PROCEEDINGS OF NRC ANNUAL PROBABILISTIC FLOOD HAZARD ASSESSMENT RESEARCH WORKSHOPS I-IV

2015–2019
Rockville, MD

Date Published: February 2020

Prepared by:
M. Carr
T. Aird
J. Kanney

U.S Nuclear Regulatory Commission
Rockville, MD 20852

Part 3: Third Annual NRC Probabilistic Flood Hazard Assessment Research Workshop

Research Information Letter
Research Office of Nuclear Regulatory Research
Disclaimer

Legally binding regulatory requirements are stated only in laws, NRC regulations, licenses, including technical specifications, or orders; not in Research Information Letters (RILs). A RIL is not regulatory guidance, although NRC’s regulatory offices may consider the information in a RIL to determine whether any regulatory actions are warranted.
The U.S. Nuclear Regulatory Commission (NRC) Office of Nuclear Regulatory Research (RES) is conducting a multiyear, multi-project Probabilistic Flood Hazard Assessment (PFHA) Research Program to enhance the NRC’s risk-informed and performance-based regulatory approach with regard to external flood hazard assessment and safety consequences of external flooding events at nuclear power plants (NPPs). 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. Risk assessment of flooding hazards and consequences of flooding events is a recognized gap in NRC’s risk-informed, performance-based regulatory framework. The objective, research themes, and specific research topics are described in the RES Probabilistic Flood Hazard Assessment Research Plan. While the technical basis research, pilot studies and guidance development are ongoing, RES has been presenting 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, as well as interagency and international collaborators and industry and public representatives.

These conference proceedings transmit the agenda, abstracts, presentation slides, summarized questions and answers, and panel discussion for the first four Annual U.S. Nuclear Regulatory Commission (NRC) Probabilistic Flood Hazard Assessment Research Workshops held at NRC Headquarters in Rockville, MD. The workshops took place on October 14–15, 2015; January 23–25, 2017; December 4–5, 2017; and April 30–May 2, 2019. The first workshop was an internal meeting attended by NRC staff, contractors, and partner Federal agencies. The following workshops were public meetings and attended by members of the public; NRC technical staff, management, and contractors; and staff from other Federal agencies. All of the workshops began with an introductory session that included perspectives and research program highlights from the NRC Office of Nuclear Regulatory Research and also may have included perspectives from the NRC Office of New Reactors and Office of Nuclear Reactor Regulation, the Electric Power Research Institute (EPRI), and industry representatives. NRC and EPRI contractors and staff as well as invited Federal and public speakers gave technical presentations and participated in various styles of panel discussion. Later workshops included poster sessions and participation from academic and interested students. The workshops included five focus areas:

1. leveraging available flood information
2. evaluating the application of improved mechanistic and climate probabilistic modeling for storm surge, climate and precipitation
3. probabilistic flood hazard assessment frameworks
4. potential impacts of dynamic and nonstationary processes
5. assessing the reliability of flood protection and plant response to flooding events
# TABLE OF CONTENTS

| ABSTRACT | ................................................................. | III |
| ABBREVIATION AND ACRONYMS | ................................................................. | X |
| INTRODUCTION | ................................................................. | XXXVII |
| BACKGROUND | ................................................................. | XXXVII |
| WORKSHOP OBJECTIVES | ................................................................. | XXXVII |
| WORKSHOP SCOPE | ................................................................. | XXXVIII |
| SUMMARY OF PROCEEDINGS | ................................................................. | XXXVIII |
| RELATED WORKSHOPS | ................................................................. | XXXIX |

## 1 FIRST ANNUAL NRC PROBABILISTIC FLOOD HAZARD ASSESSMENT RESEARCH WORKSHOP

### 1.1 INTRODUCTION

#### 1.1.1 Organization of Conference Proceedings

### 1.2 WORKSHOP AGENDA

#### 1.3 PROCEEDINGS

##### 1.3.1 Day 1: Session I: Program Overview

1.3.1.1 Opening Remarks...

1.3.1.2 NRC PFHA Research Program Overview...

1.3.1.3 NRO Perspectives on Flooding Research Needs...

1.3.1.4 Office of Nuclear Reactor Regulation Perspectives on Flooding Research Needs...

##### 1.3.2 Day 1: Session II: Climate

1.3.2.1 Regional Climate Change Projections—Potential Impacts to Nuclear Facilities...

##### 1.3.3 Day 1: Session III: Precipitation

1.3.3.1 Estimating Precipitation—Frequency Relationships in Orographic Regions...

1.3.3.2 Numerical Simulation of Local Intense Precipitation...

1.3.3.3 SHAC-F (Local Intense precipitation)...

##### 1.3.4 Day 2: Session IV: Riverine and Coastal Flooding Processes

1.3.4.1 PFHA Technical Basis for Riverine Flooding...

1.3.4.2 PFHA Framework for Riverine Flooding...

1.3.4.3 State of Practice in Flood Frequency Analysis...

1.3.4.4 Quantification and Propagation of Uncertainty in Probabilistic Storm Surge Models...

1.3.4.5 USBR Dam Breach Physical Modeling...

##### 1.3.5 Day 2: Session V: Plant Response to Flooding Events

1.3.5.1 Effects of Environmental Factors on Flood Protection and Mitigation Manual Actions...

1.3.5.2 Flooding Information Digests...

1.3.5.3 Framework for Modeling Total Plant Response to Flooding Events...

1.3.5.4 Performance of Penetration Seals...

### 1.4 SUMMARY

### 1.5 WORKSHOP PARTICIPANTS

## 2 SECOND ANNUAL NRC PROBABILISTIC FLOOD HAZARD ASSESSMENT RESEARCH WORKSHOP

...
2.1 INTRODUCTION ........................................................................................................................................ 2-1
  2.1.1 Organization of Conference Proceedings .......................................................................................... 2-1

2.2 WORKSHOP AGENDA ................................................................................................................................. 2-3

2.3 PROCEEDINGS ........................................................................................................................................... 2-7
  2.3.1 Day 1: Session 1A - Introduction ......................................................................................................... 2-7
  2.3.1.1 Welcome ........................................................................................................................................ 2-7
  2.3.1.2 PFHA Research Needs for New and Operating Reactors .............................................................. 2-12
  2.3.1.3 Use of Flooding Hazard Information in Risk-Informed Decision-making .................................. 2-22
  2.3.1.4 Flooding Research Needs: Industry Perspectives on Development of External Flood Frequency Methods .................................................................................................................. 2-30
  2.3.1.5 NRC Flooding Research Program Overview ............................................................................... 2-38
  2.3.1.6 EPRI Flooding Research Program Overview ............................................................................. 2-46
  2.3.2 Day 1: Session 1B - Storm Surge Research ....................................................................................... 2-50
  2.3.2.1 Quantification of Uncertainty in Probabilistic Storm Surge Models .......................................... 2-50
  2.3.2.2 Probabilistic Flood Hazard Assessment—Storm Surge ............................................................... 2-75
  2.3.3 Day 1: Session 1B - Storm Surge Research ....................................................................................... 2-50
  2.3.3.1 Welcome ...................................................................................................................................... 2-50
  2.3.3.2 Probabilistic Flood Hazard Assessment—Storm Surge ............................................................... 2-75
  2.3.3.3 Extreme Precipitation Frequency Estimates for Orographic Regions ........................................ 2-98
  2.3.3.4 Local Intense Precipitation Frequency Studies ......................................................................... 2-165
  2.3.4 Day 1: Session 1B - Storm Surge Research ....................................................................................... 2-50
  2.3.4.1 Regional Climate Change Projections: Potential Impacts to Nuclear Facilities ......................... 2-85
  2.3.4.2 At-Streamgage Flood Frequency Analyses for Very Low Annual Exceedance Probabilities from a Perspective of Multiple Distributions and Parameter Estimation Methods ...................................................... 2-184
  2.3.4.3 Extending Frequency Analysis beyond Current Consensus Limits ............................................ 2-199
  2.3.5 Day 2: Session 2A - Climate and Precipitation ................................................................................. 2-213
  2.3.5.1 Collection of Paleoflood Evidence .............................................................................................. 2-213
  2.3.5.2 Paleofloods on the Tennessee River—Assessing the Feasibility of Employing Geologic Records of Past Floods for Improved Flood Frequency Analysis .............................................................................. 2-224
  2.3.6 Day 2: Session 2B - Leveraging Available Flood Information I ....................................................... 2-243
  2.3.6.1 EPRI Flood Protection Project Status .......................................................................................... 2-243
  2.3.6.2 Performance of Flood-Rated Penetration Seals ........................................................................ 2-256
  2.3.7 Day 2: Daily Wrap-Up Question and Answer Period ........................................................................ 2-266
  2.3.8 Day 3: Session 3A - Reliability of Flood Protection and Plant Response II ..................................... 2-267
  2.3.8.1 Effects of Environmental Factors on Manual Actions for Flood Protection and Mitigation at Nuclear Power Plants ........................................................................................................................................ 2-267
  2.3.8.2 Modeling Total Plant Response to Flooding Event ..................................................................... 2-284
  2.3.9 Day 3: Session 3B - Frameworks I .................................................................................................... 2-303
  2.3.9.1 Technical Basis for Probabilistic Flood Hazard Assessment ...................................................... 2-303
  2.3.10 Day 3: Session 3C - Frameworks II ................................................................................................. 2-318
  2.3.10.1 Evaluation of Deterministic Approaches to Characterizing Flood Hazards ............................. 2-318
  2.3.10.2 Probabilistic Flood Hazard Assessment Framework Development ....................................... 2-334
  2.3.10.3 Riverine Flooding and Structured Hazard Assessment Committee Process for Flooding (SHAC-F) ........................................................................................................................................ 2-349
  2.3.11 Day 3: Session 3D - Panel Discussion ............................................................................................... 2-367
  2.3.11.1 National Oceanic and Atmospheric Administration/National Weather Service (NOAA/NWS) ........................................................................................................................................ 2-367
  2.3.11.2 U.S. Army Corps of Engineers .................................................................................................. 2-370
  2.3.11.3 Tennessee Valley Authority (TVA) .............................................................................................. 2-375
  2.3.11.4 U.S. Department of Energy (DOE) ............................................................................................. 2-387
  2.3.11.5 Institut de Radioprotection et de Sûreté Nucléaire ................................................................. 2-391
3 THIRD ANNUAL NRC PROBABILISTIC FLOOD HAZARD ASSESSMENT RESEARCH WORKSHOP .......................................................... 3-1

3.1 INTRODUCTION ........................................................................................................................................... 3-1
  3.1.1 Organization of Conference Proceedings .................................................................................. 3-1

3.2 WORKSHOP AGENDA .................................................................................................................................. 3-3

3.3 PROCEEDINGS ............................................................................................................................................... 3-9
  3.3.1 Day 1: Session 1A - Introduction ................................................................................................................. 3-9
    3.3.1.1 Welcome .............................................................................................................................................. 3-9
    3.3.1.2 NRC Flooding Research Program Overview .................................................................................. 3-11
    3.3.1.3 EPRI Flooding Research Program Overview .................................................................................. 3-20
  3.3.2 Day 1: Session 1B - Climate and Precipitation ...................................................................................... 3-29
    3.3.2.1 Regional Climate Change Projections: Potential Impacts to Nuclear Facilities ............................ 3-29
    3.3.2.2 Numerical Modeling of Local Intense Precipitation Processes .................................................... 3-42
    3.3.2.3 Research on Extreme Precipitation Estimates in Orographic Regions ........................................... 3-70
  3.3.3 Day 1: Session 1C - Storm Surge .................................................................................................................. 3-94
    3.3.3.1 Quantification of Uncertainty in Probabilistic Storm Surge Models ............................................ 3-94
    3.3.3.2 Probabilistic Flood Hazard Assessment – Storm Surge ................................................................. 3-109
  3.3.4 Day 1: Session 1D - Leveraging Available Flood Information I ............................................................. 3-116
    3.3.4.1 Flood Frequency Analyses for Very Low Annual Exceedance Probabilities using Historic and Paleoflood Data, with Considerations for Nonstationary Systems ........................................... 3-116
    3.3.4.2 Extending Frequency Analysis beyond Current Consensus Limits .............................................. 3-135
    3.3.4.3 Development of External Hazard Information Digests for Operating NPP sites ......................... 3-149
  3.3.5 Day 1: Session 1E - Paleoflood Studies ...................................................................................................... 3-163
    3.3.5.1 Improving Flood Frequency Analysis with a Multi-Millennial Record of Extreme Floods on the Tennessee River near Chattanooga .......................................................... 3-163
    3.3.5.2 Collection of Paleoflood Evidence .................................................................................................. 3-179
  3.3.6 Day 2: Daily Wrap-up Session / Public Comments .................................................................................. 3-191
  3.3.7 Day 2: Poster Session .................................................................................................................................. 3-195
    3.3.7.1 Poster Abstracts ................................................................................................................................. 3-195
    3.3.7.2 Posters .............................................................................................................................................. 3-200
  3.3.8 Day 2: Session 2A - Reliability of Flood Protection and Plant Response I ........................................... 3-227
    3.3.8.1 Performance of Flood- Rated Penetration Seals ............................................................................. 3-227
    3.3.8.2 EPRI Flood Protection Project Status ............................................................................................. 3-234
    3.3.8.3 A Conceptual Framework to Assess Impacts of Environmental Conditions on Manual Actions for Flood Protection and Mitigation at Nuclear Power Plants ........................................ 3-240
    3.3.8.4 External Flooding Walkdown Guidance ......................................................................................... 3-250
    3.3.8.5 Erosion Testing of Zoned Rockfill Embankments ........................................................................ 3-258
  3.3.9 Day 2: Session 2B - Frameworks I ................................................................................................................ 3-295
    3.3.9.1 A Framework for Inland Probabilistic Flood Hazard Assessments: Analysis of Extreme Snow Water Equivalent in Central New Hampshire ......................................................... 3-295
    3.3.9.2 Structured Hazard Assessment Committee Process for Flooding (SHAC-F) for Riverine Flooding .............................................................................................................................................. 3-304
4 FOURTH ANNUAL NRC PROBABILISTIC FLOOD HAZARD ASSESSMENT RESEARCH WORKSHOP ................................................................. 4-1

4.1 INTRODUCTION .................................................................................................................. 4-1

4.1.1 Organization of Conference Proceedings ................................................................. 4-1

4.2 WORKSHOP AGENDA ...................................................................................................... 4-2

4.3 PROCEEDINGS .................................................................................................................. 4-9

4.3.1 Day 1: Session 1A - Introduction .................................................................................. 4-9

4.3.1.1 Introduction ........................................................................................................... 4-9

4.3.1.2 NRC Flooding Research Program Overview ....................................................... 4-12

4.3.1.3 EPRI External Flooding Research Program Overview ....................................... 4-23

4.3.1.4 Nuclear Energy Agency, Committee on the Safety of Nuclear Installations (CSNI): Working Group on External Events (WGEV) ............................................................................................ 4-28

4.3.2 Day 1: Session 1B - Coastal Flooding ......................................................................... 4-33

4.3.2.1 KEYNOTE: National Weather Service Storm Surge Ensemble Guidance .......... 4-33

4.3.2.2 Advancements in Probabilistic Storm Surge Models and Uncertainty Quantification Using Gaussian Process Metamodelling .............................................................................. 4-56

4.3.2.3 Probabilistic Flood Hazard Assessment Using the Joint Probability Method for Hurricane Storm Surge .................................................................................................................. 4-72

4.3.2.4 Assessment of Epistemic Uncertainty for Probabilistic Storm Surge Hazard Assessment Using a Logic Tree Approach ...................................................................................... 4-80

4.3.2.5 Coastal Flooding Panel ............................................................................................ 4-91

4.3.3 Day 1: Session 1C - Precipitation .................................................................................. 4-98

4.3.3.1 KEYNOTE: Satellite Precipitation Estimates, GPM, and Extremes ...................... 4-98

4.3.3.2 Hurricane Harvey Highlights: Need to Assess the Adequacy of Probable Maximum Precipitation Estimation Methods ......................................................................................... 4-111

4.3.3.3 Reanalysis Datasets in Hydrologic Hazards Analysis ........................................... 4-112

4.3.3.4 Current Capabilities for Developing Watershed Precipitation-Frequency Relationships and Storm-Related Inputs for Stochastic Flood Modeling for Use in Risk-Informed Decisionmaking .................................................................................................................. 4-125

4.3.3.5 Factors Affecting the Development of Precipitation Areal Reduction Factors ...... 4-142

4.3.3.6 Precipitation Panel Discussion .................................................................................. 4-156

4.3.4 Day 2 Session 2A - Riverine Flooding ......................................................................... 4-162

4.3.4.1 KEYNOTE: Watershed Level Risk Analysis with HEC-WAT .................................. 4-162

4.3.4.2 Global Sensitivity Analyses Applied to Riverine Flood Modeling ....................... 4-195

4.3.4.3 Detection and Attribution of Flood Change Across the United States .................. 4-206

4.3.4.4 Bulletin 17C: Flood Frequency Extrapolations for Dams and Nuclear Facilities .... 4-206

4.3.4.5 Riverine Paleoflood Analyses in Risk-Informed Decisionmaking: Improving Hydrologic Loading Input for USACE Dam Safety Evaluations ...................................................... 4-227
4.3.4.6 Improving Flood Frequency Analysis with a Multi-Millennial Record of Extreme Floods on the Tennessee River near Chattanooga, TN ................................................................. 4-243
4.3.4.7 Riverine Flooding Panel Discussion ........................................................................ 4-252
4.3.5 Day 2: Session 2B - Modeling Frameworks .................................................................. 4-261
  4.3.5.1 Structured Hazard Assessment Committee Process for Flooding (SHAC-F) .......... 4-261
  4.3.5.2 Overview of the TVA PFHA Calculation System .................................................... 4-272
  4.3.5.3 Development of Risk-Informed Safety Margin Characterization Framework for Flooding of Nuclear Power Plants .............................................................. 4-287
  4.3.5.4 Modeling Frameworks Panel Discussion ................................................................. 4-306
4.3.6 Day 2: Poster Session 2C .......................................................................................... 4-311
  4.3.6.1 Coastal Storm Surge Assessment using Surrogate Modeling Methods ................. 4-312
  4.3.6.3 Modelling Dependence and Coincidence of Flooding Phenomena: Methodology and Simplified Case Study in Le Havre in France ......................................................... 4-315
  4.3.6.4 Current State-of-Practice in Dam Risk Assessment ................................................ 4-315
  4.3.6.5 Hurricane Harvey Highlights Challenge of Estimating Probable Maximum Precipitation. 4-320
  4.3.6.6 Uncertainty and Sensitivity Analysis for Hydraulic Models with Dependent Inputs .... 4-320
  4.3.6.7 Development of Hydrologic Hazard Curves Using SEFM for Assessing Hydrologic Risks at Rhinedollar Dam, CA .......................................................... 4-323
  4.3.6.8 Probabilistic Flood Hazard Analysis of Nuclear Power Plant in Korea .................. 4-328
4.3.7 Day 3: Session 3A - Climate and Non-Stationarity ....................................................... 4-329
  4.3.7.1 KEYNOTE: Hydroclimatic Extremes Trends and Projections: A View from the Fourth National Climate Assessment ................................................................. 4-329
  4.3.7.2 Regional Climate Change Projections: Potential Impacts to Nuclear Facilities ........ 4-349
  4.3.7.3 Role of Climate Change/Variability in the 2017 Atlantic Hurricane Season ........... 4-364
  4.3.7.4 Climate Panel Discussion ....................................................................................... 4-374
4.3.8 Day 3: Session 3B - Flood Protection and Plant Response ........................................... 4-378
  4.3.8.1 External Flood Seal Risk-Ranking Process .............................................................. 4-378
  4.3.8.2 Results of Performance of Flood-Rated Penetration Seals Tests ............................ 4-386
  4.3.8.3 Modelling Overtopping Erosion Tests of Zoned Rockfill Embankments ............... 4-398
  4.3.8.4 Flood Protection and Plant Response Panel Discussion ......................................... 4-419
4.3.9 Day 3: Session 3C - Towards External Flooding PRA ............................................... 4-423
  4.3.9.1 External Flooding PRA Walkdown Guidance ........................................................ 4-423
  4.3.9.2 Updates on the Revision and Expansion of the External Flooding PRA Standard .... 4-435
  4.3.9.3 Update on ANS 2.8: Probabilistic Evaluation of External Flood Hazards for Nuclear Facilities Working Group Status ................................................................. 4-446
  4.3.9.4 Qualitative PRA Insights from Operational Events of External Floods and Other Storm-Related Hazards .............................................................. 4-456
  4.3.9.5 Towards External Flooding PRA Discussion Panel ............................................... 4-464
4.4 SUMMARY .................................................................................................................... 4-475
4.5 WORKSHOP PARTICIPANTS ....................................................................................... 4-477

5 SUMMARY AND CONCLUSIONS .................................................................................. 5-489
  5.1 SUMMARY ................................................................................................................ 5-489
  5.2 CONCLUSIONS ....................................................................................................... 5-489

ACKNOWLEDGEMENTS ................................................................................................. 5-490
ABBREVIATION AND ACRONYMS

\[ \sigma \] sigma, standard deviation

\[^{\circ}C\] degrees Celsius

\[^{\circ}F\] degrees Fahrenheit

\[^{13}C\text{-NMR}\] carbon-13 nuclear magnetic resonance

\[^{14}C\] carbon-14


17C Guidelines for Determining Flood Flow Frequency—Bulletin 17C, 2018

1-D one dimensional

20C 20th Century Reanalysis

2BCMB Level 2—DPR and GMI Combine

2-D two dimensional

3-D three dimensional

AAB Accident Analysis Branch in NRC/RES/DSA

AB auxiliary building

AC, ac alternating current

ACCP Alabama Coastal Comprehensive Plan

ACE accumulated cyclone energy, an approximation of the wind energy used by a tropical system over its lifetime

ACM alternative conceptual model

ACME Accelerated Climate Modeling for Energy (DOE)

ACWI Advisory Committee on Water Information

AD anno Domini

ADAMS Agencywide Documents Access and Management System

ADICRSCIRCUSTion model

AEP annual exceedance probability

AEP4 Asymmetric Exponential Power distribution

AFW auxiliary feedwater

AGCMLE Assistant General Counsel for Materials Litigation and Enforcement in NRC/OGC/GCHA

