hazard Assessments

Project Objective:

Provide technical background for the development of flood hazard curves for multi-mechanism floods (MMFs)

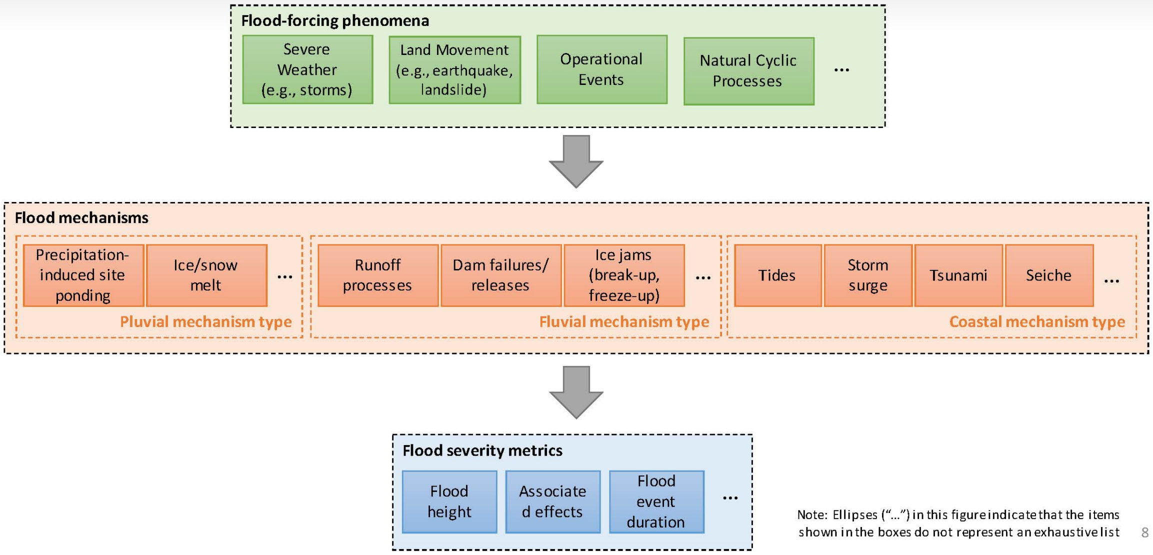
Project Overview

Project Objective:

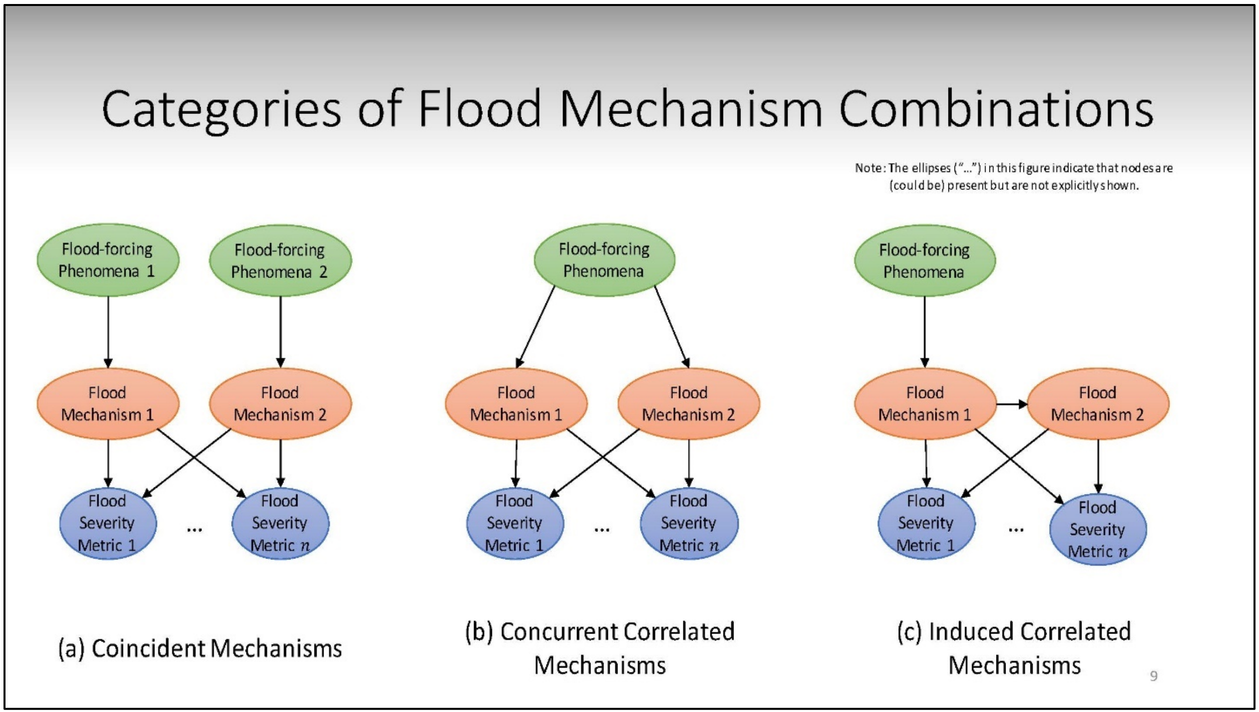
Provide technical background for the development of flood hazard curves for multi-mechanism floods (MMFs)

Task	Description	Status
1	Survey of current concepts and methods in MMF hazards	Complete
2	Critical assessment of selected methods and approaches for quantifying probabilistic MMF hazard risk	Complete [Under Review]
3	Development of example case studies to illustrate best practices for quantifying probabilistic MMF hazard risk	In-Progress

Terminology Hierarchy



Note: Ellipses ("…") in this figure indicate that the items shown in the boxes do not represent an exhaustive list



Categories of Flood Mechanism Combinations

Note: The ellipses ("…") in this figure indicate that nodes are (could be) present but are not explicitly shown.

Flood-forcing Phenomena 1
Flood-forcing Phenomena 2
Flood Mechanism 1
Flood Mechanism 2
Flood Severity Metric 1
…
Flood Severity Metric n

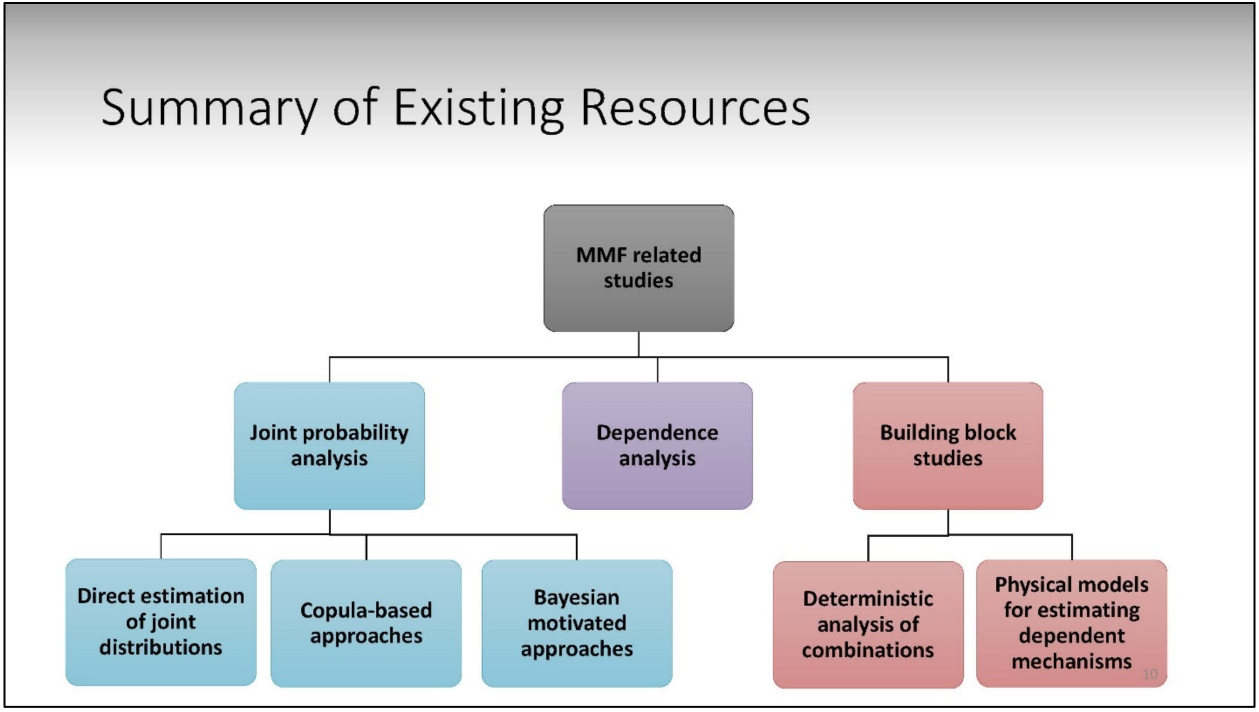
(a) Coincident Mechanisms

Flood-forcing Phenomena
Flood Mechanism 1
Flood Mechanism 2
Flood Severity Metric 1
…
Flood Severity Metric n

(b) Concurrent Correlated Mechanisms

Flood-forcing Phenomena
Flood Mechanism 1
Flood Mechanism 2
Flood Severity Metric 1
…
Flood Severity Metric n

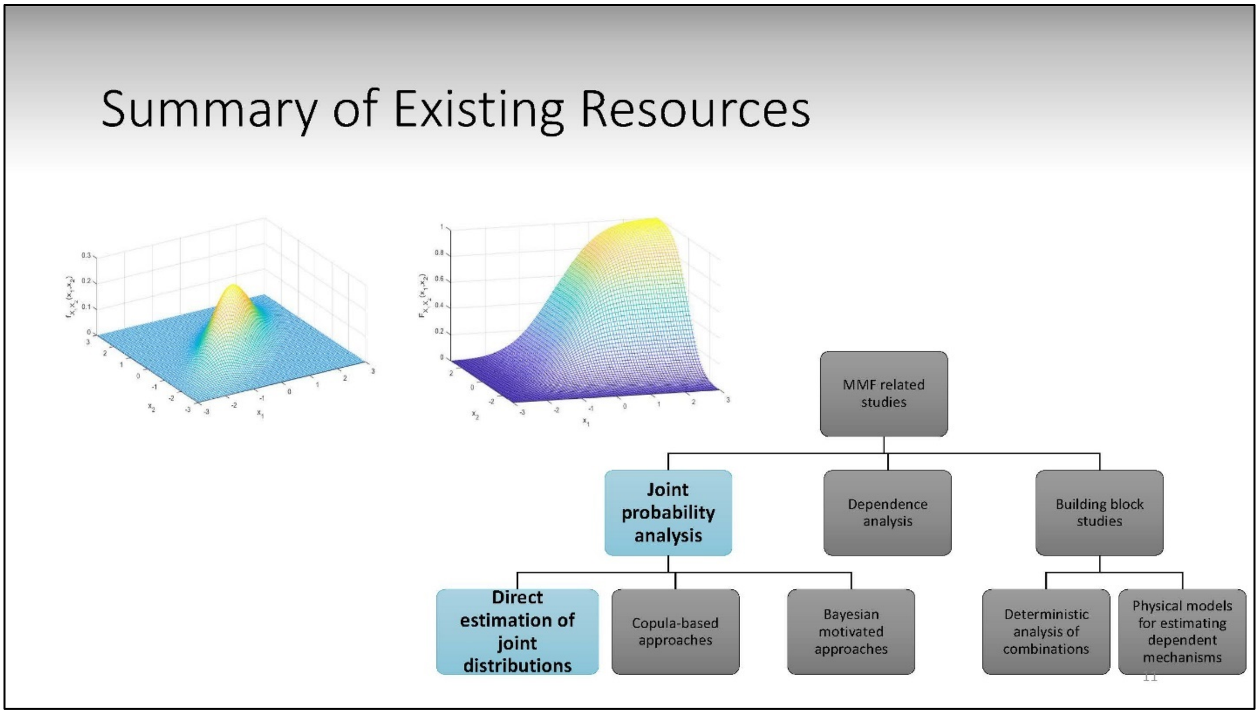
(c) Induced Correlated Mechanisms



Summary of Existing Resources

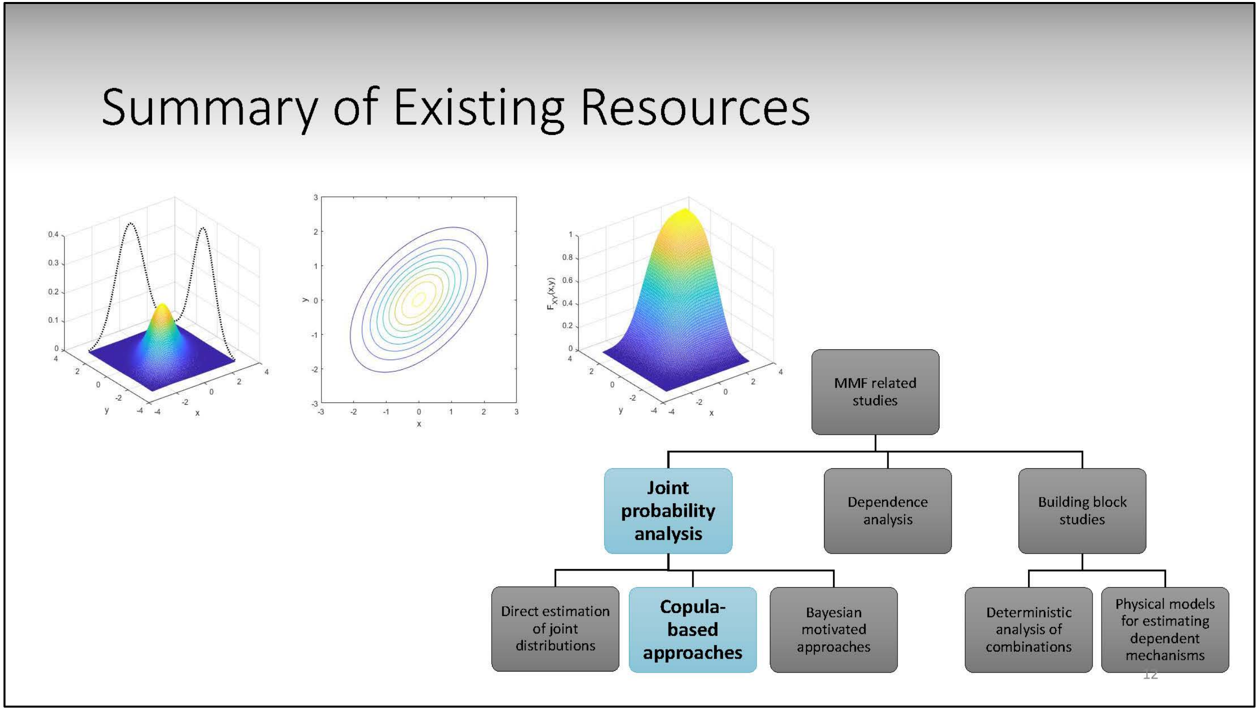
MMF related studies

- Joint probability analysis
  - Direct estimation of joint distributions
  - Copula-based approaches
  - Bayesian motivated approaches
- Dependence analysis
- Building block studies
  - Deterministic analysis of combinations
  - Physical models for estimating dependent mechanisms



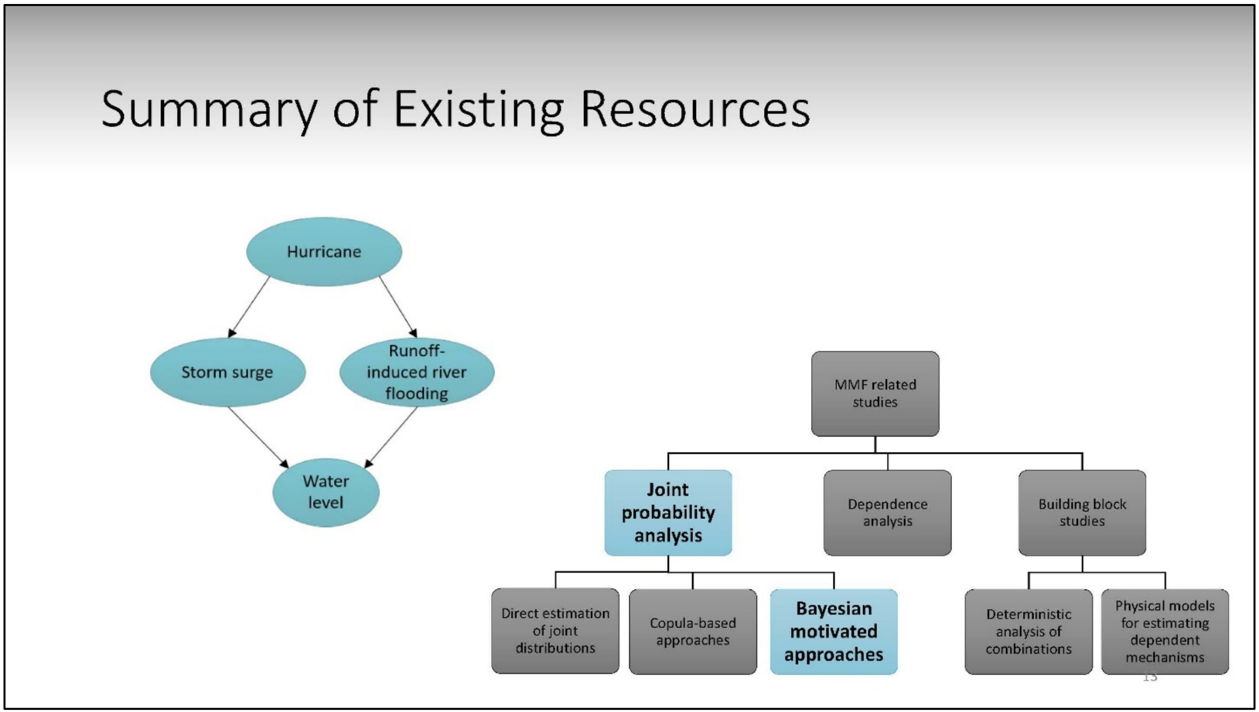
Summary of Existing Resources

- MMF related studies
  - **Joint probability analysis**
    - **Direct estimation of joint distributions**
    - Copula-based approaches
    - Bayesian motivated approaches
  - Dependence analysis
  - Building block studies
    - Deterministic analysis of combinations
    - Physical models for estimating dependent mechanisms



Summary of Existing Resources

- MMF related studies
  - **Joint probability analysis**
    - Direct estimation of joint distributions
    - **Copula-based approaches**
    - Bayesian motivated approaches
  - Dependence analysis
  - Building block studies
    - Deterministic analysis of combinations
    - Physical models for estimating dependent mechanisms



Summary of Existing Resources

Hurricane

Storm surge

Runoff-induced river flooding

Water level

MMF related studies

Joint probability analysis

Dependence analysis

Building block studies

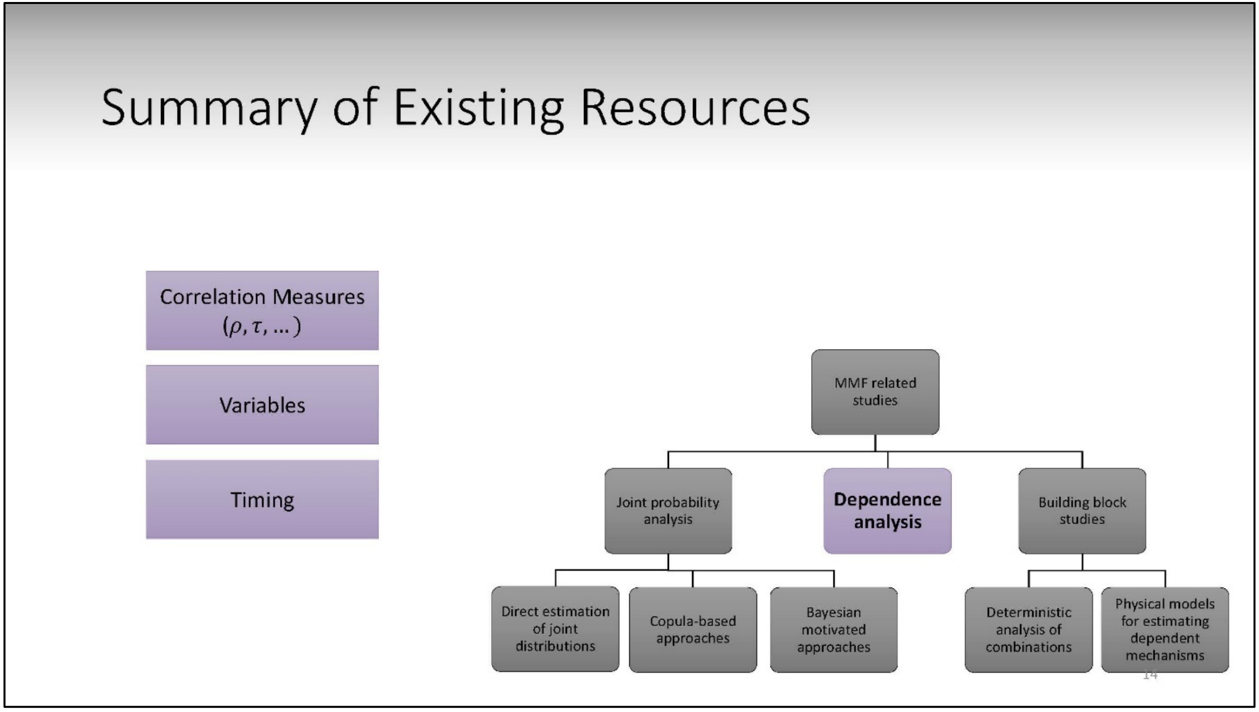
Direct estimation of joint distributions

Copula-based approaches

Bayesian motivated approaches

Deterministic analysis of combinations

Physical models for estimating dependent mechanisms



Summary of Existing Resources

Correlation Measures $(\rho, \tau, \dots)$

Variables

Timing

MMF related studies

Joint probability analysis

Dependence analysis

Building block studies

Direct estimation of joint distributions

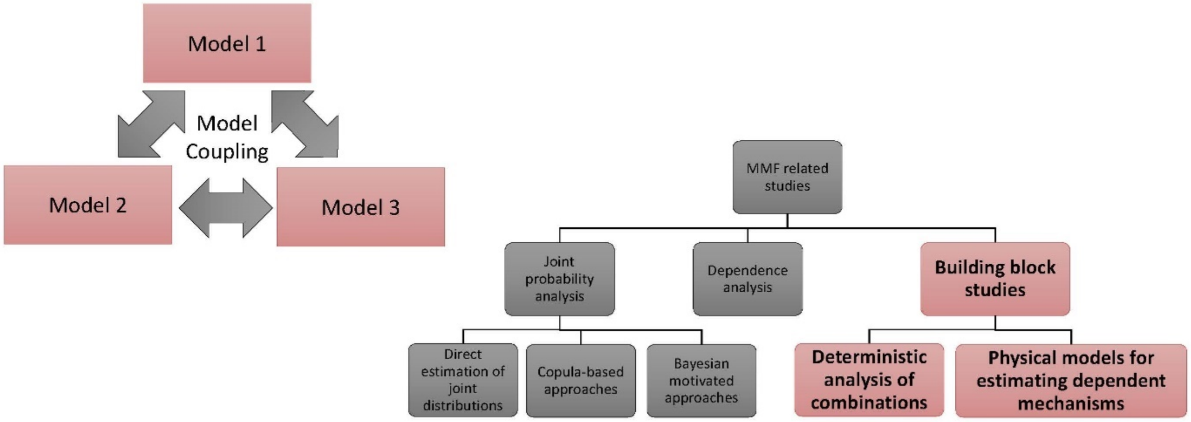
Copula-based approaches

Bayesian motivated approaches

Deterministic analysis of combinations

Physical models for estimating dependent mechanisms

Summary of Existing Resources



Scope of Existing Studies

Coastal MMFs	Storm surge combined with precipitation and/or river flow
	Surge, waves, and water levels
	Tides and tsunamis (process interactions)
Non-coastal MMFs	Combined river discharges at river confluences (copula based flood frequency analysis)
	Other hazards (e.g., rain on snow)

Key Insights from Existing Studies

Key characteristics

- Site-specific (but geographically diverse)
- Focus on (relatively) short return periods
- Diversity in phenomena considered and definition of flood severity metrics

Diversity of modeling considerations

- Return periods considered (typically "short")
- Data source and length of record (often "short")
- Statistical modeling approaches and choices
  Ex:
  - Direct estimation? Bayesian Approach? Copula?
  - Why type of copula is better?
  - How to address concurrence of extrema?
- Model validation approach

Challenges and Gaps

- **Inconsistencies in terminology**
  Same words ↔ Different concepts
  Same concepts ↔ Different words
- **Scope and focus of studies (intended results)**
  Development of hazard curve (surface)
  vs.
  "building blocks"
- **Lack of comprehensive frameworks**
- **Limited treatment of certain phenomena and mechanisms**

Next Steps

Project Objective:

Provide technical background for the development of flood hazard curves for multi-mechanism floods (MMFs)

Task	Description	Status
1	Survey of current concepts and methods in MMF hazards	Complete
2	Critical assessment of selected methods and approaches for quantifying probabilistic MMF hazard risk	Complete [Under Review]
3	Development of example case studies to illustrate best practices for quantifying probabilistic MMF hazard risk	In-Progress

Next Steps

Case Study 1: Inland Flooding

Flood-Forcing Phenomena: Severe Weather

Flood Mechanisms: Snowmelt-Driven Flooding

Flood Severity Metric: Flow (Discharge)

Overall Approach: Copula

Data Sources: Observed (streamflow) and Synthetic (hydrologic [VIC] model output)

Key Models: Statistical, Numerical/Hydrologic

Anticipated Outcomes

Demonstrate:
- General procedures to construct multivariate joint distributions using copulas
- Selection of suitable marginal distributions and copula functions
- Potential applications of copula-derived joint distributions in PFHA
- Strengths and limitations of the copula-based MMF assessment approach

---

Next Steps

Case Study 2: Coastal Flooding

Flood-Forcing Phenomena: Hurricane

Flood Mechanisms: Surge and Precipitation/Flow

Flood Severity Metric: Water Level

Overall Approach: Bayesian

Data Sources: Observed (tidal, streamflow, precipitation, hurricane track) and Synthetic (numerical model output)

Key Models: Statistical, Surrogate

Anticipated Outcomes

Demonstrate:
- General conceptual approach to construct multivariate joint distributions using Bayesian modeling approaches
- Development and use of requisite marginal and conditional distributions
- Quantification of joint distributions and development of hazard curves through forward inference
- Strengths and limitations of the Bayesian-motivated MMF assessment approach

Questions?