AGCNRP Assistant General Counsel for New Reactor Programs in NRC/OGC/GCHA

AGFZ Azores–Gibraltar Transform Fault

AGL above ground level

AIC Akaike Information Criterion
<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Full Form</th>
</tr>
</thead>
<tbody>
<tr>
<td>AIMS</td>
<td>assumptions, inputs, and methods</td>
</tr>
<tr>
<td>AIRS</td>
<td>Advanced InfraRed Sounder</td>
</tr>
<tr>
<td>AIT</td>
<td>air intake tunnel</td>
</tr>
<tr>
<td>AK</td>
<td>Alaska</td>
</tr>
<tr>
<td>AM</td>
<td>annual maxima</td>
</tr>
<tr>
<td>AMJ</td>
<td>April, May, June</td>
</tr>
<tr>
<td>AMM</td>
<td>Atlantic Meridional Mode</td>
</tr>
<tr>
<td>AMO</td>
<td>Atlantic Multi-Decadal Oscillation</td>
</tr>
<tr>
<td>AMS</td>
<td>annual maxima series</td>
</tr>
<tr>
<td>AMSR-2</td>
<td>Advance Microwave Scanning Radiometer</td>
</tr>
<tr>
<td>AMSU</td>
<td>Advanced Microwave Sounding Unit</td>
</tr>
<tr>
<td>ANN</td>
<td>annual</td>
</tr>
<tr>
<td>ANO</td>
<td>Arkansas Nuclear One</td>
</tr>
<tr>
<td>ANOVA</td>
<td>analysis of variance decomposition</td>
</tr>
<tr>
<td>ANS</td>
<td>American Nuclear Society</td>
</tr>
<tr>
<td>ANSI</td>
<td>American National Standards Institute</td>
</tr>
<tr>
<td>ANVS</td>
<td>Netherlands Authority for Nuclear Safety and Radiation Protection</td>
</tr>
<tr>
<td>AO</td>
<td>Assistant for Operations in NRC/OEDO</td>
</tr>
<tr>
<td>AOP</td>
<td>abnormal operating procedure</td>
</tr>
<tr>
<td>APF</td>
<td>annual probability of failure</td>
</tr>
<tr>
<td>APHB</td>
<td>Probabilistic Risk Assessment Operations and Human Factors Branch</td>
</tr>
<tr>
<td>API</td>
<td>application programming interface</td>
</tr>
<tr>
<td>APLA/APLB</td>
<td>Probabilistic Risk Assessment Licensing Branch A/B in NRC/NRR/DRA</td>
</tr>
<tr>
<td>APOB</td>
<td>PRA Oversight Branch in NRC/NRR/DRA</td>
</tr>
<tr>
<td>AR</td>
<td>atmospheric river</td>
</tr>
<tr>
<td>AR</td>
<td>Arkansas</td>
</tr>
<tr>
<td>AR4, AR5</td>
<td>climate scenarios from the 4th/5th Intergovernmental Panel on Climate Change Reports / Working Groups</td>
</tr>
<tr>
<td>ARA</td>
<td>Applied Research Associates</td>
</tr>
<tr>
<td>ArcGIS</td>
<td>geographic information system owned by ESRI</td>
</tr>
<tr>
<td>ARF</td>
<td>areal reduction factor</td>
</tr>
<tr>
<td>ARI</td>
<td>average return interval</td>
</tr>
<tr>
<td>ARR</td>
<td>Australian Rainfall-Runoff Method</td>
</tr>
<tr>
<td>AS</td>
<td>adjoining stratiform</td>
</tr>
<tr>
<td>ASM</td>
<td>annual series maxima</td>
</tr>
<tr>
<td>Abbreviation</td>
<td>Description</td>
</tr>
<tr>
<td>--------------</td>
<td>-------------</td>
</tr>
<tr>
<td>ASME</td>
<td>American Society of Mechanical Engineers</td>
</tr>
<tr>
<td>ASN</td>
<td>French Nuclear Safety Authority (Autorité de Sûreté Nucléaire)</td>
</tr>
<tr>
<td>ASTM</td>
<td>American Society for Testing and Materials</td>
</tr>
<tr>
<td>ATMS</td>
<td>Advance Technology Microwave Sounder</td>
</tr>
<tr>
<td>ATWS</td>
<td>anticipated transient without scram</td>
</tr>
<tr>
<td>AVHRR</td>
<td>Advance Very High Resolution Radiometer</td>
</tr>
<tr>
<td>B&amp;A</td>
<td>Bittner &amp; Associates</td>
</tr>
<tr>
<td>BATEA</td>
<td>Bayesian Total Error Analysis</td>
</tr>
<tr>
<td>BB</td>
<td>backbuilding/quasistationary</td>
</tr>
<tr>
<td>BC</td>
<td>boundary condition</td>
</tr>
<tr>
<td>Bel V</td>
<td>subsidiary of Belgian Federal Agency for Nuclear Control (FANC)</td>
</tr>
<tr>
<td>BHM</td>
<td>Bayesian Hierarchical Model</td>
</tr>
<tr>
<td>BIA</td>
<td>Bureau of Indian Affairs</td>
</tr>
<tr>
<td>BMA</td>
<td>Bayesian Model Averaging</td>
</tr>
<tr>
<td>BQ</td>
<td>Bayesian Quadrature</td>
</tr>
<tr>
<td>BWR</td>
<td>boiling-water reactor</td>
</tr>
<tr>
<td>CA</td>
<td>California</td>
</tr>
<tr>
<td>CAC</td>
<td>common access card</td>
</tr>
<tr>
<td>CAPE</td>
<td>Climate Action Peer Exchange</td>
</tr>
<tr>
<td>CAPE</td>
<td>convective available potential energy</td>
</tr>
<tr>
<td>CAS</td>
<td>corrective action study</td>
</tr>
<tr>
<td>CAS2CD</td>
<td>CAScade 2-Dimensional model (Colorado State)</td>
</tr>
<tr>
<td>Cat.</td>
<td>category on the Saffir-Simpson Hurricane Wind Scale</td>
</tr>
<tr>
<td>CBR</td>
<td>center, body, and range</td>
</tr>
<tr>
<td>CC</td>
<td>Clausius-Clapeyron</td>
</tr>
<tr>
<td>CC</td>
<td>climate change</td>
</tr>
<tr>
<td>CCCR</td>
<td>Center for Climate Change Research</td>
</tr>
<tr>
<td>CCDP</td>
<td>conditional core damage probability</td>
</tr>
<tr>
<td>CCI</td>
<td>Coppersmith Consulting Inc.</td>
</tr>
<tr>
<td>CCSM4</td>
<td>Community Climate System Model version 4</td>
</tr>
<tr>
<td>CCW</td>
<td>closed cooling water</td>
</tr>
<tr>
<td>CDB</td>
<td>current design basis</td>
</tr>
<tr>
<td>CDF</td>
<td>core damage frequency</td>
</tr>
<tr>
<td>CDF</td>
<td>cumulative distribution function</td>
</tr>
<tr>
<td>Abbreviation</td>
<td>Description</td>
</tr>
<tr>
<td>--------------</td>
<td>-------------</td>
</tr>
<tr>
<td>CE</td>
<td>common era</td>
</tr>
<tr>
<td>CEATI</td>
<td>Centre for Energy Advancement through Technological Innovation</td>
</tr>
<tr>
<td>CEET</td>
<td>cracked embankment erosion test</td>
</tr>
<tr>
<td>CENRS</td>
<td>National Science and Technology Council Committee on Environment, Natural Resources, and Sustainability</td>
</tr>
<tr>
<td>CESM</td>
<td>Community Earth System Model</td>
</tr>
<tr>
<td>CFD</td>
<td>computational fluid dynamics</td>
</tr>
<tr>
<td>CFHA</td>
<td>comprehensive flood hazard assessment</td>
</tr>
<tr>
<td>CFR</td>
<td><em>Code of Federal Regulations</em></td>
</tr>
<tr>
<td>CFSR</td>
<td>Climate Forecast System Reanalysis</td>
</tr>
<tr>
<td>CHIPS</td>
<td>Coupled Hurricane Intensity Prediction System</td>
</tr>
<tr>
<td>CHiRPs</td>
<td>Climate Hazards Group infraRed Precipitation with Station Data</td>
</tr>
<tr>
<td>CHL</td>
<td>Coastal and Hydraulics Laboratory</td>
</tr>
<tr>
<td>CHRP</td>
<td>Coastal Hazard Rapid Prediction, part of StormSIM</td>
</tr>
<tr>
<td>CHS</td>
<td>Coastal Hazards System</td>
</tr>
<tr>
<td>CI</td>
<td>confidence interval</td>
</tr>
<tr>
<td>CICS-NC</td>
<td>Cooperative Institute for Climates and Satellites—North Carolina</td>
</tr>
<tr>
<td>CIPB</td>
<td>Construction Inspection Management Branch in NRC/NRO/DLSE</td>
</tr>
<tr>
<td>CIRES</td>
<td>Cooperative Institute for Research in Environmental Sciences</td>
</tr>
<tr>
<td>CL</td>
<td>confidence level</td>
</tr>
<tr>
<td>CL-ML</td>
<td>homogeneous silty clay soil</td>
</tr>
<tr>
<td>CMC</td>
<td>Canadian Meteorological Center forecasts</td>
</tr>
<tr>
<td>CMIP5</td>
<td>Coupled Model Intercomparison Project Phase 5</td>
</tr>
<tr>
<td>CMORPH / C-MORPH</td>
<td>Climate Prediction Center Morphing Technique</td>
</tr>
<tr>
<td>CNE</td>
<td>Romania Consiliul National al Elevilor</td>
</tr>
<tr>
<td>CNSC</td>
<td>Canadian Nuclear Safety Commission</td>
</tr>
<tr>
<td>CO</td>
<td>Colorado</td>
</tr>
<tr>
<td>CoCoRaHS</td>
<td>Community Collaborative Rain, Hail &amp; Snow Network (NWS)</td>
</tr>
<tr>
<td>COE</td>
<td>U.S. Army Corps of Engineers (see also USACE)</td>
</tr>
<tr>
<td>COL</td>
<td>combined license</td>
</tr>
<tr>
<td>COLA</td>
<td>combined license application</td>
</tr>
<tr>
<td>COM-SECY</td>
<td>NRC staff requests to the Commission for guidance</td>
</tr>
<tr>
<td>CONUS</td>
<td>Continental United States</td>
</tr>
<tr>
<td>COOP</td>
<td>Cooperative Observer Network (NWS)</td>
</tr>
<tr>
<td>Abbreviation</td>
<td>Full Form</td>
</tr>
<tr>
<td>--------------</td>
<td>-----------</td>
</tr>
<tr>
<td>COR</td>
<td>contracting officer’s representative</td>
</tr>
<tr>
<td>CPC</td>
<td>Climate Prediction Center (NOAA)</td>
</tr>
<tr>
<td>CPFs</td>
<td>cumulative probability functions</td>
</tr>
<tr>
<td>CR</td>
<td>comprehensive review</td>
</tr>
<tr>
<td>CRA</td>
<td>computational risk assessment</td>
</tr>
<tr>
<td>CRB</td>
<td>Concerns Resolution Branch in NRC/OE</td>
</tr>
<tr>
<td>CRL</td>
<td>coastal reference location</td>
</tr>
<tr>
<td>CRPS</td>
<td>continuous ranked probability score</td>
</tr>
<tr>
<td>CSNI</td>
<td>Committee on the Safety of Nuclear Installations</td>
</tr>
<tr>
<td>CSRB</td>
<td>Criticality, Shielding &amp; Risk Assessment Branch in NRC/NMSS/DSFM</td>
</tr>
<tr>
<td>CSSR</td>
<td>Climate Science Special Report (by the U.S. Global Change Research Program)</td>
</tr>
<tr>
<td>CSTORM</td>
<td>Coastal Storm Modeling System</td>
</tr>
<tr>
<td>CTA Note</td>
<td>note to Commissioners’ Assistants</td>
</tr>
<tr>
<td>CTXS</td>
<td>Coastal Texas Study</td>
</tr>
<tr>
<td>CV</td>
<td>coefficient of variation</td>
</tr>
<tr>
<td>CZ</td>
<td>capture zone</td>
</tr>
<tr>
<td>DC</td>
<td>District of Columbia</td>
</tr>
<tr>
<td>DAD</td>
<td>depth-area-duration</td>
</tr>
<tr>
<td>DAMBRK</td>
<td>Dam Break Flood Forecasting Model (NWS)</td>
</tr>
<tr>
<td>DAR</td>
<td>Division of Advanced Reactors in NRC/NRO</td>
</tr>
<tr>
<td>DayMet</td>
<td>daily surface weather and climatological summaries</td>
</tr>
<tr>
<td>dBz</td>
<td>decibel relative to z, or measure of reflectivity of radar</td>
</tr>
<tr>
<td>DCIP</td>
<td>Division of Construction Inspection and Operational Programs in NRC/NRO</td>
</tr>
<tr>
<td>DDF</td>
<td>depth-duration-frequency curve</td>
</tr>
<tr>
<td>DDM</td>
<td>data-driven methodology</td>
</tr>
<tr>
<td>DDST</td>
<td>database of daily storm types</td>
</tr>
<tr>
<td>DE</td>
<td>Division of Engineering in NRC/RES</td>
</tr>
<tr>
<td>DHSVM</td>
<td>distributed hydrology soil vegetation model, supported by University of Washington</td>
</tr>
<tr>
<td>DIRS</td>
<td>Division of Inspection and Regional Support in NRC/NRR</td>
</tr>
<tr>
<td>DJF</td>
<td>December, January, February</td>
</tr>
<tr>
<td>DLBreach</td>
<td>Dam/Levee Breach model developed by Weiming Wu, Clarkson University</td>
</tr>
<tr>
<td>DLSE</td>
<td>Division of Licensing, Siting, and Environmental Analysis in NRC/NRO</td>
</tr>
<tr>
<td>Acronym</td>
<td>Description</td>
</tr>
<tr>
<td>---------</td>
<td>-------------</td>
</tr>
<tr>
<td>DOE</td>
<td>U.S. Department of Energy</td>
</tr>
<tr>
<td>Dp</td>
<td>pressure deficit</td>
</tr>
<tr>
<td>DPI</td>
<td>power dissipation index</td>
</tr>
<tr>
<td>DPR</td>
<td>Division of Preparedness and Response in NRC/NSIR</td>
</tr>
<tr>
<td>DPR</td>
<td>Dual Frequency Precipitation Radar</td>
</tr>
<tr>
<td>DQO</td>
<td>data quality objective</td>
</tr>
<tr>
<td>DRA</td>
<td>Division of Risk Assessment in NRC/NRR</td>
</tr>
<tr>
<td>DRA</td>
<td>Division of Risk Analysis in NRC/RES</td>
</tr>
<tr>
<td>DREAM</td>
<td>Differential Evolution Adaptive Metropolis</td>
</tr>
<tr>
<td>DRP</td>
<td>Division of Reactor Projects in NRC/R-I</td>
</tr>
<tr>
<td>DRS</td>
<td>Division of Reactor Safety In NRC/R-I and R-IV</td>
</tr>
<tr>
<td>DSA</td>
<td>Division of Systems Analysis in NRC/RES</td>
</tr>
<tr>
<td>DSEA</td>
<td>Division of Site Safety and Environmental Analysis, formerly in NRC/NRO, now in DLSE</td>
</tr>
<tr>
<td>DSFM</td>
<td>Division of Spent Fuel Management in NRC/NMSS</td>
</tr>
<tr>
<td>DSI3240</td>
<td>NCEI hourly precipitation data</td>
</tr>
<tr>
<td>DSMS</td>
<td>Dam Safety Modification Study</td>
</tr>
<tr>
<td>DSS</td>
<td>Division of Safety Systems in NRC/NRR</td>
</tr>
<tr>
<td>DSS</td>
<td>Hydrologic Engineering Center Data Storage System</td>
</tr>
<tr>
<td>DTWD</td>
<td>doubly truncated Weibull distribution</td>
</tr>
<tr>
<td>DUWP</td>
<td>Division of Decommissioning, Uranium Recovery, and Waste Programs in NRC/NMSS</td>
</tr>
<tr>
<td>DWOPER</td>
<td>Operational Dynamic Wave Model (NWS)</td>
</tr>
<tr>
<td>dy</td>
<td>day</td>
</tr>
<tr>
<td>EAD</td>
<td>expected annual damage</td>
</tr>
<tr>
<td>EB2/EB3</td>
<td>Engineering Branch 2/3 in NRC/R-IV/DRS</td>
</tr>
<tr>
<td>EBTRK</td>
<td>Tropical Cyclone Extended Best Track Dataset</td>
</tr>
<tr>
<td>EC</td>
<td>Eddy Covariance Method</td>
</tr>
<tr>
<td>EC</td>
<td>environmental condition</td>
</tr>
<tr>
<td>ECC</td>
<td>ensemble copula coupling</td>
</tr>
<tr>
<td>ECCS</td>
<td>emergency core cooling systems pump</td>
</tr>
<tr>
<td>Abbreviation</td>
<td>Full Form</td>
</tr>
<tr>
<td>--------------</td>
<td>-----------</td>
</tr>
<tr>
<td>ECs</td>
<td>environmental conditions</td>
</tr>
<tr>
<td>EDF</td>
<td>Électricité de France</td>
</tr>
<tr>
<td>EDG</td>
<td>emergency diesel generator</td>
</tr>
<tr>
<td>EF</td>
<td>environmental factor</td>
</tr>
<tr>
<td>EFW</td>
<td>emergency feedwater</td>
</tr>
<tr>
<td>EGU</td>
<td>European Geophysical Union</td>
</tr>
<tr>
<td>EHC0E</td>
<td>NRC External Hazard Center of Expertise</td>
</tr>
<tr>
<td>EHID</td>
<td>External Hazard Information Digest</td>
</tr>
<tr>
<td>EIRL</td>
<td>equivalent independent record length</td>
</tr>
<tr>
<td>EIS</td>
<td>environmental impact statement</td>
</tr>
<tr>
<td>EKF</td>
<td>Epanechnikov kernel function</td>
</tr>
<tr>
<td>EMA</td>
<td>expected moments algorithm</td>
</tr>
<tr>
<td>EMCFW</td>
<td>European Centre for Medium-Range Weather Forecasts</td>
</tr>
<tr>
<td>EMDR</td>
<td>eastern main development region (for hurricanes)</td>
</tr>
<tr>
<td>EMERALD</td>
<td>Event Model Risk Assessment using Linked Diagrams</td>
</tr>
<tr>
<td>ENSI</td>
<td>Swiss Federal Nuclear Safety Inspectorate</td>
</tr>
<tr>
<td>ENSO</td>
<td>El Niño Southern Oscillation</td>
</tr>
<tr>
<td>EPA</td>
<td>U.S. Environmental Protection Agency</td>
</tr>
<tr>
<td>EPRI</td>
<td>Electric Power Research Institute</td>
</tr>
<tr>
<td>ER</td>
<td>engineering regulation (USACE)</td>
</tr>
<tr>
<td>ERA-40</td>
<td>European ECMWF reanalysis dataset</td>
</tr>
<tr>
<td>ERB</td>
<td>Environmental Review Branch in NRC/NMSS/FCSE</td>
</tr>
<tr>
<td>ERDC</td>
<td>Engineer Research and Development Center (USACE)</td>
</tr>
<tr>
<td>ERL</td>
<td>equivalent record length</td>
</tr>
<tr>
<td>ESSC</td>
<td>Environmental and Siting Consensus Committee (ANS)</td>
</tr>
<tr>
<td>ESEB</td>
<td>Structural Engineering Branch in NRC/RES/DE</td>
</tr>
<tr>
<td>ESEWG</td>
<td>Extreme Storm Events Work Group (ACWI/SOH)</td>
</tr>
<tr>
<td>ESP</td>
<td>early site permit</td>
</tr>
<tr>
<td>ESRI</td>
<td>Environmental Systems Research Institute</td>
</tr>
<tr>
<td>ESRL</td>
<td>Earth Systems Research Lab (NOAA/OAR)</td>
</tr>
<tr>
<td>EST</td>
<td>Eastern Standard Time</td>
</tr>
<tr>
<td>EST</td>
<td>empirical simulation technique</td>
</tr>
<tr>
<td>ESTP</td>
<td>enhanced storm transposition procedure</td>
</tr>
<tr>
<td>Acronym</td>
<td>Full Form</td>
</tr>
<tr>
<td>---------</td>
<td>-----------</td>
</tr>
<tr>
<td>ET</td>
<td>event tree</td>
</tr>
<tr>
<td>ET</td>
<td>evapotranspiration</td>
</tr>
<tr>
<td>ET/FT</td>
<td>event tree/fault tree</td>
</tr>
<tr>
<td>ETC</td>
<td>extratropical cyclone</td>
</tr>
<tr>
<td>EUS</td>
<td>eastern United States</td>
</tr>
<tr>
<td>EV4</td>
<td>extreme value with four parameters distribution function</td>
</tr>
<tr>
<td>EVA</td>
<td>extreme value analysis</td>
</tr>
<tr>
<td>EVT</td>
<td>extreme value theory</td>
</tr>
<tr>
<td>EXHB</td>
<td>External Hazards Branch in NRC/NRO/DLSE</td>
</tr>
<tr>
<td>Exp</td>
<td>experimental</td>
</tr>
<tr>
<td>f</td>
<td>annual probability of failure (USBR, USACE)</td>
</tr>
<tr>
<td>F1, F5</td>
<td>tornado strengths on the Fujita scale</td>
</tr>
<tr>
<td>FA</td>
<td>frequency analysis</td>
</tr>
<tr>
<td>FADSU</td>
<td>fluvial activity database of the Southeastern United States</td>
</tr>
<tr>
<td>FAQ</td>
<td>frequently asked question</td>
</tr>
<tr>
<td>FAST</td>
<td>Fourier Analysis Sensitivity Test</td>
</tr>
<tr>
<td>FBPS</td>
<td>flood barrier penetration seal</td>
</tr>
<tr>
<td>FBS</td>
<td>flood barrier system</td>
</tr>
<tr>
<td>FCM</td>
<td>flood-causing mechanism</td>
</tr>
<tr>
<td>FCSE</td>
<td>Division of Fuel Cycle Safety, Safeguards &amp; Environmental Review in NRC/NMSS</td>
</tr>
<tr>
<td>FD</td>
<td>final design</td>
</tr>
<tr>
<td>FDC</td>
<td>flood design category (DOE terminology)</td>
</tr>
<tr>
<td>FEMA</td>
<td>Federal Emergency Management Agency</td>
</tr>
<tr>
<td>FERC</td>
<td>Federal Energy Regulatory Commission</td>
</tr>
<tr>
<td>FFA</td>
<td>flood frequency analysis</td>
</tr>
<tr>
<td>FFC</td>
<td>flood frequency curve</td>
</tr>
<tr>
<td>FHRR</td>
<td>flood hazard reevaluation report</td>
</tr>
<tr>
<td>FITAG</td>
<td>Flooding Issues Technical Advisory Group</td>
</tr>
<tr>
<td>FL</td>
<td>Florida</td>
</tr>
<tr>
<td>FLDFRQ3</td>
<td>U.S. Bureau of Reclamation flood frequency analysis tool</td>
</tr>
<tr>
<td>FLDWAV</td>
<td>flood wave model (NWS)</td>
</tr>
<tr>
<td>FLEX</td>
<td>diverse and flexible mitigation strategies</td>
</tr>
<tr>
<td>Flike</td>
<td>extreme value analysis package developed University of Newcastle, Australia</td>
</tr>
<tr>
<td>Abbreviation</td>
<td>Description</td>
</tr>
<tr>
<td>--------------</td>
<td>-------------</td>
</tr>
<tr>
<td>FLO-2D</td>
<td>two-dimensional commercial flood model</td>
</tr>
<tr>
<td>FM Approvals</td>
<td>Testing and Certification Services Laboratories, originally Factory Mutual Laboratories</td>
</tr>
<tr>
<td>f-N</td>
<td>annual probability of failure vs. average life loss, N</td>
</tr>
<tr>
<td>FOR</td>
<td>peak flood of record</td>
</tr>
<tr>
<td>FPM</td>
<td>flood protection and mitigation</td>
</tr>
<tr>
<td>FPS</td>
<td>flood penetration seal</td>
</tr>
<tr>
<td>FRA</td>
<td>Flood Risk Analysis Compute Option in HEC-WAT</td>
</tr>
<tr>
<td>FRM</td>
<td>Fire Risk Management, Inc.</td>
</tr>
<tr>
<td>FSAR</td>
<td>final safety analysis report</td>
</tr>
<tr>
<td>FSC</td>
<td>flood-significant component</td>
</tr>
<tr>
<td>FSG</td>
<td>FLEX support guidelines</td>
</tr>
<tr>
<td>FSP</td>
<td>flood seal for penetrations</td>
</tr>
<tr>
<td>FT</td>
<td>fault tree</td>
</tr>
<tr>
<td>ft</td>
<td>foot</td>
</tr>
<tr>
<td>FXHAB</td>
<td>Fire and External Hazards Analysis Branch in NRC/RES/DRA</td>
</tr>
<tr>
<td>FY</td>
<td>fiscal year</td>
</tr>
<tr>
<td>G&amp;G</td>
<td>geology and geotechnical engineering</td>
</tr>
<tr>
<td>GA</td>
<td>generic action</td>
</tr>
<tr>
<td>GCHA</td>
<td>Deputy General Counsel for Hearings and Administration in NRC/OGC</td>
</tr>
<tr>
<td>GCM</td>
<td>Global Climate Model</td>
</tr>
<tr>
<td>GCRP</td>
<td>U.S. Global Change Research Program</td>
</tr>
<tr>
<td>GCRPS</td>
<td>Deputy General Counsel for Rulemaking and Policy Support in NRC/OGC</td>
</tr>
<tr>
<td>GEFS</td>
<td>Global Ensemble Forecasting System</td>
</tr>
<tr>
<td>GeoClaw</td>
<td>routines from Clawpack-5 (&quot;Conservation Laws Package&quot;) that are specialized to depth-averaged geophysical flows</td>
</tr>
<tr>
<td>GEO-IR</td>
<td>Geostationary Satellites—InfraRed Imagery</td>
</tr>
<tr>
<td>GEV</td>
<td>generalized extreme value</td>
</tr>
<tr>
<td>GFDL</td>
<td>Geophysical Fluid Dynamics Lab (NOAA)</td>
</tr>
<tr>
<td>GFS</td>
<td>Global Forecast System</td>
</tr>
<tr>
<td>GHCN</td>
<td>Global Historical Climatology Network</td>
</tr>
<tr>
<td>GHCN Daily</td>
<td>Global Historical Climatology Network-Daily</td>
</tr>
<tr>
<td>GIS</td>
<td>geographic information system</td>
</tr>
<tr>
<td>GISS</td>
<td>Goddard Institute for Space Studies (NASA)</td>
</tr>
<tr>
<td>Abbreviation</td>
<td>Description</td>
</tr>
<tr>
<td>--------------</td>
<td>-------------</td>
</tr>
<tr>
<td>GKF</td>
<td>Gaussian Kernel Function</td>
</tr>
<tr>
<td>GL</td>
<td>generic letter</td>
</tr>
<tr>
<td>GLO</td>
<td>generalized logistic distribution</td>
</tr>
<tr>
<td>GLRCM</td>
<td>Great Lakes Regional Climate Model</td>
</tr>
<tr>
<td>GLUE</td>
<td>generalized likelihood uncertainty estimation</td>
</tr>
<tr>
<td>GMAO</td>
<td>Global Modeling and Assimilation Office (NASA)</td>
</tr>
<tr>
<td>GMC</td>
<td>ground motion characterization</td>
</tr>
<tr>
<td>GMD</td>
<td>geoscientific model development</td>
</tr>
<tr>
<td>GMI</td>
<td>GPM microwave imager</td>
</tr>
<tr>
<td>GMSL</td>
<td>global mean sea level</td>
</tr>
<tr>
<td>GNO</td>
<td>generalized normal distribution</td>
</tr>
<tr>
<td>GoF</td>
<td>goodness-of-fit</td>
</tr>
<tr>
<td>GPA/GPD</td>
<td>generalized Pareto distribution</td>
</tr>
<tr>
<td>GPCP SG</td>
<td>Global Precipitation Climatology Project—Satellite Gauge</td>
</tr>
<tr>
<td>GPLLLJ</td>
<td>Great Plains lower level jet</td>
</tr>
<tr>
<td>GPM</td>
<td>Gaussian process metamodel</td>
</tr>
<tr>
<td>GPM</td>
<td>global precipitation measurement</td>
</tr>
<tr>
<td>GPO</td>
<td>generalized Pareto distribution</td>
</tr>
<tr>
<td>GPROF</td>
<td>Goddard profile algorithm</td>
</tr>
<tr>
<td>GRADEX</td>
<td>rainfall-based flood frequency distribution method</td>
</tr>
<tr>
<td>Grizzly</td>
<td>simulated component aging and damage evolution events RISMC tool</td>
</tr>
<tr>
<td>GRL</td>
<td>Geophysical Research Letters</td>
</tr>
<tr>
<td>GRS</td>
<td>Gesellschaft für Anlagen- und Reaktorsicherheit—Global Research for Safety</td>
</tr>
<tr>
<td>GSA</td>
<td>global sensitivity analysis</td>
</tr>
<tr>
<td>GSFC</td>
<td>Goddard Space Flight Center</td>
</tr>
<tr>
<td>GSI</td>
<td>generic safety issue</td>
</tr>
<tr>
<td>GUI</td>
<td>graphical user interface</td>
</tr>
<tr>
<td>GW-GC</td>
<td>Well-graded gravel with clay and sand</td>
</tr>
<tr>
<td>GZA</td>
<td>a multidisciplinary consulting firm</td>
</tr>
<tr>
<td>h</td>
<td>second shape parameter of four-parameter Kappa distribution</td>
</tr>
<tr>
<td>h/hr</td>
<td>hour</td>
</tr>
<tr>
<td>H&amp;H</td>
<td>hydraulics and hydrology</td>
</tr>
<tr>
<td>HAMC</td>
<td>hydraulic model characterization</td>
</tr>
<tr>
<td>Acronym</td>
<td>Description</td>
</tr>
<tr>
<td>---------</td>
<td>-------------</td>
</tr>
<tr>
<td>HBV</td>
<td>rainfall runoff model Hydrologiska Byrons Vattenbalansavdelning, supported by the Swedish Meteorological and Hydrological Institute</td>
</tr>
<tr>
<td>HCA</td>
<td>hierarchical clustering analysis</td>
</tr>
<tr>
<td>HCTISN</td>
<td>Supreme Committee for Transparency and Information on Nuclear Safety (France)</td>
</tr>
<tr>
<td>HCW</td>
<td>hazardous convective weather</td>
</tr>
<tr>
<td>HDSC</td>
<td>NOAA/NWS/OWP Hydrometeorological Design Studies Center</td>
</tr>
<tr>
<td>HEC</td>
<td>Hydrologic Engineering Center, part of USACE/Institute for Water Resources</td>
</tr>
<tr>
<td>HEC-1</td>
<td>see HEC-HMS</td>
</tr>
<tr>
<td>HEC-FIA</td>
<td>Hydrologic Engineering Center Flood Impact Analysis Software</td>
</tr>
<tr>
<td>HEC-HMS</td>
<td>Hydrologic Modeling System</td>
</tr>
<tr>
<td>HEC-LifeSim</td>
<td>Hydrologic Engineering Center life loss and direct damage estimation software</td>
</tr>
<tr>
<td>HEC-MetVue</td>
<td>Hydrologic Engineering Center Meteorological Visualization Utility Engine</td>
</tr>
<tr>
<td>HEC-RAS</td>
<td>Hydrologic Engineering Center River Analysis System</td>
</tr>
<tr>
<td>HEC-ResSim</td>
<td>Hydrologic Engineering Center Reservoir System Simulation</td>
</tr>
<tr>
<td>HEC-SSP</td>
<td>Hydrologic Engineering Center Statistical Software Package</td>
</tr>
<tr>
<td>HEC-WAT</td>
<td>Hydrologic Engineering Center Watershed Analysis Tool</td>
</tr>
<tr>
<td>HEP</td>
<td>human error probability</td>
</tr>
<tr>
<td>HF</td>
<td>human factors</td>
</tr>
<tr>
<td>HFRB</td>
<td>Human Factors and Reliability Branch in NRC/RES/DRA</td>
</tr>
<tr>
<td>HHA</td>
<td>hydrologic hazard analysis</td>
</tr>
<tr>
<td>HHC</td>
<td>hydrologic hazard curve</td>
</tr>
<tr>
<td>HI</td>
<td>Hawaii</td>
</tr>
<tr>
<td>HLR</td>
<td>high-level requirement</td>
</tr>
<tr>
<td>HLWFCNS</td>
<td>Assistant General Counsel for High-Level Waste, Fuel Cycle and Nuclear Security in NRC/OGC/GCRPS</td>
</tr>
<tr>
<td>HMB</td>
<td>Hazard Management Branch in NRC/NRR/JLD, realigned</td>
</tr>
<tr>
<td>HMC</td>
<td>hydraulic/hydrologic model characterization</td>
</tr>
<tr>
<td>HMR</td>
<td>NOAA/NWS Hydrometeorological Report</td>
</tr>
<tr>
<td>HMS</td>
<td>hydrologic modeling system</td>
</tr>
<tr>
<td>HOMC</td>
<td>hydrologic model characterization</td>
</tr>
<tr>
<td>hPa</td>
<td>hectopascals (unit of pressure)</td>
</tr>
<tr>
<td>Abbreviation</td>
<td>Description</td>
</tr>
<tr>
<td>--------------</td>
<td>-------------</td>
</tr>
<tr>
<td>HR</td>
<td>homogenous region</td>
</tr>
<tr>
<td>HRA</td>
<td>human reliability analysis</td>
</tr>
<tr>
<td>HRL</td>
<td>Hydrologic Research Lab, University of California at Davis</td>
</tr>
<tr>
<td>HRRR</td>
<td>NOAA High-Resolution Rapid Refresh Model</td>
</tr>
<tr>
<td>HRRs</td>
<td>Fukushima Hazard Reevaluation Reports (EPRI term)</td>
</tr>
<tr>
<td>HRU</td>
<td>hydrologic runoff unit approach</td>
</tr>
<tr>
<td>HUC</td>
<td>hydrologic unit code for watershed (USGS)</td>
</tr>
<tr>
<td>HUNTER</td>
<td>human actions RISMC tool</td>
</tr>
<tr>
<td>HURDAT</td>
<td>National Hurricane Centers HURricane DATabases</td>
</tr>
<tr>
<td>Hz</td>
<td>hertz (1 cycle/second)</td>
</tr>
<tr>
<td>IA</td>
<td>integrated assessment</td>
</tr>
<tr>
<td>IA</td>
<td>Iowa</td>
</tr>
<tr>
<td>IAEA</td>
<td>International Atomic Energy Agency</td>
</tr>
<tr>
<td>IBTrACS</td>
<td>International Best Track Archive for Climate Stewardship</td>
</tr>
<tr>
<td>IC</td>
<td>initial condition</td>
</tr>
<tr>
<td>ICOLD</td>
<td>International Commission on Large Dams</td>
</tr>
<tr>
<td>ID</td>
<td>information digest</td>
</tr>
<tr>
<td>IDF</td>
<td>intensity-duration frequency curve</td>
</tr>
<tr>
<td>IDF</td>
<td>inflow design flood</td>
</tr>
<tr>
<td>IE</td>
<td>initiating event</td>
</tr>
<tr>
<td>IEF</td>
<td>initiating event frequency</td>
</tr>
<tr>
<td>IES</td>
<td>Dam Safety Issue Evaluation Studies</td>
</tr>
<tr>
<td>IES</td>
<td>Dam Safety Issue Evaluation Studies</td>
</tr>
<tr>
<td>IHDM</td>
<td>Institute of Hydrology Distributed Model, United Kingdom</td>
</tr>
<tr>
<td>IID</td>
<td>independent and identically distributed</td>
</tr>
<tr>
<td>IL</td>
<td>Illinois</td>
</tr>
<tr>
<td>IMERG</td>
<td>Integrated Multi-satellite Retrievals for GPM</td>
</tr>
<tr>
<td>IMPRINT</td>
<td>Improved Performance Research Integration Tool</td>
</tr>
<tr>
<td>in</td>
<td>inch</td>
</tr>
<tr>
<td>IN</td>
<td>information notice</td>
</tr>
<tr>
<td>INES</td>
<td>International Nuclear and Radiological Event Scale</td>
</tr>
<tr>
<td>INL</td>
<td>Idaho National Laboratory</td>
</tr>
<tr>
<td>IPCC</td>
<td>Intergovernmental Panel on Climate Change</td>
</tr>
<tr>
<td>IPE</td>
<td>individual plant examination</td>
</tr>
<tr>
<td>IPEEEE</td>
<td>individual plant examination for external events</td>
</tr>
<tr>
<td>Acronym</td>
<td>Full Form</td>
</tr>
<tr>
<td>---------</td>
<td>-----------</td>
</tr>
<tr>
<td>IPET</td>
<td>Interagency Performance Evaluation Taskforce for the Performance Evaluation of the New Orleans and Southeast Louisiana Hurricane Protection System</td>
</tr>
<tr>
<td>IPWG</td>
<td>International Precipitation Working Group</td>
</tr>
<tr>
<td>IR</td>
<td>infrared</td>
</tr>
<tr>
<td>IR</td>
<td>inspection report</td>
</tr>
<tr>
<td>IRIB</td>
<td>Reactor Inspection Branch in NRC/NRR/DIRS</td>
</tr>
<tr>
<td>IRP</td>
<td>Integrated Research Projects (DOE)</td>
</tr>
<tr>
<td>IRSN</td>
<td>Institut de Radioprotection et de Sûreté Nucléaire (France’s Radioprotection and Nuclear Safety Institute)</td>
</tr>
<tr>
<td>ISG</td>
<td>interim staff guidance</td>
</tr>
<tr>
<td>ISI</td>
<td>inservice inspection</td>
</tr>
<tr>
<td>ISR</td>
<td>interim staff response</td>
</tr>
<tr>
<td>IT</td>
<td>information technology</td>
</tr>
<tr>
<td>IVT</td>
<td>integrated vapor transport</td>
</tr>
<tr>
<td>IWR</td>
<td>USACE Institute for Water Resources</td>
</tr>
<tr>
<td>IWVT</td>
<td>integrated water vapor tendency</td>
</tr>
<tr>
<td>J</td>
<td>joule</td>
</tr>
<tr>
<td>JJA</td>
<td>June, July, August</td>
</tr>
<tr>
<td>JLD</td>
<td>Japan Lesson-learned Directorate or Division in NRC/NRR, realigned</td>
</tr>
<tr>
<td>JPA</td>
<td>Joint Powers Authority (FEMA Region II)</td>
</tr>
<tr>
<td>JPA</td>
<td>joint probability analysis</td>
</tr>
<tr>
<td>JPM</td>
<td>joint probability method</td>
</tr>
<tr>
<td>JPM-OS</td>
<td>Joint Probability Method with Optimal Sampling</td>
</tr>
<tr>
<td>K</td>
<td>degrees Kelvin</td>
</tr>
<tr>
<td>KAERI</td>
<td>Korea Atomic Energy Research Institute</td>
</tr>
<tr>
<td>KAP</td>
<td>Kappa distribution</td>
</tr>
<tr>
<td>$k_d$</td>
<td>erodibility coefficient</td>
</tr>
<tr>
<td>kg</td>
<td>kilogram</td>
</tr>
<tr>
<td>kHz</td>
<td>kilohertz (1000 cycles/second)</td>
</tr>
<tr>
<td>km</td>
<td>kilometer</td>
</tr>
<tr>
<td>KS</td>
<td>Kansas</td>
</tr>
<tr>
<td>LA</td>
<td>Louisiana</td>
</tr>
<tr>
<td>LACPR</td>
<td>Louisiana Coastal Protection and Restoration Study</td>
</tr>
<tr>
<td>LAR</td>
<td>license amendment request</td>
</tr>
<tr>
<td>Abbreviation</td>
<td>Full Form</td>
</tr>
<tr>
<td>--------------</td>
<td>-----------</td>
</tr>
<tr>
<td>L-Cv</td>
<td>coefficient of L-variation</td>
</tr>
<tr>
<td>LEO</td>
<td>low earth orbit</td>
</tr>
<tr>
<td>LER</td>
<td>licensee event report</td>
</tr>
<tr>
<td>LERF</td>
<td>large early release frequency</td>
</tr>
<tr>
<td>LIA</td>
<td>Little Ice Age</td>
</tr>
<tr>
<td>LiDAR</td>
<td>light imaging, detection and ranging; surveying method using reflected pulsed light to measure distance</td>
</tr>
<tr>
<td>LIP</td>
<td>local intense precipitation</td>
</tr>
<tr>
<td>LMI</td>
<td>lifetime maximum intensity</td>
</tr>
<tr>
<td>LMOM / LMR</td>
<td>L-moment</td>
</tr>
<tr>
<td>LN4</td>
<td>Slade-type four parameter lognormal distribution function</td>
</tr>
<tr>
<td>LOCA</td>
<td>localized constructed analog</td>
</tr>
<tr>
<td>LOCA</td>
<td>loss-of-coolant accident</td>
</tr>
<tr>
<td>LOOP</td>
<td>loss of offsite power event</td>
</tr>
<tr>
<td>LOUHS</td>
<td>loss of ultimate heat sink event</td>
</tr>
<tr>
<td>LPIII / LP-III, LP3</td>
<td>Log Pearson Type III distribution</td>
</tr>
<tr>
<td>LS</td>
<td>leading stratiform</td>
</tr>
<tr>
<td>LS</td>
<td>local storm</td>
</tr>
<tr>
<td>LSHR</td>
<td>late secondary heat removal</td>
</tr>
<tr>
<td>LTWD</td>
<td>Left-truncated Weibull distribution</td>
</tr>
<tr>
<td>LULC</td>
<td>land use and land cover</td>
</tr>
<tr>
<td>LWR</td>
<td>light-water reactor</td>
</tr>
<tr>
<td>LWRS</td>
<td>Light-Water Reactor Sustainability Program</td>
</tr>
<tr>
<td>m</td>
<td>meter</td>
</tr>
<tr>
<td>MA</td>
<td>Massachusetts</td>
</tr>
<tr>
<td>MA</td>
<td>manual action</td>
</tr>
<tr>
<td>MAAP</td>
<td>coupling accident conditions RISMC tool</td>
</tr>
<tr>
<td>MAE</td>
<td>mean absolute error</td>
</tr>
<tr>
<td>MAM</td>
<td>March, April, May</td>
</tr>
<tr>
<td>MAP</td>
<td>mean annual precipitation</td>
</tr>
<tr>
<td>MASTODON</td>
<td>structural dynamics, stochastic nonlinear soil-structure interaction in a risk framework RISMC tool</td>
</tr>
<tr>
<td>mb</td>
<td>millibar</td>
</tr>
<tr>
<td>MCA</td>
<td>medieval climate anomaly</td>
</tr>
<tr>
<td>MCC</td>
<td>mesoscale convective complex</td>
</tr>
</tbody>
</table>
MCI  Monte Carlo integration
MCLC  Monte Carlo Life-Cycle
MCMC  Markov chain Monte Carlo method
MCRAM  streamflow volume stochastic modeling
MCS  mesoscale convective system
MCS  Monte Carlo simulation
MCTA  Behrangi Multisatellite CloudSat TRMM Aqua Product
MD  Maryland
MDL  Meteorological Development Laboratory (NWS)
MDR  Main Development Region (for hurricanes)
MDT  Methodology Development Team
MEC  mesoscale storm with embedded convection
MEOW  Maximum Envelopes of Water
MetStorm  storm analysis software by MetStat, second generation of SPAS
MGD  meta-Gaussian distribution
MGS Engineering  engineering consultants
MHS  microwave humidity sounder
MIKE SHE/ MIKE 21  integrated hydrological modeling system
MLC  mid-latitude cyclone
MLE  maximum likelihood estimation
mm  millimeter
MM5  fifth-generation Penn State/NCAR mesoscale model
MMC  mesh-based Monte Carlo method
MMC  meteorological model characterization
MMF  multimechanism flood
MMP  mean monthly precipitation
MN  Minnesota
MO  Missouri
Mode 3  Reactor Operation Mode: Hot Standby
Mode 4  Reactor Operation Mode: Hot Shutdown
Mode 5  Reactor Operation Mode: Cold Shutdown
MOM  Maximum of MEOWs
MOU  memorandum of understanding
MPE  multisensor precipitation estimates
mph  miles per hour
MPS  maximum product of spacings
MRMS Multi-Radar Multi-Sensor project (NOAA/NSSL)
MS  Mississippi
MSA  mitigating strategies assessment
MSFHI  mitigating strategies flood hazard information
MSL  mean sea level
MSWEP multisource weighted-ensemble precipitation dataset
MVGC  multivariable Gaussian copula
MVGD  multivariable Gaussian distribution
MVTC  multivariable student’s t copula
N  average life loss (USBR, USACE)
NA14  NOAA National Atlas 14
NACCS  North Atlantic Coast Comprehensive Study
NAEFS  North American Ensemble Forecasting System
NAIP  National Agricultural Imagery Program
NAM-WRF North American Mesoscale Model—WRF
NAO  North Atlantic Oscillation
NARCCAP North American Regional Climate Change Assessment Program
NARR North American Regional Reanalysis (NOAA)
NARSIS  European Research Project New Approach to Reactor Safety Improvements
NASA National Aeronautics and Space Administration
NAVD88 North American Vertical Datum of 1988
NBS  net basin scale
NCA3/NCA4 U.S. Global Change Research Program Third/Fourth National Climate Assessment
NCAR  National Center for Atmospheric Research
NCEI  National Centers for Environmental Information
NCEP  National Centers for Environmental Prediction (NOAA)
ND  North Dakota
NDFD  National Digital Forecast Database (NWS)
NDSEV  number of days with severe thunderstorm environments
NE  Nebraska
NEA  Nuclear Energy Agency
NEB  nonexceedance bounds
NEI  Nuclear Energy Institute
NESDIS  NOAA National Environmental Satellite, Data, and Information Service
NEUTRINO  a general-purpose simulation and visualization environment including an SPH solver
NEXRAD  next-generation radar
NHC  National Hurricane Center
NI DAQ  National Instruments Data Acquisition Software
NID  National Inventory of Dams
NIOSH  National Institute for Occupational Safety and Health
NLDAS  North American Land Data Assimilation System
nm  nautical miles
NM  New Mexico
NMSS  NRC Office of Nuclear Material Safety and Safeguards
NOAA  National Oceanic and Atmospheric Administration
NOED  notice of enforcement discretion
NPDP  National Performance of Dams Program
NPH  Natural Phenomena Hazards Program (DOE)
NPP  nuclear power plant
NPS  National Park Service
NRC  U.S. Nuclear Regulatory Commission
NRCS  Natural Resources Conservation Service
NRO  NRC Office of New Reactors
NRR  NCEP-NCAR Reanalysis
NRR  NRC Office of Nuclear Reactor Regulation
NSE  Nash-Sutcliffe model efficiency coefficient
NSIAC  Nuclear Strategic Issues Advisory Committee
NSIR  NRC Office of Nuclear Security and Incident Response
NSSL  National Severe Storms Laboratory (NOAA)
NSTC  National Science and Technology Council
NTTF  Near-Term Task Force
NUREG  NRC technical report designation
NUVIA  a subsidiary of Vinci Construction Group, offering expertise in services and technology supporting safety performance in nuclear facilities
NWS  National Weather Service
<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>NY</td>
<td>New York</td>
</tr>
<tr>
<td>OAR</td>
<td>NOAA Office of Oceanic and Atmospheric Research</td>
</tr>
<tr>
<td>OE</td>
<td>NRC Office of Enforcement</td>
</tr>
<tr>
<td>OECD</td>
<td>Organization for Economic Co-operation and Development</td>
</tr>
<tr>
<td>OEDO</td>
<td>NRC Office of the Executive Director for Operations</td>
</tr>
<tr>
<td>OGC</td>
<td>NRC Office of the General Counsel</td>
</tr>
<tr>
<td>OHC</td>
<td>ocean heat content</td>
</tr>
<tr>
<td>OK</td>
<td>Oklahoma</td>
</tr>
<tr>
<td>OR</td>
<td>Oregon</td>
</tr>
<tr>
<td>ORNL</td>
<td>Oak Ridge National Laboratory</td>
</tr>
<tr>
<td>OSL</td>
<td>optically stimulated luminescence</td>
</tr>
<tr>
<td>OTC</td>
<td>once-through cooling</td>
</tr>
<tr>
<td>OWI</td>
<td>Ocean Wind Inc.</td>
</tr>
<tr>
<td>OWP</td>
<td>NOAA/NWS Office of Water Prediction</td>
</tr>
<tr>
<td>P</td>
<td>present</td>
</tr>
<tr>
<td>P/PET</td>
<td>precipitation over PET ratio, aridity</td>
</tr>
<tr>
<td>Pa</td>
<td>pascal</td>
</tr>
<tr>
<td>PB1</td>
<td>Branch 1 in NRC/R-I/DRP</td>
</tr>
<tr>
<td>PBL</td>
<td>planetary boundary layer</td>
</tr>
<tr>
<td>PCA</td>
<td>principal component analysis</td>
</tr>
<tr>
<td>PCHA</td>
<td>probabilistic coastal hazard assessment</td>
</tr>
<tr>
<td>PCMQ</td>
<td>Predictive Capability Maturity Quantification</td>
</tr>
<tr>
<td>PCMQBN</td>
<td>Predictive Capability Maturity Quantification by Bayesian Net</td>
</tr>
<tr>
<td>PD</td>
<td>performance demand</td>
</tr>
<tr>
<td>PDF</td>
<td>probability density function</td>
</tr>
<tr>
<td>PDF</td>
<td>performance degradation factor</td>
</tr>
<tr>
<td>PDS</td>
<td>partial-duration series</td>
</tr>
<tr>
<td>PE3</td>
<td>Pearson Type III distribution</td>
</tr>
<tr>
<td>PeakFQ</td>
<td>USGS flood frequency analysis software tool based on Bulletin 17C</td>
</tr>
<tr>
<td>PERSIANN-CCS</td>
<td>Precipitation Estimation from Remotely Sensed Information using Artificial Neural Networks—Cloud Classification System (University of California at Irvine Precipitation Algorithm)</td>
</tr>
<tr>
<td>PERT</td>
<td>program evaluation review technique</td>
</tr>
<tr>
<td>PET</td>
<td>potential evapotranspiration</td>
</tr>
<tr>
<td>P-ETSS</td>
<td>Probabilistic Extra-Tropical Storm Surge Model</td>
</tr>
<tr>
<td>Abbreviation</td>
<td>Full Form</td>
</tr>
<tr>
<td>--------------</td>
<td>-----------</td>
</tr>
<tr>
<td>PF</td>
<td>paleoflood</td>
</tr>
<tr>
<td>PF/P-F</td>
<td>precipitation frequency</td>
</tr>
<tr>
<td>PFAR</td>
<td>precipitation field area ratio</td>
</tr>
<tr>
<td>PFHA</td>
<td>probabilistic flood hazard assessment</td>
</tr>
<tr>
<td>PFM</td>
<td>potential failure mode</td>
</tr>
<tr>
<td>PI</td>
<td>principal investigator</td>
</tr>
<tr>
<td>P-I</td>
<td>pressure-impulse curve</td>
</tr>
<tr>
<td>PIF</td>
<td>performance influencing factor</td>
</tr>
<tr>
<td>PILF</td>
<td>potentially influential low flood</td>
</tr>
<tr>
<td>PM</td>
<td>project manager</td>
</tr>
<tr>
<td>PMDA</td>
<td>Program Management, Policy Development &amp; Analysis in NRC/RES</td>
</tr>
<tr>
<td>PMF</td>
<td>probable maximum flood</td>
</tr>
<tr>
<td>PMH</td>
<td>probable maximum hurricane</td>
</tr>
<tr>
<td>PMP</td>
<td>probable maximum precipitation</td>
</tr>
<tr>
<td>PMW</td>
<td>passive microwave</td>
</tr>
<tr>
<td>PN</td>
<td>product number</td>
</tr>
<tr>
<td>PNAS</td>
<td>Proceedings of the National Academy of Sciences of the United States of America</td>
</tr>
<tr>
<td>PNNL</td>
<td>Pacific Northwest National Laboratory</td>
</tr>
<tr>
<td>POANHI</td>
<td>Process for Ongoing Assessment of Natural Hazard Information</td>
</tr>
<tr>
<td>POB</td>
<td>Regulatory Policy and Oversight Branch in NRC/NSIR/DPR</td>
</tr>
<tr>
<td>POR</td>
<td>period of record</td>
</tr>
<tr>
<td>PPRP</td>
<td>participatory peer review panel</td>
</tr>
<tr>
<td>PPS</td>
<td>Precipitation Processing System</td>
</tr>
<tr>
<td>PR</td>
<td>Puerto Rico</td>
</tr>
<tr>
<td>PRA</td>
<td>probabilistic risk assessment</td>
</tr>
<tr>
<td>PRAB</td>
<td>Probabilistic Risk Assessment Branch in NRC/RES/DRA</td>
</tr>
<tr>
<td>PRB</td>
<td>Performance and Reliability Branch in NRC/RES/DRA</td>
</tr>
<tr>
<td>PRISM</td>
<td>a gridded dataset developed through a partnership between the NRCS National Water and Climate Center and the PRISM Climate Group at Oregon State University, developers of PRISM (the Parameter-elevation Regressions on Independent Slopes Model)</td>
</tr>
<tr>
<td>PRMS</td>
<td>USGS Precipitation Runoff Modelling System</td>
</tr>
<tr>
<td>Prométhée</td>
<td>IRSN software based on PROMETHEE, the Preference Ranking Organization METHod for Enrichment Evaluation</td>
</tr>
<tr>
<td>PRPS</td>
<td>Precipitation Retrieval Profiles Scheme</td>
</tr>
</tbody>
</table>
PS parallel stratiform
PSA probabilistic safety assessment, common term for PRA in other countries
PSD Physical Sciences Division in NOAA/OAR/ESRL
PSF performance shaping factor
psf pounds per square foot
PSHA probabilistic seismic hazard assessment
PSI paleostage indicators
PSSHA probabilistic storm surge hazard assessment
P-Surge probabilistic tropical cyclone storm surge model
PTI project technical integrator
PVC polyvinyl chloride
Pw/PW precipitable water
PWR pressurized-water reactor
Q quarter
QA quality assurance
QC quality control
QI Quality Index
QPE quantitative precipitation estimates
QPF quantitative precipitation forecast
R a statistical package
R 2.1 NTTF Report Recommendation 2.1
R&D research and development
R2 coefficient of determination
RAM regional atmospheric model
RASP Risk Assessment of Operational Events Handbook
RAVEN risk analysis in a virtual environment probabilistic scenario evolution RISMC tool
RC reinforced concrete
RCP (4.5, 8.5) representative concentration pathways
RELAP-7 reactor excursion and leak analysis program transient conditions RISMC tool
RENV Environmental Technical Support Branch in NRC/NRO/DLSE
REOF rotated empirical orthogonal function
RES NRC Office of Nuclear Regulatory Research
<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>RF</td>
<td>riverine flooding</td>
</tr>
<tr>
<td>RFA</td>
<td>regional frequency analysis</td>
</tr>
<tr>
<td>RFC</td>
<td>River Forecast Center (NWS)</td>
</tr>
<tr>
<td>RG</td>
<td>regulatory guide</td>
</tr>
<tr>
<td>RGB</td>
<td>red, green, and blue imagery (NAIP)</td>
</tr>
<tr>
<td>RGB-IF</td>
<td>red, green, blue, and infrared imagery (NAIP)</td>
</tr>
<tr>
<td>RGC</td>
<td>regional growth curve</td>
</tr>
<tr>
<td>RGGIB</td>
<td>Regulatory Guidance and Generic Issues Branch in NRC/RES/DE</td>
</tr>
<tr>
<td>RGS</td>
<td>Geosciences and Geotechnical Engineering Branches now in NRC/NRO/DLSE, formerly in NRC/NRO/DSEA</td>
</tr>
<tr>
<td>RHM</td>
<td>Hydrology and Meteorology Branch formerly in NRC/NRO/DSEA</td>
</tr>
<tr>
<td>RI</td>
<td>Rhode Island</td>
</tr>
<tr>
<td>R-I, R-II, R-III, R-IV</td>
<td>NRC Regions I, II, III, IV</td>
</tr>
<tr>
<td>RIC</td>
<td>Regulatory Information Conference, NRC</td>
</tr>
<tr>
<td>RIDM</td>
<td>risk-informed decisionmaking</td>
</tr>
<tr>
<td>RILIT</td>
<td>Risk-Informed Licensing Initiative Team in NRC/NRR/DRA/APLB</td>
</tr>
<tr>
<td>RISMC</td>
<td>risk information safety margin characterization</td>
</tr>
<tr>
<td>R (_{\text{max}})</td>
<td>radius to maximum winds</td>
</tr>
<tr>
<td>RMB</td>
<td>Renewals and Materials Branch in NRC/NMSS/DSFM</td>
</tr>
<tr>
<td>RMC</td>
<td>USACE Risk Management Center</td>
</tr>
<tr>
<td>RMSD</td>
<td>root-mean-square deviation</td>
</tr>
<tr>
<td>RMSE</td>
<td>root mean square error</td>
</tr>
<tr>
<td>ROM</td>
<td>reduce order modeling</td>
</tr>
<tr>
<td>ROP</td>
<td>Reactor Oversight Process</td>
</tr>
<tr>
<td>RORB-MC</td>
<td>an interactive runoff and streamflow routing program</td>
</tr>
<tr>
<td>RPAC</td>
<td>formerly in NRC/NRO/DSEA</td>
</tr>
<tr>
<td>RRTM</td>
<td>Rapid Radiative Transfer Model Code in WRF</td>
</tr>
<tr>
<td>RRTMS</td>
<td>RRTM with GCM application</td>
</tr>
<tr>
<td>RS</td>
<td>response surface</td>
</tr>
<tr>
<td>RTI</td>
<td>an independent, nonprofit institute</td>
</tr>
<tr>
<td>RV</td>
<td>return values</td>
</tr>
<tr>
<td>SA</td>
<td>storage area</td>
</tr>
<tr>
<td>SACCS</td>
<td>South Atlantic Coastal Comprehensive Study</td>
</tr>
<tr>
<td>SAPHIR</td>
<td>Sounding for Probing Vertical Profiles of Humidity</td>
</tr>
<tr>
<td>Abbreviation</td>
<td>Description</td>
</tr>
<tr>
<td>--------------</td>
<td>-------------</td>
</tr>
<tr>
<td>SAPHIRE</td>
<td>Systems Analysis Programs for Hands-on Integrated Reliability Evaluations</td>
</tr>
<tr>
<td>SBDFAs</td>
<td>simulation-based dynamic flooding analysis framework</td>
</tr>
<tr>
<td>SBO</td>
<td>station blackout</td>
</tr>
<tr>
<td>SBS</td>
<td>simulation-based scaling</td>
</tr>
<tr>
<td>SC</td>
<td>safety category (ANS 58.16-2014 term)</td>
</tr>
<tr>
<td>SC</td>
<td>South Carolina</td>
</tr>
<tr>
<td>SCAN</td>
<td>Soil Climate Analysis Network</td>
</tr>
<tr>
<td>SCRAM</td>
<td>immediate shutdown of nuclear reactor</td>
</tr>
<tr>
<td>SCs</td>
<td>curve number method</td>
</tr>
<tr>
<td>SD</td>
<td>standard deviation</td>
</tr>
<tr>
<td>SDC</td>
<td>shutdown cooling</td>
</tr>
<tr>
<td>SDP</td>
<td>significance determination process</td>
</tr>
<tr>
<td>SDR</td>
<td>Subcommittee on Disaster Reduction</td>
</tr>
<tr>
<td>SECY</td>
<td>written issues paper the NRC staff submits to the Commission</td>
</tr>
<tr>
<td>SEFM</td>
<td>Stochastic Event-Based Rainfall-Runoff Model</td>
</tr>
<tr>
<td>SER</td>
<td>safety evaluation report</td>
</tr>
<tr>
<td>SGSEB</td>
<td>Structural, Geotechnical and Seismic Engineering Branch in NRC/RES/DE</td>
</tr>
<tr>
<td>SHAC-F</td>
<td>Structured Hazard Assessment Committee Process for Flooding</td>
</tr>
<tr>
<td>SHE</td>
<td>Système Hydrologique Européan</td>
</tr>
<tr>
<td>SITES</td>
<td>model that uses headcut erodibility index by USDA-ARS and University of Kansas &quot;Earthen/Vegetated Auxiliary Spillway Erosion Prediction for Dams&quot;</td>
</tr>
<tr>
<td>SLC</td>
<td>sea level change</td>
</tr>
<tr>
<td>SLOSH</td>
<td>Sea Lake and Overland Surges from Hurricanes (NWS model)</td>
</tr>
<tr>
<td>SLR</td>
<td>sea level rise</td>
</tr>
<tr>
<td>SMR</td>
<td>small modular reactor</td>
</tr>
<tr>
<td>SNOTEL</td>
<td>snow telemetry</td>
</tr>
<tr>
<td>SNR</td>
<td>signal-to-noise ratio</td>
</tr>
<tr>
<td>SOH</td>
<td>Subcommittee on Hydrology</td>
</tr>
<tr>
<td>SOM</td>
<td>self-organizing map</td>
</tr>
<tr>
<td>SON</td>
<td>September, October, November</td>
</tr>
<tr>
<td>SOP</td>
<td>standard operating pressure</td>
</tr>
<tr>
<td>SPAR</td>
<td>standardized plant analysis risk</td>
</tr>
<tr>
<td>SPAS</td>
<td>Storm Precipitation Analysis System (MetStat, Inc.)</td>
</tr>
</tbody>
</table>