Storm Surge

Dam Failures/ Releases

Other Mechanism

Tsunami

River (Fluvial) Flooding

Local Intense Precipitation

3.8 Day 3: Session 3B – External Flooding Operating Experience

Session Chair: Thomas Aird, NRC/RES/DRA

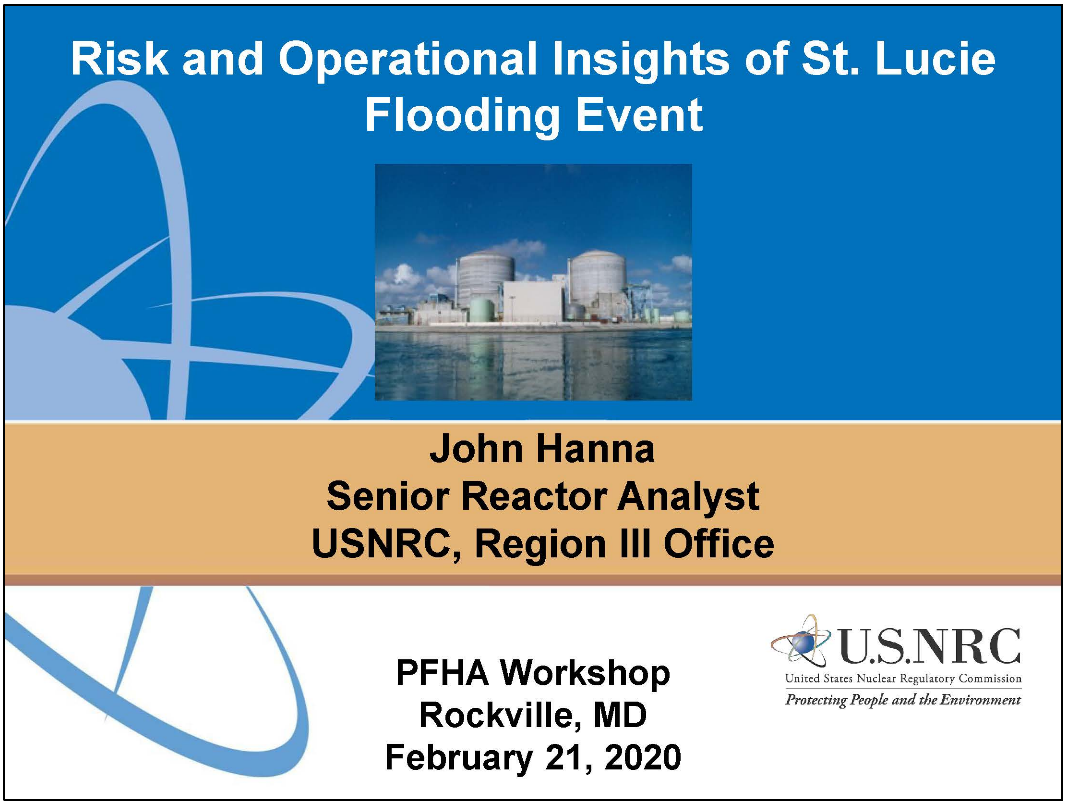
3.8.1 Presentation 3B-1: Risk and Operational Insights of the St. Lucie Flooding Event

Speaker: John David Hanna, NRC Region III

3.8.1.1 Abstract

While working in Region II, Mr. Hanna analyzed the risk impact of the St. Lucie findings/violations associated with degraded flood barriers. These impaired barriers revealed themselves during a Localized Intense Precipitation event in January 2014 which deposited 50,000 gallons of water in the Reactor Auxiliary Building. The presenter will discuss the (sometimes counter-intuitive) risk and operational insights associated with these findings, with an eye towards providing recommendations to nuclear plant operators, risk analysts and maintenance personnel.

3.8.1.2 Presentation (ADAMS Accession No. ML20080M153)

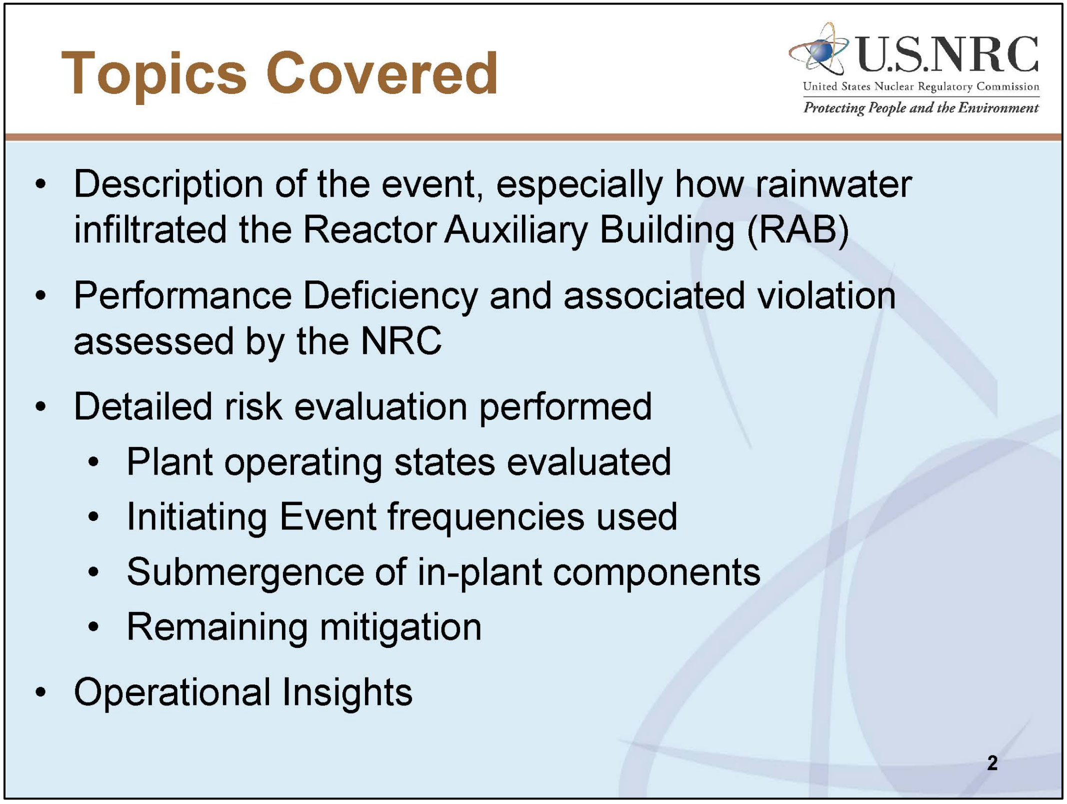


Risk and Operational Insights of St. Lucie Flooding Event

John Hanna
Senior Reactor Analyst
USNRC, Region III Office

PFHA Workshop
Rockville, MD
February 21, 2020

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



Topics Covered

U.S.NRC
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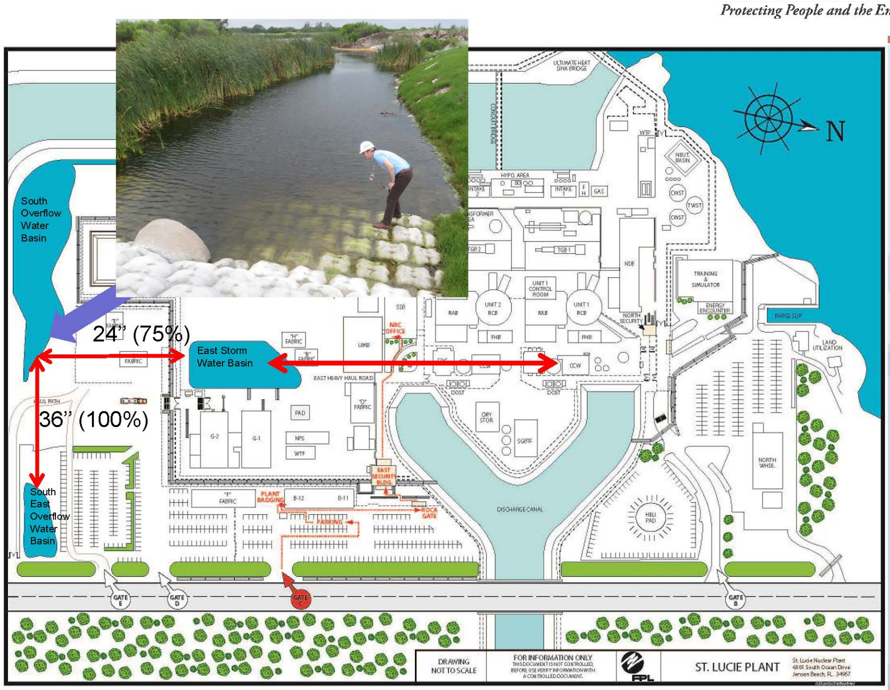
- Description of the event, especially how rainwater infiltrated the Reactor Auxiliary Building (RAB)
- Performance Deficiency and associated violation assessed by the NRC
- Detailed risk evaluation performed
    - Plant operating states evaluated
    - Initiating Event frequencies used
    - Submergence of in-plant components
    - Remaining mitigation
- Operational Insights

January 9, 2014 Event

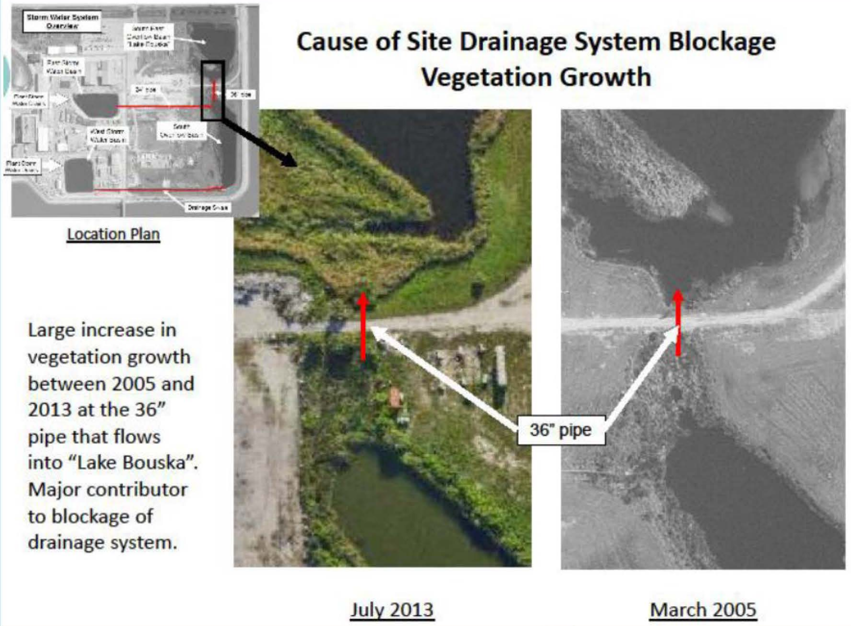
- Extreme localized rainfall at the St. Lucie site
  - 5''+ (2 hours), 6.5''+ (4 hours), 7.3'' (24 hours)
- Blocked pipes in storm drain basin caused backup into Component Cooling Water (CCW) open pit
- Flood waters entered non safety-related electrical conduits in a pipe tunnel
- Missing flood seals in conduits allowed water to enter Reactor Auxiliary Building (RAB)
- Total of 50,000 gallons (190,000 liters) entered RAB
- Both units remained at 100% power and no safety-related equipment was affected during the event

Root Cause – Storm Drain



Root Cause – Storm Drain

Cause of Site Drainage System Blockage
Vegetation Growth



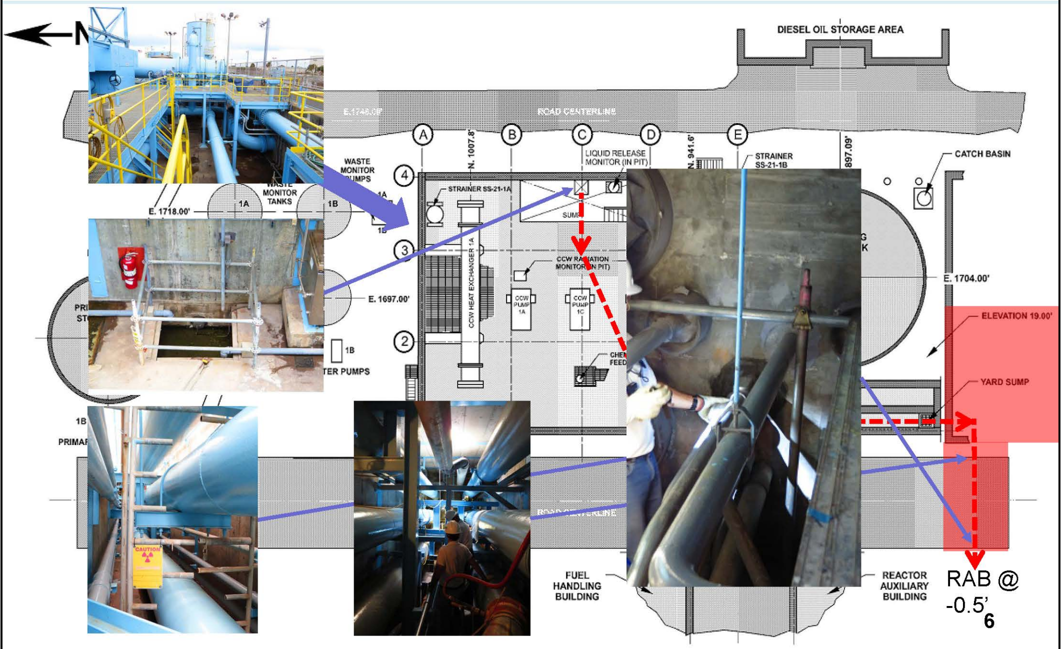
Location Plan

Large increase in vegetation growth between 2005 and 2013 at the 36" pipe that flows into "Lake Bouska". Major contributor to blockage of drainage system.

July 2013

March 2005

Root Cause – CCW Pit



RAB @ -0.5'

Root Cause – RAB U1

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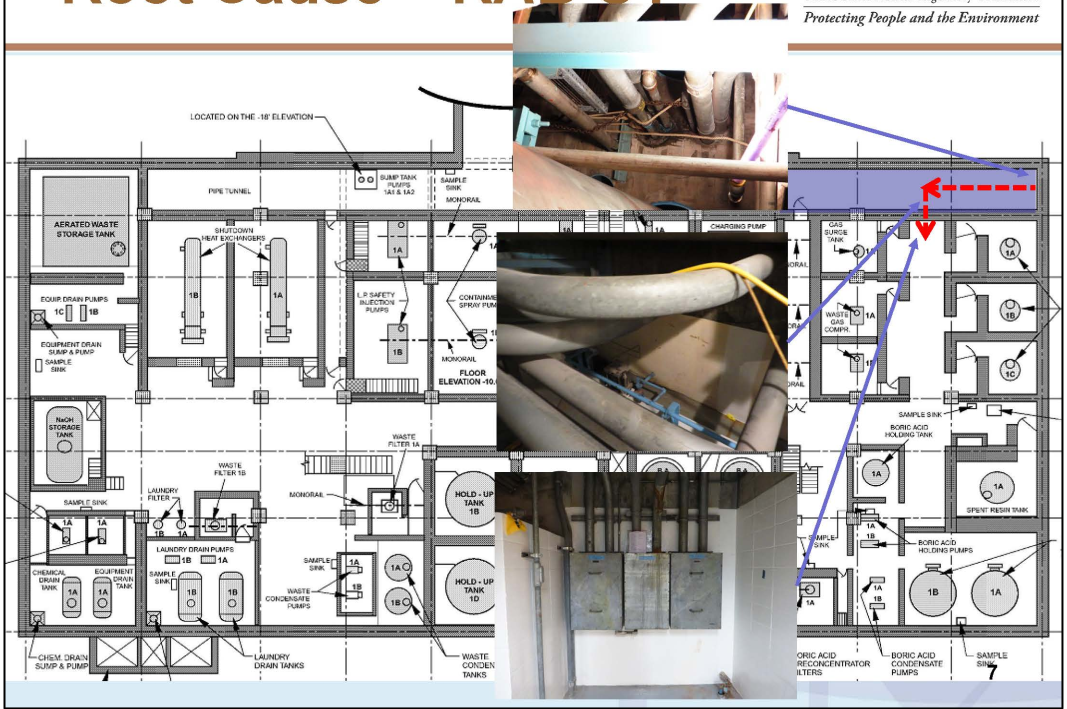
United States Nuclear Regulatory Commission
Protecting People and the Environment



RAB (-0.5') on Jan 9, 2014

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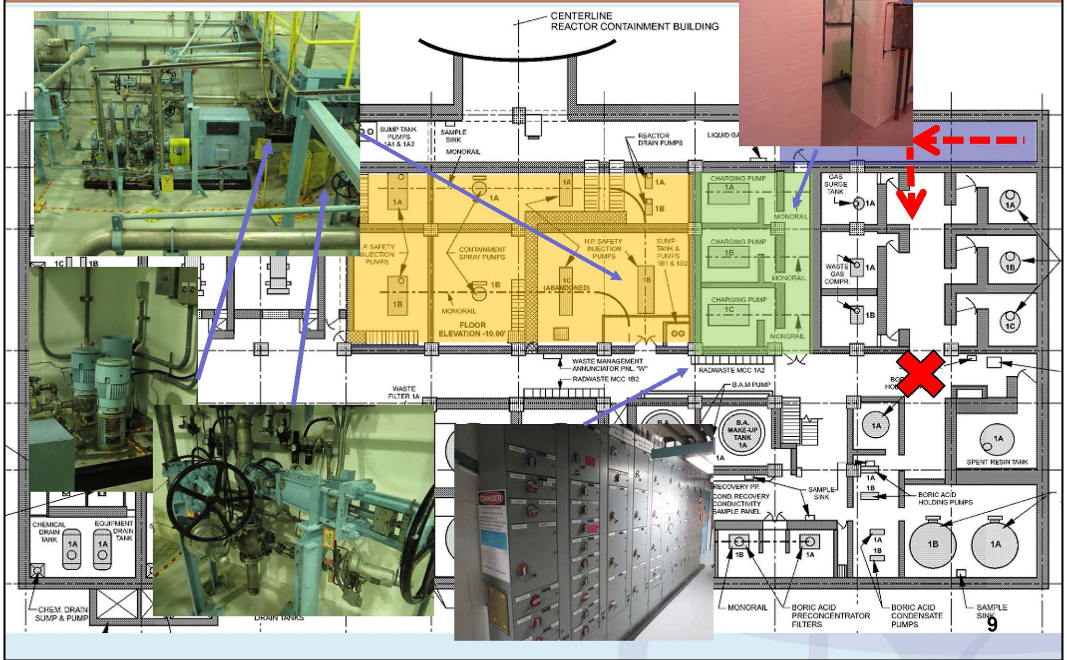
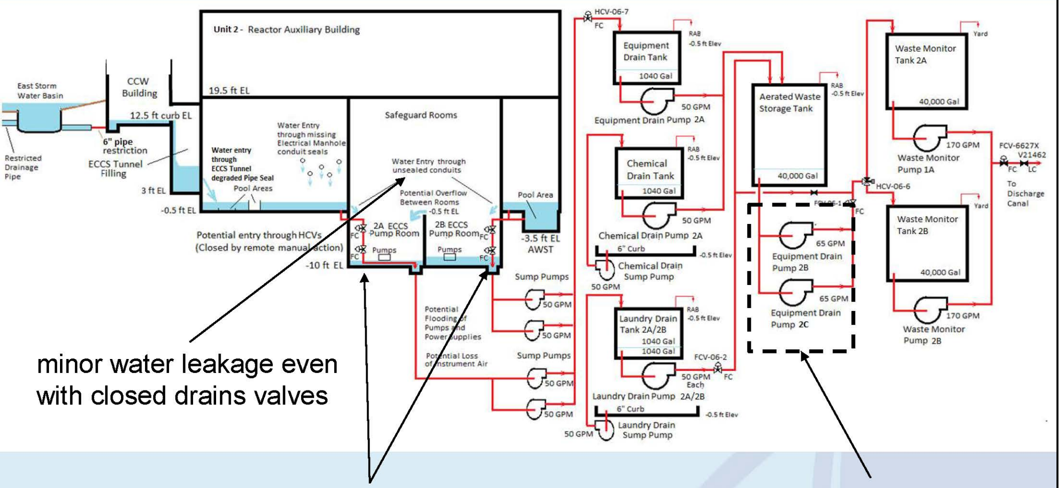
Protecting People and the Environment

Root Cause – RAB U1



Hydraulic Paths – RAB U1



minor water leakage even with closed drains valves

HCVs 4x drain lines (parallel) into ECCS room sumps (2x in series)

1B/1C Drain Tank Pumps impacted early during flood

Performance Deficiency

- Licensing bases states RAB protected against flooding at +19.5' above mean low water (MLW), PMP = 47.1"
- Units 1 & 2 Near Term Task Force flooding walkdowns stated RAB is protected against external flood
  - RAB U1 had significant flood via degraded conduits
  - RAB U2 had minor leakage at piping boots
- Failure to ensure that all below grade conduits that enter U1 and U2 RABs were sealed to prevent water ingress
- Self-revealing violation of Title 10 Code of Federal Regulations Part 50, App. B, Criterion III, "Design Control"
- Degraded flood protection existed since original plant construction (i.e., SDP full exposure time of 1 year)

Risk Analysis – operating states

- Initiating Events considered
  - At-power, localized rain event
  - At-power (initially), hurricane coastal surge (Cat 1-3)
  - At-power (initially), hurricane coastal surge (Cat 4-5)
  - Refueling Outage, localized rain event
  - Refueling Outage, hurricane-induced coastal surge
  - Pipe rupture in ECCS Tunnel (internal flooding)
- Event/Scenarios considered
  - Drain valves Open/Closed, TRANS
  - Drain valves Open/Closed, LOOP

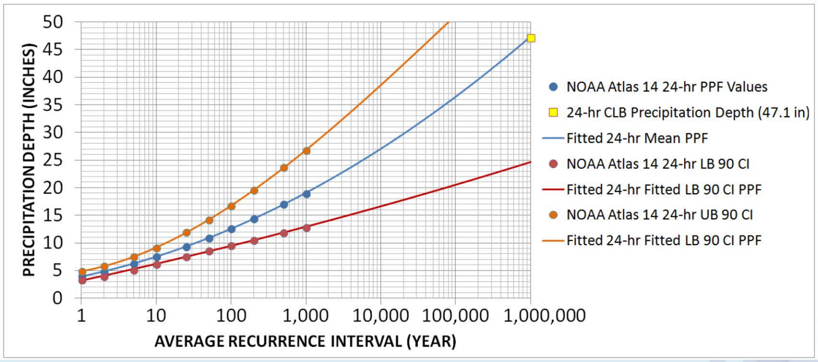
Precipitation Data

- Precipitation frequency from NOAA Atlas 14 @ St. Lucie based on a 24-hour duration storm

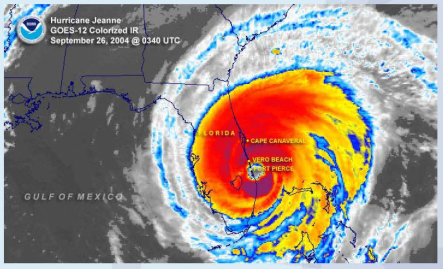
Precipitation frequency estimates (in inches) at St. Lucie

Duration	Average recurrence interval(years)									
	1	2	5	10	25	50	100	200	500	1000
5-min	0.557	0.634	0.763	0.873	1.03	1.15	1.28	1.41	1.59	1.73
10-min	0.815	0.928	1.12	1.28	1.51	1.69	1.88	2.07	2.33	2.54
15-min	0.994	1.13	1.36	1.56	1.84	2.06	2.29	2.53	2.85	3.1
30-min	1.51	1.72	2.08	2.38	2.81	3.15	3.49	3.85	4.34	4.72
60-min	2.01	2.29	2.76	3.15	3.69	4.12	4.55	4.99	5.57	6.02
2-hr	2.5	2.86	3.44	3.92	4.58	5.09	5.6	6.12	6.8	7.31
3-hr	2.76	3.17	3.82	4.36	5.11	5.68	6.25	6.83	7.59	8.17
6-hr	3.18	3.68	4.51	5.22	6.23	7.03	7.85	8.7	9.85	10.7
12-hr	3.57	4.19	5.29	6.27	7.72	8.92	10.2	11.5	13.4	15
24-hr	4.01	4.81	6.21	7.48	9.37	10.9	12.6	14.4	17	19
2-day	4.67	5.63	7.28	8.74	10.9	12.6	14.4	16.4	19.1	21.2
3-day	5.25	6.22	7.9	9.37	11.5	13.3	15.1	17.1	19.8	21.9

Frequency – Rain/Hurricane

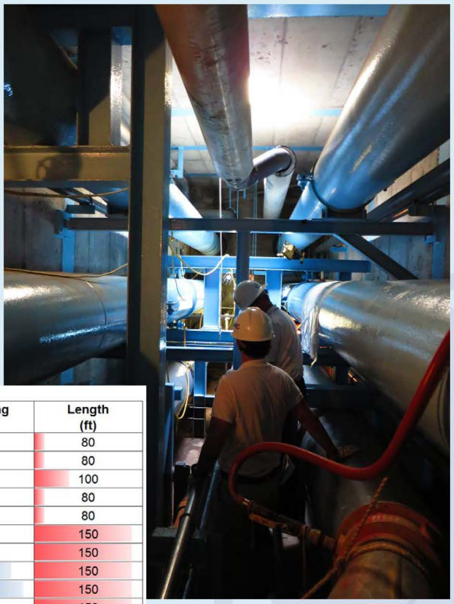


- Based on available historical hurricane data from NOAA
  - All Categories ~ 0.125/yr
  - Above Cat 3 ~ 0.053/yr



Frequency – Int. Flooding

- Licensee provided list of piping in ECCS Pipe Tunnel Area
- Available pipe rupture frequencies in the range of 6E-6/year to less than 1E-6/year
- Additional mitigation expected to be at least 0.1
- Not a significant ΔCDF contributor



List of Piping in ECCS Pipe Tunnel Area

Piping	Line	Water Source	Operating (psi)	Length (ft)
A Train Containment Spray	I-24"-CS-3	RWT (500 Kgal)[1]	45	80
B Train Containment Spray	I-24"-CS-2	RWT (500 Kgal)[1]	45	80
Safeguard Pumps Return	6"-CS-500	RWT (0 Kgal)[2]	60	100
Charging System Return	3"-CH-938	RWT (360 Kgal)[2]	60	80
Fuel Pool Return	3"-FS-555	RWT, SFP (9 Kgal)[2]	60	80
Primary Water Supply	4"-PMW-6	PWT (150 Kgal)[1]	60	150
Primary Water Supply	3"-PMW-16	PWT (150 Kgal)[1]	95	150
Waste Management Discharge	3"-WM-48	WMT (0 Kgal)[2]	130	150
Demineralized Water Supply	3"-DWS-11	DWST (10 Kgal)[1]	150	150
SG Blowdown	8"-B-5	Discharge Canal (0 Kgal)[2]	5	150

1. Nominal Tank Volume 2. Volume reflects line elevation/configuration/isolation

Affected Components- Rain

- Based on licensee's site hydraulic model coupled with a plant flooding model (precipitation→ elevation→ SSCs)

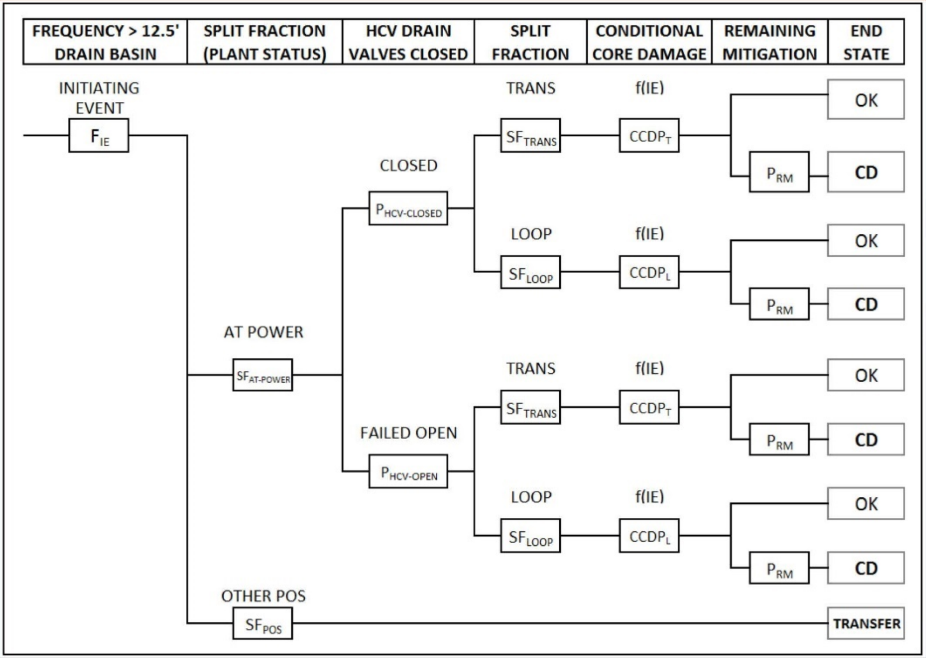
Correlation of Precipitation and Impacted SSCs (HCVs Open)

BIN	IMPACTED SSCs	PrecipRange (in) (Non- LOOP)	PrecipFreq (/yr) (Non- LOOP)	PrecipRange (in) (LOOP)	PrecipFreq (/yr) (LOOP)
1	B HPSI	9.36 - 9.55	3.40E-03	9.55 - 9.75	3.24E-03
2	B HPSI/LPSI	9.55 - 11.16	1.87E-02	9.75 - 10.73	1.19E-02
3	A/B HPSI + B LPSI			10.73 - 10.93	1.79E-03
4	A/B HPSI/LPSI	11.16 - 11.72	3.76E-03	10.93 - 11.72	5.62E-03
5	A/B HPSI/LPSI + BAM	11.72 - 11.99	1.49E-03	11.72 - 12.02	1.65E-03
6	A/B HPSI/LPSI + BAM + CHG	11.99 - 12.92	3.95E-03	12.02 - 14.68	8.05E-03
7	A/B HPSI/LPSI + BAM + CHG + SDC Valves	>=12.92	8.75E-03	>=14.68	4.49E-03

Correlation of Precipitation and Impacted SSCs (HCVs Closed)

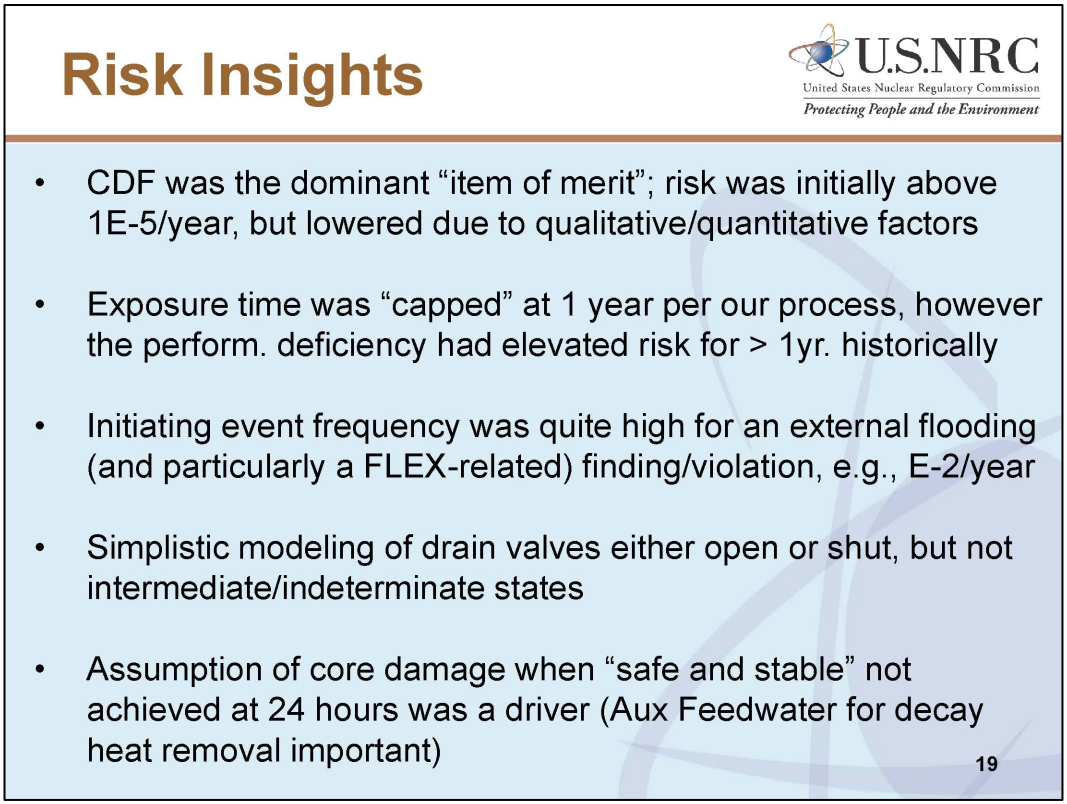
BIN	IMPACTED SSCs	PrecipRange (in) (Non-LOOP)	PrecipFreq (/yr) (Non-LOOP)	PrecipRange (in) (LOOP)	PrecipFreq (/yr) (LOOP)
1	BAM	11.44 - 11.72	1.76E-03	11.47 - 11.56	5.82E-04
2	BAM + B HPSI			11.56 - 11.66	6.19E-04
3	BAM + B HPSI + CHG	11.72 - 11.75	1.75E-04		
4	BAM + B HPSI/LPSI			11.66 - 11.75	5.32E-04
5	BAM + B HPSI/LPSI + CHG	11.75 - 13.32	6.53E-03	11.75 - 13.32	6.53E-03
6	BAM + B HPSI/LPSI + CHG + SDC Valves	>=13.32	7.48E-03	>=13.32	7.48E-03
7	BAM + CHG + B HPSI/LPSI + SDC + A HPSI	"A" train HPSI/LPSI pumps not affected during 24-hour mission time with valves closed.			
8	BAM + CHG + B HPSI/LPSI + SDC + A HPSI/LPSI				

Risk Assessment



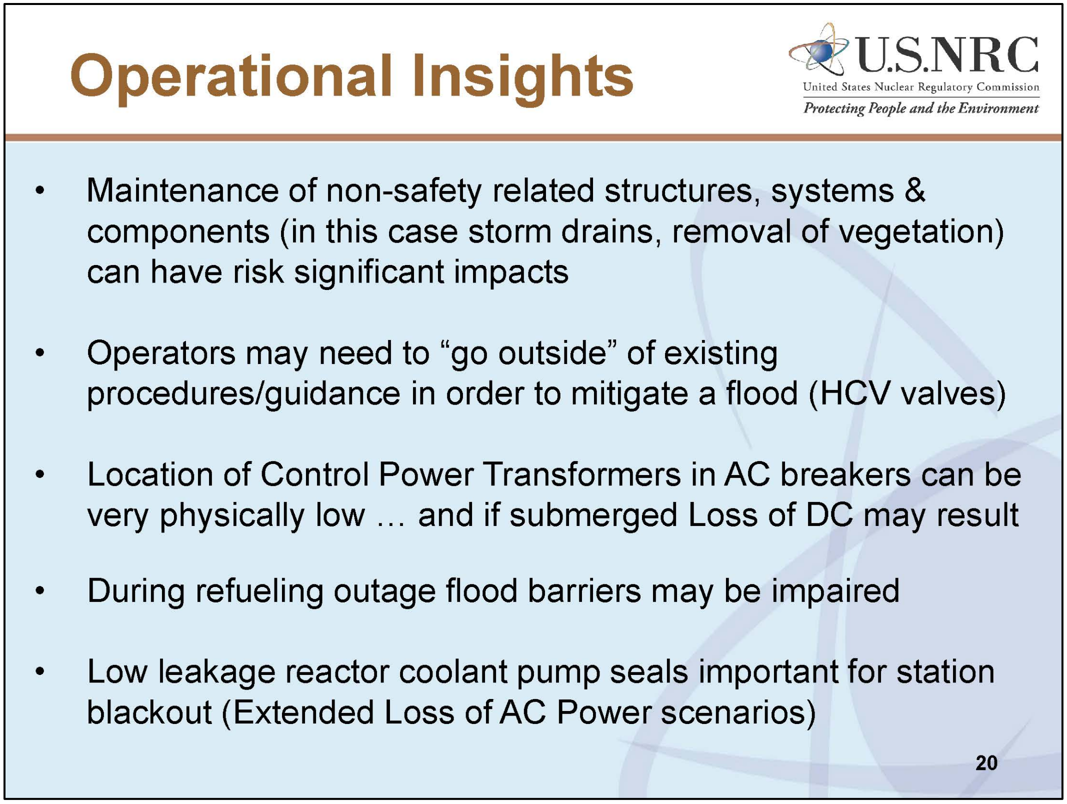
Risk Analysis Approach

- Split fraction for plant operational states from available data
- Failure to close drain valves treated in NRC, licensee analyses
  - Includes HEP screening value of 1E-2 in licensee analysis
  - Similar value obtained using generic data, estimating CCF
  - Success/failure due to cycling of valves not considered
- Split fraction of LOOP/non-LOOP obtained from available data
  - Mostly insensitive to various splits (e.g., 99/1, 95/5, 90/10)
  - LOOP assumed for Category 4 and 5 hurricanes
- Calculated CCDP values for TRANS/LOOP depend on SSCs
  - Results from SPAR model in the range of E-4/year to E-6/year
  - Licensee values lower (e.g., additional CST refill credit)
- Credit for additional mitigation in NRC analysis
  - Significant change from full credit (low white) to no credit for specific sequences (yellow/red threshold)



Risk Insights

- CDF was the dominant “item of merit”; risk was initially above 1E-5/year, but lowered due to qualitative/quantitative factors
- Exposure time was “capped” at 1 year per our process, however the perform. deficiency had elevated risk for > 1yr. historically
- Initiating event frequency was quite high for an external flooding (and particularly a FLEX-related) finding/violation, e.g., E-2/year
- Simplistic modeling of drain valves either open or shut, but not intermediate/indeterminate states
- Assumption of core damage when “safe and stable” not achieved at 24 hours was a driver (Aux Feedwater for decay heat removal important)



Operational Insights

- Maintenance of non-safety related structures, systems & components (in this case storm drains, removal of vegetation) can have risk significant impacts
- Operators may need to “go outside” of existing procedures/guidance in order to mitigate a flood (HCV valves)
- Location of Control Power Transformers in AC breakers can be very physically low … and if submerged Loss of DC may result
- During refueling outage flood barriers may be impaired
- Low leakage reactor coolant pump seals important for station blackout (Extended Loss of AC Power scenarios)

Questions/Comments

Any comments or questions?

Backup Slides

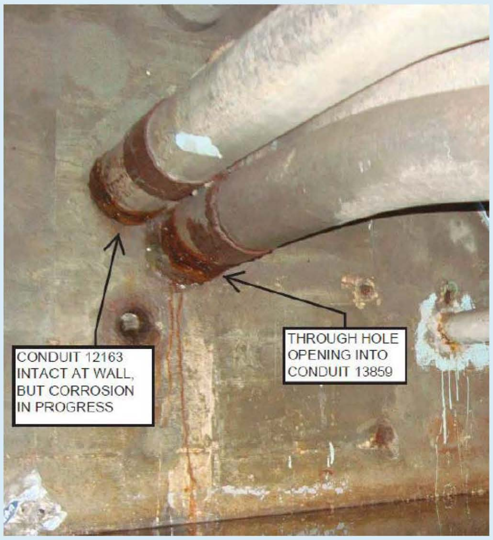
BACKUP SLIDES

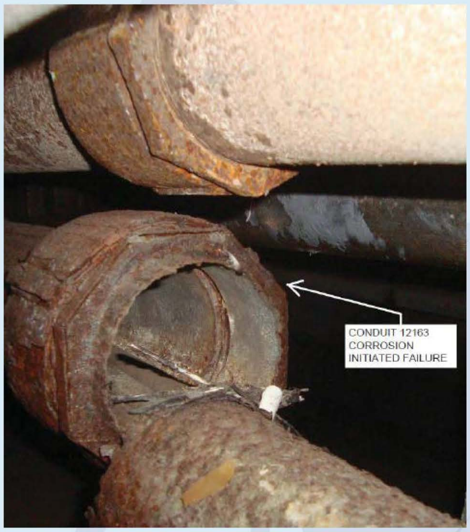
Additional Info. Resources

- NRC Inspection Report 05000335/389/2014-009, "Preliminary White Finding and Apparent Violations"
- Licensee Event Report 50-335/2014-001, "Internal RAB Flooding During Heavy Rain Due to Degraded Conduits Lacking Internal Flood Barriers"
- NUREG/CR-5820 "Consequences of the Loss of the Residual Heat Removal Systems in Pressurized Water Reactors"
- WCAP -17601-P, "Reactor Coolant System Response to the Extended Loss of AC Power Event for Westinghouse, Combustion Engineering and Babcock & Wilcox NSSS Designs"

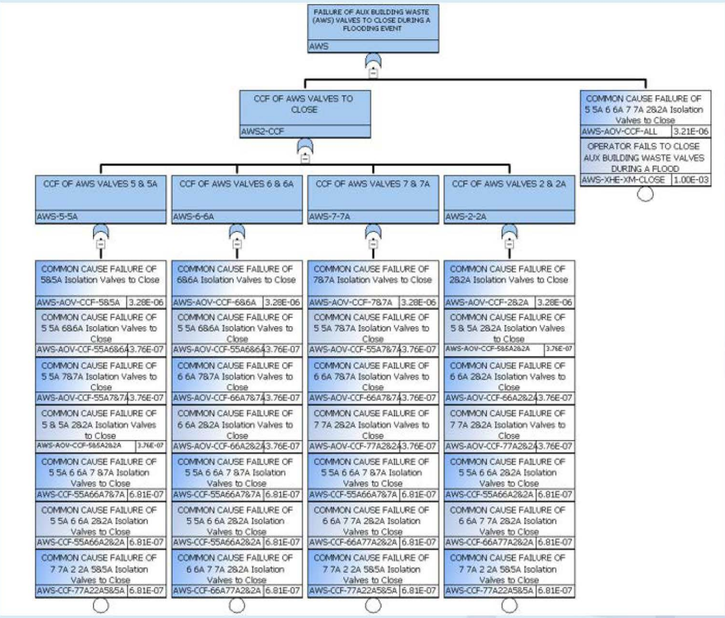
Drainage Detail

Penetration Details





Fault Tree Modeling HCV



Rain, At-power (NRC)

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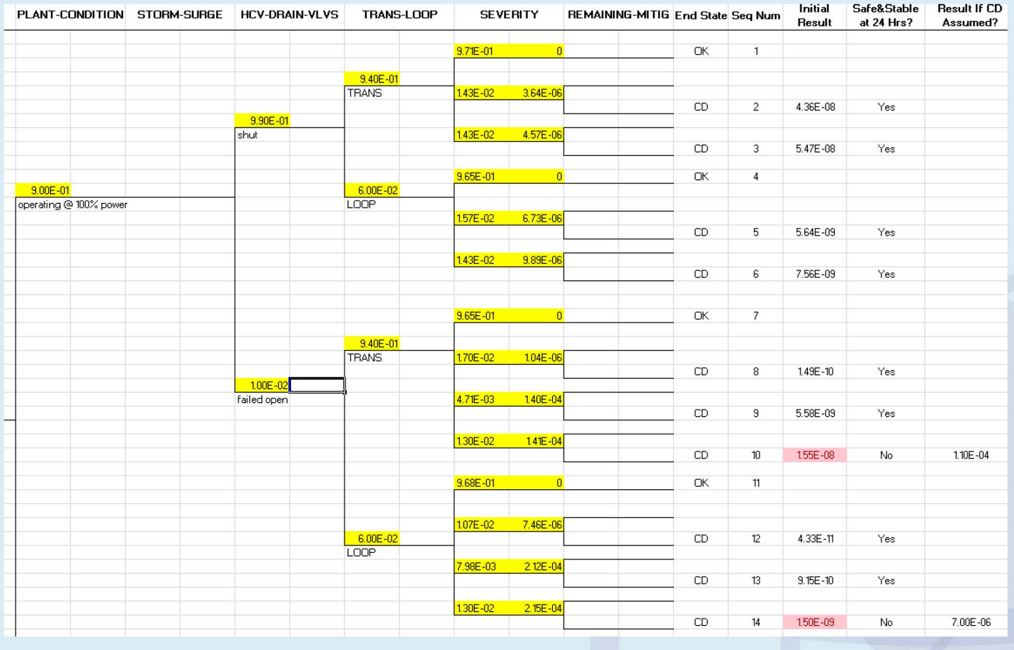

End State	Seq Num	Initial Result	Safe&Stable at 24 Hrs?	Result If CD Assumed?
OK	1			
CD	2	4.36E-08	Yes	
CD	3	5.47E-08	Yes	
OK	4			
CD	5	5.64E-09	Yes	
CD	6	7.56E-09	Yes	
OK	7			
CD	8	1.49E-10	Yes	
CD	9	5.58E-09	Yes	
CD	10	1.55E-08	No	1.10E-04
OK	11			
CD	12	4.33E-11	Yes	
CD	13	9.15E-10	Yes	
CD	14	1.50E-09	No	7.00E-06

Rain, Other POS (NRC)

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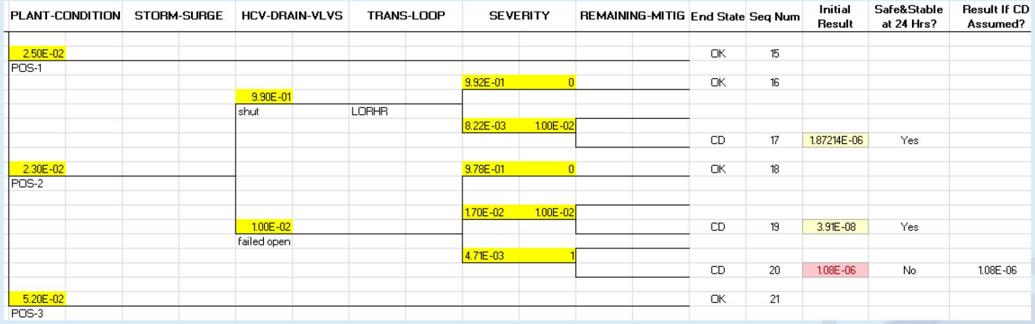
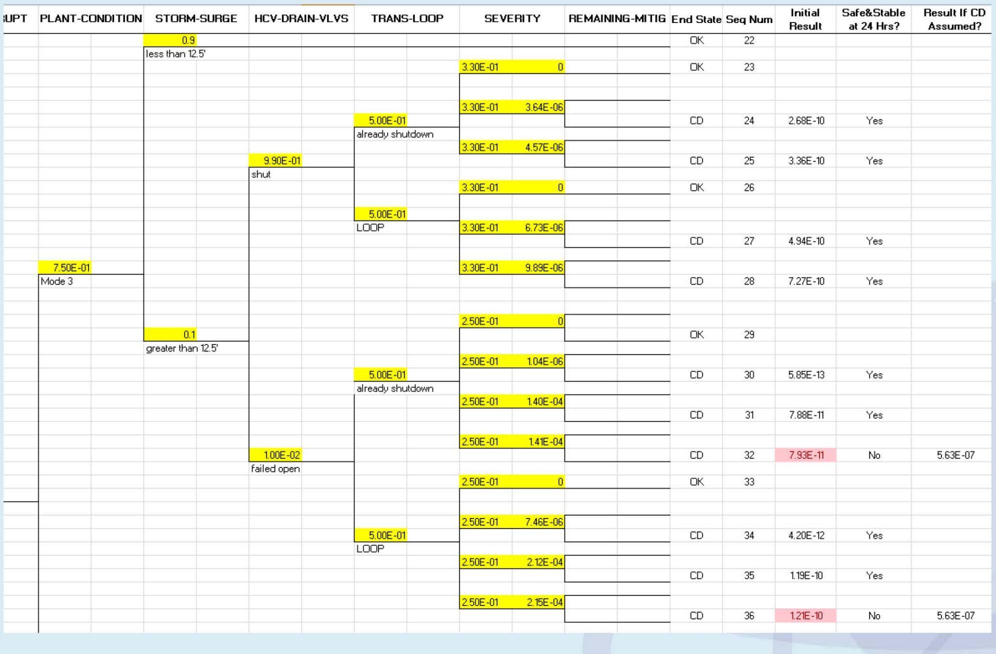


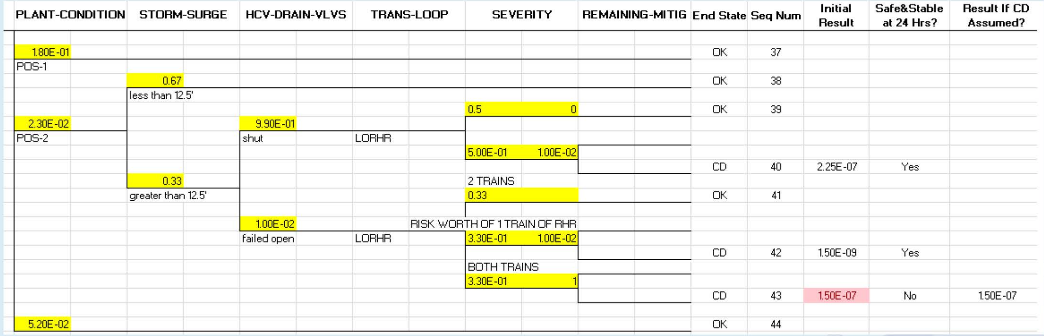
End State	Seq Num	Initial Result	Safe&Stable at 24 Hrs?	Result If CD Assumed?
OK	15			
OK	16			
CD	17	1.87214E-06	Yes	
OK	18			
CD	19	3.91E-08	Yes	
CD	20	1.08E-06	No	1.08E-06
OK	21			

Hurricane, Mode 3 (NRC)



End State	Seq Num	Initial Result	Safe&Stable at 24 Hrs?	Result If CD Assumed?
OK	22			
OK	23			
CD	24	2.68E-10	Yes	
CD	25	3.36E-10	Yes	
OK	26			
CD	27	4.94E-10	Yes	
CD	28	7.27E-10	Yes	
OK	29			
CD	30	5.85E-13	Yes	
CD	31	7.88E-11	Yes	
CD	32	7.93E-11	No	5.63E-07
OK	33			
CD	34	4.20E-12	Yes	
CD	35	1.19E-10	Yes	
CD	36	1.21E-10	No	5.63E-07

Hurricane, Other POS (NRC)



End State	Seq Num	Initial Result	Safe&Stable at 24 Hrs?	Result If CD Assumed?
OK	37			
OK	38			
OK	39			
CD	40	2.25E-07	Yes	
OK	41			
CD	42	1.50E-09	Yes	
CD	43	1.50E-07	No	1.50E-07
OK	44			

ICCW Pipe Break (NRC)

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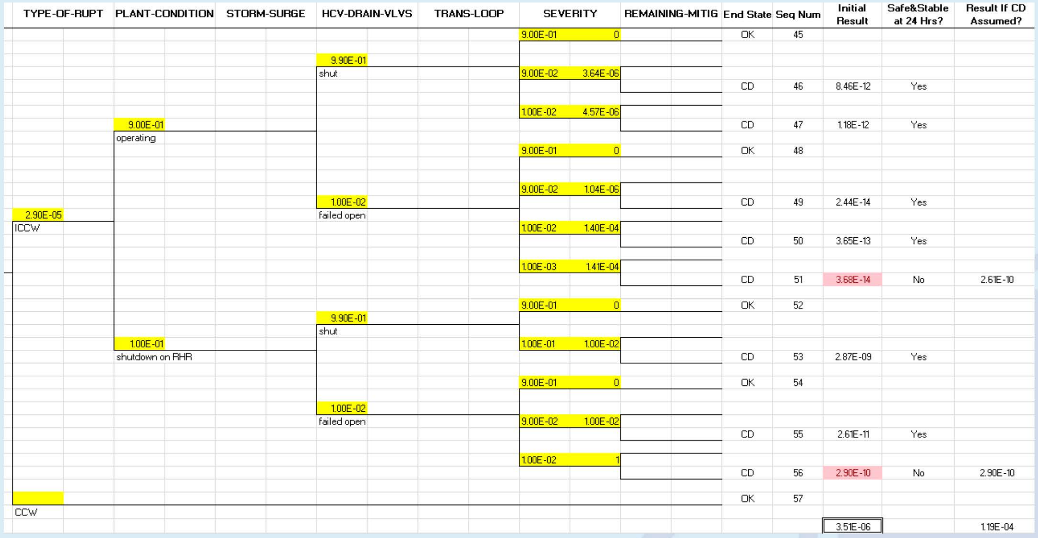


TYPE-OF-RUPT	PLANT-CONDITION	STORM-SURGE	HCV-DRAIN-VLVS	TRANS-LOOP	SEVERITY		REMAINING-MITIG	End State	Seq Num	Initial Result	Safe&Stable at 24 Hrs?	Result If CD Assumed?
2.90E-05 ICCW	9.00E-01 operating		9.90E-01 shut		9.00E-01	0		OK	45			
					9.00E-02	3.64E-06		CD	46	8.46E-12	Yes	
					1.00E-02	4.57E-06		CD	47	1.18E-12	Yes	
			1.00E-02 failed open		9.00E-01	0		OK	48			
					9.00E-02	1.04E-06		CD	49	2.44E-14	Yes	
					1.00E-02	1.40E-04		CD	50	3.65E-13	Yes	
					1.00E-03	1.41E-04		CD	51	3.68E-14	No	2.61E-10
	1.00E-01 shutdown on RHR		9.90E-01 shut		9.00E-01	0		OK	52			
					1.00E-01	1.00E-02		CD	53	2.87E-09	Yes	
			1.00E-02 failed open		9.00E-01	0		OK	54			
					9.00E-02	1.00E-02		CD	55	2.61E-11	Yes	
					1.00E-02	1		CD	56	2.90E-10	No	2.90E-10
CCW								OK	57			
										3.51E-06		1.19E-04

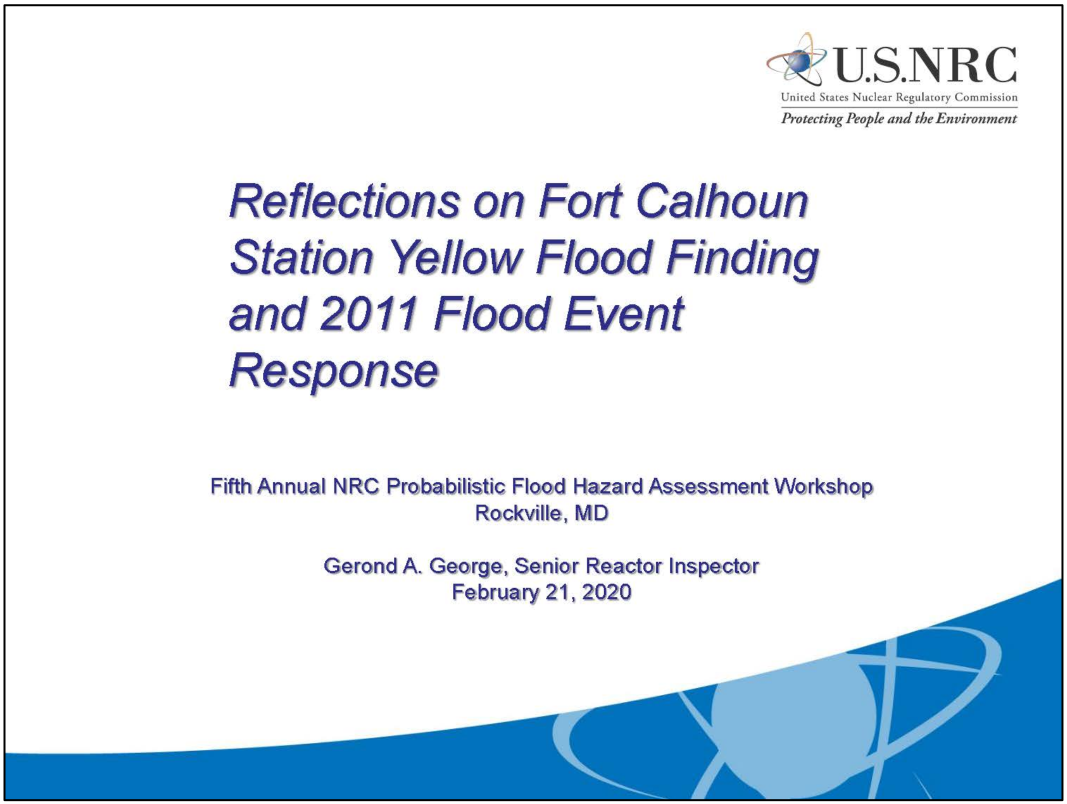
3.8.2 Presentation 3B-2: Reflections on Fort Calhoun Flooding Yellow Finding and 2011 Flooding Event Response