xxxi
SPH  smoothed-particle hydrodynamics
SPRA  PRA and Severe Accidents Branch in NRC/NRO/DESR (formerly in DSRA)
SRA  senior reactor analyst
SRES A2  NARCCAP A2 emission scenario
SRH2D/SRH-2D  USBR Sedimentation and River Hydraulics—Two-Dimensional model
SRM  staff requirements memorandum
SRP  standard review plan
SRR  storm recurrence rate
SSAI  Science Systems and Applications, Inc.
SSC  structure, system, and component
SSHAC  Senior Seismic Hazard Assessment Committee
SSM  Swedish Radiation Safety Authority (Strålsäkerhetsmyndigheten)
SSMI  Special Sensor Microwave Imager
SSMIS  Special Sensor Microwave Imager/Sounder
SSPMP  site-specific probable maximum precipitation
SST  sea surface temperature
SST  stochastic simulation technique
SST  stochastic storm transposition
SSURGO  soil survey geographic database
ST4 or Stage IV  precipitation information from multisensor (radar and gauges) precipitation analysis
STEnv  severe thunderstorm environment
STM  stochastic track method
StormSIm  stochastic storm simulation system
STSB  Technical Specifications Branch in NRC/NRR/DSS
STUK  Finland Radiation and Nuclear Safety Authority
STWAVE  STEady-state spectral WAVE model
SÚJB  Czech Republic State Office for Nuclear Safety
SWAN  Simulation Waves Nearshore Model
SWE  snow-water equivalent
SWL  still water level
SWMM  EPA Storm Water Management Model
SWT  Schaefer-Wallis-Taylor Climate Region Method
TAG  EPRI Technical Assessment Guide
TC  tropical cyclone
TCI  TRMM Combined Instrument
Td  daily temperature
TDF  transformed extreme value type 1 distribution function (four parameter)
TDI  technically defensible interpretations
TELEMAC  two-dimensional hydraulic model
TELEMAC 2D  a suite of finite element computer programs owned by the Laboratoire National d'Hydraulique et Environnement (LNHE), part of the R&D group of Électricité de France
T-H  thermohydraulic
TI  technical integration
TI  technology innovation project
TL  training line
TMI  Three Mile Island
TRMM Microwave Imager
TMPA  TRMM Multisatellite Precipitation Analysis
TN  Tennessee
TOPMODEL  two-dimensional distributed watershed model by Keith Beven, Lancaster University
TOVS  Television-Infrared Observation Satellite (TIROS) Operational Vertical Sounder
TP-#  Test Pit #
TP-29  U.S. Weather Bureau Technical Paper No. 29
TR  USACE technical report
TREX  two-dimensional, runoff, erosion, and export model
TUFORM  Tropical Rainfall Measuring Mission
TRVW  Tennessee River Valley Watershed
TS  technical specification
TS  trailing stratiform
TSR  tropical-storm remnant
TUFORM  two-dimensional hydraulic model
TVA  Tennessee Valley Authority
TX  Texas
U.S. or US  United States
UA  uncertainty analysis

xxxiii
UC  University of California
UH  unit hydrograph
UKF  uniform kernel function
UKMET  medium-range (3- to 7-day) numerical weather prediction model operated by the United Kingdom METeorological Agency
UL  Underwriters Laboratories
UMD  University of Maryland
UNR  user need request
UQ  uncertainty quantification
URMDB  Uranium Recovery and Materials Decommissioning Branch in NRC/NMSS/DUWP
USACE  U.S. Army Corps of Engineers (see also COE)
USACE-NWD  USACE NorthWest Division
USBR  U.S. Bureau of Reclamation
USDA  U.S. Department of Agriculture
USDA-ARS  United State Department of Agriculture—Agricultural Research Service
USFWS  U.S. Fish and Wildlife Service
USGS  United States Geological Survey
UTC  coordinated universal time
VA  Virginia
VDB  validation database
VDMS  Validation Data Management System
VDP  validation data planning
VIC  Variable Infiltration Capacity model
VL-AEP  very low annual exceedance probability
W  watt
WAK  Wakeby distribution
WASH-1400  Reactor Safety Study: An Assessment of Accident Risks in U.S. Commercial Nuclear Power Plants [NUREG-75/014 (WASH-1400)]
WB  U.S. Weather Bureau
WBT  wet bulb temperature
WEI  Weibull distribution
WGEV  Working Group on External Events
WGI  Working Group I
WI  Wisconsin
<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>WinDamC</td>
<td>USDA/NRCS model for estimating erosion of earthen embankments and auxiliary spillways of dams</td>
</tr>
<tr>
<td>WL</td>
<td>water level</td>
</tr>
<tr>
<td>WMO</td>
<td>World Meteorological Organization</td>
</tr>
<tr>
<td>WRB</td>
<td>Willamette River Basin</td>
</tr>
<tr>
<td>WRF</td>
<td>Weather Research and Forecasting model</td>
</tr>
<tr>
<td>WRR</td>
<td>Water Resources Research (journal)</td>
</tr>
<tr>
<td>WSEL / WSL</td>
<td>water surface elevation</td>
</tr>
<tr>
<td>WSM6</td>
<td>WRF Single-Moment 6-Class Microphysics Scheme</td>
</tr>
<tr>
<td>WSP</td>
<td>USGS Water Supply Paper</td>
</tr>
<tr>
<td>XF</td>
<td>external flooding</td>
</tr>
<tr>
<td>XFEL</td>
<td>external flood equipment list</td>
</tr>
<tr>
<td>XFOAL</td>
<td>external flood operation action list</td>
</tr>
<tr>
<td>XFPRA</td>
<td>external flooding PRA</td>
</tr>
<tr>
<td>yr</td>
<td>year</td>
</tr>
<tr>
<td>yrBP</td>
<td>years before present</td>
</tr>
<tr>
<td>Z</td>
<td>Zulu time, equivalent to UTC</td>
</tr>
</tbody>
</table>
INTRODUCTION

Background

The NRC is conducting a multiyear, multi-project Probabilistic Flood Hazard Assessment (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 (ADAMS Accession Nos. ML14318A070 and ML14296A442). The PFHA Research Plan was endorsed in a joint user need request by the NRC Office of New Reactors and Office of Nuclear Reactor Regulation (UNR NRO-2015-002, 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 (SDPs), notices of enforcement discretion (NOEDs)) as well as licensing of new facilities (e.g., early site permit applications, combined license (COL) applications), including proposed small modular reactors (SMRs) and advanced reactors. This methodology will give 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 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.

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 the NRC Office of Nuclear Regulatory Research (RES), (2) inform internal and external stakeholders about RES research collaborations with Federal agencies, the Electric Power Research Institute (EPRI) and the French Institute for Radiological and Nuclear
Security (IRNS) and (3) provide a forum for presentation and discussion of notable domestic and international PFHA research activities.

Workshop Scope

Scope of the workshop presentations and discussions included:

- 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
- Probabilistic flood hazard assessment frameworks
- Reliability of flood protection and mitigation features and procedures
- External flooding probabilistic risk assessment

Summary of Proceedings

These proceedings transmit the agenda, abstracts, and slides from presentations and posters presented, and chronicle the question and answer sessions and panel discussions held, at the U.S. Nuclear Regulatory Commission’s (NRC’s) Annual Probabilistic Flood Hazard Assessment (PFHA) Research Workshops, which take place approximately annually at NRC Headquarters in Rockville, MD. The first four workshops took place as follows:

- 1st Annual NRC PFHA Research Workshop, October 14–15, 2015
- 2nd Annual NRC PFHA Research Workshop, January 23–25, 2017 (Agencywide Documents Access and Management System (ADAMS) Accession No. ML17040A626)
- 3rd Annual NRC PFHA Research Workshop, December 4–5, 2017 (ADAMS Accession No. ML17355A071)
- 4th Annual NRC PFHA Research Workshop, April 30–May 2. 2019 (ADAMS Accession No. ML19156A446)

These proceedings include presentation abstracts and slides and a summary of the question and answer sessions. The first workshop was limited to NRC technical staff and management, NRC contractors, and staff from other Federal agencies. The three workshops that followed were meetings attended by members of the public; NRC technical staff, management, and contractors; and staff from other Federal agencies. Public attendees over the course of the workshops included industry groups, industry members, consultants, independent laboratories, academic institutions, and the press. Members of the public were invited to speak at the workshops. The fourth workshop included more invited speakers from the public than from the NRC and the NRC’s contractors.

The proceedings for the second through fourth workshops include all presentation abstracts and slides and submitted posters and panelists’ slides. Workshop organizers took notes and audio-recorded the question and answer sessions following each talk, during group panels, and during end-of-day question and answer session. Responses are not reproduced here verbatim and were generally from the presenter or co-authors. Descriptions of the panel discussions identify the speaker when possible. Questions were taken orally from attendees, on question cards, and over the telephone.
Related Workshops

An international workshop on PFHA took place on 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).
3 THIRD ANNUAL NRC PROBABILISTIC FLOOD HAZARD ASSESSMENT RESEARCH WORKSHOP

3.1 Introduction

This chapter details the 3rd Annual NRC Probabilistic Flood Hazard Assessment (PFHA) Research Workshop held at the U.S. Nuclear Regulatory Commission (NRC) Headquarters in Rockville, MD, on December 4-5, 2017. These proceedings include abstracts for the presentations, the slides from the presentations themselves, and a summary of question and answer sessions. The workshop was a public meeting attended by members of the public; NRC technical staff, management, and contractors; and staff from other Federal agencies.

The workshop began with an introduction from Mike Weber, Director, NRC Office of Nuclear Regulatory Research (RES). Following the introduction, NRC RES and Electric Power Research Institute (EPRI) staff presented descriptions of their flooding research programs.

Following the introduction session, NRC and EPRI contractors and staff gave technical presentations and answered clarifying questions. Partner Federal agencies took part in two panel discussions on their PFHA and external PRA efforts. At the end of each day, participants had an opportunity to provide feedback and ask generic questions about research related to PFHA for nuclear facilities.

3.1.1 Organization of Conference Proceedings

Section 3.2 provides the agenda for this workshop. The program is also located at ADAMS Accession No. ML17355A081.

Section 3.3 presents the proceedings from the workshop, including abstract, presentation slides, and summaries of the question and answer session for each of the technical sessions.

The summary document of session abstracts for the technical presentations can be viewed in the PFHA Research Workshop Program at ADAMS Accession No. ML17355A081. The complete workshop presentation package is available at ADAMS Accession No. ML17355A071.

Section 0 is a summary of the proceedings and Section 0 provides a list of the workshop attendees, including remote participants.
3.2 Workshop Agenda (ADAMS Accession No. ML17355A081)

3rd Annual NRC Probabilistic Flood Hazard Assessment Research Workshop at NRC headquarters in Rockville, Maryland

AGENDA: MONDAY, DECEMBER 4, 2017

08:10 – 08:20 Welcome

Session 1A - Introduction
Session Chair: Meredith Carr, NRC/RES

08:20 – 08:30 Introduction
Mike Weber*, Director, Office of Nuclear Regulatory Research 1A-1

08:30 – 09:00 NRC Flooding Research Program Overview
Joseph Kanney*, Meredith Carr, Tom Aird, Elena Yegorova, Mark Fuhrmann and Jacob Philip, NRC/RES 1A-2

09:00 – 09:30 EPRI Flooding Research Program Overview
John Weglian*, Electric Power Research Institute (EPRI) 1A-3

09:30 – 09:45 BREAK

Session 1B - Climate and Precipitation
Session Chair: Elena Yegorova, NRC/RES

09:45 – 10:15 Regional Climate Change Projections: Potential Impacts to Nuclear Facilities
L. Ruby Leung* and Rajiv Prasad, Pacific Northwest National Laboratory 1B-1

10:15 – 10:45 Numerical Modeling of Local Intense Precipitation Processes
M. Levent Kavvas, Mathieu Mure-Ravaud* and Alain Dib*
Hydrologic Research Laboratory, Department of Civil and Environmental Engineering, University of California, Davis 1B-2

10:45 – 11:15 Research to Develop Guidance on Extreme Precipitation Estimates in Orographic Regions
Kathleen Holman^, Andrew Verdin and D. Keeney, U.S. Bureau of Reclamation, Technical Service Center, Flood Hydrology and Meteorology 1B-3

* denotes presenter, ^ denotes remote presenter
Session 1C - Storm Surge
Session Chair: Joseph Kanney, NRC/RES

11:15 – 11:45 Quantification of Uncertainty in Probabilistic Storm Surge Models
Norberto C. Nadal-Carabalbo, and Victor Gonzalez*, U.S. Army Engineer R&D Center, Coastal and Hydraulics Laboratory

11:45 – 12:15 Probabilistic Flood Hazard Assessment – Storm Surge
John Weglian*, EPRI

12:15 – 13:15 LUNCH

Session 1D - Leveraging Available Flood Information
Session Chair: Nebiyu Tiruneh, NRC/NRO

13:15 – 13:45 Flood Frequency Analyses for Very Low Annual Exceedance Probabilities using Historic and Paleoflood Data, with Considerations for Nonstationary Systems

13:45 – 14:15 Extending Frequency Analysis Beyond Current Consensus Limits
Keil Neff* and Joseph Wright, U.S. Bureau of Reclamation, Technical Service Center, Flood Hydrology & Meteorology

14:15 – 14:45 Development of External Hazard Information Digests for Operating NPP sites
Kellie Kvarfordt* and Curtis Smith, Idaho National Laboratory

14:45 – 15:00 BREAK

Session 1E - Paleoflood Studies
Session Chair: Mark Fuhrmann, NRC/RES

15:00 – 15:30 Improving Flood Frequency Analysis with a Multi-Millennial Record of Extreme Floods on the Tennessee River near Chattanooga, TN
Tessa Harden*, Jim O’Connor and Mackenzie Keith, U.S. Geological Survey

15:30 – 16:00 Collection of Paleoflood Evidence
Lisa Davis*, University of Alabama and Gary Stinchcomb, Murray State University

16:00 – 16:30 Daily Wrap-up and Public Comments/Questions

16:30 – 18:00 Posters (Session 1F), Session Chair: Tom Aird, NRC/RES
Session 1F: Posters
Session Chair: Tom Aird, NRC/RES

Probability-Based Flow Modeling Using the Hydrologic Engineering Center Hydrologic Modeling System (HEC-HMS)
Brian Skahill, U.S. Army Corps of Engineers, Engineer Research and Development Center, Coastal and Hydraulics Laboratory

Reclamation’s Paleoflood Database: Design, Structure and Application
Jeanne E. Godaire, Kurt Wille, and Ralph E. Klinger, U.S. Bureau of Reclamation, Technical Services Center

Late Holocene Paleofloods Along the Middle Tennessee River Valley
C. Lance Stewart and Gary E. Stinchcomb, Department of Geosciences and Watershed Studies Institute, Murray State University; Steven L. Forman, Department of Geology, Baylor University; Lisa Davis and Rachel Lombardi, Department of Geography, University of Alabama; Emily Blackaby, Owen Craven and William Hockaday, Department of Geology, Baylor University

A regional chronology of floods and river activity during the last 10,000 years in the Eastern U.S.
Lisa Davis and Rachel Lombardi, Department of Geography, University of Alabama; Gary Stinchcomb, Watershed Studies Institute, Murray State University; C. Lance Stewart, Department of Geosciences, Murray State University; Matthew D. Therrell, Department of Geography, University of Alabama; Matthew Gage, Office of Archeological Research, University of Alabama

Critical Review of State of Practice in Dam Risk Assessment
David Watson, Scott DeNeale, Brennan Smith, Shih-Chieh Kao, Oak Ridge National Laboratory (ORNL); Gregory Baecher, University of Maryland

Application of Point Precipitation Frequency Estimates to Watersheds
Shih-Chieh Kao and Scott DeNeale, Oak Ridge National Laboratory

Quantification of Uncertainty in Probabilistic Storm Surge Models
Norberto Nadal-Caraballo, Victor Gonzalez and Efrain Ramos-Santiago
U.S. Army Corps of Engineers, Engineer Research and Development Center, Coastal and Hydraulics Laboratory

Modeling Plant Response to Flooding Events
Zhegang Ma, Curtis L. Smith and Steven R. Prescott, Idaho National Laboratory, Risk Assessment and Management Services; Ramprasad Sampath, Centroid PIC, Research and Development

Stratigraphic Records of Paleofloods, Geochronology and Hydraulic Modeling to Improve Flood Frequency Analysis
Tessa Harden, U.S. Geological Survey, Oregon Water Science Center
AGENDA: TUESDAY, DECEMBER 5, 2017

08:00 – 08:10  Day 2 Welcome

**Session 2A - Reliability of Flood Protection and Mitigation**

Session Chair: Mehdi Reisi-Fard, NRC/NRR

<table>
<thead>
<tr>
<th>Time</th>
<th>Topic</th>
<th>Speaker(s)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>08:40 – 09:10</td>
<td>EPRP Flood Protection Project Status</td>
<td>David Ziebell^ and John Weglian, EPRI</td>
<td>2A-2</td>
</tr>
<tr>
<td>09:40 – 09:55</td>
<td>BREAK</td>
<td></td>
<td></td>
</tr>
<tr>
<td>09:55 – 10:25</td>
<td>External Flooding PRA Walkdown Guidance</td>
<td>John Weglian*, EPRI</td>
<td>2A-4</td>
</tr>
</tbody>
</table>

**Session 2B - PFHA Frameworks**

Session Chair: John Weglian, EPRI

<table>
<thead>
<tr>
<th>Time</th>
<th>Topic</th>
<th>Speaker(s)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>11:25 – 11:55</td>
<td>Structured Hazard Assessment Committee Process for Flooding (SHAC-F) for Riverine Flooding</td>
<td>Rajiv Prasad* and Philip Meyer, Pacific Northwest National Laboratory; Kevin Coppersmith, Coppersmith Consulting</td>
<td>2B-2</td>
</tr>
<tr>
<td>11:55 – 13:00</td>
<td>LUNCH</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Session 2C - Panel Discussions

13:00 – 14:20 Flood Hazard Assessment Research and Guidance Activities in Partner Agencies
Session Chair: Joseph Kanney, NRC/RES
Panelists:
Norberto Nadal-Caraballo, U.S. Army Corps of Engineers, Engineer Research and Development Center
Kenneth Fearon, Federal Energy Regulatory Commission, Office of Energy Projects, Division of Dam Safety and Inspections
Sharon Jasim-Hanif, Department of Energy, Office of Nuclear Safety
Gabriel Miller, Tennessee River Valley Authority, River Management Department

14:20 – 15:45 External Flooding Probabilistic Risk Assessment: Perspectives on Gaps and Challenges
Session Chair: Fernando Ferrante, EPRI
Panelists:
John Weglian, EPRI
Zhegang Ma, Idaho National Laboratory
Ray Schneider, Westinghouse
Frances Pimentel and Victoria Anderson, Nuclear Energy Institute
Nathan Siu, NRC/RES
Christopher Cook, NRC/NRO

15:45 – 15:55 BREAK

Session 2D - Future Work at NRC and EPRI
Session Chair: Mark Fuhrmann, NRC/RES

15:55 – 16:15 Future Work in PFHA at EPRI
John Weglian*, EPRI

16:15 – 16:35 Future Work in PFHA at NRC
Joseph Kanney, Meredith Carr*, Tom Aird, Elena Yegorova, Mark Fuhrmann and Jacob Philip, NRC/RES

16:35 – 17:00 Final Wrap-up and Public Comments/Questions
3.3  Proceedings

3.3.1  Day 1: Session 1A - Introduction

Session Chair: Meredith Carr, NRC/RES/DRA/FXHAB

There are no abstracts for this introductory session.

3.3.1.1  Welcome  Michael Weber, Director, Office of Nuclear Regulatory Research (Session 1A-1; ADAMS Accession No. ML17355A082)
Why PFHA Research?

- Address gap in Risk-Informed Regulatory Framework
  - Commission policy to use risk-informed approaches to the extent practical
  - Other external hazards (e.g., wind, seismic) are evaluated using probabilistic approaches and metrics.
  - Current regulatory basis wrt flooding hazards (Reg Guides, Standard Review Plan, etc.) is deterministic
- Recent experience has highlighted importance of risk-informing flood hazard assessment and consequence analysis
  - Flooding events at NPPs in U.S. and abroad
  - Post-Fukushima flood hazard reevaluations

Progress and Next Steps

- Phased Approach
  - Technical basis and draft guidance
  - Pilot Studies
  - Finalize Guidance
- Bulk of technical basis research should be completed in FY19
  - Precipitation
  - Local Intense precipitation (LIP) flooding
  - Riverine flooding
  - Storm surge
  - Reliability of flood protection and mitigation
  - PFHA frameworks
- Need to turn our focus towards meaningful pilot studies
  - Site-specific issues
    - e.g., coastal/estuary vs. inland/river location
  - Full hazard curves
    - Coincident and correlated flooding processes
  - Integrating flood hazard assessment information into plant risk assessment models
3.3.1.2  **NRC Flooding Research Program Overview** Joseph Kanney*, Ph.D., Meredith Carr, Ph.D., P.E., Thomas Aird, Elena Yegorova, Ph.D., and Mark Fuhrmann, Ph.D., Fire and External Hazards Analysis Branch, Division of Risk Analysis; and Jacob Philip, P.E, Division of Engineering, Structural, Geotechnical and Seismic Engineering Branch, Office of Regulatory Research, U.S. NRC (Session 1A-2; ADAMS Accession No. ML17355A083https://www.nrc.gov/docs/ML1705/ML17054C500.pdf)

---

**Outline**

- Objectives
- Key Challenges
- Main Themes
- Current Projects
PFHA Research Objectives

- Support development of risk-informed licensing and oversight guidance and tools for assessing flooding hazards and consequences
  - Addresses significant gap in probabilistic basis for external hazards
    • Seismic and wind hazard assessments currently have probabilistic basis
- Support both new reactor licensing and oversight of operating reactors
  - Design basis flood hazard assessments for new facilities
    • 10 CFR Part 50 - traditional construction permits and operating licenses
    • 10 CFR Part 52 - early site permits (ESPs), combined operating licenses (COLs)
  - Operating reactor oversight program (ROP)
    • Significance determination process (SDP) analyses for evaluating deficiencies related to flood protection at operating facilities

Implementation

- Phased Approach
  - Phase 1 (Technical basis, draft guidance)
  - Phase 2 (Pilot studies)
  - Phase 3 (Finalize guidance)
- Implementation time-frame
  - ~5 years for Phase 1
    • now into 4th year of implementation
  - ~2 years for Phases 2+3
    • need to begin discussion of pilot studies
- Contract technical support
  - Interagency Agreements
    • DOE Laboratories, USACE, USBR, USGS
  - Commercial contracts
- External Collaborations
  - Federal Working Groups (e.g., ACWI/SOH)
  - EPRI (MOU in place)
  - International (e.g., IRSN)
Risk-informed Assessment of Flooding Hazards and Consequences

Hazard Curves: Quantitative probabilistic assessment of flood hazard(s)

Fragility Curves: Quantitative Reliability of Passive and Active Flood Protection Features

Impact Curves: Human Reliability Assessment (HRA) issues with flood protection and/or mitigation procedures

PRA?
Risk-informed Assessment of Flooding Hazards and Consequences

Key Challenges

- Interested in range of annual exceedance probabilities (AEPs) from moderately rare to extreme floods
  - *Full hazard curves needed*
    - Aleatory and epistemic uncertainties
  - *AEPs in the range 1e-4 to 1e-6 desired*
- Large uncertainties
- Component fragility and human reliability information is sparse
- Flooding impacts exhibit cliff-edge effects
- Complexity
  - Coincident and correlated mechanisms
  - Associated effects
Main Research Themes

- Approaches and methods to leverage available flood hazard information
- Application of improved modeling techniques for processes and mechanisms associated with flooding
- PFHA modeling framework(s) for range of flooding scenarios and range of AEPs
- Methods to assess potential impacts of dynamic and nonstationary processes on flood hazard assessments and flood protection
- Methods to assess reliability of flood protection, mitigation, and plant response to flooding events
Research Themes

Improved Modeling Methods
potential impacts of dynamic and nonstationary processes
PFHA Frameworks

Leverage Available Flooding Information
Reliability of Flood Protection and Plant Response

Phase 2 and Phase 3 Activities
Impacts
Internal Plant Model

Current Projects
Leverage Available Flooding Information

- Development of Flood Hazard Information Digests for Operating NPP Sites
  - Contractor: Idaho National Laboratory (INL)
  - NRC PM: Meredith Carr

- Guidance on Application of State-of-Practice Flood Frequency Analysis Methods and Tools
  - Contractor: U.S. Geological Survey (USGS)
  - NRC PM: Meredith Carr

Leverage Available Flooding Information

- Technical Basis for Extending Frequency Analysis Beyond Current Consensus Limits
  - Contractor: U.S. Bureau of Reclamation (USBR)
  - NRC PM: Joseph Kanney

- Research to Develop Guidance on Extreme Precipitation Frequency in Orographic Regions
  - Contractor: USBR
  - NRC PM: Joseph Kanney

- Detailed TN River Paleoflood Study
  - Contractor: USGS
  - NRC PM: Mark Fuhrmann
PFHA Frameworks

• Technical Basis for Probabilistic Flood Hazard Assessment – Riverine Flooding
  – Contractor: Pacific Northwest National Laboratory (PNNL)
  – NRC PM: Joseph Kanney

• Probabilistic Flood Hazard Assessment Framework Development
  – Contractor: U.S. Army Corps of Engineers (USACE)
  – NRC PM: Joseph Kanney

• Structured Hazard Assessment Committee Process for Flooding
  – Contractor: PNNL
  – NRC PM: Joseph Kanney

Improved Process Modeling

• Numerical Modeling of Local Intense Precipitation Processes
  – Contractor: University of California Davis/USGS
  – NRC PM: Elena Yegorova

• Quantifying Uncertainties in Probabilistic Storm Surge Models
  – Contractor: USACE
  – NRC PM: Joseph Kanney

• Erosion Processes in Embankment Dams
  – Contractor: USBR
  – NRC PM: Jacob Philip
Reliability of Flood Protection and Plant Response to Flooding Events

• Performance of Flood Penetration Seals at NPPs
  – Contractor: Fire Risk Management (FRM)
  – NRC PM: Tom Aird

• Effects of Environmental Factors on Manual Actions for Flood Protection and Mitigation at NPPs
  – Contractor: PNNL
  – NRC PM: Meredith Carr

• Modeling Plant Response to Flooding Events
  – Contractor: INL
  – NRC PM: Joseph Kanney

Dynamic and Nonstationary Processes

• Regional Climate Change Projections: Potential Impacts to Nuclear Facilities
  – Contractor: PNNL
  – NRC PM: Elena Yegorova
3.3.1.3 EPRI Flooding Research Program Overview

John Weglian, EPRI (Session 1A-3; ADAMS Accession No. ML17355A084)

Challenge with External Flooding

- External flooding hazards are assessed based on limited data
- In most places the historical record for events of interest are limited to just over 100 years
- Design basis analyses use the concept of a Probable Maximum Flood (PMF), but make no attempt to calculate the frequency of occurrence of such a flood
- Extrapolation to extremely low frequencies is required to probabilistically assess risk at nuclear power plants
  - PRA models assess risks down to a frequency of $10^{-7}$/yr or lower
  - The PFHA may be required to assess the hazard frequency down to as low as $10^{-6}$/yr – equivalent to an Annual Exceedance Probability (AEP) of $10^{-5}$
Techniques to Assess Low Frequency Flooding

- Extrapolation beyond twice the historical record is not considered to be credible
- A variety of methods are used to extend the effective historical record
  - Use of independent, but applicable measurements (e.g., rain gauges)
  - Transposition of observed storms from one location to another
  - Development of synthetic storms to simulate flooding impact with Monte Carlo analysis
  - Use of paleo (i.e., outside of the historical record) evidence to inform the data
- All of these techniques involve uncertainty, so it is important to characterize the uncertainty

EPRI Flooding Research Topics

- Hazard Assessment
  - State of knowledge of external flooding analysis – 3002005292
  - Riverine flooding – 3002003013
  - Local intense precipitation – 3002004400
  - Storm surge – 3002008111
  - Deterministic hazard assessment – 3002008113
- Analysis Techniques
  - Use of 3-D modeling techniques for flooding – 3002010673
- Managing existing design and licensing bases for flood protection barriers
  - Flood Protection Systems Guide – 3002005423
State of Knowledge of External Flooding Analysis

- **3002005292** – External Flooding Hazard Analysis: State of Knowledge Assessment
- Freely available to the public
- Examines the probabilistic methods currently available to assess external flooding hazard
  - Local intense precipitation
  - Riverine flooding
  - Dam failure
  - Storm surge

Riverine Flooding

- **3002003013** – Riverine Probabilistic Flooding Hazard Analysis Pilot: Proof-of-Concept Study for a Nuclear Power Plant
- Two stochastic models used to simulate riverine flooding at a site
  - Stochastic Event Flood Model (SEFM)
  - Stochastic Runoff Routing Monte Carlo (RORB_MC)
- Includes evaluation of uncertainties, expert judgement, and sensitivities of flood-hazard estimates to the various modeling components
Local Intense Precipitation

- **3002004400** – Local Precipitation-Frequency Studies: Development of 1-Hour/1-Square Mile Precipitation-Frequency Relationships for Two Example Nuclear Power Plant Sites
- Freely available to the public
- Maximizes available data by finding independent and applicable data sources and combining them

---

Storm Surge

- **3002008111** – Probabilistic Flooding Hazard Assessment for Storm Surge with an Example Based on Historical Water Levels
- Provides process for performing a probabilistic storm surge hazard assessment
- Provides an example using historical water levels rather than simulating the storm parameters
Deterministic Hazard Assessment

- **3002008113** – Evaluation of Deterministic Approaches to Characterizing Flood Hazards
- Freely available to the public
- Uses the Hierarchical Hazard Assessment (HHA) process in NUREG/CR-7046
- Examines the assumptions, inputs, and methods used for assessing external flooding hazards
  - Provides suggestions where changing of assumptions, inputs, and methods might provide a more realistic, yet still bounding assessment

Use of 3-D Modeling Techniques for Flooding

- **3002010673** - Investigation into the Use of Three-Dimensional Modeling Techniques to Assess Internal Flooding Scenarios
- Freely available to the public
- EPRI examined the use of Smoothed Particle Hydrodynamics (SPH) for modeling of internal flooding scenarios
  - Conclusions found that in most cases, the use of 1-D techniques is sufficient
  - SPH can be beneficial to capture spray or splash effects or when the PRA is sensitive to the timing of component failures
- EPRI did not investigate the use of SPH for external flooding, but the technique may be useful for those scenarios
EPRI’s NMAC Flood Protection Research

- **3002005423** – Flood Protection Systems Guide
  - Characterizes the flood protection systems in place
- **3002010620** - External Flood Protection Design/License Basis Management Best Practices Guide
  - Collects the administrative best practices across the industry on how to manage the design and licensing bases

Near-Term EPRI External Flooding Research

- Collection of paleoflood evidence - 3002010667
  - Report at end of 2017
- Guidance on conducting PRA external flooding walkdowns
  - Publication and training in 2018
Potential Future External Flooding Research

- Hazard assessment
  - Use of paleoflood data in risk-informed approaches
  - Estimation of frequency of hurricane-driven storm surge
  - Seiche and tsunami frequency estimation
  - Dam failure
- Analysis technique
  - External flooding PRA model development guidance
  - Correlated hazards modeling (e.g., storm surge and wind)
- Flood barrier fragility

Together...Shaping the Future of Electricity

John E. Weglian  Hasan Charkas
Senior Technical Leader  Senior Technical Leader
jweglian@epri.com  hcharkas@epri.com
704-595-2763  704-595-2645
3.3.1.3.1 Question and Answers

Question:

Are the EPRI reports discussed in this presentation free to the general public?

Response:

So, the report’s that specifically say they’re freely available to the public, anybody can get to them if you go to EPRI.com and you type in the number. In fact, this presentation has hyperlinks so if you follow that hyperlink for the public ones, it should take you to the public side of EPRI.com, where you can download that report for free. For those that did not specifically say “freely available” to the public, they are not free to the public. Members have access to those information and members of the public who choose to pay for them could also buy them in that way. EPRI prefers that you, even for the free to the public reports, that you go to the site and download your own copy rather than sharing it -just so we know how useful our materials are. We track that information so that we would know if everybody in this room downloaded one report, that report must be pretty important.

Question:

You commented on your 3D modeling the smooth vertical hydrodynamic model and it was for internal flooding only –not external.

Response:

But the research that we did was using internal flooding. We simulated flooding in a particular room that propagated through a stairway into another room and the point of that research was to see if there are new risk insights using this approach compared to what the industry is currently using. That’s why we used an internal flooding scenario because there are internal flooding models that are out there that we could compare against and so that’s why we looked at the internal flooding for that.

Question:

With regard to your correlated hazard models…have you thought about it at the Blayais site, the argument is that when the water table obviously exceeds the surface and it could be as you just described with the water cascading down the stair, coming through pipes, whatever…how have you thought about combing the external hazard with the internal?

Response:

So, that’s a good point. If the water sticks around long enough it can get into the groundwater and you may have…the utility that I came from, they had a pipe to measure groundwater and it’s just an open pipe and if the groundwater got high enough, you would expect water to be coming out of that. So, to do an external flooding hazard assessment, you need to take that into account and that’s a function of how long/high the water is around the site and how long it stays there. Local intense precipitation–probably not an impact. Riverine flooding, if it stays there for a couple months, almost certainly is and that would part of your hazard assessment. We tend to think, well maybe some of the practitioners are a little more nuanced but people that are not flooding experts, and before this, I was certainly in that category, think of flooding as just a water level. But there’s a
lot that goes into it. NRC had in their slides a bunch of different things and time of water staying there is part of it which can feed into it. So, to do an overall hazard assessment, you have to look at these other effects that the flooding can bring with it and that’s certainly part of it. And if you had that effect then you would have to start looking at the retention capability of some pumps that can remove that and determine what’s your ingress rate and your removal rate and does that cause you a problem or not.

**Question:**

You mentioned bounding assessments specifically to say a basin average three-day precipitation what scientific evidence do you have for bounds? In that research? Given the modeling that has been done in the community the past five years with WRF and uncertainties. We’re searching for that elusive bound…

**Response:**

Yeah, I did not mean to imply that EPRI has come up with one. I was saying the techniques used try to do that kind of bounding assessment on the deterministic side. I should not imply that EPRI has looked at that at all because none of the research that I talked about actually focused on estimating a bound to how much water can be provided or it can be like held in the atmosphere or things like that.

**Question:**

Yeah, I just bring this up to point out two things that are currently at hot topics in the literature. One is: we see no evidence of bounds from observations and two: in a warming environment there are open questions on to what a bound might be on precipitation.

**Response:**

Yeah that's a good point. I know I've seen when you estimate that the hazard curve there's usually two different forms that the hazard curve takes. One looks at the discharge rate as a function of frequency, and using the statistical approaches that we use, it usually does not look asymptotic. Right it looks like it just gets a bigger and bigger, faster and faster as you go lower in frequency. But then, when you convert that to what you have at a site, now this takes into account: are you in a narrow canyon or are you in a plane that they can spread out widely. So even if the discharge, say for riverine flooding, is continuing to increase without a bound, the flood level at your site may be more asymptotic. It depends on the topography near your site but typically the flood hazard curves at least for riverine flooding –I do see them -not the discharge itself- the amount of water coming is not typically shown as being asymptotic. So, it shows that there may not be a bound. It's just lower and lower frequency to get these higher and higher levels.

**Question:**

What is the cost-benefit comparison between using the SEFM model versus the RORB_MC model?

**Response:**

I was not involved in that study during my time at EPRI, so I was about to answer your question until you said cost-benefit. I don't know the cost-benefit analysis. I do know from looking at the two
models, they seem to be in relative agreement. They were certainly within the uncertainty bounds of each other. The means diverged a little bit at the lower frequencies. I would have to ask the people that actually focus on that research in terms of “was one more time-intensive to perform than the other?” I’m just not familiar with those details. The RORB model did take less resources than the SEFM model.

3.3.2 Day 1: Session 1B - Climate and Precipitation

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

Development of guidance for application of improved mechanistic and probabilistic modeling techniques for key flood generating processes and flooding scenarios.

Assessment of the potential impacts of dynamic and nonstationary processes on flood hazard assessments and flood protection at nuclear facilities.

3.3.2.1 Regional Climate Change Projections: Potential Impacts to Nuclear Facilities L. Ruby Leung^, Ph.D. and Rajiv Prasad*, Ph.D., Pacific Northwest National Laboratory (Session 1B-1; ADAMS Accession No. ML17355A085)

3.3.2.1.1 Abstract

This project is part of the NRC’s Probabilistic Flood Hazard Assessment (PFHA) research plan in support of developing a risk-informed licensing framework for flood hazards and design standards at proposed new facilities and significance determination tools for evaluating potential deficiencies related to flood protection at operating facilities. The PFHA plan aims to build upon recent advances in deterministic, probabilistic, and statistical modeling of extreme precipitation events to develop regulatory tools and guidance for NRC staff regarding PFHA for nuclear facilities. An improved understanding of large-scale climate pattern changes such as changes in the occurrence of extreme precipitation, flood/drought, storm surge, and severe weather events can help inform the probabilistic characterization of extreme events for NRC’s permitting, licensing, and oversight reviews.

This project provides a literature review, focusing on recent studies that improve understanding of the mechanisms of how the climate parameters relevant to the NRC may change in a warmer climate, including discussions of the robust and uncertain aspects of the changes and future directions for reducing uncertainty in projecting those changes. During the first year, the project reviewed various aspects of climatic changes across the U.S., while the second year focused on more detailed changes in the southeastern U.S. The current focus is on the Midwest region consisting of 8 states (Minnesota, Wisconsin, Michigan, Iowa, Missouri, Illinois, Indiana, and Ohio) in the conterminous U.S. Except for Indiana, all states have currently operating nuclear power plants. The literature review includes an overview of the climate of Midwest U.S., including temperature and precipitation extremes, floods and droughts, severe storms and strong winds including mesoscale convective systems, tornadoes, hail storms, and lake effect snow storms, Great Lakes water level, and flooding due to various mechanisms including heavy precipitation from convective storms in the summer and extratropical cyclones in the winter and snowmelt in spring. For each climate variable or phenomenon, the report discusses the climatological features over the Midwest region, the historical changes observed in the past, and the projected changes in the future, drawing on major reports from the National Climate Assessment and peer-reviewed
papers in the literature. Overall, mean and annual 5-day maximum temperatures are projected to increase in the future. With increasing moisture accompanying the warmer temperatures, precipitation is projected to increase in the cool season, but the changes in warm season precipitation are not statistically significant. Despite inconsistency in mean precipitation changes across the seasons, extreme precipitation (99th percentile) is projected to increase by more than 10% and 30% by the end of the 21st century under the RCP4.5 and RCP8.5 emissions scenarios, respectively. A regional climate modeling study at 4 km resolution projected more than tripling in the frequency of intense mesoscale convective systems in the summer. This is consistent with observational evidence of an increase in mean and extreme precipitation associated with mesoscale convective systems over the Midwest in the past 35 years. Lake effect snow storms are projected to increase as reduction of the surface area of lake ice with warming increases evaporation from the surface, but larger warming farther into the future may shift snowfall events into rain events. The Great Lake level has exhibited large variability historically. Models projected small decreases in the lake level but the range of uncertainty across model projections is large. Observational records over the Midwest show strong evidence of increasing flood frequency but limited evidence of increasing flood peaks. With the increase in extreme precipitation and storm events projected for the future, flooding is projected to increase notably in the future. Projected increase in average number of days without precipitation could lead to agricultural drought and increased cooling water temperatures.

3.3.2.1.2 Presentation

Regional Climate Change Projections - Potential Impacts to Nuclear Facilities

L. Ruby Leung and Rajiv Prasad
Pacific Northwest National Laboratory

3rd Annual Probabilistic Flood Hazard Assessment Workshop
NRC Headquarters, Rockville, MD
December 4, 2017
The Midwest region

- Midwest Region in NCA3 and NCA4: Illinois, Indiana, Iowa, Michigan, Minnesota, Missouri, Ohio, Wisconsin
- All states in the Midwest Region except for Indiana, have operating nuclear power plants

Changes in hot days

- Increase in heat extremes can pose challenges to infrastructure (e.g., material stress) and rising stream temperature may affect power plant operations

Consecutive days with Tmax > 95°F

Projected number of days > 100°F for Chicago
Seasonal precipitation changes

- Annual precipitation in the Midwest has increased by 5% to 15% from 1901–1960 compared to 1986–2015.
- Increase in cold season precipitation due to poleward shift of storm tracks.

Changes in extreme precipitation

- Observed changes are largest over the Midwest.
- Projected changes are largest over the Midwest and western U.S.

(USGCRP 2017)

Observed Change in Total Annual Precipitation Above the 99th Percentile

Regional extreme precipitation event frequency

(USGCRP 2017)
Contribution of MCS to mean and extreme precipitation

- Mesoscale convective systems (MCSs) play a critical role in producing heavy rainfall in the tropics and mid-latitudes during warm seasons.
- In Midwest, MCSs contribute 30%-60% of the total warm-season rainfall.
- Most of 100-yr, 24-h extreme rainfall events east of the Rocky Mountains were caused by MCSs in the warm season (Stevenson & Schumacher 2014).

15-year MCS precipitation climatology

![Map of MCS precipitation climatology](Feng et al. (2016) Nature Commun.)

Extreme Event Types

![Bar chart of extreme event types](Stevenson & Schumacher 2014 MWR)

MCS rainfall increased in the past

- Some regions in Midwest experienced 0.4-0.8 mm day⁻¹ (20-40%) increase in MCS precipitation.
- 95th percentile MCS hourly rain-rate increased consistent with mean MCS precipitation increase.

(Feng et al. 2016 Nature Commun.)
Changes in large-scale environment

Surface warming over land and lack of warming in surrounding oceans increase pressure gradient across central US

Low-level moistening associated with enhanced GLLJ moisture transport facilitates more intense MCS precipitation

(Feng et al. 2016 Nature Commun.)

Changes in hourly extreme precipitation from convection permitting simulations

Precipitation change (%) for 2071-2100 relative to 1976-2005:
increase in 99.95% hourly precipitation everywhere

(Prein et al. 2016 Nature Climate Change)
Changes in MCS precipitation

- Intense summertime MCS frequency will more than triple in North America
- MCSs that move slower than 20 km h⁻¹ reduce their speed by up to 20% in the Midwest, Mid-Atlantic, and Canada

(Prein et al. 2017 Nature Climate Change)

Simulating changes in HCW

Average difference between 2080–2090 and 1980–1990 modeled severe weather reports

Environmental conditions explain over 80% of the variance associated with modeled reports during March–May

(Gensini and Mote 2015 Climatic Change)
Midwest droughts - historical

- Meteorological (precipitation deficit), Agricultural (soil moisture deficit), and Hydrological (runoff/streamflow deficit)
- 2012 Great Plains/Midwest drought, most severe observed meteorological drought caused by large-scale meteorology reducing rain during summer (May-August, 2012)

Standardized anomalies over May – Aug 2012 relative to 1979-2011

- Precipitation
- Runoff
- Temperature
- Soil Moisture

(Hoerling et al., 2014 BAMS)

Midwest droughts - projected

- Increases in temperatures in the future are expected to result in increases in evapotranspiration exceeding increases in precipitation, leading to increased soil moisture deficits and agricultural droughts

(USGCRP 2017)
Midwest floods - historical

- 2008 floods (USGS Professional Paper 1775)
  - Above-average snowpack, record precipitation, saturated soils, remnants of two hurricanes
  - Separate flooding events in January through July, and September 2008
  - Affected all states in the Midwest Region except Ohio

- 2011 floods (USGS Professional Paper 1798-B)
  - Large snowpack, near-record spring rainfall, large releases from dams
  - Flooding from February through September 2011

- Mallakpour and Villarini, 2015, 2016

Midwest floods - projected

- Projected future floods
  - NCA3: Increases in rainfall and flooding are expected to continue in the future
    - Total amount of precipitation to increase
    - Number of days with top 2% of rainfalls to increase
    - Wettest 5-day total precipitation to increase
    - Consecutive dry days to increase (related to droughts)
    - Warm-season precipitation to increase
  - NCA4:
    - Frequency and intensity of heavy precipitation events to increase (high confidence); based on physical reasoning local flooding in some catchments or regions would increase (medium confidence)
Midwest streamflow - historical

- EPA Climate Change Indicators, 2016
  - Mean annual streamflow
  - 3-day high streamflow
  - 7-day low streamflow
  - Timing of spring runoff
- Kelly et al., 2016; Gupta et al., 2015

Midwest streamflow - projected

- Projected future streamflow
  - Demaria et al., 2016
  - Chien et al., 2013

---

Fig. 5. Trends in GCM-driven simulations of 3-day peak flows (left column), 7-day peak flows (middle column), and annual mean streamflow (right column), during the historical (1912–2000) and future (2021–2080) periods. The blocks of colors indicate the location of basins with statistically significant (α=0.05) joint changes in the mean using the t-test test in Fig. 4. The numbers in the lower right corners indicate the percentage of basins with statistically significant trends.
Great Lakes water levels - historical

- Historical water levels

  ![Water Levels of the Great Lakes, 1860-2015](image)

  *Water levels in the Great Lakes have fluctuated since 1860. Over the last ten decades, they appear to have declined for most of the Great Lakes. Recent water levels are all within the range of historical variation, however.*

Great Lakes water levels - projected

- Projected future water levels
  - International Upper Great Lakes Study, 2012

Fig. 3  NBS mean seasonal cycle for: a Lake Superior; b Lake Michigan – Huron; c Lake Erie, blue-observed (EC residual method); red-GLCRM 1962–1990; green-GLCRM 2021–2050. Units are mm over lake surface area.
3.3.2.1.3 Questions and Answers

Question:
Have you had the opportunity to read Marty McCann’s study on the 2002 drought? It was interesting. So, the question is on persistence and what the variable of interest is? So, for those who haven't looked in the Midwest drought in 2012, they're claiming a record. The interesting story hydrologically and for maybe some of the facilities may be the persistence of droughts where the thirties duration was longer. So, the question is, have you had the opportunity to look at durational effects rather than single magnitudes? And whether there be a precipitation or on either end of the tales?

Response:
I haven't looked at that yet but there are certain papers which say that the durations of the droughts are going to increase. Those are very relevant in terms of if you are operating a plan and you have low water supplies combined with if you are getting the water supply from the Great Lakes. Obviously with the lower levels going down, you have a concern not in terms of flooding but in terms of operating the plant itself. Yes.

Question:
David Bowles, emeritus Utah State. I'm curious in the percentiles that you showed in your various results, do you incorporate aleatory variability in that or is there epistemic uncertainty associated with the various types of modeling that go into those estimates as well?
Response:

So, I assume that you're talking about the precipitation. So, those are based on a collection of global climate model projections and so essentially the kind of uncertainty that has been incorporated include several things. One is that they look at both the so-called high-end scenario versus the low-end scenarios so that would if you're kind of like the range. And then because it is a multi-model that also gives you some uncertainty related to how processes are being represented in different climate models. As well as looking at a longer range, looking at the internal variability as well. So, it's really essentially three sources of uncertainty can be considered using that type of approach but there are obviously other types of sources as well that that may not have been considered.

Question:

Bill Kappel from Applied Weather Associates. Great presentation just a quick two-part question one on the modeling aspect and one on the meteorological aspect of the presentation. Early on in the slides you had a slide which showed the hot days in Chicago which had an observed normal period from 1986 to 2005 then two periods after that what showed significant warming starting in 2016 and the question I have on that is first of all the observed data at least for Chicago doesn't show the same trend. In fact, the hottest days in Chicago happened in the 1940s, 50s, and 80s, and so the first question is if the observed data isn't fitting the trend that's showing in that graphic and specifically between 2005 and 2016 there has not been any increase, how does that marry up of the modeling environment if it's not correct in the beginning? Why would we think would be good going forward? And this is not specific for uses of any model, so that's the first question of how we deal with that uncertainty in the models it's not matching observations. The second part of the question is the highest temperatures recorded in Chicago just being specific to Chicago have been in the 1930s, 50s, 1988, and 2012. All those periods were significant drought periods, and that makes sense. Yet on your model projections, you showed that precipitation was going to be increasing significantly in Chicago. So, I'm just trying to figure out that incongruity there where if it's going to have higher precipitation you would expect it to actually have not as extreme temperatures. Anyway, so just those two kinds of questions on the modeling environment if you can answer those please.

Response:

Okay so I can comment on the on the first question. I think you're right that what basically these results showing here from the NCA full report is only based on model projections so there's no particular process in terms of reconciling the model projection into the future with what the models simulate in the past. That could be inconsistent with regard to that and also for the point that these are based on results from mostly four models that have pretty close resolution. So, if you look at a specific city like Chicago, there might be local effects in terms of urbanization, as well as lake effects, and other things that are not being captured by these global climate model projections. So obviously, a lot more needs to be done in terms of reconciling the observed record, especially for a particular location with climate model projections that are much broader scale. The second part of the question about the increasing precipitation but at the same time why do we have that sort of this drought?

Question:

Sorry, and by the way, I understand these are all models. I'm just trying to clear this up. In the temperature records for Chicago, specifically, all the hottest days have been during significant
Response:

One thing the studies are mentioning is that there is not really a local scale assessment that is available for you to look at and try to make these determinations. But at the same time, generally speaking, they're saying if the temperatures are increasing in the future then you might be having elevated evapotranspiration and if that is happening, basically taking the conditions that are predicted by the larger scale modeling and trying to put in context of the physical nature in which the hydrology actually works. So, if you look at that, then they're just making a general statement that this is what we expect to happen. Now with the NCA4 Volume 2 coming out which is going to describe a lot of the regional studies, we might be able to see some more evidence of this thing.

3.3.2.2 Numerical Modeling of Local Intense Precipitation Processes M. Lev Kavvas, Ph.D. Mathieu Mure-Ravaud**, and Alain Dib*, Hydrologic Research Laboratory, Department of Civil and Environmental Engineering, University of California, Davis (Session 1B-2; ADAMS Accession No. ML17355A086)

3.3.2.2.1 Abstract

As population and infrastructure continue to increase, our society has become more vulnerable to extreme events. Flood is an example of a hydro-meteorological disaster that has a strong societal impact. Tropical Cyclones (TCs) and Mesoscale Convective Systems (MCSs) are recognized for their ability to generate intense precipitation that may in turn create disastrous floods. TCs are intense atmospheric vortices that form over the warm tropical oceans, while MCSs are organized collections of several cumulonimbus clouds which interact at the meso-scale (regional-scale) to form an extensive and nearly contiguous region of precipitation. In this study, the suitability of a regional atmospheric model (RAM) to simulate local intense precipitation processes within intense MCSs was first assessed. More specifically, the Weather Research and Forecasting (WRF) model was used at 5-km resolution in order to reconstruct the intense precipitation fields associated with several historical MCSs which affected the United States. The storm systems were selected within the time period from 2002 to the present, based on the NCEP Stage-IV precipitation dataset, which is a mosaic of regional multi-sensor analysis generated by the National Weather Service River Forecast Centers (RFCs) since 2002. These storms correspond to the most severe storms, in terms of the generation of an intense precipitation field containing pockets of extreme rainfall. The model's simulation nested domains were set up over a region in the Midwest so that the innermost domain covered the severe precipitation areas caused by these storm systems. The WRF model was configured to obtain the best results for the simulation of each of the selected severe MCSs storm events with respect to the simulated and observed precipitation fields. The simulations results were compared with the observations from the Stage IV precipitation dataset. More precisely, on one hand, the simulation results were evaluated by means of several metrics: the relative error for the simulation inner-domain total precipitation, the percentage of overlapping between the simulated and observed fields for several precipitation thresholds, and the precipitation field area ratio. On the other hand, the simulated and observed precipitation fields were plotted so as to visually appreciate the similarities and differences in the fields' structure and intensity.
It was shown that under an appropriate choice of the model’s options and boundary conditions, the WRF model provided satisfactory results in reproducing the location, intensity, and structure of the intense precipitation fields of the historical MCSs. The model’s options that were investigated are the parameterization schemes including microphysics, cumulus parameterization, planetary boundary layer physics, long wave and short wave radiation physics, etc. Although certain combinations of the parameterization schemes provided in each case realistic results in terms of the precipitation fields’ structures and intensity, placing these fields in the correct spatial locations required additional efforts, so that the best set of model’s options varied from one storm system to the other. Second, in this study, a new storm transposition method designed for the transposition of TCs is presented. This method is fully physically based, as it uses a RAM to numerically simulate a TC and its precipitation field. As a result, it has the fundamental advantage of conserving the mass, momentum, and energy in the system since the RAM numerically solves the equations governing the conservation of these quantities. The objective of this method is to find the amount of shift which maximizes the precipitation depth over a given target area. The transposition method was applied to four hurricanes that had spawned torrential precipitation in the United States, namely Hurricanes Floyd (1999), Frances (2004), Ivan (2004), and Isaac (2012). The drainage basin of the city of Asheville, NC was selected as the target. It was observed that the precipitation fields changed in both structure and intensity after transposition. The convergence of the vertically integrated vapor transport (IVT) was found to play a central role in the generation of intense precipitation in these hurricanes.

3.3.2.2.2 Presentation

![Image of the cover page of the report](image-url)
Plan

1. Extreme precipitation events in the USA
2. Modeling framework
3. Metrics used for model validation
4. Reconstruction of the intense Mesoscale Convective Systems (MCSs)
5. Reconstruction of the intense Tropical Cyclones (TCs)
6. Transposition of the intense TCs
7. Ongoing and future work

Classifications of extreme precipitation events in the USA

- Various classifications of extreme precipitation events in the literature
- In general, a distinction between tropical and non-tropical origin
- Classification proposed by Schumacher and Johnson (2005) and Stevenson and Schumacher (2014):
  - **Mesoscale Convective Systems**: convective systems with areal extents greater than 100 km and with durations between 3 and 24 h
  - **Synoptic Systems**: events characterized by the strong large-scale ascent commonly associated with synoptic-scale features (e.g., extratropical cyclones) and/or events lasting longer than 24 h
  - **Tropical Systems**: hurricanes and events that are a direct result of a tropical cyclone or its remnants
Objective

Assess the suitability of a regional numerical weather model to

- Simulate local intense precipitation processes, such as MCSs and TCs
- Serve as a test bed for moisture maximization and storm transposition techniques, ultimately updating maximum precipitation estimates and quantifying uncertainty bounds

Selection of intense storms

- We selected 13 TCs and 14 MCSs which generated intense precipitation fields in the USA

  - Hurricane Floyd (1999)
  - Hurricane Isaac (2002)
  - Hurricane Frances (2004)
  - Hurricane Ernesto (2006)
  - Tropical Storm Fay (2008)
  - Hurricane Gustav (2008)
  - Hurricane Irene (2011)
  - Tropical Storm Lee (2011)
  - Hurricane Isaac (2012)
  - Hurricane Sandy (2012)
  - Hurricane Matthew (2016)
  - June 22, 2002 MCS
  - August 22, 2002 MCS
  - September 15, 2004 MCS
  - June 25, 2005 MCS
  - August 17, 2005 MCS
  - September 25, 2005 MCS
  - July 18, 2007 MCS
  - August 19, 2007 MCS
  - June 5, 2008 MCS
  - August 8, 2009 MCS
  - July 23, 2010 MCS
  - September 23, 2010 MCS
  - July 26, 2011 MCS
  - June 22, 2013 MCS

- Intense precipitation events were identified using the website [http://schumacher.atmos.colostate.edu/precip_monitor/](http://schumacher.atmos.colostate.edu/precip_monitor/) from the Precipitation Systems Research Group in Colorado State University

- This website lists every event for which a given threshold (e.g., 100 year, 24 hour) was exceeded for at least one grid cell in the Stage IV precipitation analyses
Plan

1. Extreme precipitation events in the USA
2. Modeling framework
3. Metrics used for model validation
4. Reconstruction of the intense Mesoscale Convective Systems (MCSs)
5. Reconstruction of the intense Tropical Cyclones (TCs)
6. Transposition of the intense TCs
7. Ongoing and future work

Modeling framework

- We used the Weather Research and Forecasting (WRF) model at 5-km resolution in order to reconstruct the intense precipitation fields

- Climate Forecast System Reanalysis (CFSR) was used for initial and boundary conditions. The provided spatial and temporal resolutions of CFSR are 0.5 x 0.5 degree and 6-hourly

- The WRF model was run in the offline mode: it was only subject to the influence of its initial and boundary conditions, and no observation was used to improve the simulations through nudging or other data assimilation techniques
Modeling framework

- The WRF model was configured to obtain satisfactory results for the simulation of each of the selected severe MCS and TC storm events with respect to the precipitation fields by trying different combinations of the parameterization schemes
  - Microphysics
  - Cumulus parameterization
  - Planetary boundary layer
  - Longwave radiation
  - Shortwave radiation

- Validation of the WRF model in the offline mode is necessary for the purposes of the project
  - Storm transposition (shifting)
  - Downscaling of a climate projection from a GCM

Plan

1. Extreme precipitation events in the USA
2. Modeling framework
3. Metrics used for model validation
   4. Reconstruction of the intense Mesoscale Convective Systems (MCSs)
   5. Reconstruction of the intense Tropical Cyclones (TCs)
6. Transposition of the intense TCs
7. Ongoing and future work
Validation of the results

The results of the WRF model were validated in two ways:

1. The observed and simulated precipitation fields were plotted in order to visually appreciate their similarities and differences, in terms of the fields' position, texture, and intensity.

2. Three statistics were used to assess the model's performances:
   A. **Relative error**: indicates if the model could adequately simulate the total precipitation depth over the period of interest.
   B. **Percentage of overlapping**: indicates if the model could place the storm system in the appropriate location.
   C. **Precipitation field area ratio (PFAR)**: indicates if the model could properly simulate the size of the precipitation field.

---

**Percentage of Overlapping and Precipitation Field Area Ratio (PFAR)**

**Percentage of Overlapping**

\[
= \left( \frac{\text{red}}{\text{green} + \text{red}} \right) \times 100
\]

\[= 54.8\%\]

**PFAR**

\[
= \left( \frac{\text{blue} + \text{red}}{\text{green} + \text{red}} \right)
\]

\[= 0.59\]

Best model performance when Percentage of Overlapping is close to 100% and PFAR is close to 1.
Plan

1. Extreme precipitation events in the USA
2. Modeling framework
3. Metrics used for model validation
4. Reconstruction of the intense Mesoscale Convective Systems (MCSs)
5. Reconstruction of the intense Tropical Cyclones (TCs)
6. Transposition of the intense TCs
7. Ongoing and future work

Simulation domains for the Mesoscale Convective Systems

Two nested domains were set up for the WRF numerical simulation so that the inner domain covers an area where intense precipitation is frequently caused by Mesoscale Convective Systems

1. Domain 1 (purple) is the outer, parent domain. It has a resolution of 15 km (76 x 58)
2. Domain 2 (light blue) is the inner, nested domain. It has a resolution of 5 km (166 x 118)
July 28, 2011 Mesoscale Convective System

Total precipitation computed from 07/27/2011 at 15:00 to 07/28/2011 at 15:00

The relative error was computed to be -7.0%

July 28, 2011 Mesoscale Convective System
For the 75th percentile (9.09 mm)

Percentage of Overlapping = 42.5%

PFAR = 0.66

Color Legend
Green: observation only
Blue: simulation only
Red: overlap
July 28, 2011 Mesoscale Convective System
For the 99th percentile (132.63 mm)

Percentage of Overlapping = 61.7%
PFAR = 1.14

Overview of additional reconstructed Mesoscale Convective Systems

**July 23, 2010 MCS**
07/22/2010 at 18:00 to 07/23/2010 at 18:00

**September 25, 2005 MCS**
09/24/2005 at 21:00 to 09/25/2005 at 21:00

**June 22, 2002 MCS**
06/21/2002 at 19:00 to 06/22/2002 at 19:00

**June 25, 2005 MCS**
06/24/2005 at 18:00 to 06/25/2005 at 18:00
Reconstruction of intense Mesoscale Convective Systems

- Visually comparing the observation and simulation figures shows that the MCSs simulated by the WRF model are quite similar in shape, texture, and location to the MCSs shown on their corresponding observation figures.