Speaker: Gerond George, NRC Region IV

3.8.2.1 Abstract

Senior Inspector Gerond George will briefly share stories and pictorial evidence that led to NRC's identification of risk significant flood protection issues at Fort Calhoun in 2009 and 2010. Mr. George will discuss the influence of the Yellow Flood Finding on OPPD's readiness to protect the plant during the 2011 Missouri River floods. Mr. George will provide pictures of the flood protection equipment installed by OPPD during the 2011 event and the result of those activities. Using this operating knowledge, Mr. George will provide his insights into how to this experience can enhance risk analysis

3.8.2.2 Presentation (ADAMS Accession No. ML20080M154)



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Reflections on Fort Calhoun Station Yellow Flood Finding and 2011 Flood Event Response

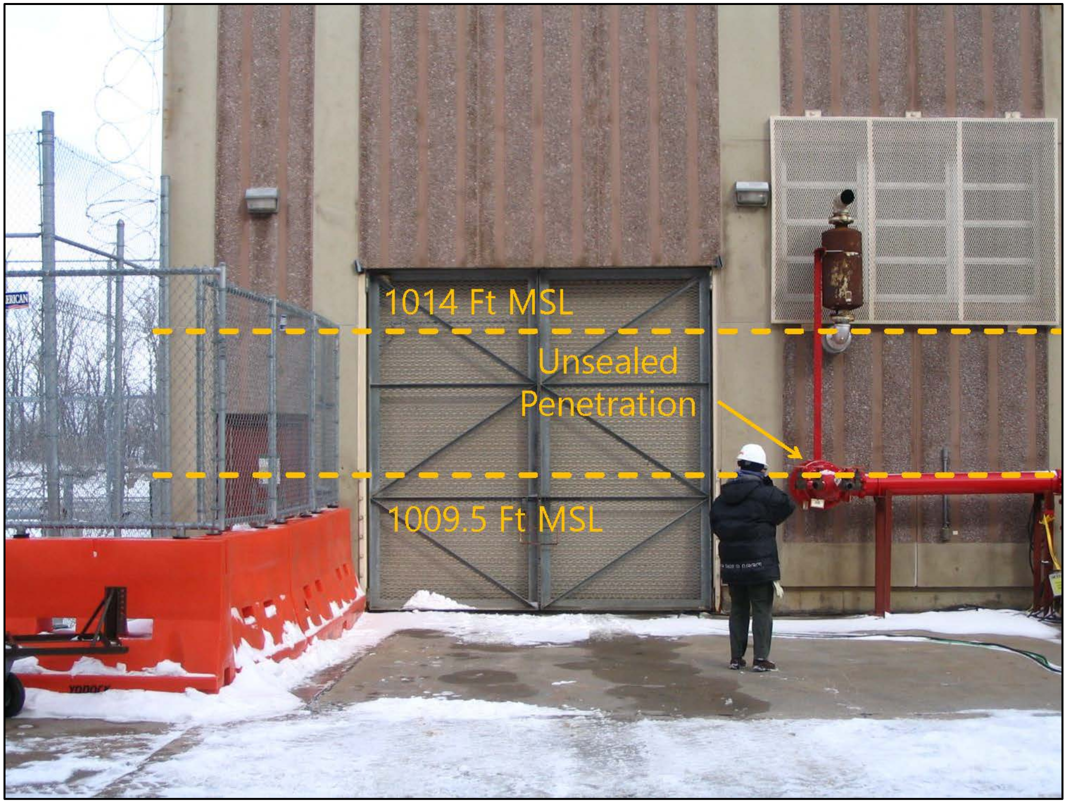
Fifth Annual NRC Probabilistic Flood Hazard Assessment Workshop
Rockville, MD

Gerond A. George, Senior Reactor Inspector
February 21, 2020

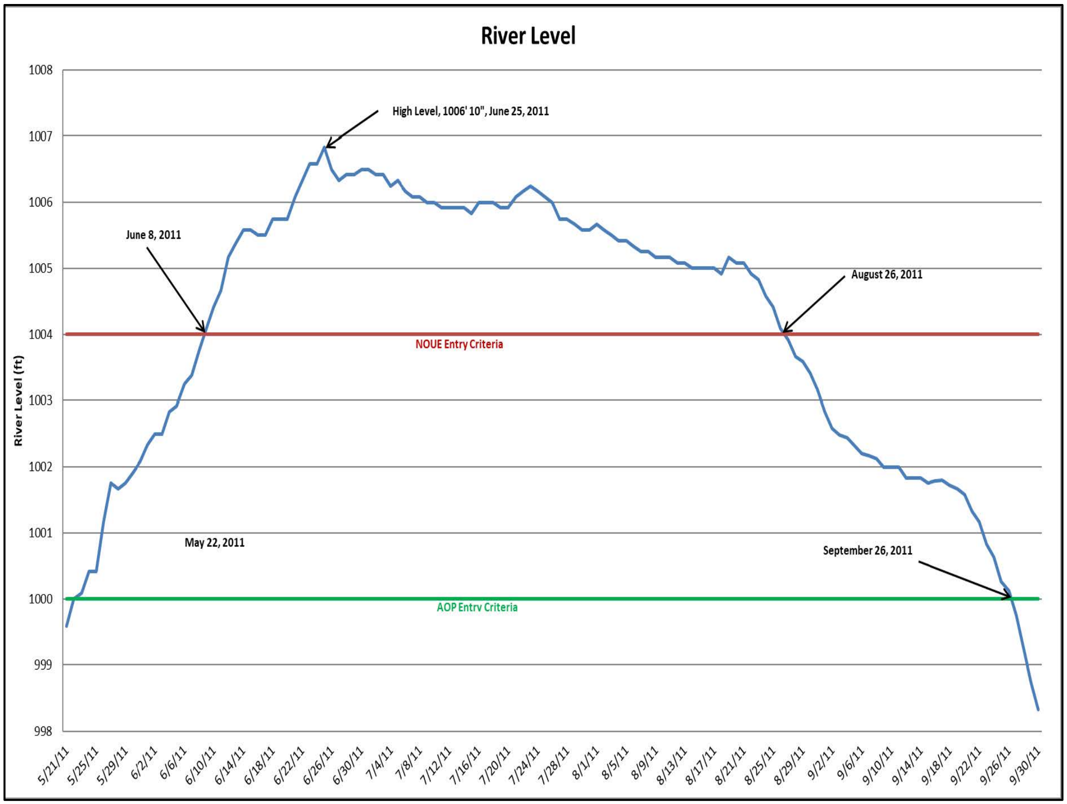
2011 Missouri River Flood Event

"THE PLANT WITHSTOOD THIS CHALLENGE INTACT IN LARGE PART BECAUSE OF COMMENDABLE PERFORMANCE BY NRC INSPECTORS, ANALYSTS, AND MANAGERS THE PREVIOUS YEAR."

-The NRC and Nuclear Power Plant Safety in 2011: Living on Borrowed Time
DAVID LOCHBAUM
Union of Concerned Scientists



SAFETY FIRST
DOOR IS-1
GLOVES REQUIRED


River Level
1008
1007
1006
1005
1004
1003
1002
1001
1000
999
998
River Level (ft)
High Level, 1006' 10", June 25, 2011
June 8, 2011
August 26, 2011
NOUE Entry Criteria
May 22, 2011
September 26, 2011
AOP Entry Criteria
5/21/11
5/25/11
5/29/11
6/2/11
6/6/11
6/10/11
6/14/11
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1017 FT
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1007 FT
7409


PRESRAY
WASSAIC, NEW YORK
AE-28
AUX BUILDING
DOOR 1011-4
FLOOD BARRIER
Number
FB33-1136
Oct. 04


CAT
CAT
DANGEROUS
KEEP AWAY

08/10/2011 09:56

NEBRASKA - IOW
SUPPLY COMPA


08/09/2011 13:52

Insights for Enhancing Flood Protection and Risk Assessment

1. Rivers Change
2. Experience with Sandbags
3. Maintenance of Structures and Barriers during the Event
4. Potential Hazardous Attitudes and Stress


1017 FT
1016 FT
1015 FT
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1012 FT
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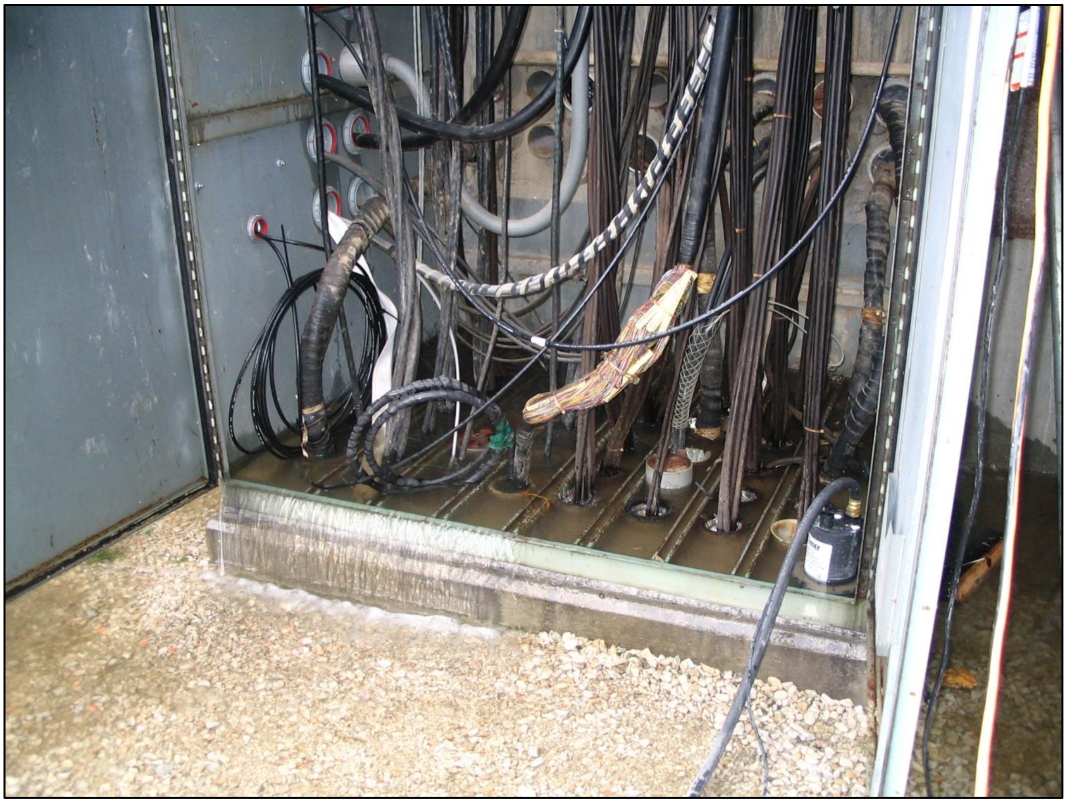

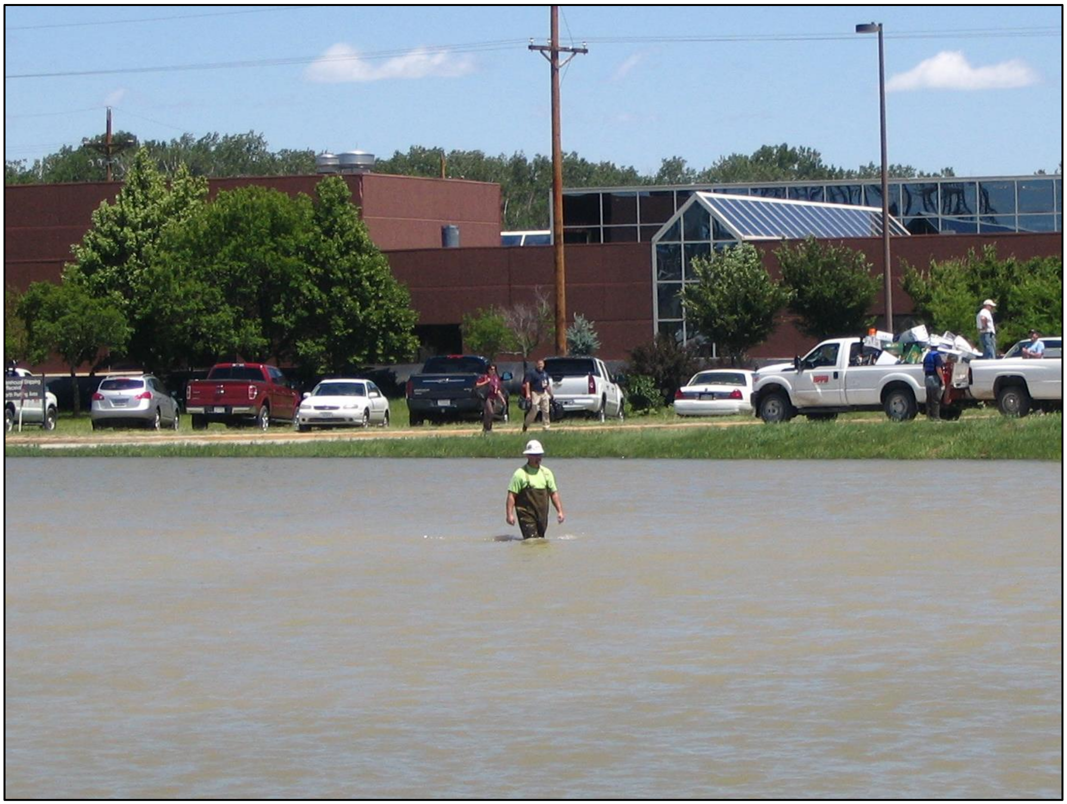

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Contact Info:
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NRC Region IV
Gerond.George@nrc.gov
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3.8.3 Presentation 3B-3: Cooper and Fort Calhoun Flooding Event Response

Speakers: Patricia Vossmar and Mike Stafford, NRC Region IV

3.8.3.1 Abstract

The NRC Resident Inspector and former Senior Resident Inspector at Cooper Nuclear Station will present information on the 2019 Missouri River flooding event that affected both Cooper and the permanently shut down Fort Calhoun Station. The presenters will discuss the impact of the flooding event on both nuclear plants, NRC and utility flood response activities, key lessons learned during the flood, and the unanticipated aftereffects of the flood. The presenters will share pictures from their experiences onsite at both nuclear plants, as well as pictures of regional damage from the 2019 flood

3.8.3.2 Presentation (ADAMS Accession No. ML20080M158)

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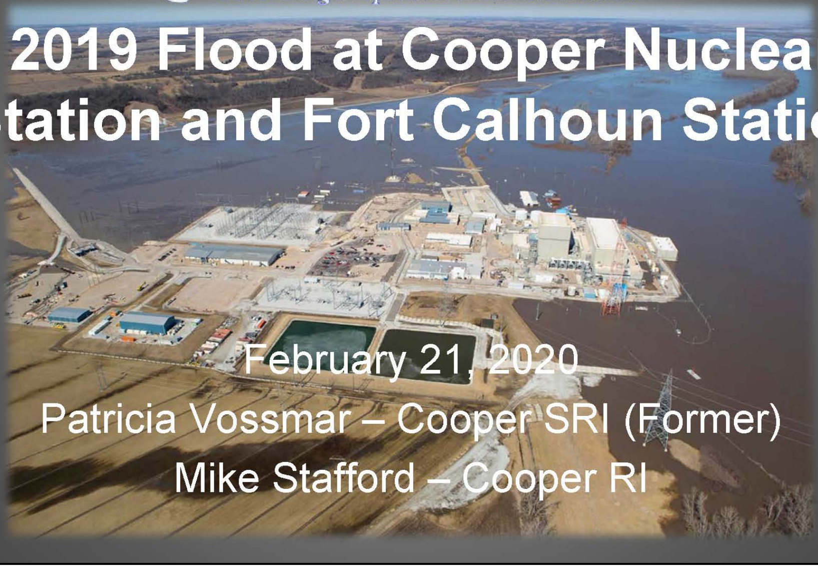
2019 Flood at Cooper Nuclear Station and Fort Calhoun Station

February 21, 2020
Patricia Vossmar – Cooper SRI (Former)
Mike Stafford – Cooper RI



2019 Flood at Cooper Nuclear Station and Fort Calhoun Station

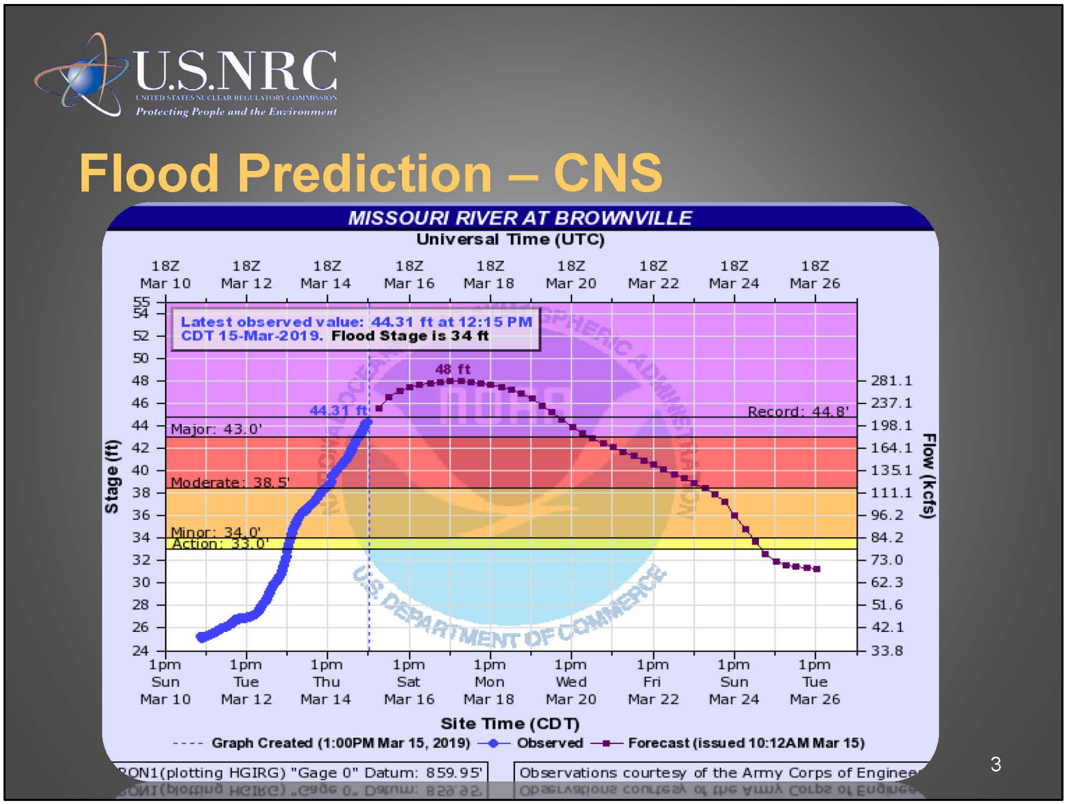
February 21, 2020

Patricia Vossmar – Cooper SRI (Former)

Mike Stafford – Cooper RI

Agenda

- Cooper (CNS) Flood
- Fort Calhoun (FCS) Flood
- Area Flooding Damage
- Unanticipated Aftereffects
- Key Lessons Learned



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Flood Prediction – CNS

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Licensee Preparation

- Flood Plan
- Schedule Scrub
- Survey Levees
- Sandbagging
- River Monitoring

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Licensee Preparation

- Staged Primary and Secondary Flood Barriers
- Staged FLEX equipment
- Obtained FHRR Crane

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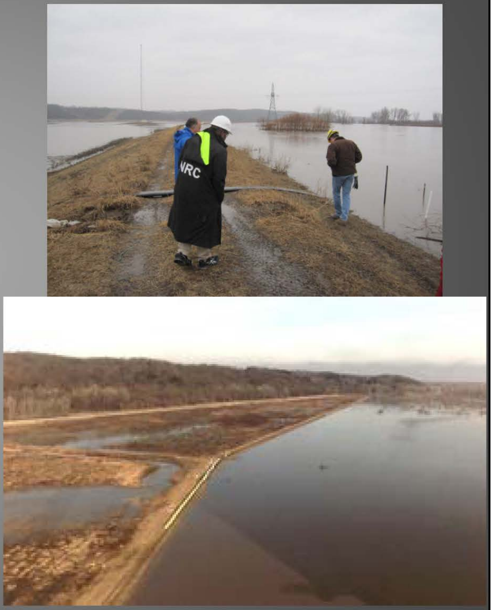
CNS Event

- **3/15 am** – CNS staffed OCC.
- **3/15 am** – Notification of Unusual Event (NOUE) Declared at 899.1'; NRC stayed in Normal Mode.
- **3/15 pm** – river level rose to 901.5' at CNS and remained stable for a few days.

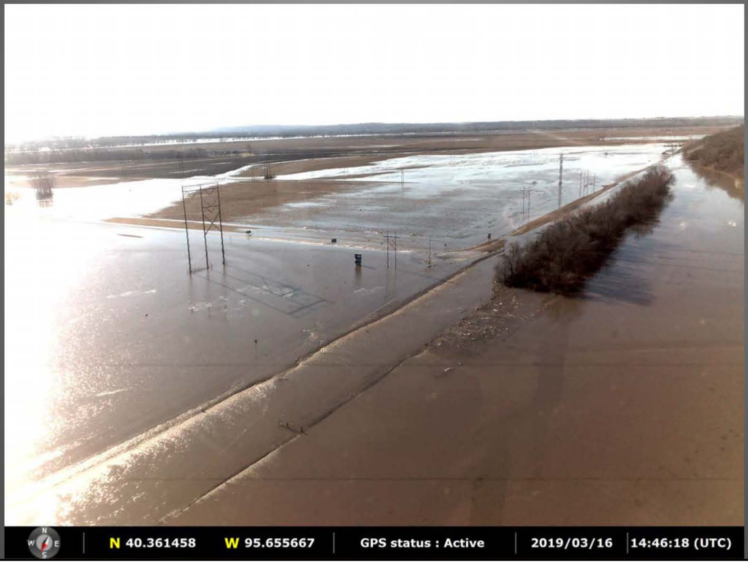


Early Site Flooding

CNS Event – Plant Access Road

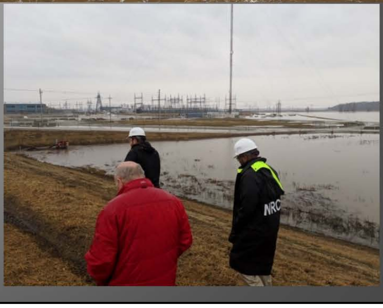
- **3/16 am** – Shuttling of employees across access road required due to road flooding caused by overtopping of North plant levee. (901.5’)
- **3/16 am** – CNS considers shutting down.

CNS Event - Plant Access Road



CNS Event

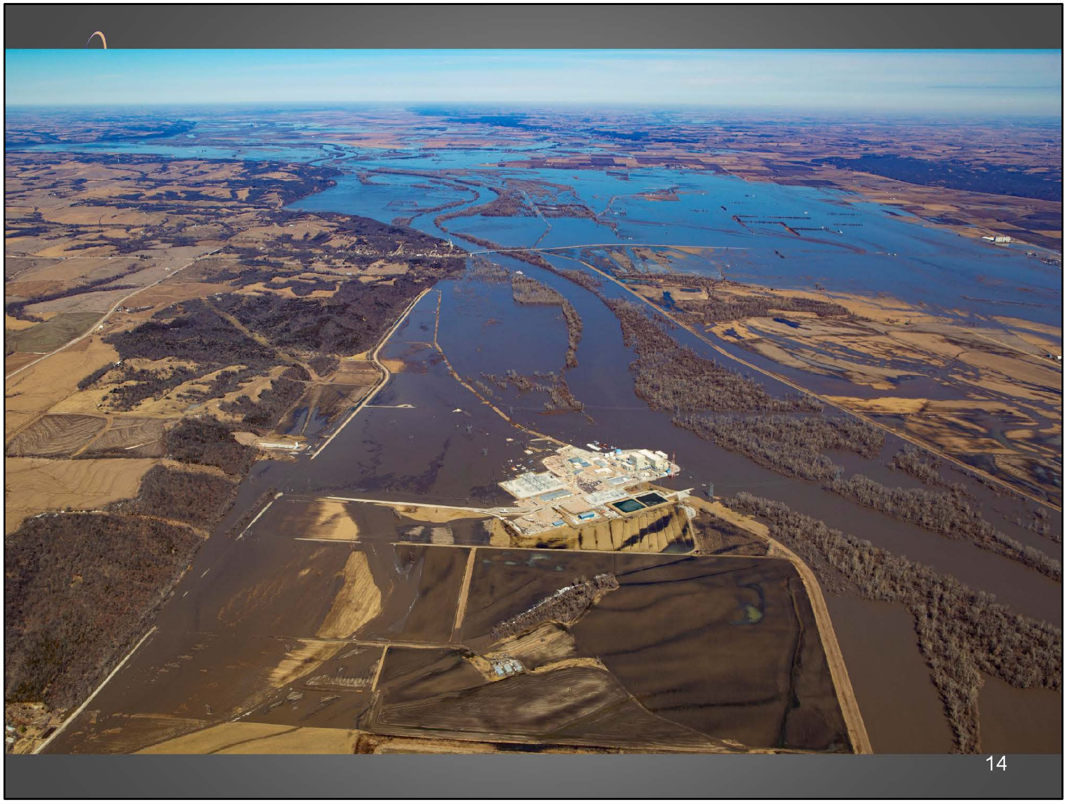
- **3/16 pm** – several large levee breaches upstream; river begins to lower ~2in/hr.
- **3/16 pm** – With levee relief, CNS decides not to shut down.
- **3/16** – River level hovers at or below 901.5’ feet for remainder of event.
- **3/24 1601** – Exited NOUE.