- The three statistics computed for each event also revealed that the WRF model simulated the total precipitation depth, the location of the storm, and the field size adequately well for all the MCSs.

- The WRF model was capable of reproducing all the selected intense MCSs very well under the appropriate model parameterization schemes.

Plan

1. Extreme precipitation events in the USA
2. Modeling framework
3. Metrics used for model validation
4. Reconstruction of the intense Mesoscale Convective Systems (MCSs)
5. Reconstruction of the intense Tropical Cyclones (TCs)
6. Transposition of the intense TCs
7. Ongoing and future work
Simulation nested domains for Hurricane Isaac (2012)

- Domain 1 (same for all storms):
  - 45 km resolution
  - 120 x 110

- Domain 2:
  - 15 km resolution
  - 127 x 127

- Domain 3:
  - 5 km resolution
  - 229 x 244

---

Hurricane Isaac (2012)

<table>
<thead>
<tr>
<th>Observed precipitation field</th>
<th>Simulated precipitation field</th>
<th>IVT and its divergence</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>Relative Error</th>
<th>50th percentile</th>
<th>75th percentile</th>
<th>90th percentile</th>
<th>95th percentile</th>
<th>97.5th percentile</th>
<th>99th percentile</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>% overlap</td>
<td>PFAR</td>
<td>% overlap</td>
<td>PFAR</td>
<td>% overlap</td>
<td>PFAR</td>
</tr>
<tr>
<td>-13%</td>
<td>56%</td>
<td>0.87</td>
<td>49%</td>
<td>0.94</td>
<td>53%</td>
<td>0.84</td>
</tr>
</tbody>
</table>

---
Plan

1. Extreme precipitation events in the USA
2. Modeling framework
3. Metrics used for model validation
4. Reconstruction of the intense Mesoscale Convective Systems (MCSs)
5. Reconstruction of the intense Tropical Cyclones (TCs)
6. Transposition of the intense TCs
7. Ongoing and future work

Storm transposition of Tropical Cyclones

* We developed a new fully physically based method for the storm transposition (i.e. shifting) of TCs.

* The objective of this method is to find the amount of shift which maximizes the precipitation depth over a given target area.

* It uses a regional atmospheric model (RAM) to numerically simulate a TC and its precipitation field. As a result, it has the fundamental advantage of conserving the mass, momentum, and energy in the system since the RAM numerically solves the equations governing the conservation of these quantities.
### Precipitation Analysis

**72 h accumulated precipitation (mm)**

<table>
<thead>
<tr>
<th>Precipitation</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>WE Shift</td>
<td>0.39 degrees</td>
</tr>
<tr>
<td>SN Shift</td>
<td>0.39 degrees</td>
</tr>
<tr>
<td>Start Date</td>
<td>08/28 22h</td>
</tr>
<tr>
<td>End Date</td>
<td>08/31 22h</td>
</tr>
</tbody>
</table>

**Watershed accumulated precipitation**

**Precipitation (mm)**

<table>
<thead>
<tr>
<th>Precipitation</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>WE Shift</td>
<td>0.59 degrees</td>
</tr>
<tr>
<td>SN Shift</td>
<td>0.59 degrees</td>
</tr>
<tr>
<td>Start Date</td>
<td>08/29 11h</td>
</tr>
<tr>
<td>End Date</td>
<td>09/01 11h</td>
</tr>
</tbody>
</table>
Precipitation | 158 mm
---|---
WE Shift | 0.74 degrees
SN Shift | 0.74 degrees
Start Date | 08/29 12h
End Date | 09/01 12h

Watershed accumulated precipitation

Precipitation | 181 mm
---|---
WE Shift | 0.79 degrees
SN Shift | 0.79 degrees
Start Date | 08/29 08h
End Date | 09/01 08h

Watershed accumulated precipitation
Precipitation: 106 mm
WE Shift: 0.88 degrees
SN Shift: 0.88 degrees
Start Date: 08/28 16h
End Date: 08/31 16h

Precipitation: 155 mm
WE Shift: 0.98 degrees
SN Shift: 0.98 degrees
Start Date: 08/28 17h
End Date: 08/31 17h
Plan

1. Extreme precipitation events in the USA
2. Modeling framework
3. Metrics used for model validation
4. Reconstruction of the intense Mesoscale Convective Systems (MCSs)
5. Reconstruction of the intense Tropical Cyclones (TCs)
6. Transposition of the intense TCs

7. Ongoing and future work

Ongoing and future work

* Perform the storm transposition exercise for one MCS

* Determine the most intense future storm for each region (for the two storm types) using the Community Climate System Model version 4 (CCSM4) climate projection, and perform transposition of these 2 storms
3.3.2.2.3 Questions and Answers:

**Question:** The first one is with your TC simulation. You showed some statistics there such as overlap per percentage and so on. You indicated that you felt those results were quite good. I'm just wondering, the statistics certainly are very useful that you use, but in terms of judging the acceptability of the simulation, it would seem like you'd need to sort of evaluate your simulation in the context of how that information is going to be used. In order to know if the errors in the simulation are acceptable, in terms of that application. That's the first question. Second question is a lot simpler. With your transposition approach, have you considered incorporating uncertainty into that approach?

**Response:** For the first question regarding the quality of the simulation, we tried hundreds of combinations of the parameterization schemes and I don't know how many of you are familiar with the numerical modeling of some system but it's extremely complicated. For those who are familiar with such modeling, you will know that these results are actually quite satisfactory. So, the idea is we want to estimate, in the case of the storm transposition exercise, what would have been the precipitation that's over a given target area. The first step is always to validate the model before using the model in order to make an estimation. So, this is what was done in the first step - to calibrate and validate the worst model. Of course, for the results that we obtained, in the perspective of the quality of the calibration, there was for example minus 13 percent relative error and the other statistics are not perfect, but we can still say that the estimation that we obtained is relevant. Now coming to the second question regarding the uncertainty, if I remember the uncertainty for the storm transposition, there would be several ways to tackle this issue, for example, one could use several combinations of the parameterization schemes. Meaning that in this case we show the results for one combination which was assessed to be the best
combination. One could use several combinations with which are assessed to be satisfactory and do the transposition exercise with all the combinations which would give several estimations of the maximum precipitation about the targets. And one would obtain some uncertainty related to the model based on these different values that are obtained by using the different combinations. Also, one could try to use different data sets for the initial and boundary conditions. Also, one could do the exercise for the Quebec projections so there are many climate projections. In this case we used only one start date for the simulation. One could use many start dates for the simulation, so there are several ways that one could tackle uncertainties of the model, of the boundary initial conditions, and so on.

**Question:** Kelly Mahoney, by how much does the storm environment change in the RAM based shifting procedure?

**Response:** So, in the middle you can see that the drainage basin is located in a mountainous area, while in the observed case, the historical system affected a region which is not mountainous. So is a very significant change in topography first of all. Then I'm not familiar with the land surface issue, but if there was a tremendous difference between the location of the historical system and the location of the maximized system.

**Question:**

John England from USACE, we struggle with transposition so I'm wondering if you have had the opportunity to start to place a hierarchy on particularly the tropical cyclones in how far you start to move them. The example I'm going to ask is if you look at Agnes and you go extra-tropical and the source is the Gulf and it recurves to the Atlantic and zooms back into Pennsylvania, Western Pennsylvania particularly, your transposition area might be determined by the tract or other features from maybe a library of TC tracks.

**Response:**

So, the technical details regarding how the transposition was performed will be given in the final reports. But the storm transposition can be performed in any conditions. If the storm transposition is legitimate or not—that's another question. For the legitimacy of the storm transposition, there are a certain number of criteria that need to be met. For example, for the storm transpositions you mentioned, I think an extra-tropical transition, if the storm has already started the historical transition, the shifting of the storm is not necessarily legitimate, except if the amount of shift is very small. You cannot put back into the Atlantic Ocean a storm which already started to interact with the land and with other systems in the mid-latitudes. So, all these criteria will be listed in the final report for this project.

**Question:**

Just to clarify, when you do the transposition, the broad moisture field stays the same, you're just moving the track? Correct?

**Response:**

Yes. We transpose this storm—not the overall field.
**Question:**

Just kind to get an idea of the levels effort to do these WRF simulations of these transformed storms, and if you did put this into a stochastic framework to get a better idea of uncertainty, what kind of level of computational time which you need?

**Response:**

With today's technologies such exercises are possible. In the case of the tropical cyclone, it is different from what has been done in the past by Professor Kavvas and his team. For example, for atmospheric rivers in which case there was a two-dimensional search for the maximum. In the case of tropical cyclone, what you can do is if the storm is moving in this direction can just shift it that way. There is no need to shift in the direction of the storm. So, in this case it is just possible to do a one-dimensional search which considerably limits the computational efforts but it's still quite demanding.

**Question:**

Bill Kappel, I'll make it quick hopefully. Just a quick question on this. When we talk about transposition ability, so Hurricane Isaac is a direct hurricane with landfall and coastal interaction processes. And there’s really no topography over Louisiana, Mississippi, and Alabama. But when it moved to the Asheville Basin, how did WRF take into account the differences in topography and moisture sources? When we talk about transpositioning storms, one of the key definitions is that they need to be moved within similar regions of meteorology and topography. Obviously New Orleans is a lot different than Asheville, North Carolina. So how do you determine where to test and move these storms? And then, if so, how do you parameterize the model differently for the two locations?

**Response:**

As far as I am familiar with the traditional PMP approaches, what was done is to shift the precipitation field module adjustments. In this case, you can see that the shifted precipitation field is fundamentally different from the original precipitation field. If I remember from the traditional PMP approach, they consider this region of homogeneity for the transposition of the precipitation field. In this case, we only manipulated the initial and the boundary conditions and the model is run as normal. I mean once this manipulation has been made, the model is run as usual and all the interactions are taken into account. I think the second part of your question was for the validity of the parameterization schemes. The fact that the model was calibrated for a given region and affects another region. Is the combination of the scheme adapted for the new region? I think it is an important point and these we will need to investigate but as we mentioned earlier for a previous question, the fact to use several combinations of parameterization schemes in order to account for uncertainties would also affect this issue of is one given combination adapted for a new region of the country. So, using several combinations would really be beneficial also for this problem.

**Question:**

Kelly Mahoney, is the best combination of model physics the same across all simulations or is the best simulation chosen individually for each storm?
**Response:**

The best combination because there are several millions of possible combinations in the WRF model. We looked for a satisfactory combination so it’s not an optimization exercise properly speaking. There was an algorithm to find the best combination. We looked for a satisfactory combination and the satisfactory combination changes from one tropical cyclone to another. But for a given tropical cyclone, the combination was the same between the calibration and the functions position.

**3.3.2.3 Research on Extreme Precipitation Estimates in Orographic Regions** Kathleen Holman*, Andrew Verdin, and David Keeney, Flood Hydrology and Meteorology Group, Technical Services Center, U.S. Bureau of Reclamation (Session 2B-3; ADAMS Accession No. ML17355A087)

**3.3.2.3.1 Abstract**

We present the findings of the research project “Phase II: Research to Develop Guidance on Extreme Precipitation. Frequency Estimates for the Tennessee Valley.” The definitive objectives of this research project are: (i) Review extreme storm precipitation techniques, precipitation-frequency methods, and databases in orographic regions; (ii) Develop a methodology to estimate precipitation-frequency in regions of complex topography; and (iii) Demonstrate the precipitation-frequency methodology and provide uncertainties and confidence intervals at the regional and reactor-site scale for a pilot region in the Tennessee River Valley watershed (TRVW). The focus of this presentation is on the development of a generalized framework for precipitation-frequency analysis in orographic regions. Obtaining reliable precipitation-frequency estimates requires confidence in the estimated extreme value distribution parameters. However, parameter estimation is sensitive to a number of influential factors, the period of record being critical. Regional frequency analysis (RFA) is a commonly used technique for extending the period of record, using a “space-for-time” substitution method. The fundamental basis of RFA is the assumption that observations from climatically similar stations can be described by the same probability distribution.

The methodology developed in this research combines a known objective clustering algorithm, the Self-Organizing Map (SOM), with two distinct frequency estimation methods, L-moments and Bayesian inference. The SOM algorithm utilizes a combination of geophysical information and observed precipitation data to identify climatically similar groups of stations (i.e., homogeneous regions, hereafter HRs) within the TRVW. L-moments and Bayesian inference are then used to estimate generalized extreme value (GEV) distribution parameters to produce regional growth curves (RGCs) for each of the HRs. Site-specific precipitation-frequency estimates are obtained by scaling the RGCs by the at-site mean for the site of interest. Only the GEV distribution was considered, as epistemic uncertainty due to probability distribution choice was not the focus of this research. Results suggest that uncertainty estimates from the L-moments analysis are consistently less than the uncertainty estimates from Bayesian inference. These differences are the result of estimating uncertainty differently between the two methods.

It may be of interest to produce precipitation-frequency estimates at locations where no historical data are available. To this end, we illustrate the benefit of using a gridded precipitation dataset as
input to RFA. Specifically, the Newman et al. (2015) dataset contains an ensemble of gridded
daily precipitation for 33 years at 1/8-degree resolution. The ensemble contains 100 members,
each of which are equally plausible precipitation totals for the grid cell of interest. We illustrate
how the ensemble members are collapsed into a single dataset, and the extreme value
distribution parameters are estimated independently at each grid cell. This presentation ends with
an illustration of the two methods’ abilities in quantifying small exceedance probability precipitation
events with associated uncertainty.

3.3.2.3.2 Presentation
Outline

Motivation
Precipitation-Frequency analysis
    Frequency Analysis Methods
    Datasets
Case study in Tennessee River Valley
    L-moments
    Bayesian
Summary & Conclusions
Motivation

Q: What is a precipitation-frequency relationship?

A: Statistical relationship relating precipitation depth to the probability of exceeding that depth.

Motivation

Probability reported as "return period" or "average recurrence interval"

Return period of:  
100 years means the probability is 1-in-100 (0.01)  
500 years means the probability is 1-in-500 (0.002)  
1,000 years means the probability is 1-in-1000 (0.001)
Precipitation-Frequency Analysis

Define relevant precipitation duration
→ e.g., 1-day, 2-day, etc.

Extract annual/seasonal maxima from daily time series

QC annual/seasonal maxima for false maxima

Fit extreme value distribution to maxima
→ Estimate $\theta = (\mu, \sigma, \xi)$

Calculate quantiles of distribution
→ Precipitation magnitudes and associated probabilities

Regional Frequency Analyses

Assume observations within homogeneous region (HR)
described by single distribution
→ Pool all annual/seasonal maxima within HR

Scale the annual/seasonal maxima by the at-site mean of the maxima
→ Mean at each site -> 1

Compute precipitation-frequency relationship, produce regional growth curve (RGC)
→ Scale by specific at-site mean for point estimates
Regional Growth Curve

Unitless curve describing all gauges in HR

Scale by site-specific ASM for site-specific PF curve

Frequency Analysis Methods
L-moments

L-Moments

Developed for *regional* frequency analysis
Identify weather stations (sites) within HR
Screen observations
  annual/seasonal/monthly maxima
  duration depends on meteorology
Quality control data
Compute L-statistics* for each site
  L-mean, L-scale, L-skewness, L-kurtosis
Test for heterogeneity
  Discordancy measures (e.g., $D_l \leq 3$)
Identify the “best” distribution
  GEV, GPD, GNO, GLO, PE3, Wakeby
Calculate regional growth curve (weighted by POR)
  Scale growth curve (point, basin, region)
L-statistics

Alternative system of describing probability distribution functions based on linear combinations of moments

**L-moments:**
- $\lambda_1$: L-location (mean)
- $\lambda_2$: L-scale (variability or dispersion)
- $\lambda_3$: L-skewness (asymmetry)
- $\lambda_4$: L-kurtosis (thickness of tail)

**L-moment ratios (dimensionless):**
- $T_r = \lambda_r / \lambda_2$
- $T = L-CV = \lambda_2 / \lambda_1$ (variability)

Fig. 2.1. Definition sketch for first L-moment.
Fig. 2.2. Definition sketch for second L-moment.
Fig. 2.3. Definition sketch for third L-moment.
Fig. 2.4. Definition sketch for forth L-moment.

Available R packages for L-moments:
- library("lmom"")
- library("lmomRFA"")

Bayesian inference
Bayesian inference

**Prior** \( p(\theta) \): the strength of our belief in \( \theta \) without the data \( Y \)

**Posterior** \( p(\theta|Y) \): the strength of our belief in \( \theta \) when the data \( Y \) are taken into account

**Likelihood** \( p(Y|\theta) \): the probability that the data \( Y \) could have been generated by the model with parameter values \( \theta \)

**Evidence** \( p(Y) \): the probability of the data according to the model, determined by summing across all possible parameter values weighted by the strength of belief in those parameter values

→ typically unknown, can be ignored with proportionality
→ essentially a normalizing constant
→ does not enter into determining relative probabilities (models)

---

Bayesian inference

Bayes’ Rule in a modeling framework:

\[
p(\theta|Y) = \frac{p(Y|\theta)p(\theta)}{p(Y)} \propto p(Y|\theta)p(\theta)
\]

e.g., \( Y = (y_1, y_2, \ldots, y_n); \theta = (\mu, \sigma, \xi) \)

Define prior distributions for model parameters \( \theta \) (a priori knowledge)
Can consider numerous likelihood functions (e.g., GEV, GNO, GLO, etc.)
Monte Carlo, acceptance criteria, builds posterior distributions of \( \theta \)

Bayesian inference derives the posterior probability as a consequence of a prior probability and a likelihood function
Regional Bayesian

Scale annual maxima by at-site mean

Assume scaled maxima within HR described by a single theoretical distribution

Generalized Extreme Value (GEV) distribution

Posterior distributions of $\theta = (\mu, \sigma, \xi)$

→ Quantification of one source of epistemic uncertainty

Datasets
Historical Observations

Global Historical Climatology Network:
Integrated database of daily climate summaries from land surface stations (100,000+) across the globe
Includes observations from multiple sources that have been subjected to a the same fully-automated quality control process (Durre et al. 2010)
- Duplication of records
- Exceedance of physical, absolute, climatological limits
- Temporal persistence
- Inconsistencies with neighboring observations

Question:
How do we obtain PF estimates at ungauged locations?
Newman et al. (2015)
Gridded observation-based ensemble dataset of daily precipitation and temperature from 1980 to 2012
Ensemble generation:
* Locally-weighted regression models are used to produce “best estimate” values of precipitation and temperature at 1/8° lat×lon grid
* Regression residuals are used to perturb the best-estimate values with correlated random samples
Resulting dataset:
* 100 plausible precipitation and temperature grids
* Each valid over same period

Newman et al. (2015)
Daily precipitation (inches) on September 15, 2004
Case Study

Study Region

Tennessee River Valley watershed

GHCN-Daily gauges with 85% data availability for 10+ years period of record (POR)
Homogeneous Regions

Methods to define HR (Hosking and Wallis 1997)

Subjective methods
- Geographical location
- Seasonal timing of peak events
- Mean annual precipitation (MAP)
- Similar forcing mechanisms (synoptics)

Objective methods
- Self-Organizing Maps (SOM)
- Hierarchical clustering analysis (HCA)
- Principle component analysis (PCA)
- Heterogeneity measure

Self-Organizing Map

Clustering algorithm used to “group” stations with similar attributes
Apply SOM algorithm to:
- Latitude
- Longitude
- Elevation
- Avg annual precipitation
- Avg annual max one-day precipitation

Each station maps to a single SOM node

Gauges mapped to same node define homogeneous regions
Homogeneous regions need not be contiguous

Available R packages for SOM analysis:
library("som")
library("kohonen")
SOM Results – At-Site Means

L-Moments

RECLAMATION
L-Moments RGCs

Data Availability

Mean Annual Precip (in) 1960-2015

GHCN-Daily dataset

Newman et al. (2015) gridded ensemble

Average Annual Precip (in) 1960-2012
Combined Ensemble

- 100 ensemble members
- 33 years of data
- 3,300 maxima/cell

Newman et al. (2015)

RECLAMATION

NOAA Atlas 14

Data from Ohio River Basin and Southeast domains use different lat/long grids

Regrid each field to the Newman resolution and then combine fields to produce a single field

In order to compare with Newman estimates, applied two scale factors
Duration correction
Areal-reduction factor
Gridded L-moments

Bayesian
Data Availability

Newman et al. (2015) gridded ensemble

Gridded Bayesian - Medians
Gridded Bayesian - Uncertainty

L-Moments vs. Bayesian

RECLAMATION
Gridded Frequency Analysis

Summary

Regional frequency analysis using two methods

- L-moments and Bayesian inference

Homogeneous regions defined using semi-objective clustering algorithm, SOM (Self-Organizing Maps)

- Lon, lat, elev, mean annual precip, mean 1-day maxima
- Effectively accounts for orographies by clustering similar stations

Precipitation-frequency results and uncertainty bounds vary by method

- L-moments uses drop-10% bootstrap resampling
- Bayesian uses Monte Carlo, prior knowledge, likelihood function, acceptance criteria to build posterior distributions

RECLAMATION
Summary

Regional frequency estimation methods possible on any gridded dataset
  • Newman used to address aleatory variability

L-moments and Bayesian produce similar estimates
  • Bayesian median and L-moments fit show good agreement (< +/- 2” at 1,000-year return period)
  • L-moments uncertainty estimation method lacking for large datasets (3,300 data points, drop-10% bootstrapping)
  • Bayesian uncertainty also likely underestimated due to correlated data

Future work could entail multi-model combination
  • Better quantify epistemic uncertainty via numerous gridded datasets, station-based datasets

Questions?

averdin@usbr.gov
+1.303.445.3647

kholman@usbr.gov
+1.303.445.2571

3.3.2.3.3 Questions and Answers

None.
3.3.3 Day 1: Session 1C - Storm Surge

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

Development of guidance for application of improved mechanistic and probabilistic modeling techniques for key flood generating processes and flooding scenarios.

3.3.3.1 Quantification of Uncertainty in Probabilistic Storm Surge Models

Norberto C. Nadal-Caraballo, Ph.D. and Victor Gonzalez*, P.E., U.S. Army Engineer R&D Center, Coastal and Hydraulics Laboratory (Session 1C-1; ADAMS Accession No. ML17355A088)

3.3.3.1.1 Abstract

Probabilistic flood hazard assessment (PFHA) of critical infrastructure located in coastal zones requires the characterization of the storm surge hazard and associated uncertainty. The joint probability method with optimal sampling (JPM-OS) has become the standard probabilistic model used to assess coastal storm hazard in hurricane-prone coastal regions of the United States. Other methods such as global climate modeling (GCM) downscaling and Monte Carlo Simulation methods have also been applied. The U.S. Army Engineer Research and Development Center, Coastal and Hydraulics Laboratory (ERDC) is performing a comprehensive assessment of uncertainties in probabilistic storm surge models in support of the NRC efforts to develop a framework for probabilistic storm surge hazard assessment for nuclear power plants. The treatment of uncertainties in the JPMX-OS methodology varies by study and is typically limited to the quantification and inclusion of uncertainty as an error term in the JPM integral. Traditionally, these errors have been regarded as epistemic uncertainties because, theoretically, they could be reduced by collecting additional data, refining the numerical models, and constructing more efficient synthetic storm suites. In practice, past individual studies, for example, have been based on a defined set of data sources and have employed a single approach for estimating each of the JPM components (e.g., computation of SRR, univariate distributions, distribution discretization method, development of synthetic storm suites, others), limiting the understanding of the range of uncertainty.

The treatment of uncertainties in the present study is based on USNRC guidance on probabilistic seismic hazard assessment (PSHA). In this paradigm, the epistemic uncertainty arises from the selection and application of technically defensible alternative data, methods, and models at each step of the probabilistic storm surge modeling. Once the epistemic uncertainty is quantified, it is propagated through the use of logic trees. This allows for the computation of a family of hazard curves, with individual curves representing each of the alternate modeling approaches. In order to quantify the epistemic uncertainty associated with probabilistic storm surge models, this study evaluated data sources and methods associated with the different applications of the JPM-OS, GCM, and MCS approaches, and determined the data and methods that should be carried forward. Specific topics that were assessed include storm recurrence rate models, methods for defining joint probability of storm parameters, methods for generating synthetic storm simulation sets, integration methods, and integration of aleatory variability. The analysis of the logic tree branches representing the center, body, and range of the data and methods employed by each probabilistic storm surge model (e.g., JPM-OS, GCM, and MCS) yielded a family of hazard curves. To convey the range of the epistemic uncertainty, a statistical analysis was performed to compute fractile storm hazard curves (equivalent to non-exceedance confidence limits) including the mean, 0.05, 0.16, 0.5 (median), 0.84, and 0.95.
Outline

- Introduction
  - Objectives and treatment of uncertainty
  - Project tasks
  - Logic tree approach
- Storm Recurrence Rate models
- Marginal (univariate) Distributions
- Generating Synthetic Storm Sets
- Characterization & Propagation of Uncertainty
Introduction

- Study objectives:
  - Identification of technically defensible data sources, models, and methods for the computation of storm surge.
  - Assessment for carrying forward for evaluation of epistemic uncertainty.

- Treatment of uncertainty in present study:
  - Follows probabilistic seismic hazard analysis (PSHA).
  - Epistemic uncertainty is quantified and propagated through logic tree approach.
  - Differences between a numerical model and the natural phenomenon is prevalent (error term) \( \rightarrow \) aleatory
  - Reduction of uncertainty in the selection and application of alternative data, methods, and models \( \rightarrow \) epistemic

Project Overview (Tasks)

- Task 1  Literature Review
- Task 2  Storm Recurrence Rate Models
- Task 3  Defining Joint Probability of Storm Parameters
- Task 4  Generating Synthetic Storm Simulation Sets
- Task 5  Probabilistic Modeling of Numerical Surge Simulation Errors
- Task 6  Synthesis and Final Report Preparation
- Task 7  Transfer of Knowledge
Logic Tree Approach

JPM Integral

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

\[ \approx \sum_i^N \lambda_i P[r(\bar{x}_i) + \varepsilon > r|\bar{x}_i, \varepsilon] \]

where:
- \( \lambda_{r(\bar{x})} \) = AEP of TC response \( r \) due to forcing vector \( \bar{x} \)
- \( \bar{x} = f(x, \theta, \Delta p, h_{max}, V_z) \)
- \( \lambda = \text{SRR (storms/yr/km)} \)
- \( \lambda_i = \text{probability mass (storms/yr) or } \lambda p_i \)
- with \( p_i \text{=product of discrete probability and TC track spacing (km)} \)
- \( P[r(\bar{x}_i) + \varepsilon > r|\bar{x}_i, \varepsilon] \text{ conditional probability that storm } i \text{ with parameters } \bar{x}_i \text{ generates a response larger than } r \)
- \( \varepsilon = \text{unbiased error or aleatory uncertainty of } r \)

Task 2: Epistemic Uncertainty in SRR Models

- Data sources and methods used for the computation of site-specific storm recurrence rate (SRR) models.
- Models for Calculating SRR
  - Uniform kernel function (UKF) or capture zone
  - Gaussian kernel function (GKF)
  - Epanechnikov kernel function (EKF)
- Topics
  - Investigate SRR aleatory uncertainty.

\[ w(d_i) = \begin{cases} 0.5, & \text{if } \frac{d_i}{h_a} < 1 \\ \frac{1}{\sqrt{2\pi h_a}} \exp \left[ -\frac{1}{2} \left( \frac{d_i}{h_a} \right)^2 \right], & \text{otherwise} \end{cases} \]

\[ w(d_i) = \begin{cases} \frac{1}{h_a} \left( 1 - \left( \frac{d_i}{h_a} \right)^2 \right)^{\frac{1}{2}}, & \text{if } \frac{d_i}{h_a} < 1 \\ 0, & \text{otherwise} \end{cases} \]
Task 2: Epistemic Uncertainty in SRR Models

- Effect of Kernel functions and sizes on WL hazard curve

The Battery, NY
Boston, MA

Task 2: Epistemic Uncertainty in SRR Models

Findings
- The lower SRR uncertainty was associated with locations with higher TC occurrences (sample size).
- Kernel function introduces small variability in hazard curve.
- Relative contributions of aleatory uncertainty ($\Delta p \geq 28$ hPa)
  - Sampling uncertainty – 65%
  - Selected period of record – 19%
  - Gaussian kernel size – 15%
  - Observational data – 1%
- Although resampling uncertainty and observational uncertainty could be classified as aleatory variability, they could also be considered epistemic from the point of view of reducibility.
  - Passage of time → increase sample size
  - Improvement in observation technologies → increase measurement accuracy
  - Discretized and incorporated as branch in logic tree.
Task 3: Data, Models and Methods for Defining Joint Probability of Storm Parameters

- **Task Description**
  - Identification of technically defensible TC parameter data sources, screening methods, and parameterization schemes for development of probability distribution.

- **Topics:**
  - Selection of probability distributions
  - Evaluate technically defensible data sources

---

Task 3: Data, Models and Methods for 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
Task 3: Data, Models and Methods for Defining Joint Probability of Storm Parameters

- Comparison of $R_{max}$ probability distributions

Similar curves resulting from the Vickery model and EBTRK reanalysis.

GCM plot suggests that extratropical transition of TCs is not being adequately represented.

Task 3: Data, Models and Methods for Defining Joint Probability of Storm Parameters

- Vickery and Wadhera and EBTRK $R_{max}$ hazard curves

Virginia Beach, VA
Small variation in hazard curves for EBTRK and Vickery and Wadhera (2008) stochastic model → both lognormal.
Task 3: Data, Models and Methods for Defining Joint Probability of Storm Parameters

- General Findings
  - The most relevant factor in choosing distribution type was how well it described the low-frequency tails.
  - More than one statistical distribution could be valid for a given TC parameter.
  - Comparison of viable fits usually did not reveal significant differences. Limited effect confirmed by hazard curve comparisons.
  - The sampling technique used for the generation of synthetic TCs may lessen the significance of selecting a given probability distribution for large discretization intervals.
  - The judgment of carry forward a given dataset, method, or model was found to be highly dependent on the location.

Task 4: Data, Models, and Methods for Generating Synthetic Storm Simulation Sets

- Task Description
  - Capture full range of technically defensible data and methods for generating synthetic storm sets required to fully characterize and propagate uncertainties in storm surge estimates.
  - Methods tested for generating synthetic storm simulation sets
    - JPM Reference – 74,430 TCs
    - JPM-OS – 1,050 TCs
    - Monte Carlo Simulation: Life Cycle – 211,997 TCs & Integration – 211,997 TCs
    - CGM Downscaling – 1,470 TCs
    - Methods for calculating probability mass that explicitly consider parameter correlations – 211,997 TCs
      - Multivariate Gaussian Distribution
      - Multivariate Gaussian Copula
      - Multivariate Student’s t Copula
Task 4: Data, Models, and Methods for Generating Synthetic Storm Simulation Sets

- Reference Set
  - Traditional JPM approach → All parameter combinations
    → Large set of storms (74,430 TCs)
  - A Gaussian process metamodel (GPM) (Jia et al. 2016) was used to develop tens of hundreds of TCs.
    - The GPM is conceptually similar to response surface.
      - Initial discretization of the joint probability distribution is refined by regression or interpolation of storm surge from additional TC parameter combinations.
    - The GPM used in this study was trained using the 1050 synthetic TCs developed as part of the NACCS (Nadal-Caraballo et al. 2015).

---

Task 4: Data, Models, and Methods for Generating Synthetic Storm Simulation Sets

- Monte Carlo Simulation
  - Monte Carlo Life-Cycle
    - Univariate distributions of TC parameters were sampled for a 1,000,000-yr period, which resulted in 200,000+ TCs.
    - No probability masses required.
      - TC's sampled based on their likelihood of occurrence and joint p. Storm surge hazard curve from empirical distribution (Weibull plotting position).
    - Mean hazard curve and confidence levels calculated through bootstrap resampling using replicated storm surge values with added discretized uncertainty.
  - Monte Carlo Integration (MCI) (Wyncoll and Gouldby 2015)
    - Probabilities are calculated as the percent of TCs with response greater than a set of surge elevation bins. No probability masses required.
    - \( P(c > c) \approx \frac{L_c}{L} \cdot \lambda \), where \( L_c \) is the number of Monte Carlo realizations that exceed \( c \), \( L \) is the total number of Monte Carlo realizations, and \( \lambda \) is the sample intensity (storms/yr).
Task 4: Data, Models, and Methods for Generating Synthetic Storm Simulation Sets

- **GCM Downscaling** (Lin et. al 2012)
  - Storm surges determined by GCM-driven statistical/deterministic hurricane model with hydrodynamic surge models.
  - Synthetic TCs tracks are generated according to large-scale atmospheric and ocean environments rather than historical TCs.
  - 1,470 tracks covering a time period from 1970-2010.
  - The storm surge responses were simulated by applying GCM parameters and tracks to the previously trained GPM
  - Stochastic simulation technique (SST) consisting of combined empirical and GPD fits was applied to the storm surge values to obtain hazard curve.

Task 4: Data, Models, and Methods for Generating Synthetic Storm Simulation Sets

- **Methods hazard curves comparison**

![StormSim JPA – NACCS Save Point 7672](image_url)
Task 4: Data, Models, and Methods for Generating Synthetic Storm Simulation Sets

- MVGC: correlation between $\Delta p$ and $R_{\text{max}}$

![Graph showing correlation between $\Delta p$ and $R_{\text{max}}$.]

The two are negatively correlated.

Independence between the two parameters results in more combinations of high intensity and large radius $\rightarrow$ larger surge.

---

Task 5: Approaches for Probabilistic Modeling of Numerical Surge Simulation Errors

- **Task Description**
  - Investigate approaches for characterizing and modeling errors within the probabilistic framework constituted by modeling of storm surge.

- **Topics:**
  - Comparison of approaches for the characterization of uncertainty
    - Constant uncertainty (e.g., 0.61m)
    - Proportional uncertainty (e.g., 20%)
    - Combined constant and proportional uncertainty (e.g., min(20%, 0.61m))
  - The significance of different numbers of discrete values (or random samples) from the Gaussian distribution will be evaluated by comparing results using 30, 100, 300, 1000, and 3000 values.
Task 5: Approaches for Probabilistic Modeling of Numerical Surge Simulation Errors

- Results – Characterization of Uncertainty

- Incorporating uncertainty in the integration

\[ W_L \rightarrow W_{L_1}, W_{L_2}, ..., W_{L_n} \]

\( n \) = number of times WL is replicated and normal distribution discretized or number of times it is sampled.

\[ W_{L_n} = \mu + \sigma(Z^*) \]

\( Z^* \) = 
Discrete \((Z_1, ..., Z_n)\)
Randomly sampled \((Z_1, ..., Z_n)\)

Random sampling increases hazard curve tail for 30 and 444 partitions.
FEMA redistribution and 444 partitions were equivalent.
Task 6: Synthesis

- Task Description
  - Develop approach to characterize, quantify, and propagate both aleatory and epistemic uncertainties through the probabilistic framework of storm surge assessment process in order to develop robust flood hazard curves for use in NPPs applications.
  - Topics:
    - Treatment of uncertainty (Logic trees)

Task 6: Synthesis

- Preliminary example: Surge hazard logic tree
Task 6: Synthesis

- Logic tree table and weight assignment

![Logic Tree Table](image)

Task 6: Synthesis

- Family of hazard curves

![Hazard Curves](image)
Task 6: Synthesis

- Median hazard curve with confidence limits

![Graph showing median hazard curve with confidence limits]

References

3.3.3.1.3 Questions and Answers
None.

3.3.3.2 Probabilistic Flood Hazard Assessment – Storm Surge John Weglian, EPRI (Session 1C-2; ADAMS Accession No. ML17355A089)

3.3.3.2.1 Abstract

A storm surge is a rise in water level driven by winds from an approaching storm. While this is typically associated with hurricanes, other storm types can also produce a storm surge. EPRI has one research report on estimating the frequency of various magnitudes of storm surge based on an analysis of historical water levels. More research is currently underway to demonstrate how simulations of a hurricane can be used to estimate the frequency of various storm surge levels at a particular location.
3.3.3.2.2 Presentation

**EPRI Report on Storm Surge**

- EPRI report [3002008111](#), Probabilistic Flooding Hazard Assessment for Storm Surge with an Example Based on Historical Water Levels
- Provides generic PFHA process as applied to Storm Surge
- Available data and storm type that leads to storm surges for site of interest determines the simulation approach
  - Controlling storm is a hurricane: atmospheric parameters such as central pressure deficit, radius of maximum wind, and maximum wind speed as well as tidal levels can be modeled in the Monte Carlo simulation
  - Controlling storm is not hurricane: historical water levels can be utilized to determine mean sea level or average lake level, storm surge level, and wind-wave effects using Monte Carlo simulation techniques
Modeling Hurricane-Driven Storm Surge

- Hurricanes can be numerically simulated through a Monte Carlo analysis evaluating a number of parameters
  - Central pressure deficit
  - Radius of maximum wind
  - Maximum wind speed
  - Storm track
  - Forward speed
- Other parameters can be treated probabilistically, such as the tidal height

Storm Meteorological Parameters

Joint Probability Method

- The Joint Probability Method (JPM) combines the simulated hurricanes with a model for the storm surge produced by the storms
- Monte Carlo analysis performed selecting hurricane parameters for each simulated hurricane
- Range of parameters based on expert judgement from historical hurricane data
  - Correlation between parameters can be explicitly included
- Time point on tidal curve chosen randomly
- Result of the Monte Carlo and storm surge modeling leads to a flood-frequency curve for the site
EPRI Research on JPM

- EPRI is currently conducting research on the use of the JPM to develop a storm surge flood-frequency curve for a site
- This research will be published in 2018

Using Historical Water Levels to Assess Storm Surge

- Example site from EPRI Report [3002008111](#) located on the Great Lakes
- Site is not subject to fully formed hurricanes, so using a Joint Probability Method that models the atmospheric parameters is not applicable
- Long history (greater than 100 years) of lake levels is available including paleo data that can extend the record to 4000 years
- Lake buoys provide water level data
- Wave height, period, and direction determined by U.S. Army Corps of Engineers hindcast datasets
Monte Carlo Simulation for Storm Surge

- Probability density functions (PDFs) created to represent:
  - Initial lake level
  - Storm surge height
  - Wind-wave parameters
- It is not always obvious which PDF provides the best fit to the existing data and which data source is most applicable
  - Logic trees used to weight alternative PDFs and data sources to each parameter
  - Process is similar to what is used by the Senior Seismic Hazard Analysis Committee (SSHAC)
- Monte Carlo simulations used to develop still water level hazard curve and total water level (including wave run-up) hazard curve
  - Sensitivity studies can be run to determine the sensitivity of the analysis results to particular assumptions

Probabilistic Storm Surge Hazard Assessment Example
Example Logic Tree to Determine Weighted PDF

<table>
<thead>
<tr>
<th>Variable</th>
<th>PDF Type</th>
<th>PDF Shape Parameter</th>
<th>Cumulative Subjective Weight</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>C9, C11</td>
<td>0.2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>C9, C11</td>
<td>0.2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>C9, C11</td>
<td>0.16</td>
</tr>
<tr>
<td></td>
<td></td>
<td>C9, C11</td>
<td>0.14</td>
</tr>
<tr>
<td></td>
<td></td>
<td>C9, C11</td>
<td>0.06</td>
</tr>
<tr>
<td></td>
<td></td>
<td>C9, C11</td>
<td>0.02</td>
</tr>
</tbody>
</table>

Expert judgement and objective criteria used to set weighting parameters

Example Still Water and Total Water Levels

Structures may be impacted by waves at a frequency of about $1 \times 10^{-5}$/year
3.3.3.2.3 Questions and Answers

Question:

I'm very interested and you didn't mention the word seiche. For your lake levels did you think in terms of that? And then a follow-up quick question is, we heard from Ruby Leung this morning about some estimates of how climate may change the Great Lakes, she didn't bring up but the idea of intense storms on the Great Lakes that would enhance the storm surge and the seiche level. Do you want to comment?

Response:

Okay so for those who don't know: seiche is a periodic motion of a closed body of water. Now I know that the Great Lakes typically use the term seiche inappropriately for anything that looks like a large increase in water level. That particular approach: basing it on historical water levels cannot distinguish between a storm surge versus a seiche from any other means. Okay so this approach would actually capture both of those. If you got your data from something different, it may not include seiche. One of the complications with external flooding is that we break it neatly into different criteria. They're not always so easily distinguished. Local intense precipitation and riverine flooding can be happening at the same time. So, you have to be careful when you do your analysis and what you are encompassing and what you're not. In order to make sure that you're not leaving something behind that you're not including. So, like I said, seiche would be included in that. If the data for whatever reason had that excluded, you would have to do a separate analysis on that EPRI has not done any research specifically for seiche or tsunami at this point for hazard assessment.
Audience Comment:

With regard to seiche, whether it's captured or not will depend upon the time scale. Because when you process the wind wave data, you're always going to use some sort of time scale that you're using. If that seiche is within that time scale, you'll capture it but if that seiche is something with a really long period that might not get captured.

Response:

With regard to climate change, this analysis did not include adding additional information to predict the future. Typically, when we do probabilistic risk assessments, you are assessing the as-built as-operated plant, so you are looking at today's conditions and so should you add something to say in the next 20 years I expect this to get worse? I'm not sure what's appropriate there. Maybe you should be updating your model every time you update it and maybe increasing the probability as you go along. It's a good question. I don't have a good answer for it. I think it's definitely something we need to consider, but we need to take into account that we're trying to assess today's risk when using a probabilistic risk assessment and unless the application is looking into the future.

3.3.4 Day 1: Session 1D - Leveraging Available Flood Information I

Session Chair: Nebiyu Tiruneh, NRC/NRO/DLSEA/RHMB

Research to develop the means by which staff can leverage available frequency information on flooding hazards at operating nuclear facilities to support the SDP.

3.3.4.1 Flood Frequency Analyses for Very Low Annual Exceedance Probabilities using Historic and Paleoflood Data, with Considerations for Nonstationary Systems Karen Ryberg*, Ph.D., Kelsey Kolars, and Julie Kiang, Ph.D., U.S. Geological Survey (Session 1D-1; ADAMS Accession No. ML17355A090)

3.3.4.1 Abstract

Exceptionally rare flood events may have an annual exceedance probability (AEP) of 0.0001 or lower, meaning the average recurrence interval may be 10,000 or more years. Standard methods for statistical estimation of flood frequency rely on a systematic streamflow record, which provides a time series of annual peak streamflow (peak flow). While few long-term streamgages in North America provide records of peak flow more than 125 years in length, estimation of peak flows with very low annual exceedance probabilities is needed to accurately portray risks to critical infrastructure, such as nuclear power plants. Uncertainties are large when extrapolating magnitudes of extremely rare events from a streamflow record that is much shorter. The addition of historical data (data outside the systematic record, yet within the period of human record, such as newspaper accounts that can be translated to flood magnitudes) or paleoflood data (information about flood occurrence or magnitude from sources like sediment deposits or tree rings) can inform flood-frequency estimates and, in some cases, reduce error bounds. In other cases, the paleoflood information can appear to come from a different population than the systematic record.
An additional complication for flood-frequency analysis is the need to satisfy the assumption that the time series is stationary; that is, peak flows vary around a constant mean within a particular envelope of variance. As concerns about land-use change and anthropogenic climate change have increased, and our understanding of natural systems has improved, we have learned that the stationarity assumption is sometimes inappropriate. The computation of flood frequencies under nonstationarity remains an active area of research without a consistent approach for dealing with nonstationarities.

Flood magnitudes were calculated for select North American sites with systematic records and historical and paleoflood information using U.S. Geological Survey software, PeakFQ (version 7.2.22429) which has been extended to provide estimates of peak-flows with AEPs as low as 0.000001. (The extended output is intended only for use in special purpose studies of exceptionally rare events. The extended output should not be used for typical flood-frequency studies where the interest is in AEPs in the range of 0.1 to 0.005.) PeakFQ analysis used the expected moments algorithm, which allows inclusion of nonstandard flood information, such as intervals. PeakFQ also identified potentially-influential low floods (PILFs) that may represent nonstationarities. Use of EMA with the identification of PILFS means that the low floods were censored and had little or no influence on estimates on the high end of the flood-frequency distribution.

Results will be presented for the Red River of the North at Winnipeg, Manitoba, a site with a long systematic record, historical peaks, and paleoflood information. The presentation will demonstrate how additional flood knowledge beyond the systematic streamflow record affects estimation of low AEP floods and error bounds. The Red River also has some nonstationary features (abrupt changes, serial correlation, and an increasing trend in flow) that violate the underlying assumptions for flood-frequency analysis. These nonstationarities and their implications for the estimation of flood events will be discussed along with possible adjustments.

3.3.4.1.2 Presentation
The Problem

Exceptionally rare flood events may have an annual exceedance probability (AEP) of 0.0001 or even lower; meaning the average recurrence interval may be 10,000 or more years.

Yet, estimation of these flood-flow frequencies is needed to accurately portray risks to critical infrastructure, such as nuclear power plants.

The Problem

Standard methods for statistical estimation of flood frequency rely on the systematic streamflow records (few of which extend beyond 125 years).

Uncertainties are large when trying to extrapolate magnitudes of extremely rare events.

The addition of historical and paleoflood data can help extend the records of floods.
The Problem

An additional complication for flood-frequency analysis is the underlying assumption that the flood series is stationary — data are stationary, independent and identically distributed, and lack any long-term persistence or autocorrelation.

Nonstationarity

- Nonstationarity refers to annual peak-flow values whose mean, variance, or distribution changes either gradually or abruptly over time.
- Nonstationarities may be attributed to one source (regulation, land-use change, climate), but often times are the result of a mixture, making detection difficult.
- Random variation at a site can be “detected” as a nonstationarity.
Assumption of Stationarity in Flood-Frequency Analysis

As more information becomes available through historical and paleo records, there have been questions about whether the hydrologic system ever was stationary.

Nonstationarity in the Interior of the Continent

“Results demonstrate that the 89 year period of observational record in this region is a poor representation of the long-term properties of the hydrologic regime, and shorter periods, e.g., 30 years periods, are by no means representative.”


Flood-Frequency Analysis with Paleoflood Data

PeakFQ and Expected Moments Algorithm

- Nonstandard flood data may be used with PeakFQ and the expected moments algorithm (EMA), including flood interval estimates and flood thresholds.

- For years with missing data in which some flood information is known, perception thresholds may contribute to additional information about the frequency of large floods.

- These thresholds are used to describe knowledge about a particular year or series of years for which a particular value would have been observed or recorded if it has occurred.
In Bulletin 17C Context

- Information that could be converted to a streamflow estimate
  - Interval estimate indicating flood was between 5,000 and 7,000 cfs
  - Estimate indicating flood was greater than 8,000 cfs (such as when a bridge was overtopped and one can estimate a gage height-streamflow relation)
  - Estimates indicating floods of size X have not occurred for Y number of years
  - Estimates indicating flood less than a value (qualification code 4)

Historical Peaks

- Peaks that occur within the human record, but outside of a systematic gaging record.
  - Newspaper accounts
    - Flood overtopped a bridge by X feet
    - Flood was the highest since 1876 according to “old-timers”
    - Flooding reached First Street
  - These are often biased toward large floods, but not to be confused with the largest flood in “history”
Example of Sources of Paleoflood and Historic Data

- Red River of the North at Winnipeg, Manitoba
  - Long-term gage
  - Three large historic flood point estimates determined by Canada Department of Resources and Development
  - Historic flood interval estimates determined by historian based on Provincial records, Hudson’s Bay Company diaries, and other sources
  - Tree-ring based flood estimates
  - Tree-ring based flood threshold and indicator that largest flood in 350 years was in 1826

Paleoflood Data

- Paleofloods refer to those that occurred before a human record and are determined using geologic and physical evidence.
  - Changes to flood plains and terraces
  - Slackwater deposits
  - Flood bars
  - Tree scars, tree ring anomalies, tree age
  - Erosional scars
PeakFQ Example

Red River of the North at Winnipeg, Manitoba, Canada
Need Exploratory Data Analysis First

- Search for nonstationarities
  - Autocorrelation/serial correlation
  - Change points/step trends
  - Trends

The Red River Has It All
How Much Autocorrelation is Too Much?

- One implication is that the effective length of the record is not as long as it appears—there is redundancy in the information.
- Burn and Goel (2001) analyzed 117 years of record for this site and determined that it was equivalent to an independent record of 45 years.
- Autocorrelation has the effect of increasing the uncertainty of flood-frequency estimates.

The Red River Has It All

[Graph showing streamflow over time]

Time, all peaks treated as consecutive
When are one or more change points concerning?

- Change points are a violation of the independent and identically distributed data assumption.

- PeakFQ can identify potentially-influential low floods (PILFs; small values that would have a large influence on the fit of the flood-frequency distribution), censor them, and then focus the distribution fit on the larger floods.

---

Red River PILFS

At least some of the floods from the period of relatively lower flows for the Red River may be identified as PILFS, discounting this period in the flood-frequency analysis.
The Red River Has It All

![Graph showing trends in river flow over time](image)

95% CI for Theil-Sen slope: -0.15 to 231.63, p-value 0.67
95% CI for Theil-Sen slope (no code 3 or 7 peaks): 33.85 to 277.76, p-value 0.01
95% CI for Theil-Sen slope, 1907-2016: 158.17 to 508.67, p-value 0.00

USGS

When is a trend a problem?

- In this case, confounded by short and long-term persistence (Nature is Trendy, Hurst phenomenon).
- Is the trend real?
- Persistence violation of Mann-Kendall
  - Many modifications to Mann-Kendall to adjust for persistence
  - Tested these on the Red River, indicated that there is persistence and a significant trend.
    - Do we have a long enough period of record to really say there is a trend?
Flood-Frequency Analysis

Systematic Data and Perception Thresholds

[Graph showing annual peak discharges (cfs) with labeled gaged peaks, censored flows, and horizontal bars representing perception thresholds.]

3-129
Flood-Frequency Curve – Systematic Record

Systematic and Historic Data, Historic Intervals, Paleo Peaks, and Perception Thresholds
Flood-Frequency Curve – Systematic and Historic, Historic Intervals, and Paleo Data

Red River of the North at Winnipeg

Scenarios
1. systematic peaks (standard at-site analysis);
2. wet period of 1948-2016, based on the change-point analysis;
3. most recent 30 years of data;
4. systematic and historic peaks and interval estimates; and
5. systematic and historic peaks, historical and paleo-derived estimates, and paleo-derived thresholds.
AEP = 0.10

AEP = 0.001

Preliminary Information—Subject to Revision. Not for Citation or Distribution
AEP = 0.000001

Limitations of EMA-LPIII

- Nonstationarities – active area of research, but no good solution
- Paleo data may help put bounds on very low AEPs
- Paleo data may increase uncertainties – can appear to come from a different population
- In addition to all the statistical assumptions, you are making assumptions about the channel and climate.
3.3.4.1.3 Questions and Answers

Question:
I have a question about the tree rings. How do you tell the difference between an event in the tree ring record, you know like a large flood, versus a wet season?

Response:
You would have to examine them with a microscope and that is something I've thought quite a bit. Because tree ring analysis is often done to estimate precipitation and a wide ring is a wet year, a narrow ring is a dry year, but if we look at this narrow ring we know this was a very wet year and it resulted in a narrow ring. So, it's one thing to measure the tree-ring width which takes some microscopic work, but you have to go into much more detail microscopic analysis to be able to see evidence for a flood. Also, one of the issues for this by this researcher Scott St. George knowing some very large floods, like the 1826 flood, he could figure out the signal in the tree rings for that and then based on that signal estimates some past floods but his estimate of these floods he says is really a minimum. It should be an interval estimate from this minimum value, but it's not known in this tree ring what is the upper value that you could detect. It would vary with river but there's probably some upper value that might kill the trees or you don't know what the upper limit is, so this really should be an interval estimate but we don't have that upper limit.

Question:
So, then you had actual discharge estimates based upon the tree rings, so then you must have been able to get an inundation level that is associated with that? Correct?

Response:
Yes. So, when you do tree rings it's a whole chronology. You get cores for multiple trees in a stand of various ages and you know that there was a flood in 1997 and you can see that result in tree rings. You know there was a flood in 1850, you line up your tree rings and you can see this consistent signal. We know there was a large flood in 1826, we can see that signal and then going back in time when we don't know much about the floods we look for that same signal. And the degree to which the tree was affected by that and then comparing it to the known floods. And how this ring looked during the known very large floods, the researcher came up with an estimate of flood magnitude. Looking at a variety of sources, stream discharge relationship, modern floods, how those look in the rings.

Question:
So, it's not just the elevation?

Response:
No.
Question:
To add on to what you're saying before... that it's a lower bound... how it affects the tree ring also
depends on when in the growing season the flood occurs. Right? Can there be floods that the
tree-ring won't represent because it wasn't adding material at that time?

Response:
Yes. That's a good question. There are a few large floods in this red river series that we know
happened. And that there's some interval or point estimates for that that did not show up in the
tree-ring series, so this is essentially a minimum estimate for magnitude and a minimum estimate
for frequency as well.

Question:
So, can you give similar information from dead trees or did it have to be alive?

Response:
It can be dead trees. For example, there's a researcher in Minnesota that has gone to settlers’
cabins. There are many cabins in Minnesota built in the 1800s that have been preserved and
ultimately been passed down through families. There's a known date when that cabin was built,
and he's gone to those cabins and got them to let him put some holes in the logs. He's developing
a tree ring chronology based on that. Also, this researcher, Scott St. George, has gone to the Red
River and done some investigation of subfossil logs pulled up from the sediment. It can be hard.
You have to compare them to other chronologies, the wet and dry rings, to figure out where they
fit because you don't know exactly when they died.

3.3.4.2 Extending Frequency Analysis beyond Current Consensus Limits
Keil Neff*, Ph.D.,
P.E. and Joseph Wright^, P.E., U.S. Bureau of Reclamation, Technical Service Center, Flood
Hydrology and Meteorology (Session 1D-2; ADAMS Accession No. ML17355A0901)

3.3.4.2.1 Abstract
This project is part of the NRC Probabilistic Flood Hazard Assessment (PFHA) research plan to
support development of a risk-informed approach for addressing flood hazards at nuclear
facilities. This work focuses on providing technical guidance for developing extreme flood
frequency estimates beyond the current consensus limits (Annual Exceedance Probabilities
(AEPs) less than $1 \times 10^{-4}$) from the context of the Bureau of Reclamation.

Reclamation, the owner of approximately 370 dams and dikes in the Western U.S., pioneered
conducting flood frequency analyses to support dam safety risk-informed decision-making. For
Reclamation dam safety risk assessments, flood estimates are needed for AEPs of $1 \times 10^{4}$ and
down to as low as 1 in 108. Developing credible estimates at these low AEPs generally requires
combining data from multiple sources and a regional approach. Reclamation has published
methodology and guidance to develop hydrologic hazard estimates over the past quarter of a
century. The primary purpose of these published guidelines, procedures, and standards was to
provide state-of-the-practice methodology for developing hydrologic hazard curves (and supporting flood hydrology information) to be used for evaluating facilities, prioritizing dam safety modifications and supporting planning and design decisions.

From a hydrologic perspective, risk estimates require an evaluation of a full range of hydrologic loading conditions and possible failure mechanisms tied to consequences of failure. The flood loading input to a dam safety risk analysis is a hydrologic hazard curve (HHC) that is developed from a hydrologic hazard analysis (HHA). Hydrologic hazard curves combine peak flow, water surface elevation, and volume probability relationships plotted with respect to their AEPs. Information derived in HHAs, including HHCs and associated flow and stage frequency hydrographs, can be used to assess the risk of potential hydrologic-related failure modes including overtopping, internal erosion under various reservoir levels, erosion in earth spillways, and overstressing of structural components.

When evaluating hydrologic hazards, a systematic means of developing flood hazard relationships is needed for risk-based assessments to determine hydrologic adequacy for Reclamation dams. The nature of the potential failure mode and characteristics of the dam and reservoir dictate the type of hydrologic information needed. The selected also considers available hydrologic data, potential analysis techniques, available resources for analysis, and an acceptable level of uncertainty. For some projects, only a peak-discharge frequency analysis may be required; while for others, flood volumes and hydrographs may be necessary. The goal of any hydrologic analysis is to provide hydrologic information to the necessary level (i.e. minimum effort and cost) to make effective dam safety decisions.

To provide flood estimates for a full range of AEPs necessary for dam safety decision-making, it is usually necessary to extrapolate beyond the period of recorded data. The type of data and the record length used in the analysis form the primary basis for establishing a range on credible extrapolation of flood estimates. Streamflow and reservoir data corresponding to current operations and watershed characteristics are data that should be used in FFAs. In higher level projects requiring more effort, data can be adjusted to represent the current conditions and operations to extend series for the entire period of record. The data used provide the only basis for verification of the analysis or modeling results, and as such, extensions beyond the data cannot be verified. The greatest gains to be made in providing credible estimates of extreme floods can be achieved by combining regional data from multiple sources. Thus, analysis approaches that pool data and information from regional precipitation, regional streamflow, and regional paleoflood sources provide the highest assurance of credible characterization of low AEP floods.

The principal components of this work include guidance on data sources and model inputs, probabilistic hydrologic hazard methods, multiple methods and other considerations, and Reclamation case studies. This presentation will provide an overview of what is described in this project including: 1) streamflow and climate data necessary; 2) statistical methods, physically based hydrologic modeling approaches, the Australian Rainfall and Runoff method, and the Stochastic Event Flood Model; 3) mixed population systems, combining multiple methods, and uncertainty; and 4) Reclamation case studies that encompass the breadth of described probabilistic hydrologic hazard methods.
Introduction

This project provides information the NRC can use to develop guidance for extending frequency analysis methods beyond current consensus limits for both rainfall and riverine flooding applications.

The focus is describing methods used by Reclamation to estimate flood loadings, which have been developed over the past 20 years. Case studies exemplifying these approaches are also included.

Uncertainty characterization and quantification is also a focus of this project.
Flood Loadings to Support Reclamation Dam Safety Risk Activities

From a hydrologic perspective, risk estimates require an evaluation of a full range of hydrologic loading conditions and possible failure mechanisms tied to consequences of failure. Hydrologic hazard curves combine peak flow, water surface elevation, duration thresholds, and volume probability relationships plotted with respect to their AEPs.

Flood loadings and associated flow and stage frequency hydrographs are used to assess the risk of potential hydrologic-related failure modes.

Reclamation primarily focuses on medium to large catchments in the Western U.S.
Credible Extrapolation

<table>
<thead>
<tr>
<th>Type of Analysis</th>
<th>Typical Range</th>
<th>Range (Best)</th>
</tr>
</thead>
<tbody>
<tr>
<td>At-Site Stream Gage</td>
<td>1 in 100</td>
<td>1 in 200</td>
</tr>
<tr>
<td>Regional Stream Gages</td>
<td>1 in 500</td>
<td>1 in 1,000</td>
</tr>
<tr>
<td>At-Site Stream Gage combined with Paleoflood Data</td>
<td>1 in 4,000</td>
<td>1 in 10,000</td>
</tr>
<tr>
<td>Regional Precipitation Data</td>
<td>1 in 2,000</td>
<td>1 in 10,000</td>
</tr>
<tr>
<td>Regional Streamflow and Regional Paleoflood Data</td>
<td>1 in 15,000</td>
<td>1 in 40,000</td>
</tr>
<tr>
<td>Combinations of regional Datasets and Extrapolation</td>
<td>1 in 40,000</td>
<td>1 in 100,000</td>
</tr>
</tbody>
</table>

Reclamation & Utah State University (1999), Reclamation (2006)

Level of Effort

The goal of any hydrologic analysis is to provide hydrologic information to the necessary level to make effective dam safety decisions. The available data, possible analysis techniques, resources available, and needs of the decision influence the selection of method(s) used.

<table>
<thead>
<tr>
<th>Method</th>
<th>Level of Effort</th>
<th>Benefits</th>
<th>Limitations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Graphical Flood Frequency</td>
<td>Low (CR, IE, CAS, FD)</td>
<td>Conservative, incorporates paleoflood information</td>
<td>Estimates far beyond credible extrapolation, conservative</td>
</tr>
<tr>
<td>EMA/FLDFRQ3</td>
<td>Low (CR, IE, CAS, FD)</td>
<td>Better estimate of uncertainty, incorporates paleoflood information</td>
<td>Estimates often extended beyond credible extrapolation</td>
</tr>
<tr>
<td>Australian Rainfall-Runoff</td>
<td>Low (CR, IE)</td>
<td>Rarer events, very conservative (pragmatic)</td>
<td>Primarily intended for largely deterministic design use, very conservative</td>
</tr>
<tr>
<td>GRADEX</td>
<td>Moderate (CR, IE)</td>
<td>Rarer events, conservative</td>
<td>Assumption of all rainfall to runoff, little physically-based modeling</td>
</tr>
<tr>
<td>Regional Precipitation Frequency</td>
<td>Moderate (IE, CAS, FD)</td>
<td>Better estimated of uncertainty, still conservative</td>
<td>Improved estimate of precipitation frequency, limited by AEP neutrality</td>
</tr>
<tr>
<td>Stochastic Rainfall-Runoff Modeling</td>
<td>High (IE, CAS, FD)</td>
<td>Currently the best estimate of uncertainty, uses information from statistical frequency methods, physical understanding of driving factors/processes</td>
<td>Extremely rare extrapolation is still uncertain and full range of aleatory variability and epistemic uncertainty is not understood, difficulties calibrating to extreme events</td>
</tr>
</tbody>
</table>
Data Sources

The sources of information used for flood hazard analyses include streamflow, precipitation, and paleoflood data.

<table>
<thead>
<tr>
<th>Data Source</th>
<th>Level of Effort (Cost)</th>
<th>Analyses</th>
</tr>
</thead>
<tbody>
<tr>
<td>Public Data Sources - Precipitation (e.g. NOAA, PRISM, NCEI)</td>
<td>Low (generally free)</td>
<td>Precipitation frequency (L-moments, Bayesian); storm templates</td>
</tr>
<tr>
<td>Public Data Sources – Gaging Stations (e.g USGS, Reclamation)</td>
<td>Low (generally free)</td>
<td>EMA, FLDFREQ3, rainfall-runoff modeling, graphical approach</td>
</tr>
<tr>
<td>Public Data Sources – GIS (e.g USGS, NRCS, states)</td>
<td>Low (generally free)</td>
<td>Rainfall runoff-modeling</td>
</tr>
<tr>
<td>Regional Paleoflood Information</td>
<td>Moderate (generally free)</td>
<td>EMA, FLDFREQ3, graphical approach</td>
</tr>
<tr>
<td>Site-Specific Paleoflood Stratigraphy</td>
<td>Moderate (moderate)</td>
<td>EMA, FLDFREQ3, graphical approach</td>
</tr>
<tr>
<td>Detailed Paleoflood Information</td>
<td>High (high)</td>
<td>EMA, FLDFREQ3, graphical approach</td>
</tr>
<tr>
<td>LiDAR Collection</td>
<td>High (high)</td>
<td>Paleoflood information, H&amp;H modeling</td>
</tr>
</tbody>
</table>

Incorporating Paleoflood Data

Paleoflood data can be combined with stream gage data to extend the time series well before the historic record. This allows for credible extrapolation to rare events having an AEP less than .01%.
Low Level Analyses

Reclamation will typically spend 5-10 days for some preliminary analyses (CRs, feasibility level, etc). This often includes EMA with regional paleoflood information. ARR (frequency PMF) is often used to deal conservatively estimate beyond credible extrapolation.

Moderate Level Analyses

15-45 day efforts are often applied to Issue Evaluation, Corrective Action, and Final Design studies (and some high level Comprehensive Reviews).
High Level Analyses

When the hydrologic risk at a facility may require expensive mitigation (i.e. operations, mechanical, construction risk reduction measure alternatives), studies often require extensive time, effort, and cost to produce flood estimates.

Case Study – Friant Dam HHA

This study provided a detailed probabilistic flood loading analysis used to quantify risks associated with various failure modes. This was accomplished by developing flood frequency hydrographs using a stochastic rainfall-runoff model (SEFM).

- Structural Height of 319 feet
- One 100x18 ft Drum Gate
- Two 100x18 ft Obermeyer Gates
- Spillway Capacity is 83,000 ft³/s
- Combined Outlet Work Capacity is 17,000 ft³/s
- Controls 1,660 ft³
- 11 Upstream facilities (six of which are large dams)
Stochastic Rainfall-Runoff Model

Develop physical based 1-dimensional rainfall-runoff using hydrologic runoff units (HRU’s)

Estimate a precipitation frequency curve using the L-Moments method of regional statistics

Randomly sample the frequency precipitation curve as well as a storm pattern to determine an annual maximum storm event

Randomly determine the initial model conditions

Repeat steps 3 and 4 to develop a simulate time-series of maximum flood events

Fit a statistical distribution to the time series of annual maximum events

Regional Precipitation Analysis
### Spatial and Temporal Storm Patterns

<table>
<thead>
<tr>
<th>Storm</th>
<th>72-hr Precipitation</th>
<th>Use</th>
</tr>
</thead>
<tbody>
<tr>
<td>November 13-22, 1950</td>
<td>10.58</td>
<td>Calibration/Production</td>
</tr>
<tr>
<td>December 18-27, 1955</td>
<td>15.09</td>
<td>Calibration/Production</td>
</tr>
<tr>
<td>February 3-17, 1962</td>
<td>9.56</td>
<td>Production</td>
</tr>
<tr>
<td>January 29 - February 7, 1963</td>
<td>14.91</td>
<td>Calibration/Production</td>
</tr>
<tr>
<td>December 17-31, 1964</td>
<td>5.69</td>
<td>Production</td>
</tr>
<tr>
<td>December 1-11, 1966</td>
<td>9.56</td>
<td>Production</td>
</tr>
<tr>
<td>January 18-22, 1969</td>
<td>10.86</td>
<td>Production</td>
</tr>
<tr>
<td>January 23-29, 1969</td>
<td>7.56</td>
<td>Production</td>
</tr>
<tr>
<td>September 1-10, 1972</td>
<td>1.67</td>
<td>Calibration</td>
</tr>
<tr>
<td>September 1-10, 1978</td>
<td>3.63</td>
<td>Calibration/Production</td>
</tr>
<tr>
<td>January 9-19, 1980</td>
<td>8.97</td>
<td>Production</td>
</tr>
<tr>
<td>September 23 - October 2, 1982</td>
<td>4.28</td>
<td>Calibration/Production</td>
</tr>
<tr>
<td>February 12-21, 1986</td>
<td>8.78</td>
<td>Production</td>
</tr>
<tr>
<td>March 8-18, 1995</td>
<td>9.84</td>
<td>Production</td>
</tr>
<tr>
<td>Dec 29, 1996 - Jan 7, 1997</td>
<td>7.29</td>
<td>Calibration/Production</td>
</tr>
<tr>
<td>November 6-16, 2002</td>
<td>7.15</td>
<td>Calibration/Production</td>
</tr>
<tr>
<td>Dec 26, 2005 - Jan 9, 2006</td>
<td>7.88</td>
<td>Production</td>
</tr>
<tr>
<td>December 15-24, 2010</td>
<td>11.2</td>
<td>Production</td>
</tr>
</tbody>
</table>

### Stochastic Storm Template

**Cumulative Precip**

**Temperature and Freeze Level Index**

15

18

3-144
Physical Based Model

- 8 soil zones
- 5 MAP zones
- 9 elevation zones
- 360 HRUs per sub-basin
- 8,280 HRUs total!

Calibration

8 Historic Flood Events were used in Calibration
Friant is a mixed population (rain and snowmelt) system – the maximum annual rainfall didn’t always yield the maximum annual flood
Fall events were used to calibrate high elevation basins because they represented snow-free ground
Runoff calibration was performed from the upstream basins to the downstream basins
Adjustments were made to the routing parameters and freeze level offsets to better fit the peak-discharge frequency
Calibration

Peak-Discharge Frequency Calibration
Friant Hydrologic Loading

U.S. Bureau of Reclamation
Technical Service Center
Flood Hydrology & Meteorology

Joseph M Wright, P.E.
Hydraulic Engineer
303-445-2463
jmwright@usbr.gov

Keil J. Neff, P.E., Ph.D.
Hydrologic Engineer
303-445-2541
kneff@usbr.gov

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

Joseph Kanney, Ph.D.
Hydrologist
301-415-1920
joseph.kanney@nrc.gov
3.3.4.2.3 Questions and Answers

**Question:** So, I noticed some of your graphs, the scale on the x-axis, if I take out the percent, went as far as 10 to the minus 10 per year, which is double the age of the earth… but the graph didn’t go that far. But some of your lines go up to about 10 to the minus 6 per year, some of them stop at 10 to the minus 4 per year. I want to know, from Reclamation’s standpoint, at which point…where do you stop being concerned or do you. As you’re going lower and lower in frequency and say below this …we’re going to screen that out because it’s too low a risk to consider?

**Response:**

Well first of all, we would never go 10 to the minus 10. So, I think Kyle had a slide up there that showed incredible extrapolation under the perfect conditions, all the planets come aligned, and everything and your data is just perfect, you can go to maybe a hundred-thousand-year event. When we’re looking at EMA curves with paleo flood data if we have a really, really good data set, I prefer to cut them off at about a twenty-thousand-year event, maybe a fifty thousand if the risk analysis justifies it. When we get beyond that, without any kind of a stochastic type approach, we tend to lean towards a pragmatic approach and that's why I like the Australian Rainfall Runoff Method (ARR). I like to call ARR our frequency PMF's because basically we're just drawing a line from a hundred-year preset to a PMP that we assume some probability to and we're just using that to scale a PMF hydrograph. And it's just a conservative, pragmatic approach that if we say that the dam can handle that then you're probably okay. SEFM… I don't think we've ever done one and that goes beyond a 1-million-year event, and when we do that we now like to incorporate some uncertainty in that and we are working on how to incorporate uncertainty in our overall risk analysis. So hopefully that answers your question.

3.3.4.3 Development of External Hazard Information Digests for Operating NPP sites

Kellie Kvarfordt and Curtis Smith*, Ph.D., Idaho National Laboratory (Session 1D-3; ADAMS Accession No. ML17355A092)

3.3.4.3.1 Abstract

The original name of this project was Development of Flood Hazard Information Digests for Operating NPP Sites, and the original objective and tasking of the project was for Idaho National Laboratory (INL) to develop, demonstrate, and help populate a database architecture for Flood Hazard Information Digests. The resulting web application facilitates gathering, organizing, and presenting a variety of flood hazard data sources. However, the database is currently undergoing expansion to include other external hazards such as seismic and high wind hazards, extreme temperatures, and snow/ice loads. This expansion will support the Commission directed activity to enhance agency processes for ongoing assessment of natural hazards information. Thus, a more accurate name for the project and digest application is now External Hazards Information Digest (EHID).

The goal of the project is to provide information and tools to support external event analysis, particularly the risk-informed aspects of the Significance Determination Process (SDP). Under the SDP the use of probabilistic external hazard information and insights is an important input in the determination for follow-up inspection actions and resource allocation, and risk-informing of licensing actions. However, NRC staff has had to improvise and only use probabilistic external hazard estimates on an ad hoc basis, in a limited manner.
A particular challenge in developing probabilistic external hazard estimates within the SDP is that
the required external hazard information is not readily accessible. It is challenging for NRC staff to
assemble and analyze the information within the time available for the SDP. Thus, there is a need
to better organize external hazard information at operating reactor sites and improve its
accessibility for NRC staff performing SDP analyses. The EHID application has been developed
to address these needs.

Major flood related data sources that have been identified for reference in EHID include data from
Fukushima NTTF Recommendation 2.1 and 2.3, precipitation frequency information from NOAA,
flood frequency information from USGS, hurricane landfall/intensity information, as well as flood
protection and mitigation strategies from NUREGs, FSARs, IPEEE submittals, and SDP analyses.
Additional data sources are being identified for other external hazard inclusion. In addition to
providing access to these and other data sources, the information digest can provide, where
needed, guidance for using the available information.