Before (Looking North)

After (Looking North)

West



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Governor Visit

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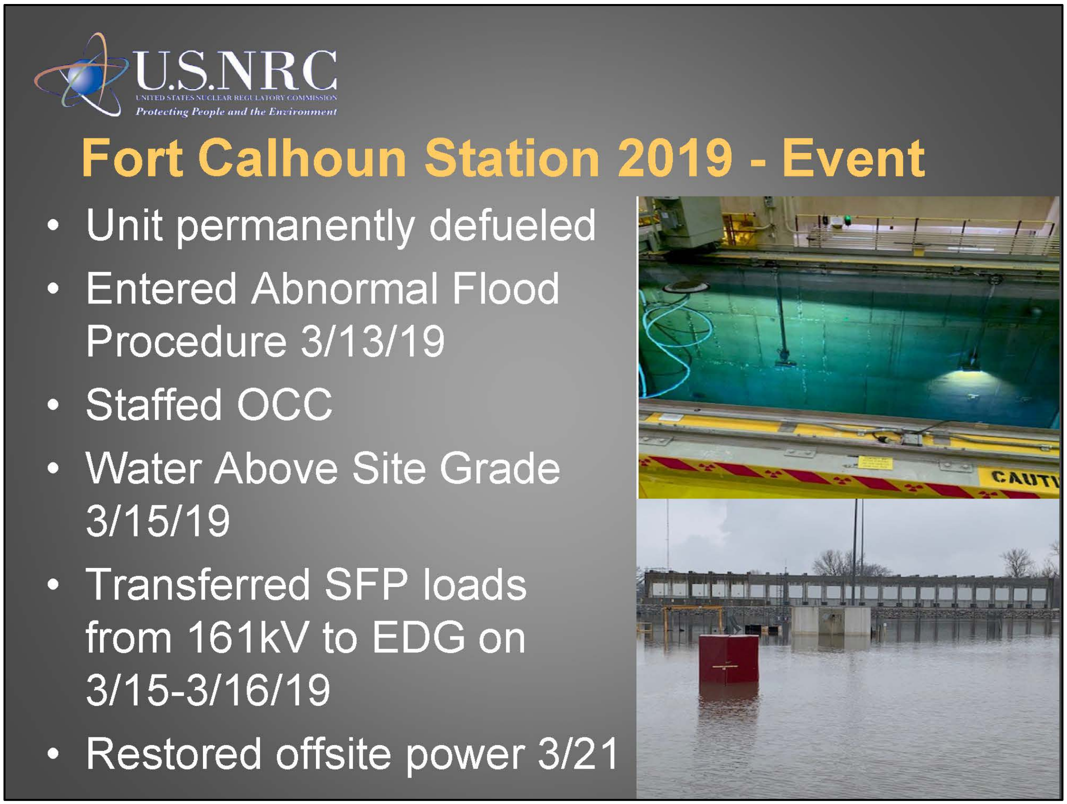
National Guard



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Fort Calhoun Station 2019 - Event

- Unit permanently defueled
- Entered Abnormal Flood Procedure 3/13/19
- Staffed OCC
- Water Above Site Grade 3/15/19
- Transferred SFP loads from 161kV to EDG on 3/15-3/16/19
- Restored offsite power 3/21

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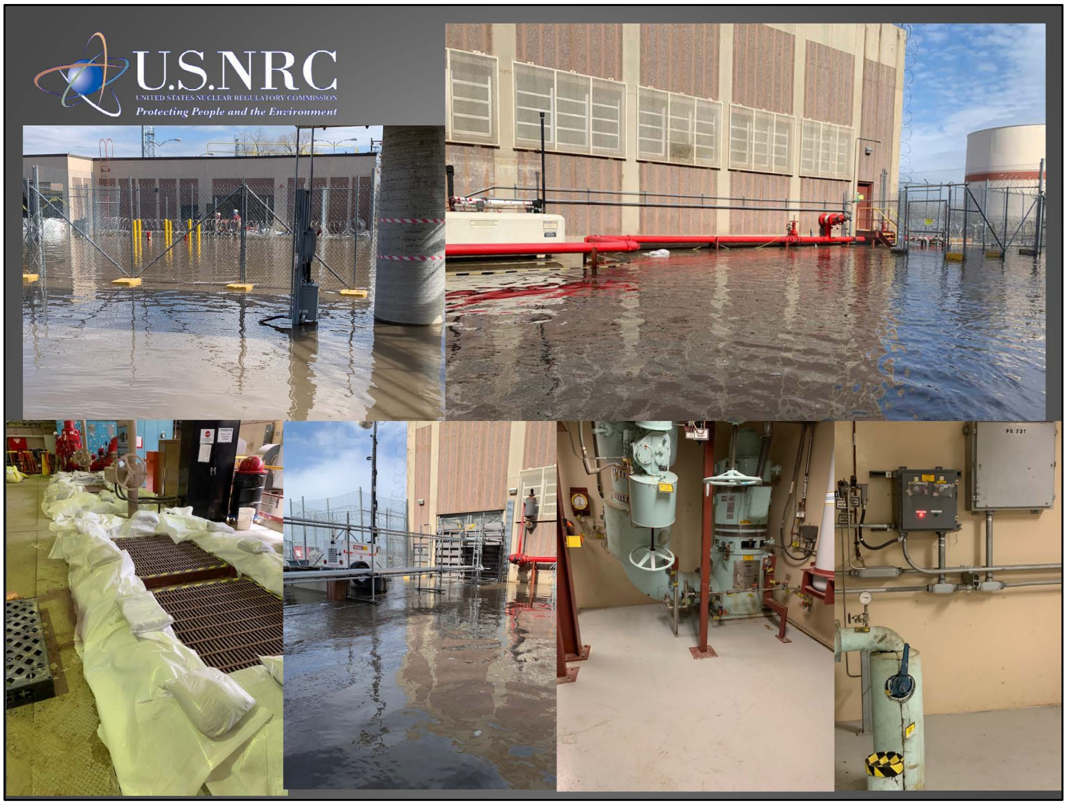
FCS 2019 – Onsite Transit



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FCS 2019 -DG Fuel Oil tank Water Intrusion

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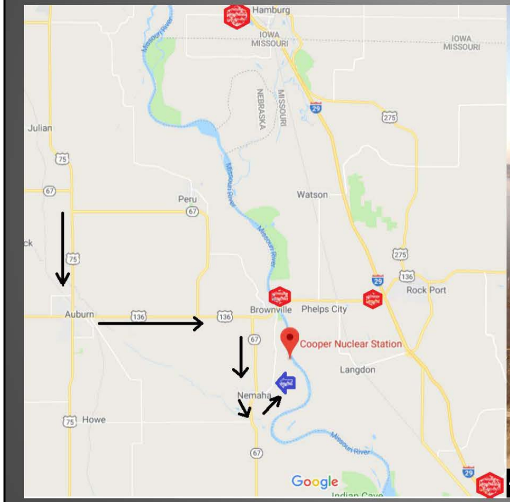
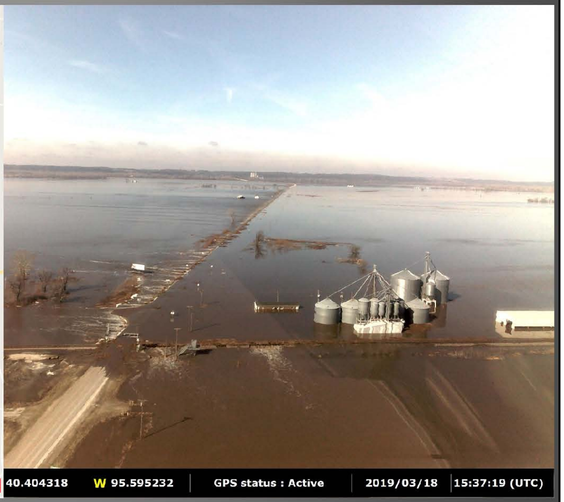
Post Flooding Damage - Roads





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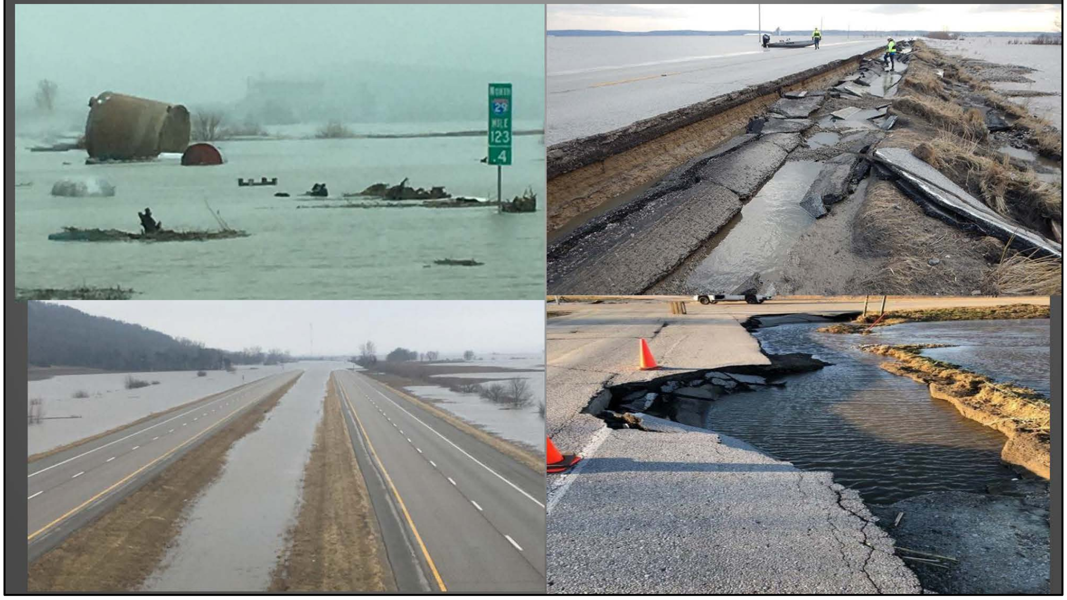
Flooding Damage - Roads



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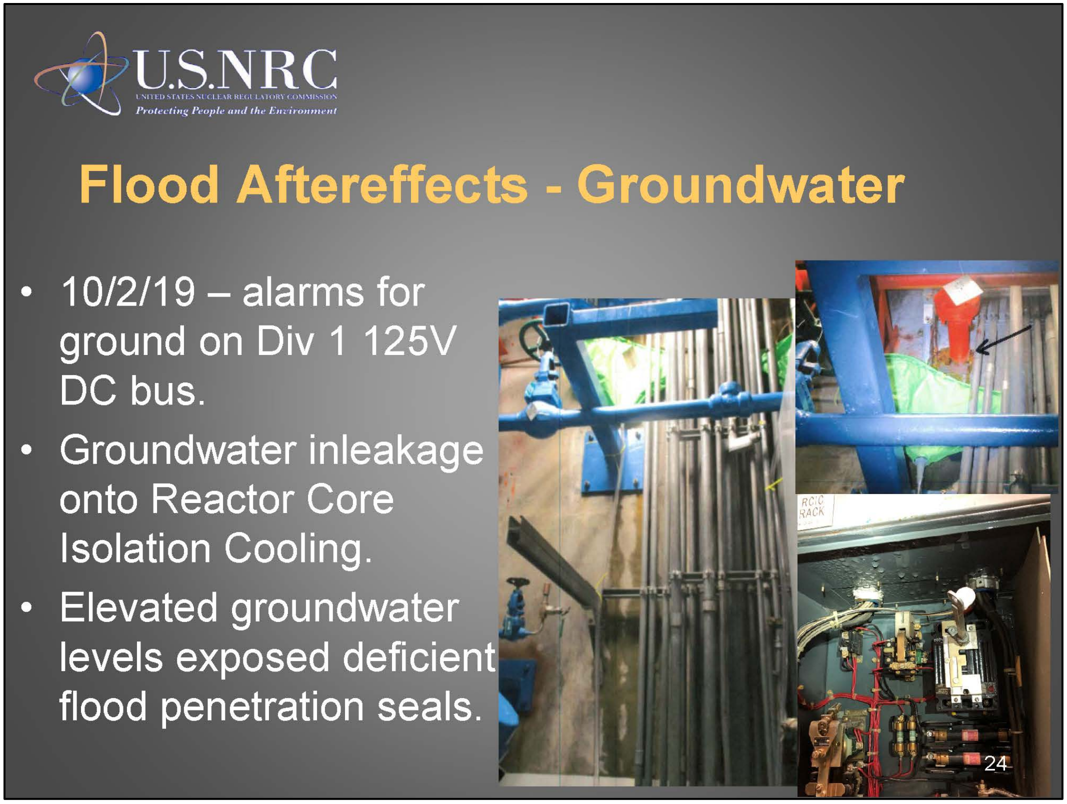
Semi trucks on levee near CNS

- Road Closures and poor GPS directions led two semi trucks to inadvertently drive and get stuck on the levee near CNS.



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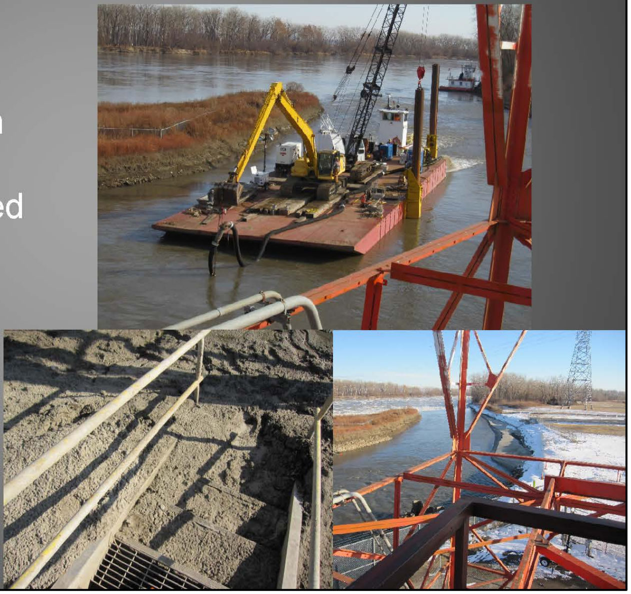
Flood Aftereffects - Groundwater

- 10/2/19 – alarms for ground on Div 1 125V DC bus.
- Groundwater inleakage onto Reactor Core Isolation Cooling.
- Elevated groundwater levels exposed deficient flood penetration seals.

Flood Aftereffects – Heat Sink

- 12/8/19 – CNS discovers one division of Service Water discharge pipe plugged
- Determines likely cause is silting
- 12/12 – CNS begins dredging discharge
- NRC sends Special Inspection Team



Spencer Dam – Nebraska (Before)

Spencer Dam – Nebraska (After)

Key Lessons Learned

- Flood vulnerabilities difficult to predict
  - Sandbags, sump pumps (defense-in-depth key)
  - DG Fuel Oil flange connection protection
  - Conduit and cable vault in-leakage likely
  - Elevated groundwater in-leakage into plant
  - Levees may overtop or fail
- Must prepare for Latent flood aftereffects
  - Groundwater in-leakage; silting of heat sink
- Highly complex flood strategies introduce additional vulnerability

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Questions?

3.9 Day 3: Session 3C – Overview of NRC PFHA Pilot Studies

Session Chair: Joseph Kanney, NRC/RES/DRA

3.9.1 Presentation 3C-1: Local Intense Precipitation (LIP) Flooding PFHA Pilot

Authors: Joseph Kanney and Meredith Carr, NRC Office of Nuclear Regulatory Research; Rajiv Prasad and Yong Yuan, Pacific Northwest National Laboratory (PNNL)

Speaker: Joseph Kanney

3.9.1.1 Abstract

This presentation will provide an overview of a recently initiated pilot study to inform development of guidance for probabilistic assessment of flooding hazards at nuclear power plants (NPPs) due to local intense precipitation (LIP) events. This pilot study is motivated by the fact that every NPP must assess the LIP flooding scenario and that LIP flooding includes unique aspects compared to other scenarios (e.g., very short warning time, complex flows). The objectives of the study are to (1) include key mechanisms and features that make LIP flooding analyses unique and challenging; (2) characterize and quantify important aleatory variability and epistemic uncertainties; (3) assess strength and weakness of available modeling tools; and (4) inform development of PFHA guidance and provide practical input for risk-informed decision-making. The major tasks in the study will be outlined and the current status of the project will be reported.

3.9.1.2 Presentation (ADAMS Accession No. ML20080M159)

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Local Intense Precipitation (LIP) PFHA Pilot Study

Joseph Kanney[1]*, *Meredith Carr[1]*, *Rajiv Prasad[2]*, *Yong Yuan[2]*

[1]U.S. Nuclear Regulatory Commission
[2]Pacific Northwest National Laboratory

5th Annual PFHA Research Workshop
NRC HQ, Rockville, MD
February 19 – 21, 2020

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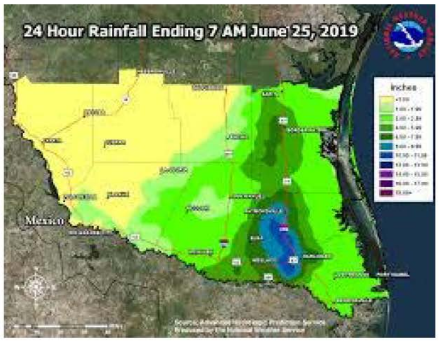
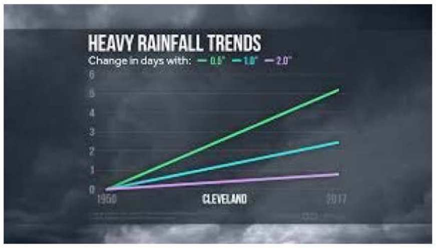
Outline

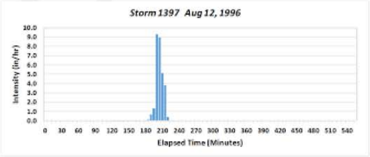
- Motivation
- Objectives
- Tasks
- Status

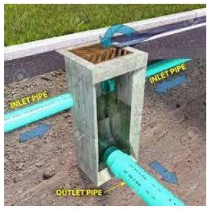




Motivation

- Local Intense Precipitation (LIP) flooding scenario must be analyzed for every NPP regardless of setting
- LIP flooding comprises unique aspects compared to other scenarios
  - Possibly very short warning time
    - Forecasting limitations
    - Short time to peak flow
      - High percentage of impervious surfaces
  - Complex flows
    - Sheet flow
    - Flow around and between buildings
    - Other structures (e.g., vehicle barrier systems)
    - Drainage from roofs
    - Subsurface drainage systems





Pilot Study Objectives

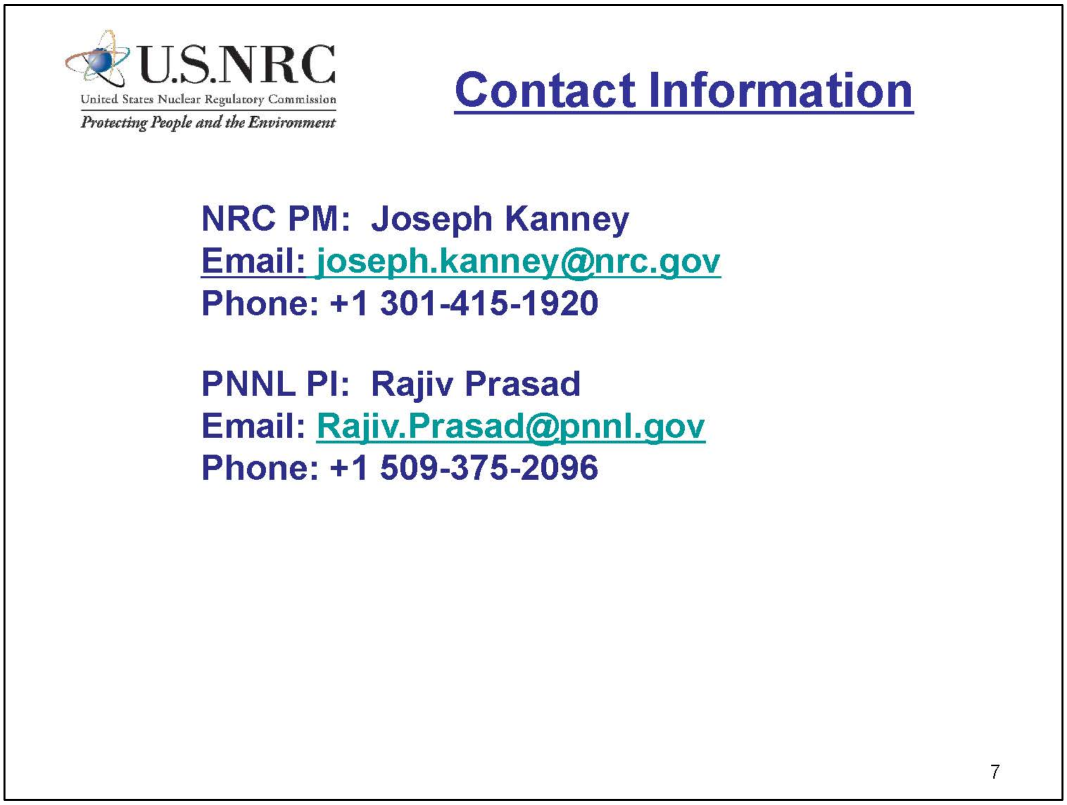
- Include key mechanisms and features that make LIP flooding unique and challenging
- Quantify aleatory variability and epistemic uncertainties and examine sensitivities
  - Structured analysis favoring realism over stylized conservatism
- Assess strength and weaknesses of available modeling tools
- Provide practical input for risk-informed decision-making (e.g. water levels, timing)
- Inform development of PFHA guidance for LIP scenario

Tasks

- Task 1 - Review characteristics of LIP flooding on industrial sites and available software to support LIP flood modeling
  - General purpose hydrologic and hydraulic models
  - Specialized stormwater models
  - Eulerian and Lagrangian (particle tracking) models
- Task 2 – Analyze LIP flooding aleatory variability and epistemic uncertainties
  - e.g., rainfall amount, temporal distribution
  - e.g., model structure, parameters, resolution
- Task 3 - Perform LIP PFHA for (hypothetical) NPP site
  - Synthetic site with features found to be significant in previous studies
- Task 4 - Knowledge Transfer
  - Presentations and seminars
  - Technical letter reports, final technical report

Status

- Task 1 in progress
  - *Technical Letter Report submitted*
    - *Under review by NRC staff*
  - *Expected completion 04/2020*
- Task 2 in progress
  - *Expected completion 07/2020*
- Task 3 - expected completion 01/2021
- Task 4 - expected completion 03/2021



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PNNL PI: Rajiv Prasad
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3.9.2 Presentation 3C-2: Riverine Flooding PFHA Pilot

Authors: Meredith Carr and Joseph Kanney, NRC Office of Nuclear Regulatory Research; William Lehman and Sarah O’Connell, U.S. Army Corps of Engineers, Institute for Water Resources, Hydrologic Engineering Center (USACE/IWR/HEC)

Speaker: Meredith Carr

3.9.2.1 Abstract

This presentation will provide an overview of a recently initiated pilot study to inform development of guidance for probabilistic assessment of flooding hazards at nuclear power plants (NPPs) due to riverine flooding. This pilot study is motivated by the fact that many NPPs are sited near rivers and thus potentially subject to riverine flooding hazards. This pilot study will inform development of PFHA guidance and provide practical input for risk-informed decision-making. The study will characterize and quantify important aleatory variability and epistemic uncertainties, and it will address key complexities such as flooding due to coincident storm runoff with dam failures. The major tasks in the study will be outlined and the current status of the project will be reported.

3.9.2.2 Presentation (ADAMS Accession No. ML20080M160)

United States Nuclear Regulatory Commission

Protecting People and the Environment

Riverine PFHA Pilot Study

Meredith Carr1*, *Joseph Kanney[1]*, *Will Lehman[2]*, *Sara O'Connell[2]*

[1]U.S. Nuclear Regulatory Commission
[2]U.S. Army Corps of Engineers,
Hydrologic Engineering Center, Institute for Water Resources

5th Annual PFHA Research Workshop
NRC HQ, Rockville, MD
February 19 – 21, 2020

Motivation

Support the application of the PFHA research results for risk-informed decision-making for riverine flood hazards

- demonstrate the development of a set of site-specific probabilistic flood hazard curves using available tools
- characterizes the uncertainty associated with these hazards to increase realism
- Inform development of PFHA guidance for riverine and dam failure scenarios

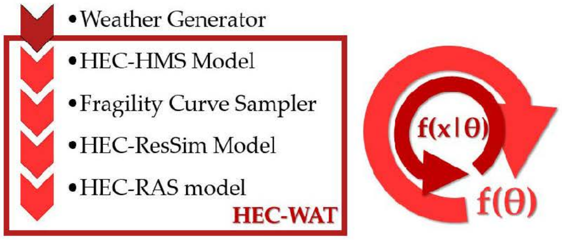
Objectives

Aleatory Variability

- Precipitation
  - Timing
  - Areal extent
  - Amount
  - Timing
- Watershed
  - Initial conditions

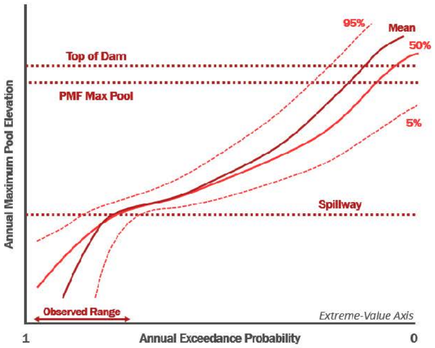
Epistemic Uncertainty

- Watershed
  - Infiltration
  - Hydrograph sub-model
  - roughness
- Treatment of dams



- Weather Generator
- HEC-HMS Model
- Fragility Curve Sampler
- HEC-ResSim Model
- HEC-RAS model

HEC-WAT



Tasks

- Task 1 - Site Selection
- Task 2 - Peer Review Plan
  - build independent team of qualified experts
  - determine level of participatory peer review
  - documentation
- Task 3 - Data Preparation
- Task 4 - Probabilistic Modeling
  - Selecting Probabilistic Modeling Approach and Options
  - Simulation and Model Refinement
  - Uncertainty Quantification (UQ) and Sensitivity Analysis (SA)
- Task 5 - Knowledge Transfer
  - Presentations and seminars
  - Technical letter reports, final technical report

Task 1: Watershed Selection

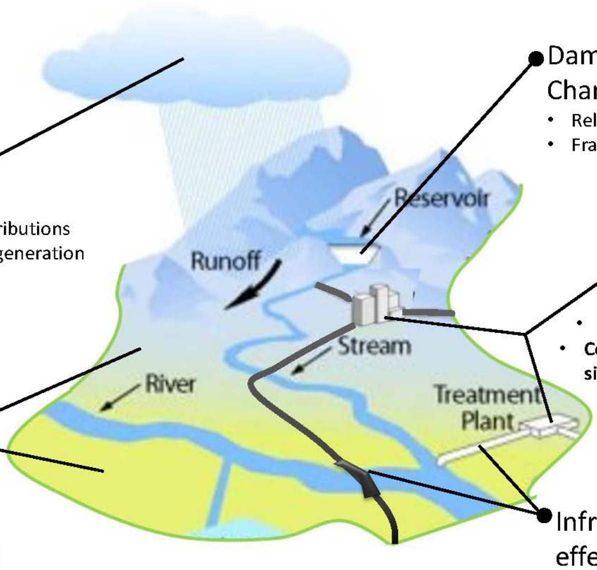
Target Flood Watershed Characteristics

- Representative complexity of existing NPP basins
- Basin size, contributing area
- Storms impact different parts of the basin
- Different Storm Types, Snowmelt
- Dam failures, sequential, distance from site

Table 1. Best Watershed Candidates

River or Watershed	State	Drainage Area (sq mi)	Snow?	Existing Models				Level of Effort Required to Develop/Adapt Models
				HMS	ResSim	RAS	WAT	
Trinity River	TX	6,000	N	Y	Y	Y	Y	high/med
Connecticut	VT	7,500	Y	Y	Y	Y	Y	high
Middle Fork Willamette	OR	1,400	Y	Y	Y	Y	Y	med/low
South Platte River	CO	4,000	Y	Y	Y	Y	N	high

Task 3: Data Gathering & Preparation



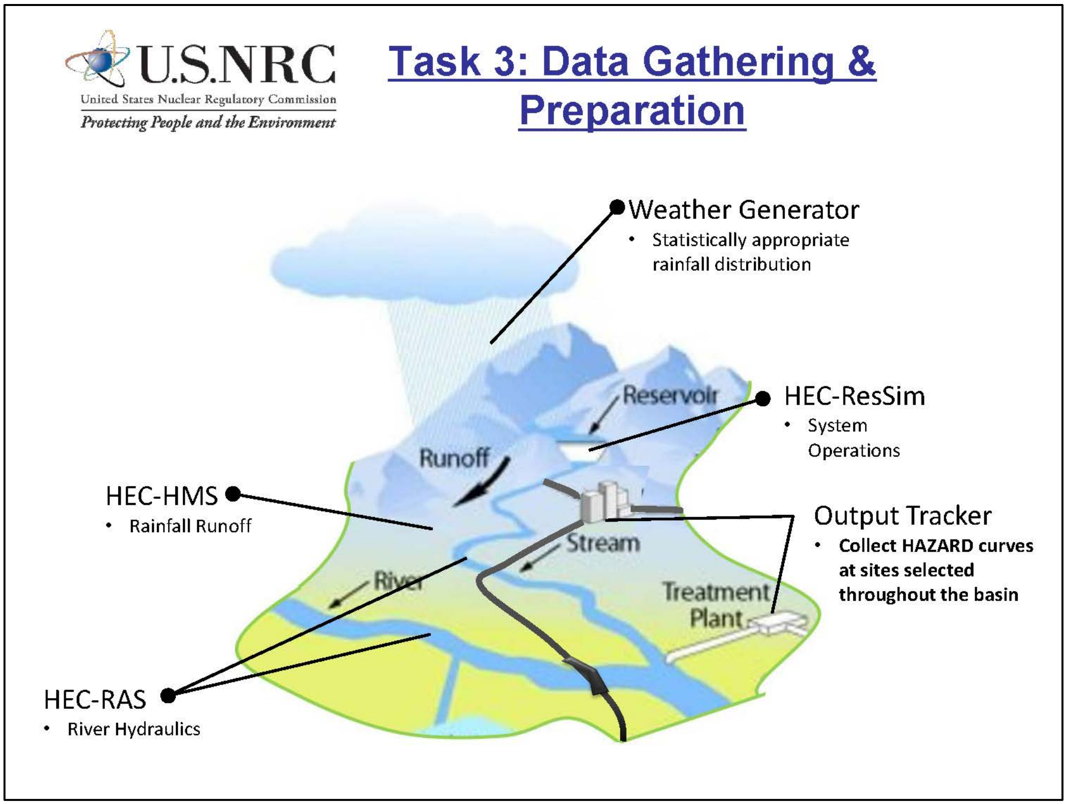
Storm Types & Frequencies
- Spatial temporal distributions
- Supporting weather generation