The EHID has been implemented as a cloud-based web application. The digest utilizes the INL’s
Safety Portal, a system that helps integrate and manage a comprehensive collection of many
different kinds of content including web pages, web applications, models, and documents where
users may store, use, share, modify, or otherwise contribute to projects. The information digest
shares available services such as user account management, file sharing, and a publications/
permissions/ subscriptions model.

Because the database contains a mixture of publicly and non-publicly available information, the
EHID application is available only to NRC staff and contractors with appropriate authorization.
Within the application access to individual items is controlled by those authoring the information.
Initial data population efforts for flooding are nearing completion, and other external hazard data
source identification and population efforts are commencing. The bulk of data population is
targeted for completion by the end of June 2018. Maintenance will be folded into other ongoing
data related activities performed by INL on behalf of the NRC.

3.3.4.3.2 Presentation

![Development of Flood Hazard Information Digits for Operating NPP sites](image)

3rd Annual Probabilistic Flood Hazard Assessment Research Workshop

December 4-5, 2017

Kellie Kvarfordt
Curtis Smith, Ph.D.
Project Overview

- Organize flooding information and build database of currently available site-specific flood hazard information to
  - Support development of a risk-informed analytical approach for flood hazards
  - Help Senior Reactor Analysts (SRAs) develop simple flooding models and reasonable hazard curves that fit into SAPHIRE modeling world

...in order to

- Develop regulatory tools and guidance for NRC staff with regard to probabilistic flood hazard assessment (PFHA) for nuclear facilities
- Support risk-informed reactor oversight activities such as evaluating the risk-significance of inspection findings

- Expand the digests to include other natural external hazard information

Status

- Completed
  - Flooding Hazard Information Needs Workshop
  - Reviewed existing NRC databases
  - Designed and implemented beta of flood hazard information database
  - Beta testing/demonstrations
  - Majority of key flood related data sources have been populated

- Remaining
  - Post Fukushima flooding reevaluation information
  - Expansion to other natural external hazards
  - User Guide Updates
External Hazards Web Application

Welcome

External Hazards Information Digest

Proceed to Site

*Available only to authorized NRC staff and contractors

External Hazards Dashboard
Drill-down to Plant Specific Activities...

...and Plant Specific Data Sources

Sources: NRR’s Mitigating Strategies Flood Hazard Information Database and Army Corp of Engineers (ACE)
Risk Models

Integration with Safety Portal
Watershed Data

Sources:
USGS and ArcGIS

Precipitation Data

Precipitation Data for Brunswick 1

Latitude & Longitude: 43.998322, -8.010278

1. NDIA Atlas 14 Precipitation Data Downloads
   Partial duration series (PDS): CSV file
   Frequency annual maximum series (AMAX): CSV file

2. NDIA Atlas 14 Database precipitation frequency information
   The Precipitation Frequency Data Server (PFDS) is a point-and-click interface developed to deliver NDIA Atlas 14 precipitation frequency estimates and associated information. Enter the latitude and longitude of the station to display its precipitation estimates.
   Naples: 100 year interval
   NDIA Atlas 14 cartographic maps of precipitation frequency estimates for selected average recurrence intervals:
   1 hour, 6 hour, 24 hour, 48 hour, 12 day, 30 day, 60 day.
Examples of precipitation data

Sources:
National Weather Service
and NOAA Atlas 14

Stream Flow Data
Examples of stream flow data

Annual maximum series of peak flow

Discharge data in the past seven days, available in 15 minute detailed increments

Source: USGS

Coastal and Great Lakes Data

Coastal Data for Brunswick

Flood Hazard Region Map

Data References

Coastal Data

NOAA Tides and Currents

Wilmington, NC - Station ID: 8658120

Station Info Today's Tides Photos Sensor Information Observation
Examples of coastal data

Source: NOAA

Activity/Report Drill Down Across Plants
Expansion to Other Natural External Hazards

- The work on other natural hazards is in progress and is being coordinated with the NRC External Hazards Center of Expertise (EHCOE)
- High winds
  - Tornado
  - Hurricane
- Extreme temperatures/humidity
  - High and low temperature extremes
  - Wet-bulb temperature
- Snow/Ice loads
- Seismic

Publications and Subscriptions
Summary

- Flood Hazard Information Digest is being adapted to be a more broadly defined External Hazards Information Digest
- The External Hazards Information Digest organizes and presents a variety of relevant, plant specific information
  - This mix of publicly and non-publicly available information is available to select NRC staff
  - Also available to contractors with appropriate authorization
  - Access to individual items is controlled by those authoring the information
- Major flood hazard data sources have been identified and most are currently available in the digest
- Additional natural external hazard data sources are being identified for inclusion to the digest during FY18
3.3.4.3.3 Questions and Answers

Question:

So, I'm curious since I know you said a lot of the information is publicly available…if a licensee has a reason to assess these things as much as the NRC. Say there's a significant determination process and they would like to simplify their research as well… is there any mechanism that they
can ask the NRC, “Can you give us all the links to publicly available information? Since you have it very readily available?”

Response:

They would go through the NRC to determine whether that was appropriate or not. I guess the licensing office would make that determination... not us here in research. So, if the licensing office wanted to make that available to the licensees and that was an appropriate thing to do, then I don't think there would be any problem with it. But that wouldn't be a decision that research makes.

Question:

Thank you very much Kelly. One thing I kept thinking about as you went through different data sets... I'm very curious... do you have the pedigree of the data? Do you have information on the QA/QC? What was done at the time of the collection of the data and how you could determine how the data was collected... who collected it? Under what procedures they collected it? Do you have that information?

Response:

I really don't. These are from external agencies and that is their mission to collect that data. I guess we could probably provide links into any background that they had on that but we're not personally validating that data. I know that the specific stuff that we make available: the stations and the gauges, hydrologists have cross-checked each other to make sure that we're providing the correct links... the things that we have control over.

Question: It's a kind of a curiosity question I guess. Do you have flood forecasts locations... say upstream of the power plants included in the database? And also, upstream dams?

Response:

We don't have the upstream dams right now but that is certainly under consideration as part of some of the other external hazard sources. We're evaluating what sort of information we want to put in there regarding upstream dams, as you're well aware, some information about upstream dams is information that we may have obtained from other agencies, so we would have to consult with the other agencies to make sure that we're not providing information that shouldn't be provided to people who don't need. On the same pages as the USGS gauge sites, there's links to the upstream and downstream forecasting sites...they've been identified, I'm not sure if they have been worked into the database - but those flood forecast sites are pretty short in history and I don't know if our turnover is that fast for looking at forecasts.

Question:

A couple of other previous speakers were focusing on other extremes. Have you had the opportunity to include climate projection information in the database? Specifically, precipitation stream flows that have been down scaled or other sources such as those?

Response:

No.
3.3.5 Day 1: Session 1E - Paleoflood Studies

Session Chair: Mark Fuhrmann, NRC/RES/DRA/FXHAB

3.3.5.1 Improving Flood Frequency Analysis with a Multi-Millennial Record of Extreme Floods on the Tennessee River near Chattanooga, Tessa Harden*, Ph.D., Jim O’Connor, Ph.D. and Mackenzie Keith, U.S. Geological Survey (Session 1E-1; ADAMS Accession No. ML17355A093)

3.3.5.1.1 Abstract

A rich history of large late-Holocene Tennessee River floods is preserved in caves and alcoves throughout the Tennessee River Gorge area near Chattanooga, Tennessee. Preliminary stratigraphic analyses, coupled with geochronologic techniques, show evidence of at least four floods occurring in the last ~3,000 years with possible discharge estimates greater than or similar to the 1867 peak of record (460,000 ft$^3$/s at Chattanooga, Tennessee). One of those floods may have occurred in the last 400 years and has an estimated discharge at least twice the magnitude of the 1867 flood. At least 1–2 additional large floods with estimated peaks similar to the 1917 flood (341,000 ft$^3$/s) occurred in the last ~3,000 years. In addition to flood evidence found in caves and alcoves, flood deposits in exposed stratigraphy at Williams Island, an alluvial island at the head of the gorge, date to ~9,000 years. Determining accurate discharge estimates in this section of the river is difficult due to the backwater from the gorge constriction during high flows, but the flood records preserved here can be used to validate flood evidence downstream in the gorge, where the stable boundary and narrow valley provide more reliable discharge estimates. Stratigraphic records of past floods to reduce uncertainty in flood frequency analyses have been used extensively in the arid western United States, especially for floods with low annual exceedance probabilities. Preliminary results indicate that previously developed techniques to develop stratigraphic records of past floods can be successfully applied to reduce uncertainty in flood frequency analyses in the temperate eastern regions of the United States.

3.3.5.1.2 Presentation

(Improving Flood Frequency Analysis with)
A Multi-Millennial Record of Extreme Floods on the Tennessee River near Chattanooga, Tennessee

Tessa Harden
Jim O’Connor
Mackenzie Keith
U.S. Geological Survey, Portland, OR
What is “Paleoflood” Hydrology

....using geologic evidence to understand flood history...

Why?
Flood-Frequency Analyses from Paleoflood Investigations for Spring, Rapid, Boxelder, and Elk Creeks, Black Hills, Western South Dakota


Prepared in Cooperation with South Dakota Department of Transportation, Federal Emergency Management Agency, City of Rapid City, and West Dakota Water Development District

3-165
A typical paleoflood study may contain a stratigraphic record of 1–10 floods in a 1,000-year period.
Screening results:

• Several southeastern US sites are potentially suitable, including several rivers with multiple sites. These include Susquehanna River, Pennsylvania; Tennessee River, Tennessee; and Catawba River, South Carolina.

“Jeff-n-Steph” site located in the Gorge at a similar elevation as the 1867 high water marks. This site contains at least 3+ flood deposits in the last ~3,000 years.
Prehistoric Floods on the Tennessee River—Assessing the Use of Stratigraphic Records of Past Floods for Improved Flood Frequency Analysis

Four floods similar to 1867 peak (459,000 ft³/s)
1-2 floods similar to 1917 peak (341,000 ft³/s)
Still need to:

- Finish fieldwork (January-February 2018)
  - A few more alcoves
  - Stratigraphy at Williams Island
- Lab results
  - OSL
  - radiocarbon
- Hydraulic model
  - discharge magnitudes
- Flood Frequency Analysis

Funding and contact information:

- National Screening, and the Tennessee River scoping (2016) and implementation (2017-2019) funded by Nuclear Regulatory Commission, Office of Nuclear Regulatory Research
- USGS Personnel: Tessa Harden thor@usgs.gov); Jim O’Connor (oconnor@usgs.gov); and Mackenzie Keith
- NRC Personnel: Mark Fuhrmann (mark.fuhrmann@nrc.gov); Meredith Carr (Meredith.Carr@nrc.gov); and Joseph Kanney (Joseph.Kanney@nrc.gov)
3.3.5.1.3 Questions and Answers

Question:

Is there any beer can chronology?

Response:

That's a good point. Beer can chronology - which is a real thing. So, people have used all sorts of things to date these things. And in the Black Hills, I've actually used socks which worked out great. People use beer cans... you can tell by when the can was made, and people use barbed wire to date these floods. We found plenty of beer cans, but they were all modern.
3.3.5.2 Collection of Paleoflood Evidence Lisa Davis*, Ph.D., University of Alabama; and Gary Stinchcomb, Ph.D., Murray State University (Session 1E-2; ADAMS Accession No. ML17355A094)

3.3.5.2.1 Abstract

Despite significant advances in meteorological and hydrological forecasting in the last 50 years, catastrophic floods constitute one of the most globally persistent natural hazards. Instrumented discharge records rarely span more than 200 years, making them less likely to contain records of large floods, which tend to occur less frequently. Additionally, using instrumented flow records to understand flood variability in relation to climate, is more challenging since these records only span the time of human occupation. Paleoflood hydrology focuses on collecting and analyzing physical evidence of past floods that occurred before the instrumented record for flood risk assessment and to understand environmental change. Our presentation will demonstrate some of the basic principles of paleohydrologic research and present preliminary findings of a paleoflood record for the Tennessee River, as part of a broader effort to develop paleoflood data for flood frequency analyses for the Tennessee River.

3.3.5.2.2 Presentation
Research Questions

Do paleoflood indicators of extreme floods exist in the Tennessee River basin?

Can these paleoflood indicators be used to estimate peak stage, discharge, and flood age?

Are the proxies reproducible among different teams?

Flood of record (1867) on the Tennessee River at Knoxville, TN (image from McClung Museum, University of Tennessee)

The Tennessee River
Methods


Methods: multi-pronged, multi-site approach

Instrumented Record  Tree Ring Record  Sedimentary Record

Present  Historic Record

Past
River Terrace Sites

- All teams sampled terrace deposits with the goal of reconstructing the number and relative size of floods experienced at each location.
- Landforms sampled on terrace surfaces included paleomeander bends, relict natural levees, and topographic lows.


Terrace Sites C-1 and C-2

4 flood deposits
Terrace Sites

4 flood deposits

Terrace Site A-6

- 5 flood deposits dated to: -1607, -1867, -1875, -1886, -1917
Terrace Site B-21

- 12 flood deposits
- Flood of record (1867) found at multiple sites
- Two sites had flood deposit that radiocarbon-dated to early 1600s

Bluff, Cave and Canyon Sites

- Slackwater deposits
- Potential for max paleostage reconstruction
Cave deposits
**Bluff deposit**

**Boulder sheltered deposits**

Flood deposit located on downhill/stream side of large in canyon of tributary to TN River
Summary of findings to date

- Extended the flood record of the TN River by ~1200 years
- Discovered evidence of several prehistoric, large floods
- Flood of 1847, validated by deposit dated to 1830 +/- 15? This flood potentially larger than the flood of record?
- Some of the (pre) historic floods correlate between all three research groups, such as the 1910, 1867, 1630 floods
- All of the surfaces predicted to be inundated by TVA’s extrapolated water surface elevations for the 1867 flood were found to have been inundated


Modeled sediment accumulation rates are faster during past 170 years, compared to older record.

These rates are consistent with pre-settlement and post-settlement sedimentation rates observed along Upper Little Tenn. R. basin (Wang and Leigh, 2015)
3.3.5.2.3 Questions and Answers

Question:
You brought up a very good point. In the northern part of Pennsylvania, there was a lumbering boom that occurred, and the mountains were literally devoid of any lumber and then sufficient flooding occurred. People would argue that because of the context of that flooding, could that repeat itself? Meaning that unless you cut down all the trees again in northern Pennsylvania, would you expect to see those kinds of floods. So, could you give us some perspective on the Tennessee River Valley with regard to the context of the various floods you've seen? Do you have any reason to understand why they occurred?

Response:
That’s something very interesting. Until we really nail down the timing of events, we can't get a good handle on the mechanisms. Right? So, the other thing to remember is that the more sites we have, the more robust picture that we get. So, for example, the 1600 flood that all of the teams picked up, that’s very interesting to us because that may speak to its magnitude. The fact that it happened everywhere in the basin is very interesting and that is a time that coincides at a time in the eastern United States where there's not a lot of written record about flood information. But we do know that and say for example in New England, the pilgrims were complaining a lot about springtime flood at that particular time. So now maybe with this information from the Tennessee River, maybe we're getting a broader picture of what the climate was like in the eastern US and not just where they were. Maybe that was a pattern that was bigger regionally. So, once we get more of the timing information and that the timing of those floods validated at more sites, we can speak more about mechanisms… weather or climatological or tied to human initiated mechanisms.
Question:

With respect to the pre-settlement and post-settlement sedimentation, obviously you'll see different rates. Do you see differences in the sediment types as well?

Response:

Yes. Initially, when we started looking at these profiles, the one thing that stood out repeatedly was that there was a well-developed soil at depth and then you would see these very weakly developed soils and flood deposits near the surface. More often than not, those date to the last two to four hundred years, but at one of the sites we did find one I think was the bond site…there's one that dated like five, six hundred years ago. My initial assumption I guess is flawed…I thought that the soil stratigraphy alone was saying something about this change from pre-settlement to post-settlement, but there's this 600-year-old flood that kind of just comes out of nowhere. It's clearly pre-European settlement so I don't know how to make sense of that yet. Now the other thing that we've been looking at is we've been looking at the types of organic molecules present in the flood material and one thing we're finding is there's abundance of charcoal or charred material in the more recent stuff. That may or may not be related to pre-versus post settlement. I don't know if charcoal was really huge in the Tennessee River basin and I know it was huge in the Northeast but if they were charcoaling, I guarantee you there was char flying about everywhere. So anyway, I don't know how you would source the char in the flood deposit back to it, but the char is a tantalizing clue we need to explore that more.

Question:

I had a similar question to the first one. Can you tell when the floods occurred? Is it in the spring or fall? Because it's a different concern whether it was snowmelt versus flash flood depending on how to mitigate against those scenarios and whether it's a big concern or not for certain facilities.

Response:

We didn't include information in this, but we do have a dendrochronologist who's working with us named Matt Farrell at the University of Alabama one of the things that he specializes in is looking at cellular damage in the tree rings. That cellular damage only has potential to happen when the trees are saturated for a length of time during the growing season so essentially when you find this you know that the flood happened in the spring or the summer. So, there is potential to find seasonal information about floods in the record, but unless we get like an oxbow lake somewhere that had seasonal deposition but as far as I'm aware, no one has found that. You do find that in glaciated environments where the melt water flow is very seasonal, you get what are called barb deposits where there's seasonal deposition, but our deposits are of an age where even if there was a seasonal signature when they were first laid down it's probably been destroyed by the weathering process.

Question:

Do you guys have any plans to maybe assimilate some of those data and maybe have some spatial characterization to gain some insight on prehistoric hydrology?
Response:

That's a good idea. That might just happen through the research publication process, us all combining data and telling sharing that through the research literature. Or it may happen as part of some other workshop or something tied to this collaborative effort. We're very much open to that and one of the things is that we feel like we're breaking new territory here in science and not just like flood science either. This is a unique opportunity for us to combine paleo study information in a way that the academic studies don't typically have. You typically do your own site, one site, and you do it very detailed and we're combining these detailed studies across the whole basin to get a basin-wide picture which is really robust in a way that hasn't typically been done. So, I think there's a lot of value to that idea and I know there's a lot of interest among the broader group in pursuing that.

Question/comment:

I wanted to add that this sort of thing is very unique in the way these studies are done... you do your own thing, you answer this question, and then you move on. For the first time now and this is a very big basin, yet we are covering different spatial scales of this big basin. I'm sure TVA is thrilled and they're going to get all this information for essentially free, but why not combine it and really nail down what's happening in the basin.

Response:

In particular that question about human occupation as a valley and its effects on flood surface hydrology... I mean that is something that interests a lot of us. In particular David Lee has been looking at whether or not there the soil marker... when that transition happened... if there's a chemical marker that coincides with that. So that others who don't have a lot of money to identify that in their site... then we can increase number of sites a lot more easily... there's momentum for that.

3.3.6 Day 2: Daily Wrap-up Session / Public Comments

Question: (Audience member)

I have a question for the paleo people. In general, do you take into account upstream infrastructure for older data and how an event would occur today vs. the past?

Response: (John Weglian, EPRI)

We have an ex TVA person at the table, I don't know if any current TVA people are in the room right now, but they do have hydraulic for both with and without the dams. So, the floods that we're looking for with this Paleo Flood information predate the existence of dams, but that tells us something about how much water came down the river and so you can use what they call a Naturals model to evaluate what that water level would have done along the river. That's how we can correlate these different floods in different locations and things like that, but then you can put that same information into their new hydraulic models that include the actions of the dams and then they can include in that if the dam models saw of this much level... how would it operate and what is going to affect the downstream flow rates. So, there are ways to correlate what an amount of flow discharge... how that would operate today with the man-made structures in place.
Comment: (Audience Member)

You're saying we use all that old data we need to remodel with the new infrastructure before we use that datum.

Response: (John Weglian)

Correct. So, if you're trying to assess risk at a particular site and you have information on how that river operated or an event that happened on that river say 400 years ago or a thousand years ago, you need to assess how that same event would look in today's watershed to assess the site that you're particularly interested in. Depending where you are in the country that may be relatively easy, it may be extremely complicated, depending on what man-made structures are now on the watershed. That's all a part of the puzzle that you have to put into your analysis to assess your current risk at a particular site.

Response: (USBR)

I was going to follow up on that. At Reclamation there's definitely multiple approaches to looking at both unregulated and regulated frequencies. And I know at Reclamation that we definitely look at both depending on the question that's being asked and there's multiple methods to address that simplified mass balance. And methods or statistical methods doing correlations to pre and post dams and there's a multiple method to do it. At the end of the day, we're mostly interested in the regulated flow frequencies, but it just depends on the question being asked.

Question:

We have a question on the webinar for Dr. Ryberg. This question comes from Keith Kelson. Dr. Ryberg how have the studies along the Red River and the Souris River handled variable stages and discharges related to ice affected floods?

Response: (Karen Ryberg)

That is a good question. The data from the Red River at Winnipeg is from Manitoba water stewardship, and its naturalized flow to take into account changes in regulation there. They have estimated flows under ice as part of that and I don't know all the details on that. On the Souris River, generally, ice jamming has not been an issue. There are ice affected flows that the USGS has marked “provisional” until they are analyzed, and then in some cases adjusted but they are considered good estimates of flow. We haven't done anything to adjust for ice on the Souris River.

Question: (Audience Member):

I have a question for Ruby, but I guess she's gone. I was curious about what the postulated mechanism that would impact the decrease in storm speed that she was talking about. Some of the forecasting of some of the storm characteristics like what caused the decrease in these storms' speeds?

Response: (Rajiv Prasad, PNNL):

Good question and I don't know the exact answer to that but some of it might lie in how the large-scale climate patterns are changing and there are some studies that are relating these climate
patterns both in the Atlantic and in the Pacific to how these tracks might be changing. But there’s a forward shift and that is moving some of the stuff to the north.

**Question: (Audience Member):**

Another question I had for her but maybe you can answer it. She was looking at some of the MLC storm types and that's great looking at these different storm types. Are you guys planning on doing any projections for tropical cyclones or any other controlling storm types in that region?

**Response: (Rajiv Prasad, PNNL):**

We are not planning on doing any projections. All we are doing in this study is compiling what is already known and published. We don't plan to do anything new in this project.

**Response: (Joe Kanney, NRC):**

For that project that we have with PNNL, what we've asked them to do is basically help us sift through a lot of the results that are coming out of the climate science community. It’s something we need a lot of help to take that on board in terms of studies are significant, what trends they are showing, and then what impact it might have on hydrology. But also, other factors that influence nuclear power plants. So yes, they're basically helping us sift through the results that are coming out of the climate science community.

**Comment: (Joe Kanney, NRC)**

Some of those questions may matter, not in terms of whether you saw it or not but how you interpret on that data and how you use it statistically. Essentially, the main question would be: do I have one population of flood causing mechanisms or should I model this as coming from multiple populations? So, to that extent that information can be useful in how you interpret that data.
Comment: (Tessa Harden, USGS)

Just to add something. I think if you look at the gauge record and for the Tennessee River, the large storms which are quite a bit larger than say everyday storms or so. They all happen in the spring so if you get maybe in the Paleo food record you see all around that certain discharge.

Comment: (Steve Prescott)

Snowmelt versus a flash flood coming through gives different response times. If there’s way to know that then you can gauge how many of these events are of those types and bin them and know how to respond and what frequency those type of events are.

Comment: (Karen Ryberg)

I just wanted to follow up a little bit more on the ice question. I'm not sure if I totally understood what they were getting at. When we measure peak streamflow and there are ice effects, someone goes out and makes a measurement because we know there's a change in the stage discharge relationship. You wouldn't use the rating curve that you would under open water, so we make those adjustments and those adjustments have been made for a long time. But even if you've got this hundred year record you're excited about, back in time less than that [100 years] you don’t know what may have happened. In particular historical floods that have a code 7 in the USGS database before the systematic record those have been entered as point estimates in the database which in retrospect was not a good thing because there's a huge degree of uncertainty, but that database was developed in the 1960s when you had to worry about every digit taking up more memory in the database. So, it's a point estimate, and if I had a huge pot of money and people to do it… it would be fantastic if the USGS would go back to all of those code seven peaks, historical peaks, and put in an interval estimate. That would give you a better sense of that uncertainty which in some cases would be caused by ice uncertainty in other places. So, as we go back further in time there's definitely more uncertainty in the data related to ice and to other things.

Comment: (Audience Member)

I have just another comment on the ice. I worked on the Delaware River a couple years ago and I was looking at these profiles much like we're doing on the Middle Tennessee River and its fine-grain alluvium, but occasionally what we would find are large cobbles showing no signs of reworking by Native Americans, and underneath the large cobbles were fine pebbles. We kept finding these layers of them in particular units and one of the things we were thinking was that these cobbles were ice wrap debris. You'd be basically plucking grains off the side of the channel, so you have bed load where you have large cobbles and underneath those large cobbles are the fine pebbles like an armoring effect I guess. There's evidence of ice wrap debris but the problem is you spend all day digging a pit and you find evidence of it but if I dig four or five meters down and dug a pit I might not see that and so it's like a shot in the dark. I think it does exist. There's potential there to identify say like a flood from ice raft debris but it is a shot in the dark.

Question: (Audience Member)

This is a question for Jennifer, Tess, and/or Joe related to the paleo flood study in the Tennessee River Gorge. I was just kind of thinking during the presentation, you're talking about the gorge being kind of like a dam in some respects and then it opens up there above Williams River and then Chattanooga so there's a lot of volume so in some ways Chattanooga and that whole valley
upstream is kind of a reservoir. I'm wondering if you guys are going to, when you're doing the hydraulic modeling, include that area upstream and get an idea of some of the volumes. Or maybe the end flow may be different than the flows that you're seeing through the gorge and what that hydraulic model going to look like.

Response:

We have some sites that are right at the mouth or a little upstream so that'll be included in the model. We haven't really talked about model parameters, but it should be included...hopefully it will be included.

3.3.7 Day 2: Poster Session

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

3.3.7.1 Poster Abstracts

3.3.7.1.1 Probability-Based Flow Modeling Using the Hydrologic Engineering Center Hydrologic Modeling System (HEC-HMS) Brian Skahill, U.S. Army Corps of Engineers, Engineer Research and Development Center, Coastal and Hydraulics Laboratory

3.3.7.1.2 Reclamation’s Paleoflood Database: Design, Structure and Application. Jeanne E. Godaire, Kurt Wille, and Ralph E. Klinger, U.S. Bureau of Reclamation, Technical Services Center

The Bureau of Reclamation paleoflood database was developed beginning in 1999 as an outgrowth of the global paleoflood database that was being developed at the University of Arizona through Dr. Katie Hirschboeck in order to provide a digital archive for paleoflood data in the United States. Currently, the database is internal to Reclamation and exists mainly as a data repository, containing some published paleoflood data and Reclamation paleoflood studies that were primarily developed at or near Reclamation facilities. This database is an important resource for paleoflood investigations and hydrologic hazard assessment but has been underutilized due to a lack of tools to effectively synthesize the data for projects and research. However, the database could be used more significantly to efficiently investigate research questions related to hydrologic hazards, climate change or other related topics. Tools associated with the database have been developed to extract data, attach related data, and create complex queries to assist in paleoflood research. Reclamation has been improving the database structure and graphical interface using a combination of Microsoft Access and ArcGIS. Data are stored as relational tables with searchable fields that can be queried using spatial or field-based queries.

3.3.7.1.3 Late Holocene Paleofloods along the Middle Tennessee River Valley. C. Lance Stewart and Gary E. Stinchcomb, Department of Geosciences and Watershed Studies Institute, Murray State University; Steven L. Forman, Department of Geology, Baylor University; Lisa Davis and Rachel Lombardi, Department of Geography, University of Alabama; Emily Blackaby, Owen Craven and William Hockaday, Department of Geology, Baylor University.

Sediment stored in floodplains and low alluvial terraces along the middle Tennessee River reflects flood frequency and magnitude during the past ca. 1500 years. This study uses the stratigraphy,
sedimentology, $^{13}$C NMR analysis (nuclear magnetic resonance) and geochronology of three alluvial terraces to infer past flooding. Buried soils at the three locations are older than ca. 630 CE and suggest a multi-century period of landscape stability. Multiple flood deposits are separated by weakly developed soils, indicating an increased flood frequency until ca. 1910 CE. Optically-stimulated luminescence dates of flood deposits yield ages of 580+/-110, 835+/-80, 1460 +/-30, 1465+/-35, 1660+/- 30, 1830+/-15, 1875+/-10 and 1910+/-10 CE. Age-depth modeling shows increased sediment accumulation rates following ca. 1800 CE. The geochronology, when combined with $^{13}$C NMR, shows an increasing flood sedimentation rate during the past 200 years associated with a decrease in the abundance of charcoal and increase in the abundance of lipids. These data suggest that the more recent flooding is more frequent and contains more C with higher oxidation potential. Particle-size analysis of historic floods demonstrates an increase in sand content with increasing flood magnitude, which is consistent with previous work upstream. The highest percentage of sand is found within flood deposits dated to 1830+/-15, 1460+/-30 and 1875 +/-10 CE, the latter of which coincides with the 1867 CE historic flood of record along the Tennessee River. The high magnitude flood of 1830+/-15 CE is consistent with a USGS paleoflood analysis upstream that documents a paleoflood occurring ca. 1600-1800 CE that was higher in elevation than the historic flood of record. The earliest observed flood deposits appear to occur during transition into the Medieval Climate Anomaly between 800 and 1300 CE with increased flood magnitude through the Little Ice Age (1400-1800 CE), and with peak magnitude occurring 1830+/-15 CE.

3.3.7.1.4 A regional chronology of floods and river activity during the last 10,000 years in the Eastern U.S. Lisa Davis, Rachel Lombardi; Department of Geography, University of Alabama, Gary Stinchcomb; Watershed Studies Institute, Murray State University, C. Lance Stewart; Department of Geosciences, Murray State University, Matthew D. Therrell; Department of Geography, University of Alabama, Matthew Gage; Office of Archeological Research, University of Alabama.

Most paleoflood analyses are conducted at a single site or a small number of sites within a single river basin. These studies provide detailed chronologies of river activity, such as flooding, spanning hundreds or thousands of years, which can be used to decrease uncertainty in flood frequency analyses. Site specific reconstructions, however, have limited applicability to understanding river activity at larger spatial scales, such as an entire basin or multiple basins within a region or for understanding drivers of regional and continental-scale changes in the timing or spatial occurrence of floods. This poster presents a regional chronology of river activity over the last 10,000 years for the Eastern U.S.—the first of its kind for this region. The chronology was developed by compiling and combining hundreds of site-specific paleoenvironmental reconstructions containing radiocarbon-dated flood and rainfall-related depositional events from the research literature and unpublished archeological reports. This Eastern U.S. regional river activity chronology is applicable to flood frequency analyses in three specific ways: (1) it can be used to understand the spatial occurrence of floods in the Eastern U.S. over millennia; (2) it can be used to examine how flood frequency has changed throughout the region and within major river basins of the Eastern U.S. over millennia; and (3) it could be used to validate site-specific reconstructions of floods and paleoenvironmental change to determine whether their findings are applicable to broader geographic areas, such as an entire river basin.
3.3.7.1.5 Critical Review of State of Practice in Dam Risk Assessment

David Watson, Scott DeNeale, Brennan Smith and Shih-Chieh Kao, Oak Ridge National Laboratory (ORNL); Gregory Baecher, University of Maryland.

Dams in the United States are aging and in dire need of refurbishment. The American Society of Civil Engineers 2017 Infrastructure Report Card states that the average age of the 90,580 U.S. dams is 56 years with 17% classified as high-hazard potential dams with potential for loss of life and another 13% labelled as significant hazard potential dams with potential for significant economic losses. An estimated $45 billion is needed to repair the high-hazard potential dams alone. Potential detrimental impacts of dam failure include flooding of downstream nuclear power plants.

This project will focus on summarizing and providing a critical review of the state of practice in dam failure risk analysis, with a particular emphasis on developing and quantifying fragility information. The objective of this project is to assist NRC in developing the technical basis for guidance on application of state-of-the-practice approaches, methods and tools for dam risk analysis to inform assessment of flood hazards due to dam failure.

This project will seek to summarize and provide a critical review of approaches and methods for developing fragility curves for key components, systems, and procedures that contribute to the overall fragility of the dam. This will include, but not be limited to:

- Probabilistic geotechnical analysis methods for assessing embankment/foundation/abutment stability
- Reliability of key components such as gates, gate hoists, valves, etc.
- Systems analysis approaches
- Reliability of operational and emergency procedures
- Methods for estimating breach initiation and progression

The project will focus on assessing methods for characterizing and quantifying key uncertainties, as well as propagating these uncertainties through the risk analysis procedure to support risk-informed decision-making. To accomplish the objectives of this project the project team will: (1) Assist the NRC in organizing and conducting a workshop to review the current state of practice in dam risk analysis. The workshop participants will include leading experts from other federal agencies, academic researchers and private industry. International perspectives will also be sought; (2) Provide a summary of the current state of practice in dam risk analysis with a particular focus on development of fragility information for key components, control systems, and operational procedures; (3) Provide a critical review of how key process uncertainties, their characterization, and the degree to which they are propagated in state of practice approaches; (4) Prepare NUREG/CR reports summarizing activities 1-3 and providing guidance on use of state-of-practice dam risk assessment approaches, methods and tools for informing assessment of flooding hazards due to dam failure; (5) Conduct a knowledge transfer seminar at the NRC Headquarters in Rockville, MD covering the topics in items 1-4 with a focus on item 3. The guidance developed under this project will support and enhance NRC’s capacity to perform thorough and efficient reviews of license applications and license amendment requests. They will also support risk-informed significance determination of inspection findings, unusual events and other oversight activities.
All nuclear power plants must consider external flooding risks, such as local intense precipitation (LIP), riverine flooding, flooding due to upstream dam failure, and coastal flooding due to storm surge or tsunami. These events have the potential to challenge offsite power, threaten plant systems and components, challenge the integrity of plant structures, and limit plant access. Detailed risk assessments of external flood hazard are often needed to provide significant insights to risk informed decision makers. Many unique challenges exist in modeling the complete plant response to the flooding event. Structures, systems, and components (SSCs), flood protection features, and flood mitigation measures to external flood may be highly spatial and time dependent and subject to the hydrometeorological, hydrological, and hydraulic characteristics of the flood event (antecedent soil moisture, precipitation duration and rate, infiltration rate, surface water flow velocities, inundation levels and duration, hydrostatic and hydrodynamic forces, debris impact forces, etc.). Simulation based methods and dynamic analysis approaches are believed to be a great tool to model the performance of structures, systems, components, and operator actions during an external flooding event. In support of the NRC PFHA research plan, INL is tasked to develop such new approaches and demonstrate a proof of concept for the advanced representation of external flooding analysis. This project was started in September 2014 and finished in April 2017. It developed a work plan and framework to perform a simulation based dynamic flooding analysis (SB DFA). The SB DFA framework was then applied to a LIP event as a case study. A 3D plant model for a typical PWR and 3D flood simulation models for the LIP event were developed. A state-based dynamic PRA modeling tool, EMRALD, was used to incorporate time-related interactions from both 3D time-dependent physical simulations and stochastic failures into traditional PRA logic models. An example EMRALD model was developed to represent two accident sequences in a simplified traditional PRA model for general transient. 3D simulation elements were incorporated into the EMRALD model and could communicate with the PRA logic. The integrated EMRALD model was run with 3D flooding simulations and millions of Monte Carlo simulations. The EMRALD model results were compared with the corresponding traditional PRA model results. Insights and lessons learned from the project are documented for future research and applications.