Dam Characteristics
- Release rules
- Fragility curves

Consequence Locations
- Location, characteristics
- **Collect HAZARD curves at sites selected throughout the basin**

Basins and Land cover
- Basin characteristics
- Data to support antecedent conditions

Infrastructure effecting flow
- Bridges, Pumps, Local inflows



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Task 3: Data Gathering & Preparation

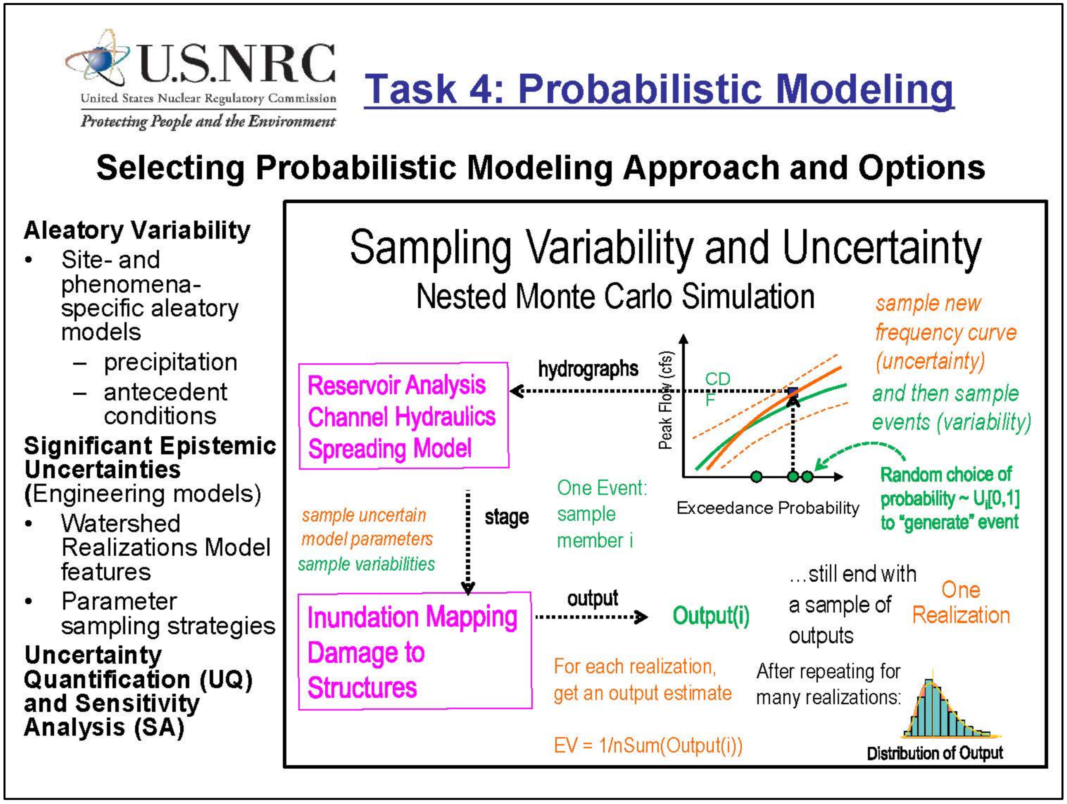
Weather Generator
- Statistically appropriate rainfall distribution

HEC-ResSim
- System Operations

Output Tracker
- **Collect HAZARD curves at sites selected throughout the basin**

HEC-HMS
- Rainfall Runoff

HEC-RAS
- River Hydraulics



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Task 4: Probabilistic Modeling

Selecting Probabilistic Modeling Approach and Options

Aleatory Variability
- Site- and phenomena-specific aleatory models
  - precipitation
  - antecedent conditions

Significant Epistemic Uncertainties (Engineering models)
- Watershed Realizations Model features
- Parameter sampling strategies

Uncertainty Quantification (UQ) and Sensitivity Analysis (SA)

Sampling Variability and Uncertainty

Nested Monte Carlo Simulation

sample new frequency curve (uncertainty)

and then sample events (variability)

Random choice of probability ~ U$_i$[0,1] to "generate" event

Reservoir Analysis
Channel Hydraulics
Spreading Model

sample uncertain model parameters
sample variabilities

One Event: sample member i

Inundation Mapping
Damage to Structures

Output(i)

…still end with a sample of outputs

One Realization

For each realization, get an output estimate

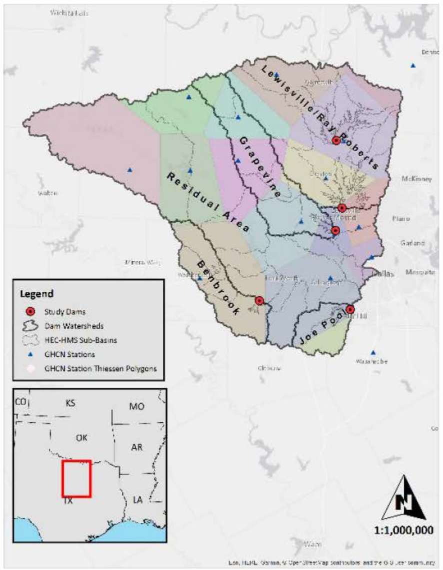
EV = 1/nSum(Output(i))

After repeating for many realizations:

Status: Task 1 - Watershed Selection

Selection complete
Draft Letter Report Submitted

- **Trinity River Watershed, TX**
- Drainage Area: 6,000 sq mi.
- Watershed characteristics
  - five major dams
  - urban centers
  - differing land use
  - Differing elevations
  - Three major headwater branches
- **Precipitation**: Existing quasi-continuous stochastic weather generator to provide storm forcing
- **Existing Engineering Models:** HMS, ResSim, WAT, 2D-RAS could be incorporated



Status

- Task 1 - Site Selection
  - *Technical Letter Report submitted*
    - *Under revision by HEC*
- Task 2 - Peer Review Plan
  - *In Progress*
- Task 3 - Data Preparation
  - *In Progress*
- Task 4 - Probabilistic Modeling
  - Selecting Probabilistic Modeling Approach and Options
    - *In Progress*
  - Simulation and Model Refinement
    - including Uncertainty Quantification (UQ) and Sensitivity Analysis (SA)
- Task 5 - Knowledge Transfer
  - Presentations and seminars
  - Technical letter reports, final technical report

3.9.3 Presentation 3C-3: Coastal Flooding PFHA Pilot.

Authors: Joseph Kanney, NRC Office of Nuclear Regulatory Research, Norberto Nadal-Caraballo and Victor Gonzalez, U.S. Army Corps of Engineers, Engineer Research & Development Center, Coastal and Hydraulics Laboratory (USACE/ERDC/CHL)

Speaker: Joseph Kanney

3.9.3.1 Abstract

This presentation will provide an overview of a recently initiated pilot study to inform development of guidance for probabilistic assessment of flooding hazards at nuclear power plants (NPPs) due to coastal flooding. Many NPPs are sited in coastal settings and are thus potentially subject to coastal flooding hazards. This pilot study will inform development of PFHA guidance and provide practical input for risk-informed decision-making. The study will characterize and quantify important aleatory variability and epistemic uncertainties, and it will address key complexities such as flooding due to coincident storm surge and riverine flooding due to storm rainfall. The major tasks in the study will be outlined and the current status of the project will be reported.

3.9.3.2 Presentation (ADAMS Accession No. ML20080M163)

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Coastal Flooding PFHA Pilot Study

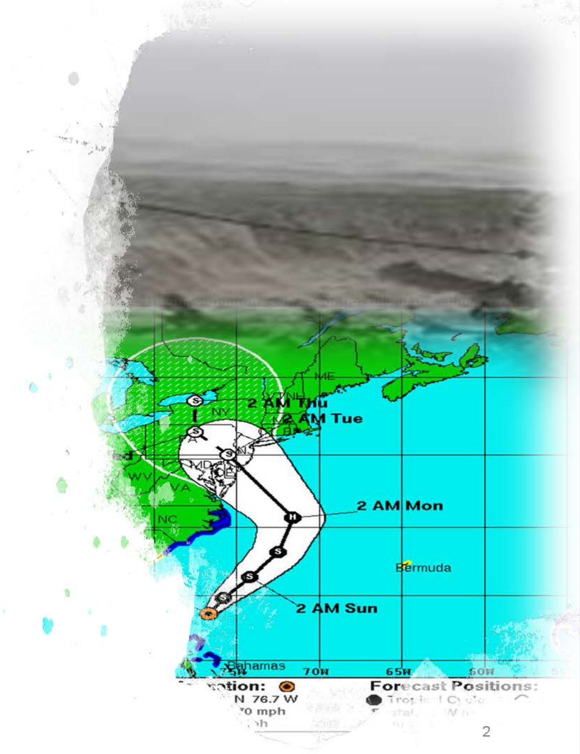
Joseph Kanney[1]*, *Norberto C. Nadal-Caraballo[2],*
Victor M. Gonzalez[2]

[1]U.S. Nuclear Regulatory Commission
[2]U.S. Army Corps of Engineers

5th Annual PFHA Research Workshop
NRC HQ, Rockville, MD
February 19 – 21, 2020

Outline

- Objectives
- Tasks
- Status



Pilot Study Objectives

- Demonstrate PFHA for external flooding due to coastal flooding phenomena
- Include key mechanisms and features that make coastal flooding unique and challenging
  - Storm surge
  - Wind wave effects
  - Riverine discharge
- Include propagation of aleatory and epistemic uncertainties
- Uncertainty and sensitivity analysis
- Inform development of PFHA guidance for coastal flooding scenario

Tasks

- **Task 1 – Site Selection**
  - – Focus on coastal areas and adjoining watersheds that are representative of settings where NPPs could be sited
  - – Priority on areas for which existing hydrodynamic (storm surge), hydrologic and hydraulic models (riverine discharge) are available
    - Leverage studies in Coastal Hazard System (CHS)
- **Task 2 – Data Collection and Analysis**
  - – Climate and precipitation information
  - – Historical information on extratropical and tropical storms affecting the region
  - – Available water level observations (e.g. river discharge, tides)
  - – Site and watershed information
  - – Hydrodynamic, hydrologic and hydraulic models

Tasks (Cont.)

- **Task 3 - Review and Selection of Probabilistic Modeling Approach and Methods**
  - – Select an overall probabilistic modeling approach and methods for probabilistic modeling of specific processes.
- **Task 4 - Construct inputs for Hydrodynamic, Hydrologic and Hydraulic Modeling**
  - – Probabilistic space-time inputs to the hydrodynamic, hydrologic, and hydraulic models used in the study.
  - – Aleatory model for stochastic aspects of these processes
  - – Characterization and quantification of epistemic uncertainties (e.g. model structure and parameter uncertainties).

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Tasks (Cont.)

- **Task 5 – Hydrodynamic, Hydrologic, and Hydraulic Modeling**
  - The types of simulations based on the outcome of the assessment performed in the previous tasks. Options are:
    - Full leverage of existing CHS data and no H&H modeling
    - Full leverage of existing CHS data with hydraulic modeling
    - Partial leverage of existing CHS data. ADCIRC and hydraulic modeling (soft-coupling) of subset of storms
    - Full coastal and H&D modeling (full-coupling) of full JPM storm suite
- **Task 6 – Construct Final Hazard Curves**
  - Hazard curves for selected flooding hazards (e.g., still water level, total waters level, forces).
  - Uncertainty quantification and sensitivity analysis

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Tasks (Cont.)

- **Task 7 - Peer Review**
  - In-process peer review
- **Task 8 - Knowledge Transfer**
  - Presentations and seminars, technical letter reports, final report

Status

- Tasks 1, 2, 3, 7, 8 in progress
  - *Tasks 1-3 expected completion 07/2020*
  - *Tasks 7,8 ongoing throughout project*
- Tasks 4,5 – expected completion 03/2021
- Task 6 - expected completion 07/2021
- Project completion expected 12/2021

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3.10 Day 3: Session 3D – Towards External Flooding PRA

Session Chair: Mehdi Reisi-Fard, NRC of Nuclear Reactor Regulation

3.10.1 Presentation 3D-1: EPRI External Flooding PRA Activities

Speaker: Marko Randelovic, Electric Power Research Institute

3.10.1.1 Abstract

Qualitative Risk Ranking Process of External Flood Penetration Seals

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.

External Flooding PRA Walkdown Guidance

As a result of the accident at Fukushima Dai-ichi, the need to understand and account for external hazards (both natural and man-made) has become more important to the industry. A major cause of loss of AC power at Fukushima Dai-ichi was a seismically induced Tsunami that inundated the plant's safety-related systems, structures and components (SSCs) with flood water. As a result, many nuclear power plants (NPPs) have reevaluated their external flooding (XF) hazards to be consistent with current regulations and methodologies. As with all new information obtained from updating previous assumptions, inputs and methods (AIMs), the desire exists to understand the changes in the characterization of the XF hazard and the potential impact to the plant's overall risk profile. This has led to an increased need to develop a comprehensive External Flooding Probabilistic Risk Assessment (XFPRA) for more NPPs. One of the steps for developing XFPRA is the plant walkdown, which is the central focus of the research. This research provides guidance on preparing for and conducting XF walkdowns to gather the necessary information to better inform the XFPRA process. Major topics that will be addressed include defining key flood characteristics, pre-walkdown preparation, performing the initial walkdown, identifying the need for refined assessments or walkdowns, and documenting the findings in a notebook. This guidance also addresses walkdown team composition, guidance on useful plant drawings and utilizing previous walkdowns or PRAs to inform the XF walkdown process.

External Flooding PRA Guidance

The objective of this report is to develop a generic roadmap and associated guidance to support the development of External Flood PRA consistent with meeting Category II requirements of Part 8 of the ASME/ANS RA-Sb-2013,” Standard for Level 1/Large Early Release Frequency Probabilistic Risk Assessment for Nuclear Power Plant Applications”, including:

(1) Identification of external flood hazards applicable to the site

(2) Definition and characterization of the external Flood Hazard considering event and plant-specific issues

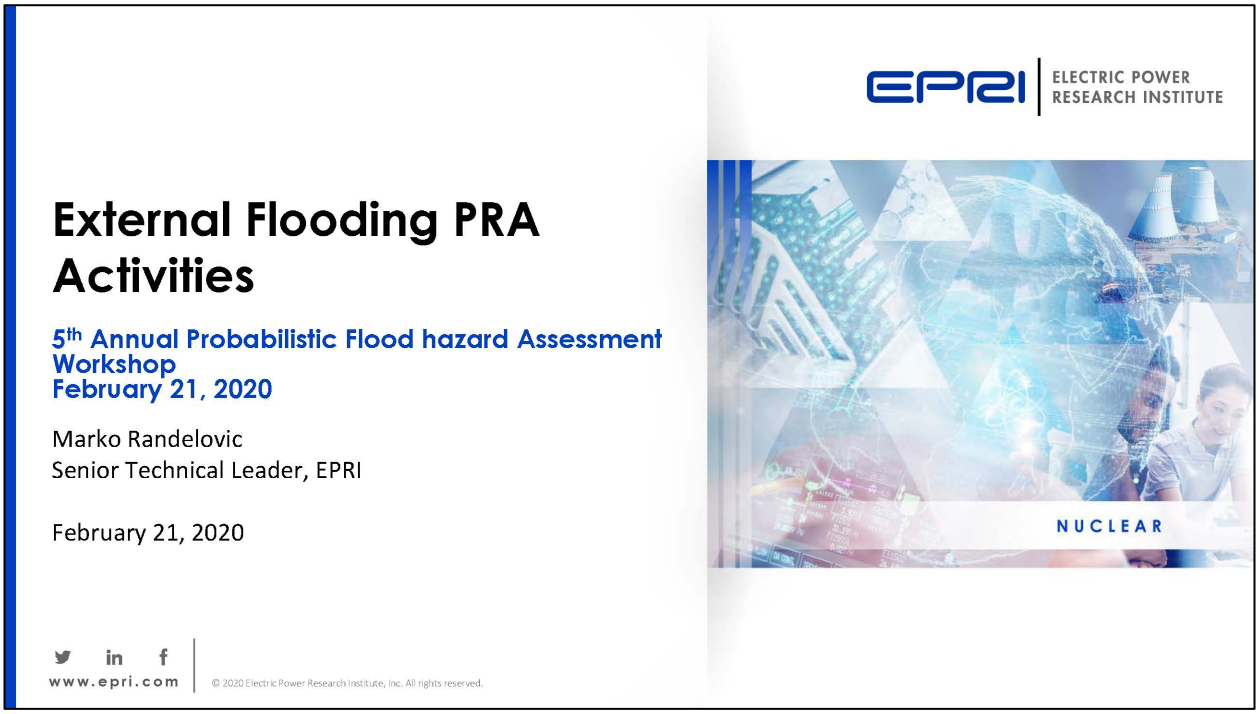
(3) Estimation of associated external flood hazard frequencies

(4) Development of external flood fragility models for flood significant Systems, Structures and Components (SSCs)

(5) Development of external flood hazard scenarios

As warning time and ad-hoc system operation may be a unique feature for some external flood scenarios, this report also addresses the role of preparatory/preventive (pre-event) and post-event human actions in mitigating and responding to the external flood hazard with considerations for modeling non-safety grade equipment for long term operation. The guidance includes example applications for representative external flooding scenarios, including those resulting from local intense precipitation, riverine flooding and storm surge scenarios.

3.10.1.2 *Presentation (ADAMS Accession No. ML20080M164)*



ELECTRIC POWER RESEARCH INSTITUTE

External Flooding PRA Activities

5th Annual Probabilistic Flood hazard Assessment Workshop
February 21, 2020

Marko Randelovic
Senior Technical Leader, EPRI

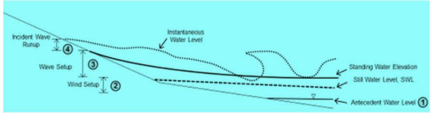
February 21, 2020

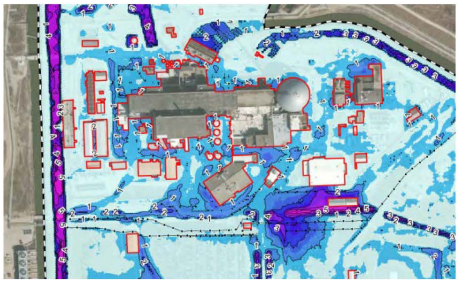
www.epri.com

External Flooding PRA Walkdown Guidance

External Flooding Walkdown Guidance (3002015989)

- EPRI developed a guidance for performing an external flooding PRA walkdown in support of developing an external flooding PRA model
- The guidance is flexible enough to support any level of risk assessment or external flooding analysis
- Report provides a framework on how to Prepare and Conduct Ext. Flooding walkdown to collect the necessary information to support Ext. Flooding Analysis/PRA
- Topics covered:
  - Key flooding characteristics and flood causing mechanisms
  - Pre-walk down preparation:
    - External flooding equipment list
    - External flood operator actions list
    - External flood protection features
  - Initial walkdown
  - Focused scope walkdown
  - Documentation
  - Team composition



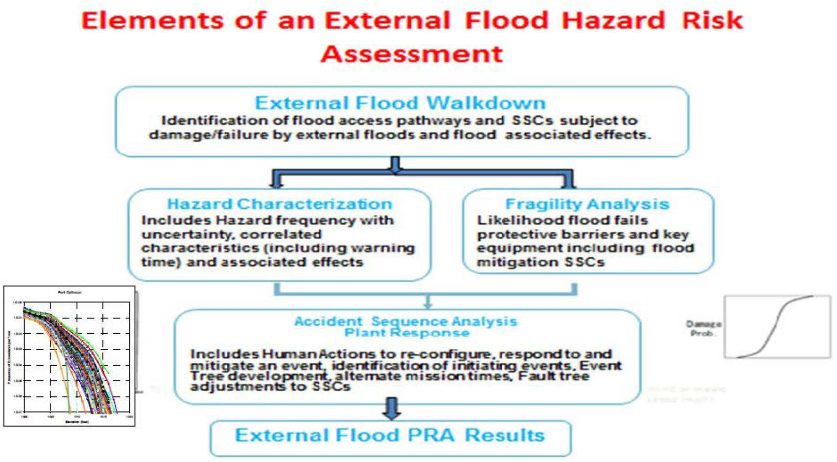


External Flooding PRA Guidance

Project Objective

- Develop External Flood Guidance Document
  - Tie guidance to Part 8 of ASME/ANS Standard (XFLD)
  - Specifically integrate:
    - Hazard characterization
    - Human performance assessment of pre-flood, “adverse environment” actions and organizational performance
    - Treatment of portable equipment (FLEX)
    - Model quantification and treatment of uncertainties

Overview of External Flood PRA Process



Elements of an External Flood Hazard Risk Assessment

External Flood Walkdown
Identification of flood access pathways and SSCs subject to damage/failure by external floods and flood associated effects.

Hazard Characterization
Includes Hazard frequency with uncertainty, correlated characteristics (including warning time) and associated effects

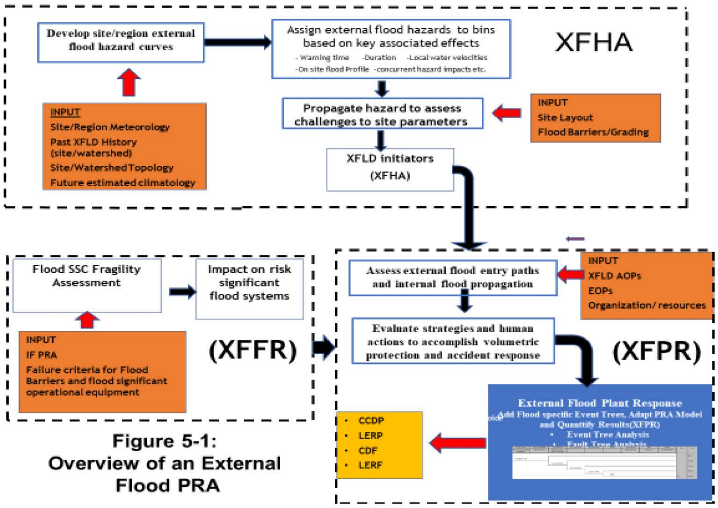
Fragility Analysis
Likelihood flood fails protective barriers and key equipment including flood mitigation SSCs

Accident Sequence Analysis Plant Response
Includes Human Actions to re-configure, respond to and mitigate an event, identification of initiating events, Event Tree development, alternate mission times, Fault tree adjustments to SSCs

External Flood PRA Results

Figure 2-1: Elements of an External Flood PRA

Structure of External Flood PRA Guidance



Develop site/region external flood hazard curves

INPUT
Site/Region Meteorology
Past XFLD History (site/watershed)
Site/Watershed Topology
Future estimated climatology

Assign external flood hazards to bins based on key associated effects
- Warning time -Duration -Local water velocities
-On site flood Profile -concurrent hazard impacts etc.

XFHA

Propagate hazard to assess challenges to site parameters

INPUT
Site Layout
Flood Barriers/Grading

XFLD initiators (XFHA)

Flood SSC Fragility Assessment

Impact on risk significant flood systems

INPUT
IF PRA
Failure criteria for Flood Barriers and flood significant operational equipment

(XFFR)

Assess external flood entry paths and internal flood propagation

INPUT
XFLD AOPs
EOPs
Organization/ resources

Evaluate strategies and human actions to accomplish volumetric protection and accident response

(XFPR)

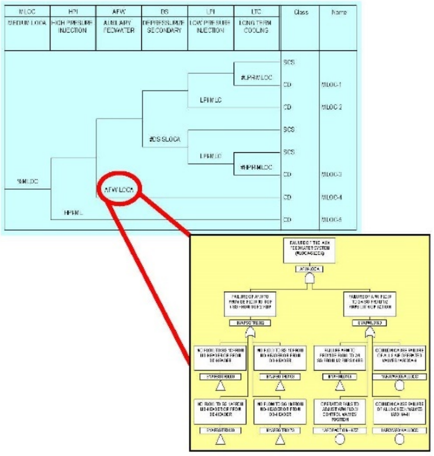
External Flood Plant Response
Add Flood specific Event Trees, Adapt PRA Model and Quantify Results(XFPR)
- Event Tree Analysis
- Fault Tree Analysis

- CCDP
- LERP
- CDF
- LERF

Figure 5-1:
Overview of an External Flood PRA

External Flood Guidance Document

- Document follows structure of ASME/ANS PRA Standard for External Flood PRA (Part 8)
- Guidance Document to includes:
  - Hazard Characterization (XHFA)
  - Fragility Assessment (XFFR)
  - Plant Response and Quantification (XFPR)
  - Example Applications
    - Local Intense Precipitation
    - Storm Surge
    - Riverine Flood

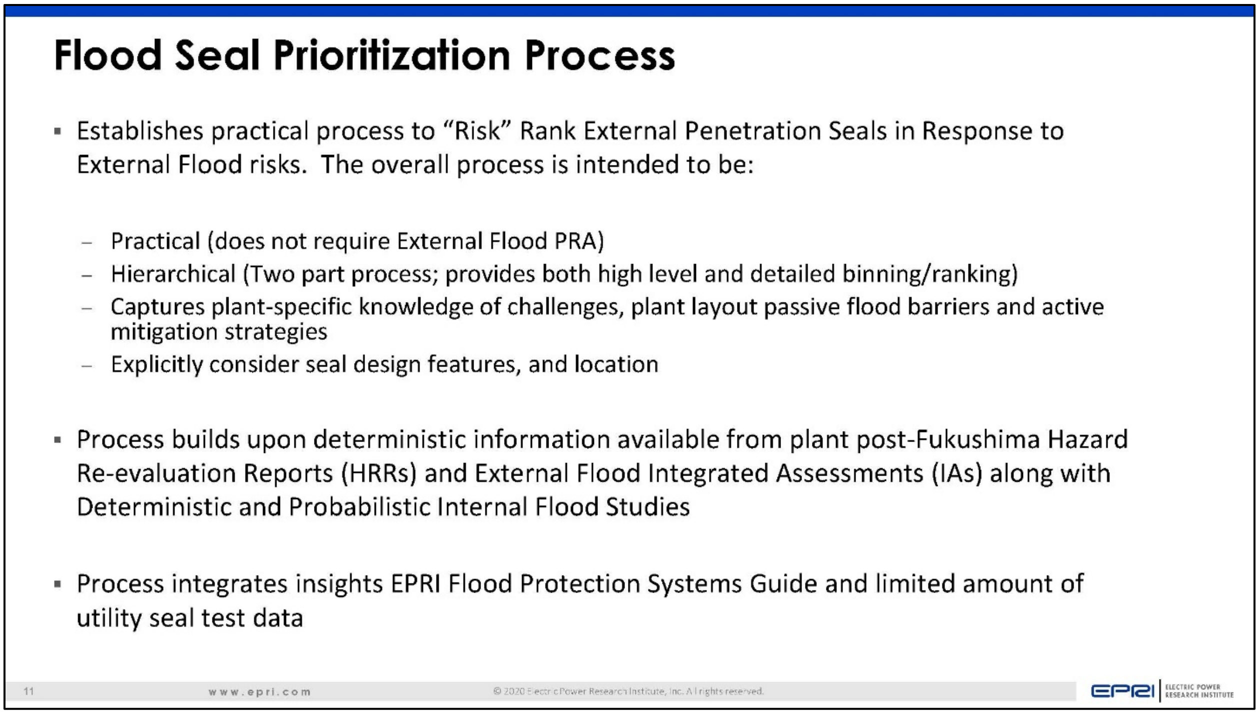


Qualitative Risk Ranking Process of External Flood Penetration Seals

Project Objective

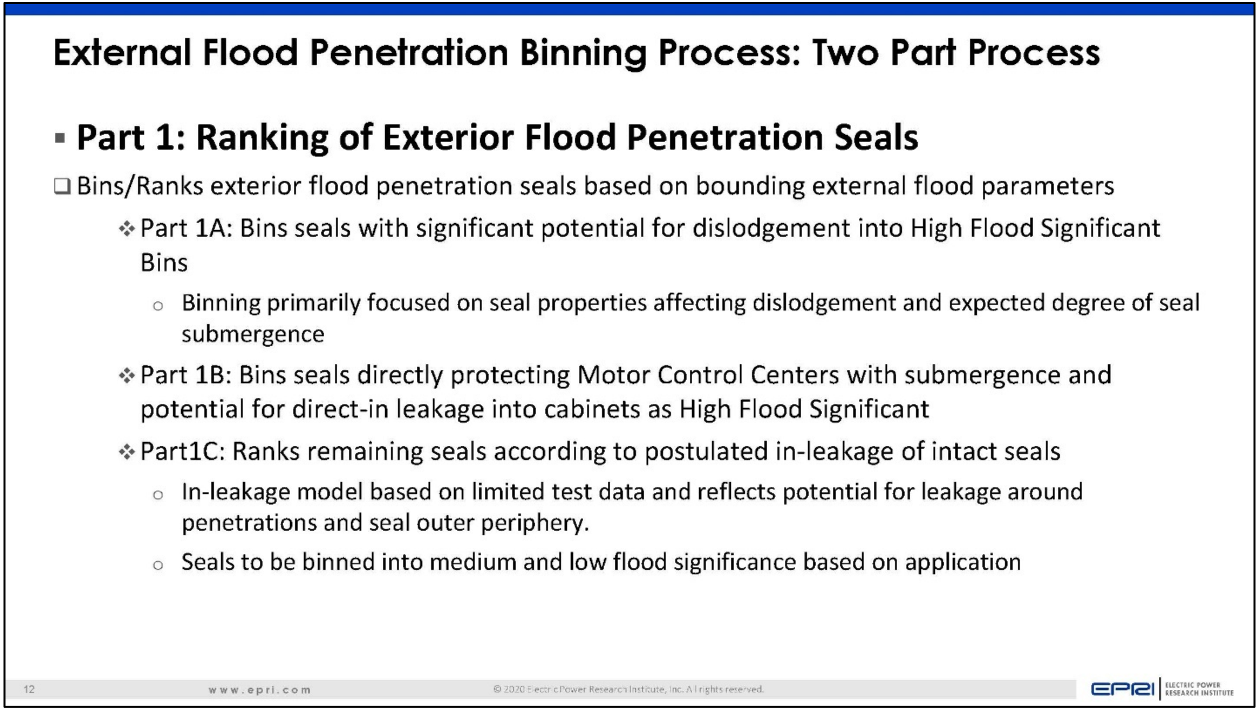
- Develop Risk Informed Strategy to Rank Plant Penetrations based on In-Leakage Potential and Potential contribution to Plant Risk
- Integrates insights from:
  - 3002005423 – Flood Protection Systems Guide
  - 3002010620 - External Flood Protection Design/License Basis Management Best Practices Guide
  - Industry experimental experience with penetration seal performance
- Uses PRA concepts to establish practical risk informed process for categorizing/ranking penetration seal risk significance.

- Focus is on providing utility with a prioritization process for establishing flood significance of penetration seals:
  - Screens low risk seals
  - Identifies seals with high and medium flood significance
- Prioritization process may be used to support seal treatment programs associated with maintenance, inspection, repair and replacement on flood penetration seals.



Flood Seal Prioritization Process

- Establishes practical process to “Risk” Rank External Penetration Seals in Response to External Flood risks. The overall process is intended to be:
  - Practical (does not require External Flood PRA)
  - Hierarchical (Two part process; provides both high level and detailed binning/ranking)
  - Captures plant-specific knowledge of challenges, plant layout passive flood barriers and active mitigation strategies
  - Explicitly consider seal design features, and location
- Process builds upon deterministic information available from plant post-Fukushima Hazard Re-evaluation Reports (HRRs) and External Flood Integrated Assessments (IAs) along with Deterministic and Probabilistic Internal Flood Studies
- Process integrates insights EPRI Flood Protection Systems Guide and limited amount of utility seal test data



External Flood Penetration Binning Process: Two Part Process

- **Part 1: Ranking of Exterior Flood Penetration Seals**

❑ Bins/Ranks exterior flood penetration seals based on bounding external flood parameters

  - ❖ Part 1A: Bins seals with significant potential for dislodgement into High Flood Significant Bins
    - ○ Binning primarily focused on seal properties affecting dislodgement and expected degree of seal submergence
  - ❖ Part 1B: Bins seals directly protecting Motor Control Centers with submergence and potential for direct-in leakage into cabinets as High Flood Significant
  - ❖ Part1C: Ranks remaining seals according to postulated in-leakage of intact seals
    - ○ In-leakage model based on limited test data and reflects potential for leakage around penetrations and seal outer periphery.
    - ○ Seals to be binned into medium and low flood significance based on application

External Flood Penetration Binning Process: Two Part Process

Part 2: Risk Ranking of Flood Penetration Seals

- ❑ Ranking based on potential Risk Impact of Flood Significant Components (FSC)
- ❑ Expands Part 1 binning to include flood relevant interior penetration seals
- ❑ Uses bounding hazard and leakage information generated in Part 1 to assess FSC Flooding
    - ❖ Extends impact assessment to directly Map seals with Flood Significant Components (FSCs) and associated enclosures
    - ❖ Characterizes FSC Water-Induced Failure Conditions
    - ❖ Building–specific flood calculations used to identify submergence potential of internal penetration seals
    - ❖ Room specific volumetric inflows
- ❑ Seals ultimately ranked/binned by their potential impact on FSCs
- ❑ Ranking/ Binning using three bins (H,M, L for flood significance)

Together...Shaping the Future of Electricity

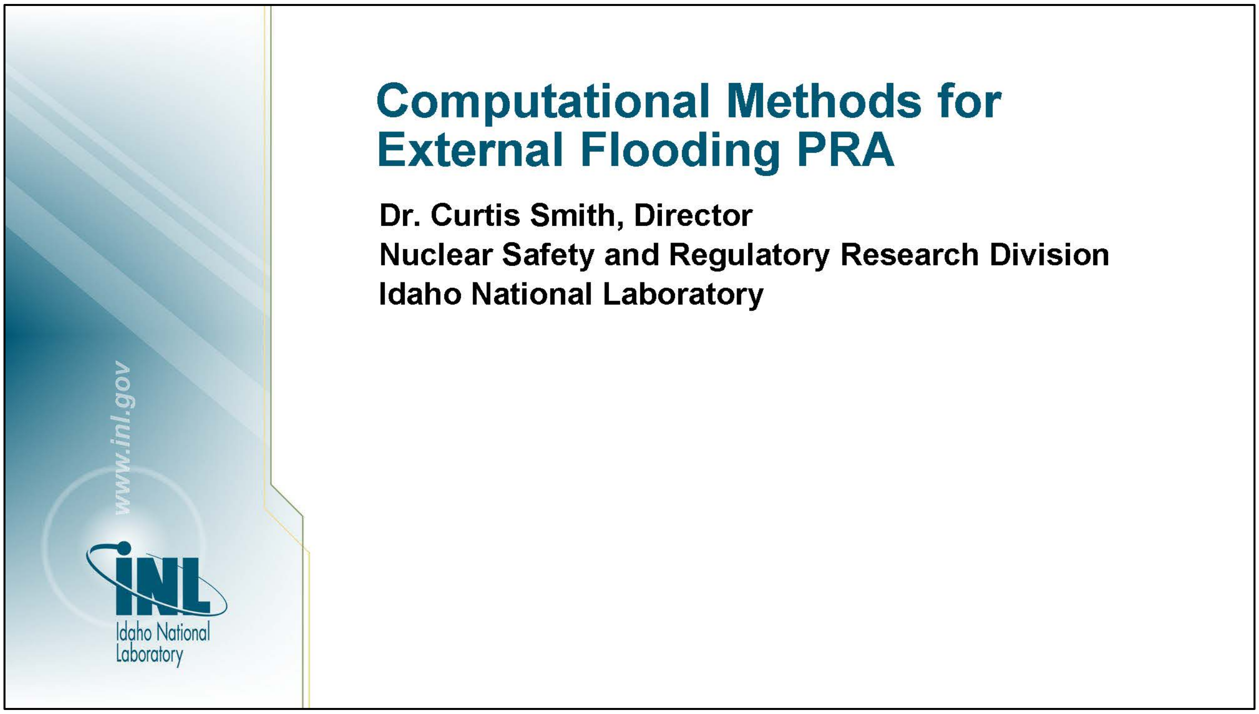
3.10.2 Presentation 3D-2 (KEYNOTE): Computational Methods for External Flooding PRA

Speaker: Curtis L. Smith, Idaho National Laboratory (INL)

3.10.2.1 Abstract

The Idaho National Laboratory is demonstrating next-generation risk-assessment methods and tools that support decision-making by combining physics-based models with probabilistic quantification approaches. Integrating the two worlds of physics and probability using a simulation framework leads us to predictions based upon an approach called “computational risk assessment.” During our external flooding research and development, we have identified four factors that are key to enhanced analysis: temporal (timing issues), spatial (location issues), mechanistic (physics issues), and topological (complexity issues). We will discuss the computational approach for external flooding risk assessment, focusing on these four factors. And, while these newer methods and tools can provide increased realism in our risk approaches, their greater benefit is to provide a risk-informed engineering framework for design and operation.

3.10.2.2 Presentation (ADAMS Accession No. ML20080M167)



Computational Methods for External Flooding PRA

Dr. Curtis Smith, Director
Nuclear Safety and Regulatory Research Division
Idaho National Laboratory

Outline of my talk today

- **Definition of Computational Risk Assessment**
- **Computational resources**
- **Simulating physical phenomena via Smoothed Particle Hydrodynamics**
- **Performing assessment via CRA**

Computational Risk Assessment (CRA)

- **Computational Risk Assessment is a focus of current research and development**
- **CRA is a combination of**
  - Probabilistic (i.e., dynamic) scenario creation where scenarios unfold and are not defined a priori
  - Mechanistic analysis representing physics of the unfolding scenarios
- **CRA relies on the availability of computational tools**
  - Processors (hardware)
  - Methods (software)
- **CRA is not simply solving traditional PRA models faster or with higher precision**
  - It is a different way of thinking about the safety problem

Integrating the worlds of physics and probability leads us to predictions based upon an approach called "computational risk assessment"

CRA driving factors

- **Computers are improving**
- **Software is improving**
  - And much of it is free
- **Analysis characteristics including**

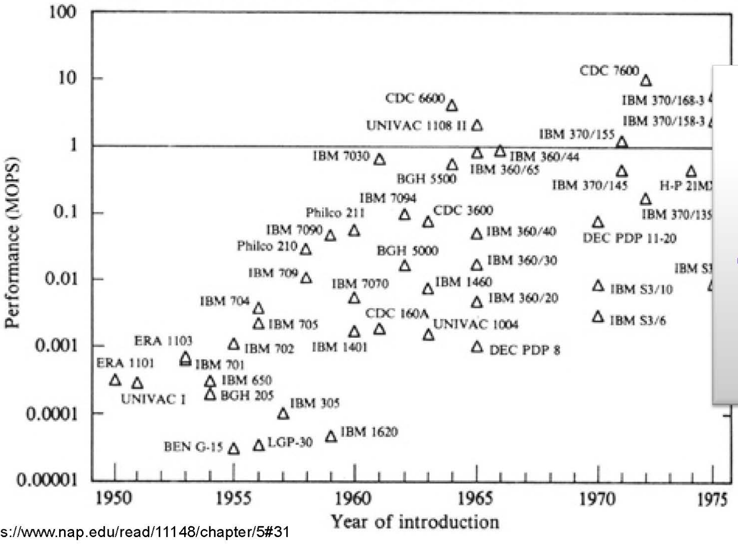
Temporal (timing issues)

Spatial (location issues)

Mechanistic (physics issues)

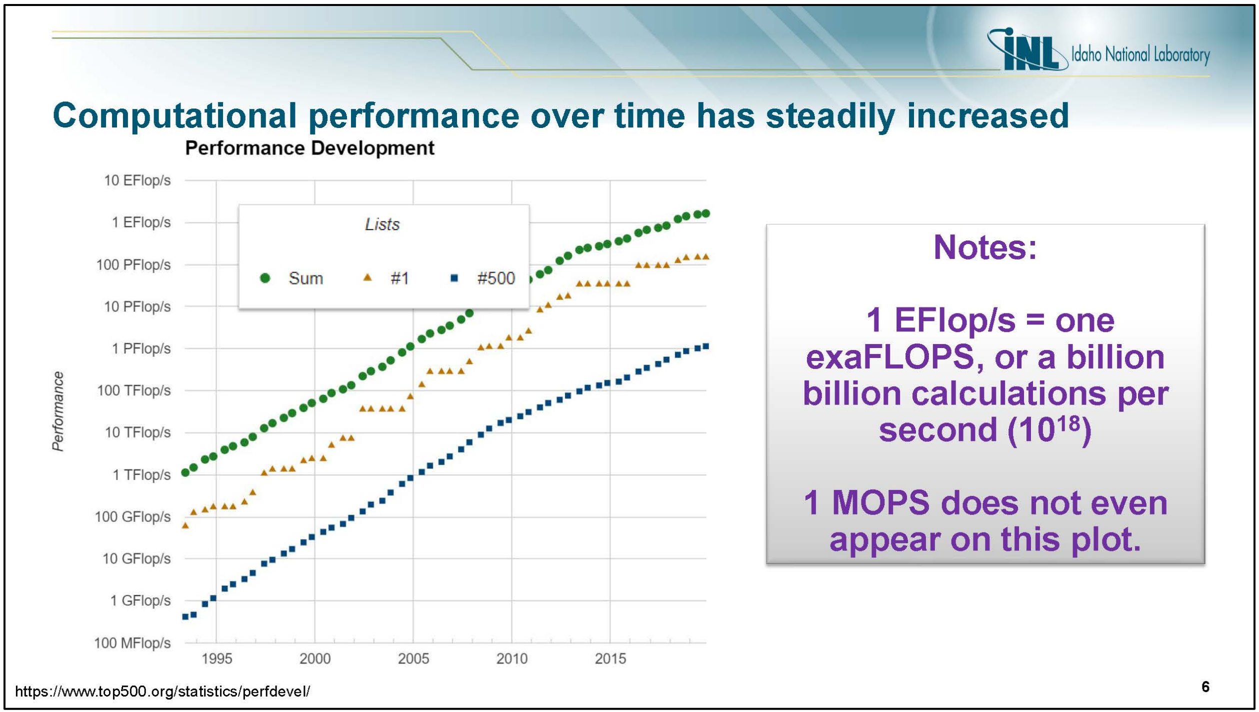
Topology (complexity issues)

Computational performance @ dawn of risk and reliability analysis



MOPS = millions of operations per second

https://www.nap.edu/read/11148/chapter/5#31



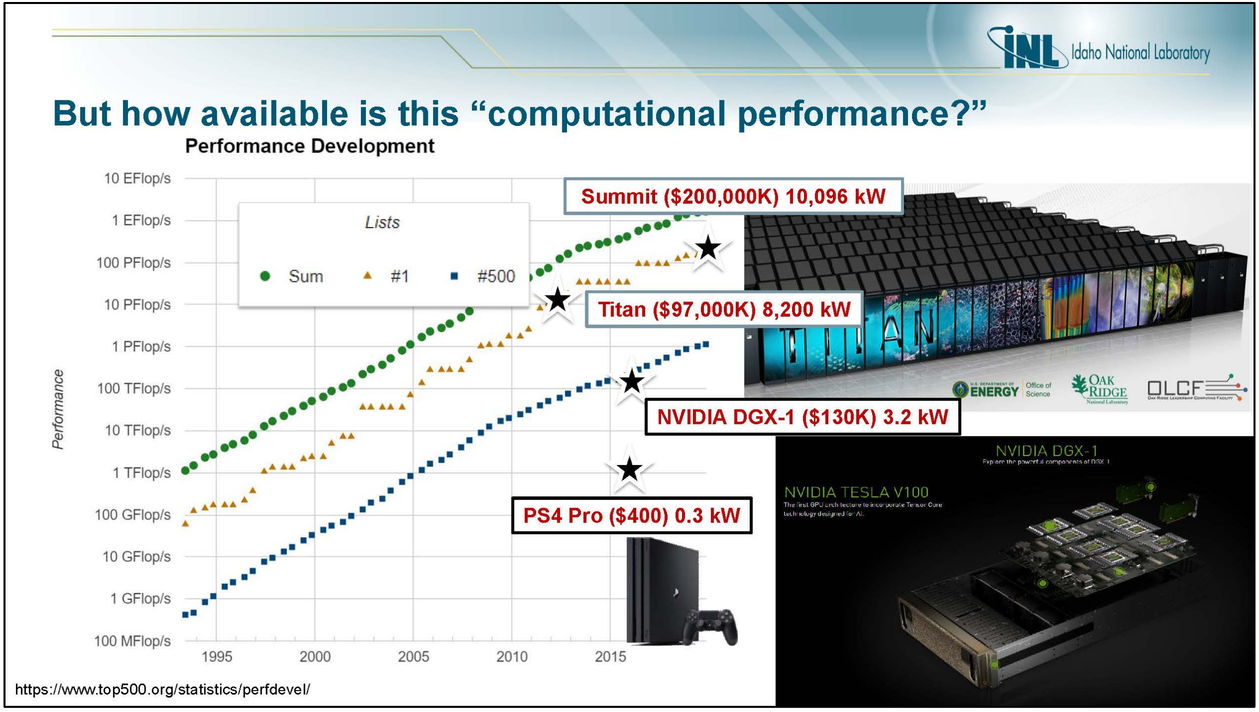
Computational performance over time has steadily increased

Notes:

1 EFlop/s = one exaFLOPS, or a billion billion calculations per second (10^{18})

1 MOPS does not even appear on this plot.

https://www.top500.org/statistics/perfdevel/



But how available is this “computational performance?”

Summit ($200,000K) 10,096 kW

Titan ($97,000K) 8,200 kW

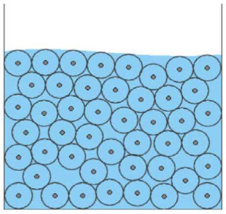
NVIDIA DGX-1 ($130K) 3.2 kW

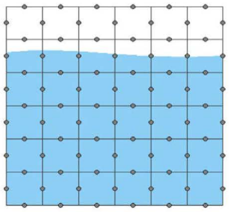
PS4 Pro ($400) 0.3 kW

https://www.top500.org/statistics/perfdevel/

Smoothed Particle Hydrodynamics

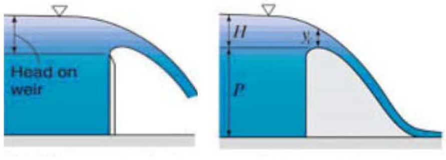
- **A way to simulate flooding scenarios is needed**
- **Smoothed Particle Hydrodynamics (SPH)**
  - Particle based method
  - Originally developed for astrophysics applications in 1977
  - Later extended for fluid dynamic applications
- **SPH allows for flooding scenarios to be simulated**
  - Does not confine fluid to meshes
  - Allows for a natural flow to be modeled
- **A reliable SPH code is needed**
  - Compare to experimental results

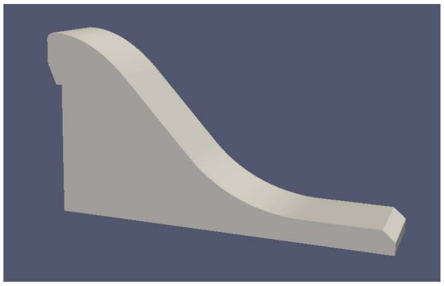




Ogee Spillway Comparison

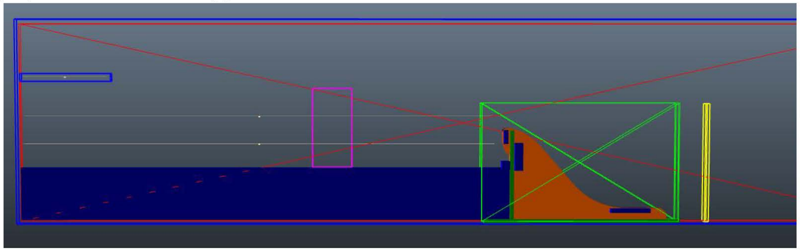
- **Comparison Model**
  - Ogee spillway with horizontal apron
  - Details of experiment provided in Flow over Ogee Spillway: Physical and Numerical Model Case Study by Bruce M. Savage and Michael C. Johnson
  - Experiment details (scaled model):
    - Measurements taken 2 m upstream
      - Flow Rate
      - Total Head
    - Ten different runs conducted
  - Prototype scale was used for the SPH comparison which required scaling the model scale up 30 times





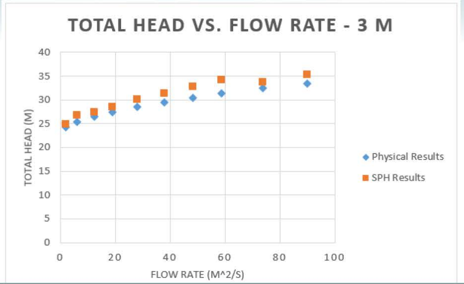
Neutrino Model

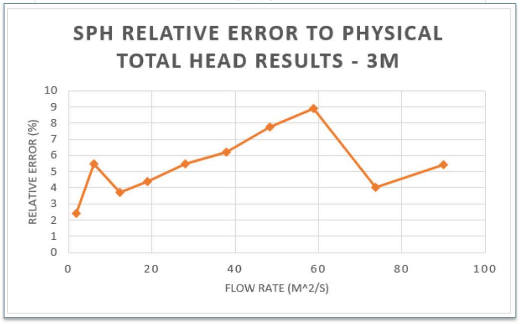
- **Developmental SPH code Neutrino was used to conduct the comparison**
- **Model construction process:**
  - Determine how to fill particles behind the spillway
  - Reduce leakage
  - Determine particle emitter location to set total head
  - Determine particle emitter location to set flow rate instead
  - Conduct parametric studies on model width and particle size
  - Reduce leakage again
  - Change particle emitter types



Comparison Results

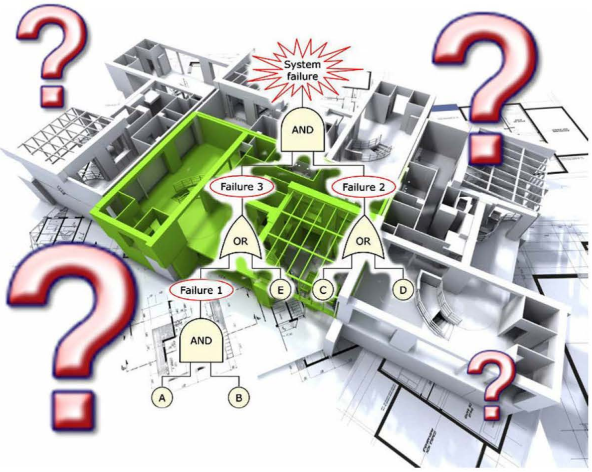
Run	Flow Rate	Physical Total Head Result	SPH Total Head Result	Relative Error
1	1.9 m^2/s ± 0.25%	24.3 m	24.9 m	2.4 %
2	6.0 m^2/s ± 0.25%	25.3 m	26.7 m	5.5 %
3	12.3 m^2/s ± 0.25%	26.5 m	27.5 m	3.7 %
4	19.0 m^2/s ± 0.25%	27.4 m	28.6 m	4.4 %
5	27.9 m^2/s ± 0.25%	28.5 m	30.0 m	5.5 %
6	37.8 m^2/s ± 0.25%	29.5 m	31.3 m	6.2 %
7	48.2 m^2/s ± 0.25%	30.4 m	32.8 m	7.7 %
8	58.9 m^2/s ± 0.25%	31.4 m	34.1 m	8.9 %
9	73.8 m^2/s ± 0.5%	32.4 m	33.7 m	4.0 %
10	89.9 m^2/s ± 0.5%	33.5 m	35.3 m	5.4 %

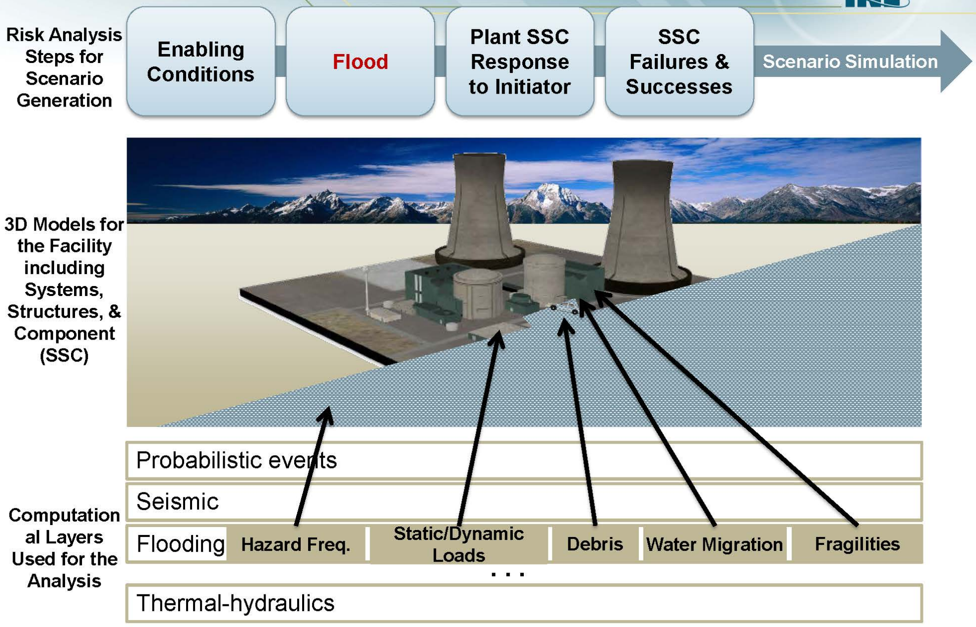




How to Join Physics Model & System Model

- **Good - Run repeated simulations and add the failure information into the existing static models**
- **Better – Dynamic PRA model that can interact with the simulation**
  - No corrections needed for time dependent calculations
  - Determine average or mean time of particular outcomes
  - Analyze time order of failures to determine early protection methods





Risk Analysis Steps for Scenario Generation

Enabling Conditions

Flood

Plant SSC Response to Initiator

SSC Failures & Successes

Scenario Simulation

3D Models for the Facility including Systems, Structures, & Component (SSC)

Computational Layers Used for the Analysis

Probabilistic events

Seismic

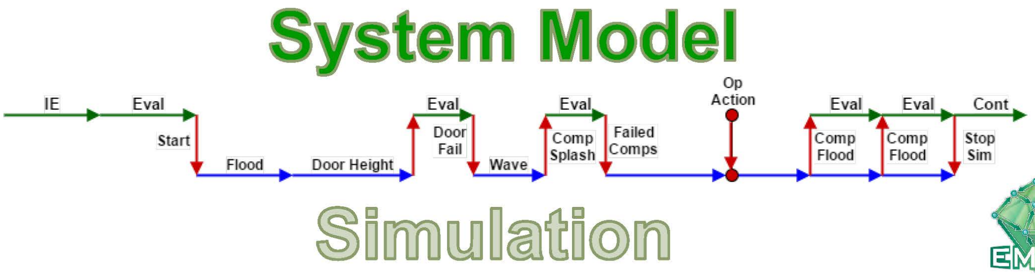
Flooding **Hazard Freq.** **Static/Dynamic Loads** **Debris** **Water Migration** **Fragilities**

. . .

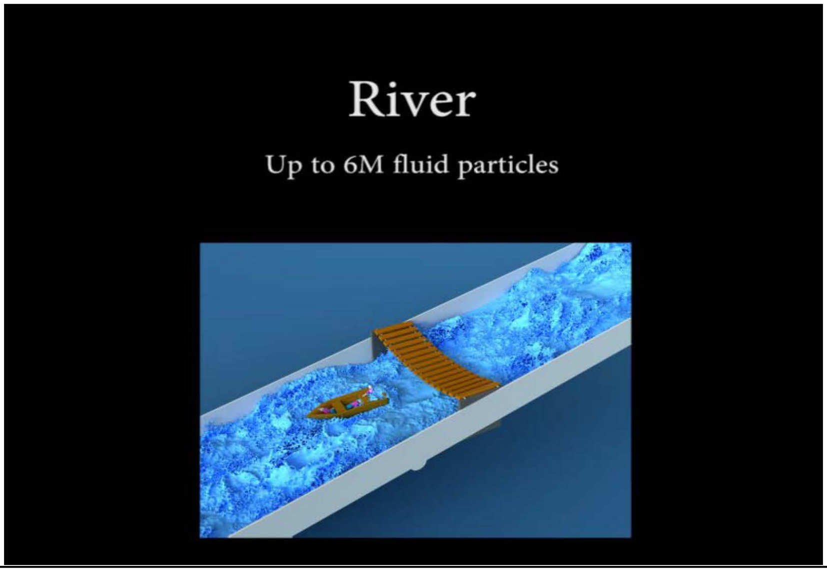
Thermal-hydraulics

Timing is Everything

- Physics simulation are dynamic and time dependent
- Control logic is not always available in simulations
- Need to modify the behavior of the simulation at during execution.

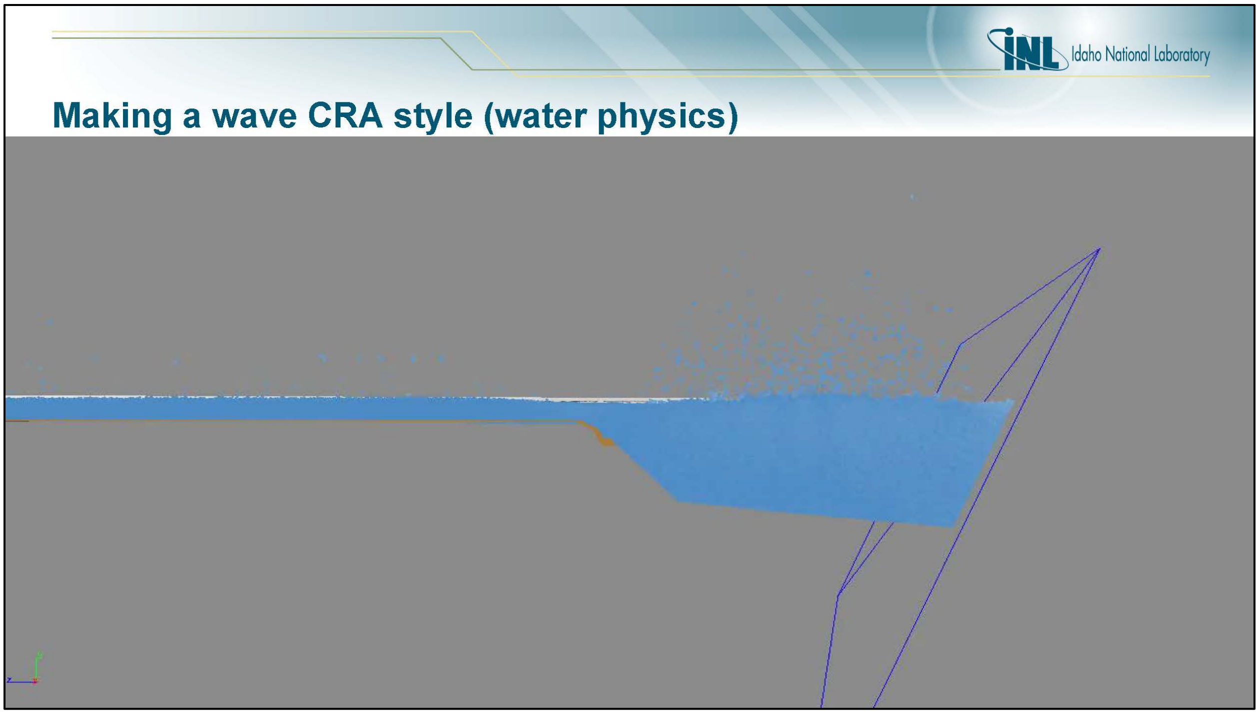


Example of a fluid solver (physics representation)

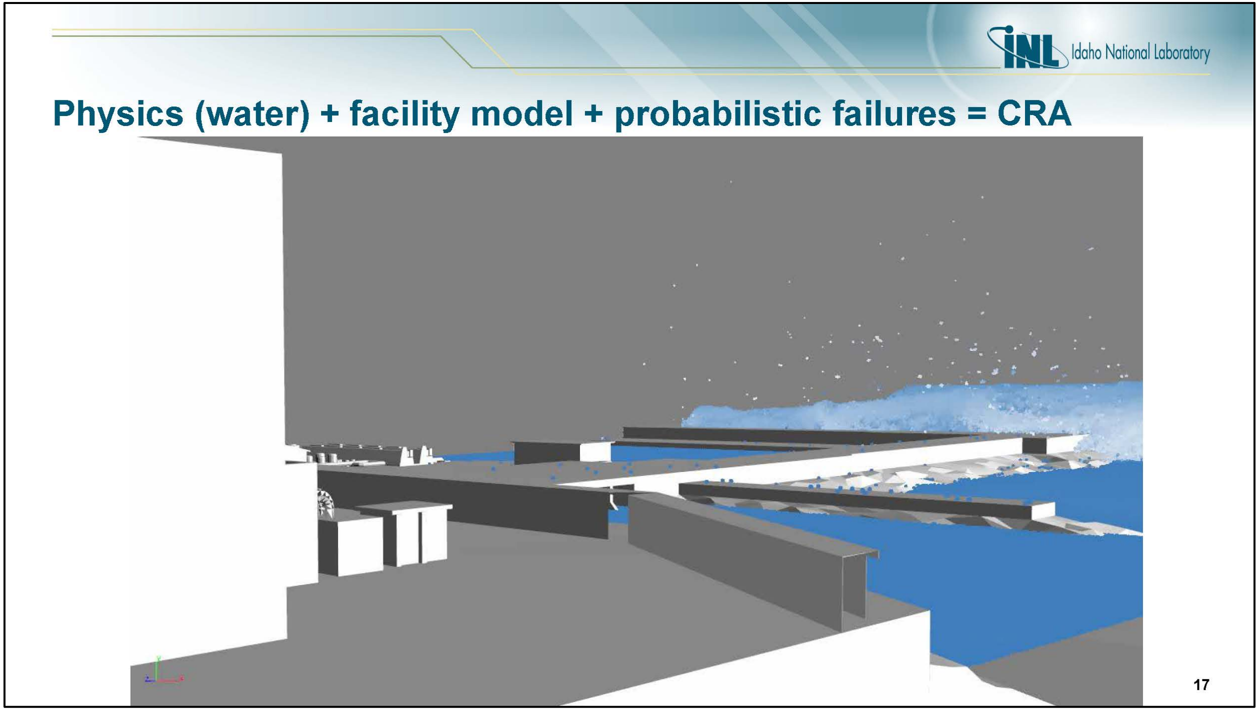


River

Up to 6M fluid particles



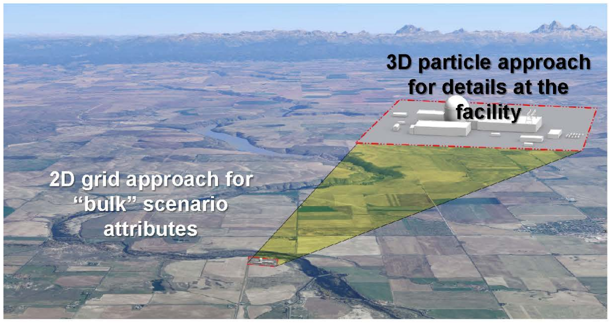
Making a wave CRA style (water physics)

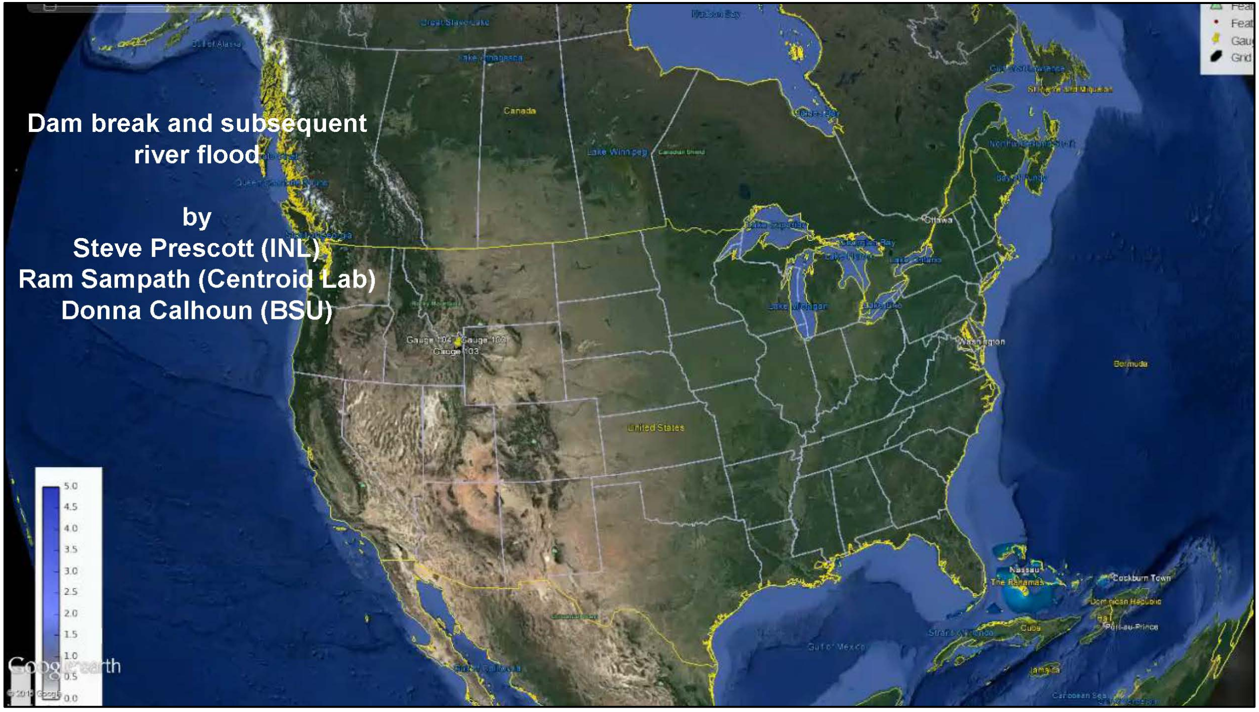


Physics (water) + facility model + probabilistic failures = CRA

River flood modeling

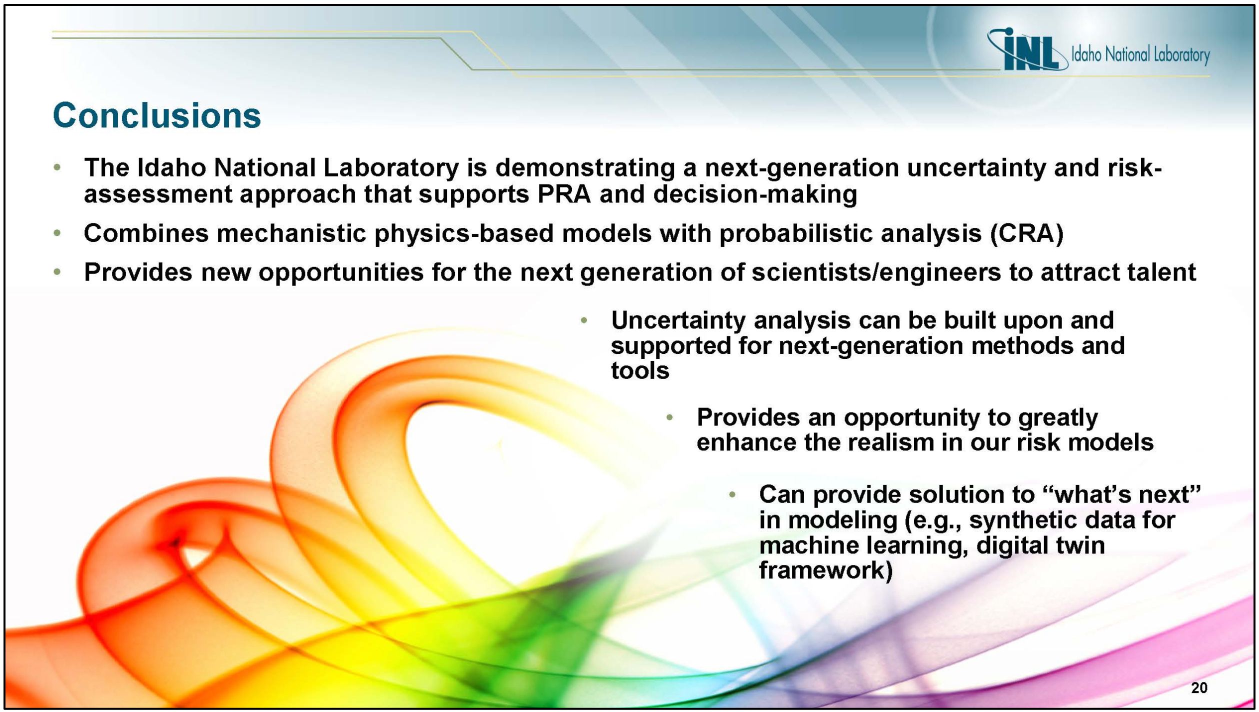
- **INL/EXT-15-37091, Flooding Capability for River-based Scenarios**
- **Evaluated two different types of potential river-based flooding tools**
  - 1D/2D grid based (GeoClaw, EPA’s SWMM code, and Army Corps HEC)
  - 3D particle based
  - Both the 2D and 3D methods have positives and negatives
- **Combination of both seems to be best approach moving forward**





Dam break and subsequent river flood

by
Steve Prescott (INL)
Ram Sampath (Centroid Lab)
Donna Calhoun (BSU)



Conclusions

- The Idaho National Laboratory is demonstrating a next-generation uncertainty and risk-assessment approach that supports PRA and decision-making
- Combines mechanistic physics-based models with probabilistic analysis (CRA)
- Provides new opportunities for the next generation of scientists/engineers to attract talent
  - Uncertainty analysis can be built upon and supported for next-generation methods and tools
    - Provides an opportunity to greatly enhance the realism in our risk models
      - Can provide solution to “what’s next” in modeling (e.g., synthetic data for machine learning, digital twin framework)

Curtis.Smith@inl.gov

Thank you!

3.10.3 Presentation D-3: External Flooding PSA in IRSN – Developments and Insights

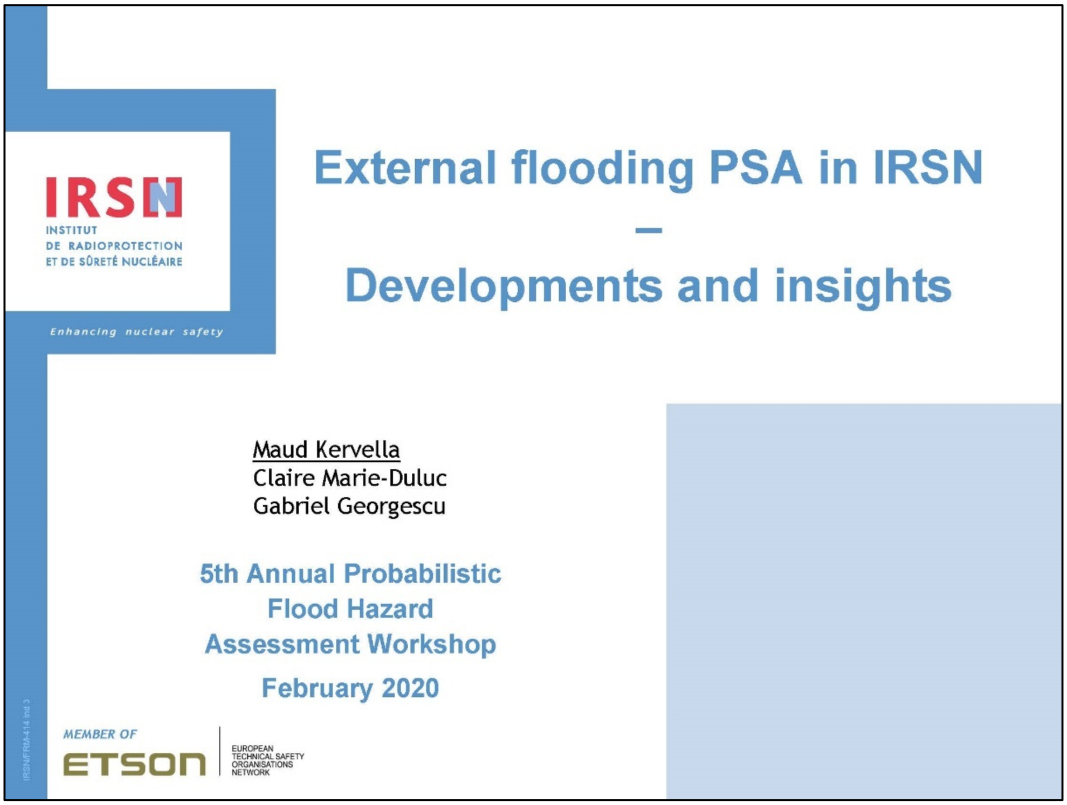
Authors: Maud Kervalla, Gabriel Georgescu, and Claire-Marie Duluc, Institute for Radiological Protection and Nuclear Safety (IRSN, France)

Speaker: Maud Kervalla

3.10.3.1 Abstract

External flooding PSA is a relatively new subject in France. The first studies have been carried out by EDF (French NPPs operator) beginning in 2018. These studies take into account riverine flooding or coastal flooding depending on sites. They have been reviewed by IRSN in the frame of the Periodic Safety Review VD4 900 (review ended in July 2019). On its side, IRSN is developing its own external flooding PSA study, which takes into account coastal flooding for the Gravelines site in France. The followed methodology is similar to EDF's one completed by several aspects, which were also discussed with EDF during the PSA review (like: reliability of flooding protection components, uncertainties on the phenomena studied taken into account, etc.). Aspects linked to HRA are also important in such studies. A working group has been created on IRSN side to discuss possible approaches to quantify the human reliability relevantly. An overview of the IRSN and EDF flooding PSA methodologies and of main insights gained from these studies will be given in the presentation.

3.10.3.2 Presentation (ADAMS Accession No. ML20080M168)



IRSN
INSTITUT
DE RADIOPROTECTION
ET DE SÛRETÉ NUCLÉAIRE

Enhancing nuclear safety

External flooding PSA in IRSN
–
Developments and insights

Maud Kervella
Claire Marie-Duluc
Gabriel Georgescu

5th Annual Probabilistic
Flood Hazard
Assessment Workshop

February 2020

IRSN/FRM-414 ind 3

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Contents

- History/Background
- Specifics of the French context
- External flooding PSA
- Methodology
- Conclusions and Insights
- IRSN PSA developments

History/Background

History/Background

- In France, the safety case relies mainly on deterministic bases
- For French operating plants, PSA was not a regulatory requirement and compliance with probabilistic safety goals was not required
- However France has acquired a valuable experience in development and use of PSAs
- The probabilistic approach takes an important place in the safety decisions: PSAs are considered as useful for improving safety

History/Background

- Order of 7 February 2012 setting the general rules relative to basic nuclear installations:

→ *“The nuclear safety demonstration shall also include probabilistic analyses of accidents and their consequences, unless the licensee demonstrates that this is irrelevant”*

→ No quantified probabilistic objectives

Specifics of the French context

Specifics of the French context

- A rather large fleet of Nuclear Power Plants (NPPs): 58 in operation
- Standardized in 3 PWR series (900MWe, 1300MWe,1400MWe)
- Built by the same manufacturer (Framatome)
- Operated by the same licensee (Electricité de France: EDF)

→ Favorable situation for data collection

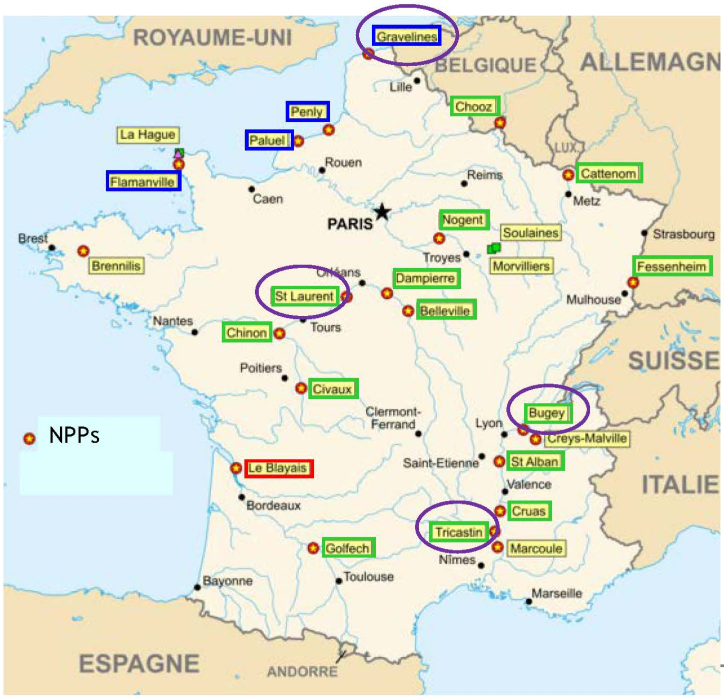
Specifics of the French context

- At the request of the Safety Authority (ASN), IRSN reviews the PSA studies provided by EDF
- In addition, IRSN develops its own PSA:
  - Valuable knowledge
  - Independent analyses from EDF PSAs
  - Possibility to perform sensitivity analyses

External flooding PSA

External flooding PSA

- External flooding PSA is a relatively new subject in France
- First studies (4 PSA studies: coastal or riverine flooding) carried out by EDF around 2018
- IRSN reviewed EDF's studies in the frame of the Periodic Safety Review of 900 MWe plants (review ended in July 2019)
- IRSN is also developing its own external flooding PSA for Gravelines site (900 MWe) → coastal flooding study (simplified) which will be finalized by the end of 2020



NPPs location:

🟩 14 river NPPs

🟦 4 sea side NPPs

🟥 1 estuary NPP

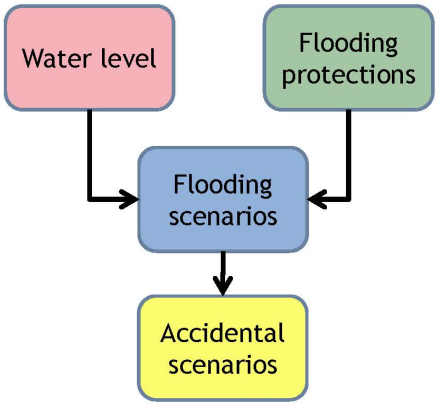
○ Ext Flood PSA (EDF)

Methodology

Methodology

- Similar flooding PSA methodology followed by EDF and IRSN → The methodology is applicable for coastal or riverine flooding PSA
- Example for coastal flooding → applied to Gravelines site

Applied approach



Water level

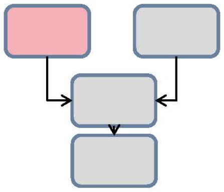
Flooding protections

Flooding scenarios

Accidental scenarios

Methodology

➚ water level



- Built of a curve “water level / frequency” by convolution between probability density of sea tides and probability density of storm surges
- Water levels of interest for PSA studies are those corresponding to the overtake or by-pass of protections against external flooding

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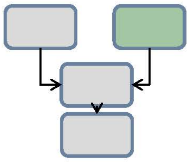
Methodology

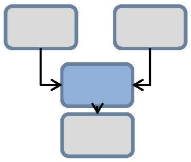
➚ Flooding protections



- Material protections
  - Peripheral protections (dams/dikes, walls)
  - Volumetric protection (all that is part of the external buildings envelope)
  - Building nearby protections (lower or higher protections, cofferdam type)
- Preventive human actions necessary to set up protections (cofferdams, closing of possible by-pass paths…)
  - →The success of these actions depends on the site alert system
  - →The failure of these actions induces external flooding scenarios for water levels lower than those overtaken the protections

Methodology

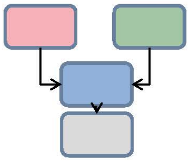
Flooding scenarios



- Flooding scenarios are built for each relevant water level, by studying their consequences on the installation, and by taking into account the role of protections
  - Equipment vulnerable to flooding failures (electrical transformer, heat sink, diesels, post-Fukushima materials…)
  - Initiators occurrence or situations which are taken into account in « internal event » PSA (such as the loss of heat sink, loss of off-site power, etc.)

Methodology

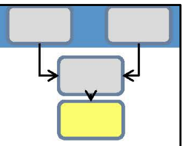
Quantification of flooding scenarios



- Quantification of each of the flooding scenarios
  - Use of curves « water level / frequency »
  - Assessment of protections failure (human error probability to set up protections or SSC failure)

Frequency of initiating events of accidental scenarios

Methodology



➚ Quantification of accidental scenarios (core damage frequency and frequency to uncover fuel assemblies in the Spent Fuel Pool)

- Quantification carried out by modifying the « internal events » PSA model
  - Frequency of initiating events (frequency of flooding scenarios)
  - Equipment vulnerable to flooding are considered failed
  - Probability of failure of human post-accidental missions taking into account the flooding context
  - Post-Fukushima materials are considered
  - Fast Action Force (FARN) is considered

- The analysis considers that the flooding affects the whole site
  - Unavailability of shared equipment
  - Impact on human factor

Conclusions and Insights

Conclusions and Insights

- IRSN review :
  - Important work carried out by EDF
  - The approach is satisfying even if simplified
  - These results highlight the importance of Post-Fukushima means and intervention of the Fast Nuclear Action Force (FARN)

→ No additional NPP modifications necessary

Conclusions and Insights

- Methodological improvement identified by IRSN :
  - Systematic evaluation of the reliability of materials → taking also into account the available operating experience
  - Evaluation of the reliability of site alert systems
  - Assessment of the uncertainties related to the hazard evaluation (couples water level / occurrence frequencies)
  - Consideration of combinations of phenomena → for example, waves are not taken into account for the sea flooding

- Regarding the human factor evaluation, EDF used a method derived from pre-accidental human errors evaluation methods → acceptable as a first approach

IRSN PSA developments

IRSN PSA developments

➚ Ongoing study for Gravelines site

- The approach followed by IRSN is similar with EDF approach, but:
  - Reliability of materials is quantified (when possible)
  - Uncertainties on the phenomenon studied are taken into account
  - More external flooding scenarios have been taken into account

- IRSN study pointed-out some aspects related to post-Fukushima protections under implementation → discussions with EDF ongoing

IRSN PSA developments

➚ Future developments

- PSA for a 1300 MWe NPP site
- Riverine flooding hazard assessment
- Sensitivity studies on the alert system reliability
- Human factor assessment → working group created at IRSN (first meeting in December 2019) to develop new HRA methods: One of the subjects will be HRA for external events PSA including flooding → need for HRA method to take into account:
    - Hazard worsened conditions (Local actions, degraded environment, Actions in multi unit accident context…)
    - Crisis organization
    - Specific hazard procedures
    - FARN…

Thank You !

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5 SUMMARY AND CONCLUSIONS

5.1 Summary

This report includes the agenda and presentations for the Fifth NRC Annual PFHA Research Workshop, including all presentation abstracts and slides and abstracts for submitted posters. The workshop was 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 workshops included have industry groups, industry members, consultants, independent laboratories, academic institutions, and the press.

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) 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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