The project shows that dynamic approaches could be used as an important tool to investigate total plant response to external flooding events with their appealing features. It can provide visual demonstration of component or system behavior during a highly spatial and time dependent flood event. It could provide additional important insights to risk informed decision makers. The dynamic approaches could also play a supplemental role by supporting the development or enhancement of a static PRA with the insights from the dynamic analysis or performing a standalone analysis that focuses on specific issues with limited sequences and components (e.g., FLEX).
A rich history of large late-Holocene Tennessee River floods is preserved in caves and alcoves throughout the Tennessee River Gorge area near Chattanooga, Tennessee. Preliminary stratigraphic analyses, coupled with geochronologic techniques, show evidence of at least four floods occurring in the last ~3,000 years with possible discharge estimates greater than or similar to the 1867 peak of record (460,000 ft³/s at Chattanooga, Tennessee). One of those floods may have occurred in the last 400 years and has an estimated discharge at least twice the magnitude of the 1867 flood. At least 1–2 additional large floods with estimated peaks similar to the 1917 flood (341,000 ft³/s) occurred in the last ~3,000 years. In addition to flood evidence found in caves and alcoves, flood deposits preserved in exposed stratigraphy at Williams Island, an alluvial island at the head of the gorge, date to ~9,000 years. Determining accurate discharge estimates in this section of the river is difficult due to the backwater from the gorge constriction during high flows, but the flood records preserved here can be used to validate flood evidence downstream in the gorge, where the stable boundary and narrow valley provide more reliable discharge estimates. Stratigraphic records of past floods to reduce uncertainty in flood frequency analyses have been used extensively in the arid western United States, especially for floods with low annual exceedance probabilities. Preliminary results indicate that previously developed techniques to develop stratigraphic records of past floods can be successfully applied to reduce uncertainty in flood frequency analyses in the temperate eastern regions of the United States.
3.3.7.2 Posters

3.3.7.2.1 Probability-Based Flow Modeling Using the Hydrologic Engineering Center Hydrologic Modeling System (HEC-HMS) Brian Skahill, U.S. Army Corps of Engineers, Engineer Research and Development Center, Coastal and Hydraulics Laboratory
Probability-Based Flow Modeling Using the Hydrologic Engineering Center Hydrologic Modeling System (HEC-HMS)

Risk Informed Hydrologic Analysis

Why Safety Programs Exist

- Johnstown, PA
  - 1889
  - 2,200 Dead
- St Francis, CA
  - 1928
  - 450 Dead
- Canyon Lake, SD
  - 1972
  - 237 Dead $60M
- Buffalo Creek, WV
  - 1972
  - 125 Dead & $50M
- Teton, ID
  - 1976
  - 11 Dead & $400M
- New Orleans, LA
  - 2005
  - 1,800 Dead $100B

Safety Programs Defined
- Art and science to ensure the integrity and viability of dams and levees so they provide benefit to the nation and do not present unacceptable risks to the public, property, and the environment
- Requires a philosophy of risk management
- Includes actions taken to identify or predict deficiencies and consequences and to document, communicate, and manage risk

Guiding Principles
- Life safety is paramount
- Decisions are risk informed (consider theory, analysis, observations, experience, judgment, and uncertainty)
- Priority, urgency, and level of detail commensurate with the risks and the decisions
- Portfolio risk management
- Do no harm
Changing Needs

Single Design Flood  Range of Hydrologic Hazards with Uncertainty

Policy—ER 1110-2-1464,
Hydrologic Analysis of Watershed Runoff

HEC-HMS Development

- With funding from the Flood and Coastal R&D program, a new calibration method has been implemented that explicitly and formally quantifies HEC-HMS model uncertainty to support risk informed hydrologic modeling.
- HEC-HMS model calibration convergence provides multiple likely parameter sets rather than one optimal parameter set.
- Its application transforms HEC-HMS from a deterministic to a probability-based hydrologic modeling analysis tool.
- It has a documented history of application for search, optimization, and inference with hydrologic models.

<table>
<thead>
<tr>
<th>Name: Thomas_CW4</th>
<th>Method: Markov Chain Monte Carlo</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pool Size: 10</td>
<td></td>
</tr>
<tr>
<td>Initial Sample: 3000</td>
<td></td>
</tr>
<tr>
<td>Min Iterations: 2000</td>
<td></td>
</tr>
<tr>
<td>Max Iterations: 50000</td>
<td></td>
</tr>
<tr>
<td>Convergence: 1.1</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Parameter Set</th>
<th>Time of Concent. (hrs)</th>
<th>Storage Coefficient (hrs)</th>
<th>Baseflow Recession</th>
<th>Hydraulic Cond. (in/hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.53</td>
<td>6.2</td>
<td>0.212</td>
<td>0.25</td>
</tr>
<tr>
<td>2</td>
<td>0.61</td>
<td>5.8</td>
<td>0.231</td>
<td>0.24</td>
</tr>
<tr>
<td>3</td>
<td>0.42</td>
<td>5.7</td>
<td>0.222</td>
<td>0.27</td>
</tr>
<tr>
<td>4</td>
<td>0.48</td>
<td>5.6</td>
<td>0.223</td>
<td>0.37</td>
</tr>
<tr>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>200000</td>
<td>0.58</td>
<td>6.1</td>
<td>0.281</td>
<td>0.21</td>
</tr>
</tbody>
</table>
- Several HEC-HMS Basin Model parameters can be selected for the optimization analysis: canopy, surface loss rate, transform, baseflow, channel routing, reservoir structures.
- Parameter sets determined from the optimization analysis can be re-used by the uncertainty analysis.
- The uncertainty analysis will randomly select from among the available parameter sets, which preserves correlation between parameters and reduces the chance of unrealistic parameters.
- HEC-HMS is integrated within HEC-WAT, which can be used to quantify boundary condition, initial condition, and model parameter uncertainties.
The newly implemented calibration method is being applied to quantify event-specific HEC-HMS rainfall-runoff model parameter uncertainty for select reservoir systems located in the Willamette River Basin (WRB). In the WRB, hydrologic loading curves are being developed at the Green Peter, Foster, Cougar, Blue River, Hills Creek, Lookout Point, and Fall Creek dams, which are undergoing IES Phase II analysis.

South Santiam River HEC-HMS Model Calibration and Uncertainty Results for calibration to Winter Flood Event I (06Feb1996 - 16Feb1996)

95% Uncertainty Envelope

Additional Application Settings
- PMF Uncertainty
- HEC-HMS Model Parameterization Guidance
- N-Year Hydrographs Reflecting Uncertainty for Levee Design and Risk Assessment
- Quantified Parameter Uncertainty in Levee and Dam Stage Frequency Curves

R&D Needs for Related HEC-HMS Development

Expand current capabilities to support the capacity to (a.) calibrate an HEC-HMS model for a watershed system (i.) using a set of discrete HEC-HMS event model configurations rather than a single event configuration. (ii.) using a set of non-intersecting time intervals for an HEC-HMS continuous simulation run. (b.) include in the objective function/calibration formulation states of the watershed system other than simply flow. (i.) add capability to construct a multi-criteria objective function where the same measurement type processed in different ways comprise separate components of a composite global objective function. (c.) weight observations. (d.) use blended methods for effective and efficient calibration. (e.) use model averaging approaches to account for the uncertainty associated with HMS model choice. (f.) pause/stop and restart a calibration run.
Reclamation’s Paleoflood Database: Design, Structure and Application
by J.E. Godaire, K. Wille, J. Murray, and R.E. Klinger

ABSTRACT

The Bureau of Reclamation paleoflood database was developed beginning in 1990 as an outgrowth of the global paleoflood database that was being developed at the University of Arizona through Dr. Kati Hornbeck in order to provide a digital archive for paleoflood data in the United States. Currently, the database is internal to Reclamation and exists mainly as a data repository, containing some published paleoflood data and Reclamation paleoflood studies that were primarily developed at or near Reclamation facilities. This database is an important resource for paleoflood investigations and hydraulic hazard assessment but has been underutilized due to the lack of tools to effectively synthesize the data for projects and research. However, the database can be used more significantly to efficiently investigate research questions related to hydraulic hazards, climate change or other related topics.

Each associated with the database are being developed to extract data, attach related data, and create complex queries to assist in paleoflood research. Reclamation has been improving the database structure and graphical interface using a combination of Microsoft Access and ArcGIS. Data are stored as relational tables with searchable fields that can be queried using spatial or field-based queries. This research seeks to solicit input in developing tools to better utilize the paleoflood database.

DATABASE STRUCTURE

The database is composed of four main tables or feature classes:

(1) Site Table: contains information about the site where data have been collected
(2) Event Table: contains event data for each paleoflood or non-paleo flood estima
ted at the site
(3) Numerical Age Data Table: contains information about each sample submitted for laboratory analysis

TOOLS IN DEVELOPMENT

This project seeks to identify the best way to query the database or retrieve paleoflood data that would be useful in a project-related, hydraulic hazard study or in answer other pertinent questions involving paleoflood hydrology. This would include utilizing existing tools from the ArcGIS toolbox, creating hypothetical tools or files, adding tools that would query and format paleoflood information into usable outputs, or reworking of the database structure in order to extract information more efficiently. Currently, we are adding the following to the database (1) new data entry forms; (2) standardized re
teports for extracting data; (3) basic definition tools; (4) ground photos and documents; and (5) special query tools.

DATABASE TABLES & FIELDS

The paleoflood database currently contains 100 paleoflood data collection sites. It is estimated that approximately 20% of sites investigated near Reclamation dams still need to be entered into the database. Paleoflood data that were collected for other agencies such as BPA, USACE, NPS and USFWS have also not been entered into the database. In addition, there are a number of paleoflood studies in the peer reviewed literature that should also be entered into the database for use in paleoflood analyses.

ACKNOWLEDGEMENTS

This project was funded by the Drought Early Warning Technology Development Program at the Bureau of Reclamation. Special thanks to Kati Hornbeck for converting the database in the first place and to Tom Hardesty for her invaluable comments and suggestions in recent years.
ABSTRACT

The Bureau of Reclamation paleoflood database was developed beginning in 1999 as an outgrowth of the global paleoflood database that was being developed at the University of Arizona through Dr. Katie Hirschboeck in order to provide a digital archive for paleoflood data in the United States. Currently, the database is internal to Reclamation and exists mainly as a data repository, containing some published paleoflood data and Reclamation paleoflood studies that were primarily developed at or near Reclamation facilities. This database is an important resource for paleoflood investigations and hydrologic hazard assessment but has been underutilized due to a lack of tools to effectively synthesize the data for projects and research. However, the database can be used more significantly to efficiently investigate research questions related to hydrologic hazards, climate change or other related topics.

Tools associated with the database are being developed to extract data, attach related data, and create complex queries to assist in paleoflood research. Reclamation has been improving the database structure and graphical interface using a combination of Microsoft Access and ArcGIS. Data are stored as relational tables with searchable fields that can be queried using spatial or field-based queries. This research seeks to solicit input in developing tools to better utilize the paleoflood database.

DATABASE STRUCTURE

The database is composed of three main tables or feature classes:
(1) Site Table: contains information about the site where data have been collected
(2) Event Table: contains information about each paleoflood or nonexceedance estimate at the site
(3) Numerical Age Data Table: contains information about each sample submitted for laboratory analysis.
TOOLS IN DEVELOPMENT

This project seeks to identify the best ways to query the database or retrieve paleoflood data that would be useful in a project-related, hydrologic hazard study or to answer other pertinent questions involving paleoflood hydrology. This could include utilizing existing tools from the ArcGIS toolbox, creating hyperlinks to various folders or files, adding icons that would query and format paleoflood information into usable output, or a reworking of the database structure in order to extract information more efficiently. Currently, we are adding the following to the database: (1) new data entry forms; (2) standardized reports for extracting data; (3) basin delineation tool; (4) ground photos and documents; and (5) spatial query tools.
DATABASE TABLES & FIELDS

The paleoflood database currently contains 300 paleoflood data collection sites. It is estimated that approximately 20% of sites investigated near Reclamation dams still need to be entered into the database. Paleoflood data that were collected for other agencies such as BIA, USAEC, NPS and USFWS have also not been entered into the database. In addition, there are a number of paleoflood studies in the peer reviewed literature that should also be entered into the database for use in paleoflood analyses.

Site Table

<table>
<thead>
<tr>
<th>Field Name</th>
<th>Domain</th>
<th>Format</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Event ID</td>
<td>none</td>
<td>auto</td>
<td>Default field</td>
</tr>
<tr>
<td>Site ID</td>
<td>none</td>
<td>auto</td>
<td>Default field</td>
</tr>
<tr>
<td>Lab no</td>
<td>none</td>
<td>text</td>
<td>Number assigned at laboratory</td>
</tr>
<tr>
<td>Mineral type</td>
<td>none</td>
<td>test</td>
<td>Number assigned when sample was collected</td>
</tr>
<tr>
<td>Data</td>
<td>none</td>
<td>number</td>
<td>Value calculated by laboratory</td>
</tr>
<tr>
<td>Error</td>
<td>none</td>
<td>number</td>
<td>Error calculated by laboratory</td>
</tr>
<tr>
<td>Depths</td>
<td>none</td>
<td>number</td>
<td>Depths from surface that sample was collected</td>
</tr>
<tr>
<td>Depth units</td>
<td>cm or</td>
<td>m</td>
<td>Units of measurement for depth</td>
</tr>
<tr>
<td>Soil/geomorph. horizon</td>
<td>none</td>
<td>test</td>
<td>Name of horizon from which sample was collected</td>
</tr>
</tbody>
</table>

Numerical Age Table

<table>
<thead>
<tr>
<th>Field Name</th>
<th>Domain</th>
<th>Format</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>U-series</td>
<td>none</td>
<td>memo</td>
<td>Comments on numeric data</td>
</tr>
<tr>
<td>Trans. discharge</td>
<td>none</td>
<td>memo</td>
<td>Discharge data are transported to a different site of interest</td>
</tr>
<tr>
<td>Trans. discharge plus</td>
<td>none</td>
<td>number</td>
<td>Positive error in discharge transposition</td>
</tr>
<tr>
<td>Trans. discharge minus</td>
<td>none</td>
<td>number</td>
<td>Negative error in discharge transposition</td>
</tr>
<tr>
<td>Trans. storage</td>
<td>none</td>
<td>memo</td>
<td>Notes on discharge transposition</td>
</tr>
<tr>
<td>Stage</td>
<td>none</td>
<td>number</td>
<td>Stage associated with discharge</td>
</tr>
</tbody>
</table>

Event Table

<table>
<thead>
<tr>
<th>Field Name</th>
<th>Domain</th>
<th>Format</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Event ID</td>
<td>none</td>
<td>none</td>
<td>Default field</td>
</tr>
<tr>
<td>Site ID</td>
<td>none</td>
<td>none</td>
<td>Default field</td>
</tr>
<tr>
<td>Event description</td>
<td>none</td>
<td>memo</td>
<td>Description of event</td>
</tr>
<tr>
<td>Date type</td>
<td>lookup</td>
<td>text</td>
<td>Type of date</td>
</tr>
<tr>
<td>Date</td>
<td>none</td>
<td>number</td>
<td>Number of occurrence of discharge</td>
</tr>
<tr>
<td>Date plus</td>
<td>none</td>
<td>number</td>
<td>Positive error</td>
</tr>
<tr>
<td>Date minus</td>
<td>none</td>
<td>number</td>
<td>Negative error</td>
</tr>
<tr>
<td>Date type</td>
<td>year BP</td>
<td>lookup</td>
<td>Age format</td>
</tr>
<tr>
<td>Date plus</td>
<td>none</td>
<td>number</td>
<td>Positive error</td>
</tr>
<tr>
<td>Date minus</td>
<td>none</td>
<td>number</td>
<td>Negative error</td>
</tr>
<tr>
<td>Date type</td>
<td>year AD</td>
<td>lookup</td>
<td>Age format</td>
</tr>
</tbody>
</table>

ACKNOWLEDGEMENTS

This project was funded by the Dam Safety Office Technology Development Program at the Bureau of Reclamation. Special thanks to Katie Hirschboeck for conceiving the database in the first place and to Tess Harden for her invaluable comments and suggestions in recent years.
3.3.7.2.3 Late Holocene Paleofloods along the Middle Tennessee River Valley. C. Lance Stewart and Gary E. Stinchcomb, Department of Geosciences and Watershed Studies Institute, Murray State University; Steven L. Forman, Department of Geology, Baylor University; Lisa Davis and Rachel Lombardi, Department of Geography, University of Alabama; Emily Blackaby, Owen Craven and William Hockaday, Department of Geology, Baylor University. Not submitted in these proceedings.

3.3.7.2.4 A regional chronology of floods and river activity during the last 10,000 years in the Eastern U.S. Lisa Davis, Rachel Lombardi, Gary Stinchcomb, C. Lance Stewart, Matthew D. Therrell, Matthew Gage.
INTRODUCTION
Paleoflood information is increasingly being used to assess flood risk, specifically flood frequency calculation (England et al. 2017). Yet paleoflood information is not readily available for most locations. Regional paleoflood analyses exist only for a few locations (see for example, Macklin et al. 2006; Starkel et al. 2006; Thorndycraft et al. 2006; Harden et al. 2010). The southeastern U.S. has not been included in a regional paleoflood analysis since the groundbreaking work of J.C. Knox (Knox 1976), in which he first developed the regional paleoflood analysis approach. Since that time, many more studies have been conducted and advances made in radiocarbon dating. We present a new paleoflood chronology for major river basins of the southeastern U.S. This chronology offers potential insights into the frequency and spatial variability of floods across a large region of the U.S. that could be used to improve stochastic flood models, in addition to understanding environmental change.

METHODS
1. Compiled Event Database, A decision-making work flow (Fig 1) was developed based on Johnstone et al. (2006).

   - Activity Group (Flood Events): overbank deposits, sand/gravelly alluvium
   - Stability Group (Stability Episodes): buried soils, wetlands, organic deposits

4. Generated Cumulative Probability Functions (CPF)
   - Calibrated dates (IntCal 13) & summed age probability curves in OxCal, v. 4.3
   - Standardized CPFs in Excel by dividing Group CPFs by total dataset CPF (see Hoffman et al. 2008)

5. Plotted CPFs Curves by Drainage Basin
   - Plotted grouped CPFs in Excel to create curves
   - Peaks form where the summed radiocarbon age probability curves are above average probability
**RESULTS**

**Table 1. Distribution of radiocarbon data per basin.**

<table>
<thead>
<tr>
<th>River Basin</th>
<th>Number of Activity Dates</th>
<th>Number of Activity Dates</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tennessee</td>
<td>31</td>
<td>12</td>
</tr>
<tr>
<td>Lower Mississippi</td>
<td>34</td>
<td>19</td>
</tr>
<tr>
<td>South Atlantic-Gulf Coast</td>
<td>25</td>
<td>10</td>
</tr>
</tbody>
</table>

**Fig 2.** Locations of site-specific fluvial studies included in FADSU.

**Fig 3.** Fluvial activity (black/positive) and stability (grey/negative) chronologies where peaks filled in with color represent above-average likelihood of either activity or stability.
KEY FINDINGS

Lower Mississippi Basin
- Cluster of fluvial activity last ~4,000 year which is followed by stability for ~ 2,000 years
- High magnitude flood events on the Upper Mississippi River occurring 5,500–5,000 yrs BP and 2,500 yrs BP correspond with high probability fluvial activity in the Lower Mississippi (Knox, 1985).

Tennessee River Basin
- Most high probability fluvial activity occurred during the Early to Mid-Holocene – this is a limitation of available literature

South Atlantic-Gulf Coast
- Fluvial activity had lower probability relative to other basin and lacked cyclicity of activity.

Climate Periods
- Only Lower Mississippi basin indicates fluvial activity during the Medieval Climate Anomalies (MCA).
- All basins indicate increased fluvial activity during the Little Ice Age (LIA).

Future Work & Applications
- FADSU will be extended to include the entire eastern US and will be publicly available for establishing flood frequency curves.
- FADSU highlights large knowledge gaps in fluvial systems spatially and temporally.
- When more paleoflood studies are available in the eastern US, associated magnitudes of events will be documented.

REFERENCES CITED


ACKNOWLEDGEMENTS

Our research is funded by a grant from the Electric Power Research Institute and a grant from the University of Alabama College of Arts and Sciences (College Academy of Research, Scholarship, and Creative Activity). We thank Tessa Herdin (IHRG) for assistance in creating cumulative probability curves in Q+GEC and for data presented less solely with the authors.

1 Department of Geography, University of Alabama; lise.davis@ua.edu
2 Department of Geosciences, Murray State University
3.3.7.2.5 Critical Review of State of Practice in Dam Risk Assessment

David Watson, Scott DeNeale, Brennan Smith and Shih-Chieh Kao, Oak Ridge National Laboratory (ORNL); Gregory Baecher, University of Maryland
Critical Review of State of Practice in Dam Risk Assessment
Oak Ridge National Laboratory – David Watson (watsondb@ornl.gov; 865-241-4749), Scott DeNeale, Brennan Smith and Shih-Chieh Kao
University of Maryland – Gregory Baecher
NRC Office of Research – Meredith Carr, Joseph Kanney and Tom Aird

Introduction

Of the large number of dams in the United States, almost 50% are privately owned. About 25 percent are owned by state or local authorities, or public utilities. Only about 5% are owned by federal agencies. The responsibility for dam safety is widely distributed.

Dams in the United States are aging and in dire need of refurbishment. The American Society of Civil Engineers 2017 Infrastructure Report Card states that the average age of the 90,580 U.S. dams is 76 years with 17% classified as high-hazard potential dams with potential for loss of life and another 13% labelled as significant hazard potential dams with potential for significant economic losses. An estimated $45 billion is needed to repair the high-hazard potential dams alone.

Major dams are defined by the US Government as those 50 feet (15 meters) or more in height with a normal storage capacity greater than 5,000 acre-feet (6 million cubic meters), and a maximum storage capacity of 26,000 acre-feet (31 million cubic meters) or more. The USGS map layer of major US dams comprises 8100 records (USGS 2017). Dams can also pose a risk to the land uses and populations that develop in areas downstream of the dam. If the dam loses containment, downstream property damage can be catastrophic with the potential for loss of life.

Potential detrimental impacts of dam failure include flooding of downstream nuclear power plants and impacts to mine tailing waste disposal facilities.

Agencies involved with dam safety:
- U.S. Department of Agriculture
  - Natural Resources Conservation Service
  - Agriculture Research Service
- Department of Defense
  - Army Corps of Engineers
  - Engineer Research and Development Center
  - Hydrologic Engineering Center (HEC)
- Department of the Interior
  - Bureau of Indian Affairs
  - Bureau of Land Management
  - Bureau of Reclamation
  - Fish & Wildlife Service
  - National Park Service
  - Office of Surface Mining
- Federal Energy Regulatory Commission
- Mine Safety and Health Administration
- International Boundary and Water Commission
- Nuclear Regulatory Commission
- Tennessee Valley Authority
- States
Dam ownership in the United States
Adapted from ASCE Infrastructure Report Card (2017)

- 55.4% Private
- 20.1% Local
- 11.6% Undetermined
- 4.8% State
- 4.7% Federal
- 2.4% Public Utility

Project Objectives

This project will focus on summarizing and providing a critical review of the state of practice in dam failure risk analysis, with a particular emphasis on developing and quantifying fragility information. The objective of this project is to assist NRC in developing the technical basis for guidance on application of state-of-the-practice approaches, methods and tools for dam risk analysis to inform assessment of flood hazards due to dam failure.

This project will seek to summarize and provide a critical review of approaches and methods for developing fragility curves for key components, systems, and procedures that contribute to the overall fragility of the dam. This will include, but not be limited to:
- Probabilistic geotechnical analysis methods for assessing embankment, foundation and abutment stability
- Reliability of key components such as gates, gate hoists, valves, etc.
- Systems analysis approaches
- Reliability of operational and emergency procedures
- Methods for estimating breach initiation and progression

Scope of Work

The project will focus on assessing methods for characterizing and quantifying key uncertainties, as well as propagating these uncertainties through the risk analysis procedure to support risk-informed decision-making. To accomplish the objectives of this project the project team will:

1) Assist the NRC in organizing and conducting a workshop to review the current state of practice in dam risk analysis. The workshop participants will include leading experts from other federal agencies, academic researchers, and private industry. International perspectives will also be sought.

2) Provide a summary of the current state of practice in dam risk analysis with a particular focus on development of fragility information for key components, control systems, and operational procedures.

3) Provide a critical review of how key process uncertainties, their characterization, and the degree to which they are propagated in state of practice approaches.

4) Prepare NUREG/CR reports summarizing activities 1-3 and providing guidance on use of state-of-the-practice dam risk assessment approaches, methods and tools for informing assessment of flooding hazards due to dam failure.

5) Conduct a knowledge transfer seminar at the NRC Headquarters in Rockville, MD covering the topics in items 1-4 with a focus on item 3.
Dam Failure Mechanisms

Why Do Dams Fail?

- Overtopping caused by floods that exceed the capacity of the dam
- Overtopping caused by operational issues (gates, human factors, SCADA systems)
- Structural failure of materials used in dam construction
- Movement or failure of the foundation or abutments
- Settlement and cracking of concrete or embankment dams
- Internal erosion of soil in embankment dams
- Inadequate maintenance and upkeep
- Malicious acts

Causes of dam failure in percent of total from historical data sets.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Overtopping or inadequate spillway</td>
<td>23</td>
<td>30</td>
<td>28</td>
<td>38</td>
<td>36</td>
</tr>
<tr>
<td>Piping or seepage</td>
<td>40</td>
<td>38</td>
<td>44</td>
<td>44</td>
<td>30</td>
</tr>
<tr>
<td>Slides</td>
<td>2</td>
<td>15</td>
<td>10</td>
<td>9</td>
<td>15</td>
</tr>
<tr>
<td>Miscellaneous</td>
<td>35</td>
<td>17</td>
<td>18</td>
<td>9</td>
<td>19</td>
</tr>
</tbody>
</table>
Probabilistic Analysis

Licensees Generally Use Deterministic Methods

- NUREG/CR-7046 "Design-Basis Flood Estimation for Site Characterization at Nuclear Power Plants in the United States of America" (U.S. NRC 2011)
- Interim Staff Guidance JLD-ISG-13-01 "Guidance for Assessment of Flooding due to Dam Failure" (U.S. NRC 2013)

Risk Analysis Steps

1) Define what 'failure' means
2) Identify initiating events
3) Build an event tree of the system
4) Develop models for individual components
5) Identify correlations among component failures or failure modes
6) Assess probabilities and correlations for events, parameters, and processes
7) Calculate system reliability

Schematic of risk assessment and management (Jonkman et al. 2015).

Frequency of historical dam failures as reported in the literature

<table>
<thead>
<tr>
<th>Area</th>
<th>Reference</th>
<th>Number of failures</th>
<th>Dam years</th>
<th>Failure rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>US</td>
<td>Gruner 1965, 1967</td>
<td>38</td>
<td>71</td>
<td>$8 \times 10^{-7}$</td>
</tr>
<tr>
<td></td>
<td>Bobb and Mermod 1968</td>
<td>12</td>
<td>42</td>
<td>$5 \times 10^{-7}$</td>
</tr>
<tr>
<td></td>
<td>US Cold 1975</td>
<td>74</td>
<td>138</td>
<td>$7 \times 10^{-7}$</td>
</tr>
<tr>
<td></td>
<td>Mark and Stuart-Alexander 1977</td>
<td>1</td>
<td>4.5</td>
<td>$2 \times 10^{-7}$</td>
</tr>
<tr>
<td>World</td>
<td>Mark and Stuart-Alexander 1977</td>
<td>125</td>
<td>3000</td>
<td>$4 \times 10^{-7}$</td>
</tr>
<tr>
<td></td>
<td>Middlebrooks 1958</td>
<td>9</td>
<td>47</td>
<td>$2 \times 10^{-7}$</td>
</tr>
<tr>
<td>Japan</td>
<td>Talase 1967</td>
<td>1046</td>
<td>30,000</td>
<td>$4 \times 10^{-7}$</td>
</tr>
<tr>
<td>Spain</td>
<td>Gruner 1967</td>
<td>130</td>
<td>285</td>
<td>$6 \times 10^{-7}$</td>
</tr>
<tr>
<td>Overall</td>
<td></td>
<td></td>
<td></td>
<td>$4 \times 10^{-7}$</td>
</tr>
</tbody>
</table>
Dam Fragility Analysis Considerations

1) Failure mode identification
2) Event and fault tree analysis and Monte Carlo simulations
3) Failure probabilities, fragility curves and expert opinions
4) Failure progression
5) Systems analysis
6) Regulatory requirements, ownership, maintenance, age, etc.
7) Operational risks, flow control reliability and emergency procedures (Human reliability and SCADA)
8) Software tools for dam safety risk analysis
9) Uncertainties in dam risk analysis

Outcomes

The research conducted under this project will support and enhance NRC's capacity to perform thorough and efficient reviews of license applications and license amendment requests. They will also support risk-informed significance determination of inspection findings, unusual events and other oversight activities.
3.3.7.2.6 Application of Point Precipitation Frequency Estimates to Watersheds

Shih-Chieh Kao and Scott DeNeale, Oak Ridge National Laboratory
Background

Frequency analysis is used to provide probabilistic precipitation estimates but is mostly conducted for point rainfall observations. While areal reduction factors (ARFs) have been used to convert these point precipitation estimates to watershed estimates, most ARF methods are decades old and were derived before high spatiotemporal resolution rainfall products became available. Existing ARF products suffer from additional limitations which must be better understood and addressed before probabilistic precipitation estimates can be more widely applied.

Project Objectives

- Provide a summary of available precipitation products that could be used to develop point to area conversions of precipitation frequency estimates.
- Provide a critical review of available point to area conversions methods with a view to addressing the deficiencies in the commonly used empirical methods.
- Demonstrate use of the most promising method/dataset combinations with a small number of test cases.
- Perform knowledge transfer activities.

Precipitation Products in the U.S.

Gauge-driven Products
- Observations from NWS
- Gridded products

Radar-driven Products
- NEXRAD, NOAA Stage II-IV, MRMS

Satellite-driven Products
- NASA TMPA and GPM

Reanalysis-driven Products
- NCEP, NARR, MERRA, JRA
Current Application

- Select a T-year point precipitation estimate for a watershed of interest (either estimated from observation or looked up from existing products such as NWS Atlas-14)
- Calculate the watershed-average T-year point rainfall depth
- Reduce T-year rainfall depth by ARF based on watershed size (looked up from TP-29 or other ARF values)
- Convert to spatiotemporal hyetograph for hydrologic and hydraulic (H&H) modeling

Example ARF curves (left, from TP-29) and methodology (right, from TR-24)

Deficiencies of Current Areal Reduction Factors

- ARFs in common use are based on very limited data
- ARFs in common use are based on outdated rain gage network data; newer data and high resolution spatial rainfall observations are not incorporated.
- ARFs in common use are for small areas (up to 400-mi²)
- ARFs in common use do not vary with geographic location, which implies that the same values apply regardless of the local climate conditions
- ARFs in common use do not vary with return period
- ARFs in common use do not vary with season
Technical Approach for ARF Demonstration

- Assimilation of high-resolution historical rainfall data
- Identification of annual maximum spatially-averaged rainfall depth
- Spatiotemporal frequency analysis
- Calculation of point-to-area rainfall conversion ratios
- Spatial smoothing and quality control

Expected Outcomes

- Provide technical basis to develop guidance for application of ARFs to nuclear power plant probabilistic flood hazard assessments.

Project Tasks (2017–2019)

- **Task 1 – Summarize available precipitation products:** Identify available precipitation products in the United States that can be used to update ARFs.
- **Task 2 – Review of point-to-area conversion methods:** Review and summarize recent point-to-area conversion methods that may address the deficiencies in the commonly used empirical approach.
- **Task 3 – Demonstrate use cases:** Demonstrate use of the most promising methods and datasets with a small number of test cases.
- **Task 4 – Knowledge transfer:** Provide knowledge transfer seminar and NUREG/CR report documenting the findings and recommendations of this study.

Project Team

**NRC Leads:**
Elena Yegorova, Nuclear Regulatory Commission
Joseph Kanney, Nuclear Regulatory Commission

**ORNL Team:**
Shih-Chieh Kao, Oak Ridge National Lab
Scott DeNeale, Oak Ridge National Lab
3.3.7.2.7 Quantification of Uncertainty in Probabilistic Storm Surge Models  Norberto Nadal-Caraballo, Victor Gonzalez and Efrain Ramos-Santiago, U.S. Army Corps of Engineers, Engineer Research and Development Center, Coastal and Hydraulics Laboratory: Not submitted for proceedings

3.3.7.2.8 Modeling Plant Response to Flooding Events  Zhegang Ma, Curtis L. Smith and Steven R. Prescott, Idaho National Laboratory, Risk Assessment and Management Services; Ramprasad Sampath, Centroid PIC, Research and Development

Modeling Plant Response to Flooding Events

Z. Ma, C. Smith, S. Prescott, and R. Sampath

External Flooding Risk

External Flooding Hazards:
- Local intense precipitation
- Hurricane flooding
- Flooding due to upstream dam failure
- Coastal flooding due to storm surge or tsunami

External Flooding Risk:
- Interrupt offshore power
- Limit plant access
- Threaten safety important SSSCs

Modeling Challenges:
- Fossil releases a function of flooding levels
- Degree of flooding influences stochastic or common cause failure
- Operator actions impacted by flooding

Dynamic vs. Static Methods

Dynamic methods become useful where one or more attributes of system components are present in a problem:
- Temporal system configuration/state is time dependent
- Spatial system model cannot be simply modeled in 2 or 3 dimensions
- Mechanics - multi-physics phenomina exist in the problem
- Topology - multi-state systems/components and network systems

EMRALD: State-Based PRA Tool

- Use states that represent and track the status of SSSCs
- Set of current states that states change over time
- Components, systems, and plant state diagrams
- Integrate 3-D simulations into plant response logic
- Could determine which components fail? When? Flood-caused or stochastic? Impact to systems and plant?

Dynamic Flooding Analysis

Case Study

- A local intense precipitation event occurred in a U.S. PWR
- Heavy rainfall peaked during one rain event
- Flood alleviation measures in auxiliary building were missing
- Water entered - 6 ft and -10.3 ft levels of Are
- Operations control the flooding by cycling ECCS sump isolation
- Event terminated with no safety-related equipment impairment

3-D Site Isen Model

3-D Plant Model

3-D Simulation Model

Impacts

- Dynamic methods provide a natural framework to represent spatial and time-dependent flood events
- Simulation-based dynamic approach is becoming more popular
- It could support traditional approach with various cases
- POC study
- Apply the approach to other flooding hazards
- Couple the flood-physics model to TH codes
- Expand to multiple flooding mechanisms, consistent hazards, and multiple units
Modeling Plant Response to Flooding Events
Z. Ma, C. Smith, S. Prescott, and R. Sampath

External Flooding Risk

External Flooding Hazards:
- Local intense precipitation
- Riverine flooding
- Flooding due to upstream dam failure
- Coastal flooding due to storm surge or tsunami

External Flooding Risk:
- Interrupt offsite power
- Limit plant access
- Threaten safety important SSCs

Modeling Challenges:
- Flood protection a function of flooding levels
- Degree of flooding influences stochastic or common cause failures
- Response relies heavily on procedures and manual actions
- Operator actions impacted by flooding

Dynamic vs. Static Methods

Dynamic methods become useful when one or more attributes of system complexity are present in a problem:
- Temporal – system configuration/state is time dependent
- Spatial – system model cannot be simply treated as 0-dimensional
- Mechanics – multi-physics phenomena exist in the problem
- Topology – multi-state systems/components and network systems
EMRALD: State-Based PRA Tool

- Use states that represent and track the status of SSCs
- Set of current states that could change over time
- Components, systems, and plant state diagrams
- Integrate 3-D simulations into plant response logic
- Could determine which components fail? When? Flood-caused or stochastic? Impact to systems and plant?

Dynamic Flooding Analysis

Task 1: Flood Hazard Analysis
- Flood Hazard Assessment
- Hazard Elements
- Hazard Hazards

Task 2: Flood Fragility Analysis
- Flood Fragility Analysis
- Flood Fragility Curves
- Flood Fragility Curves

Task 3: Plant Response Modeling
- Plant Response Modeling
- Plant Response Modeling
- Plant Response Modeling
- Plant Response Modeling

Task 4: Safety Graphs and PRA
- Safety Graphs
- Graphs
- Graphs
- Graphs

Verification and Validation
- Uncertainty Analysis

Hazards

Fragilities

Structures

Components

Procedures

Operator Action
### Case Study

- A local intense precipitation event occurred in a U.S. PWR
- Heavy rainfall plus degraded site drain system
- Flood seal of penetration in auxiliary building was missing
- Water entered -0.5 ft and -10.0 ft levels of AB
- Operators control the flooding by cycling ECCS sump isolation valves
- Event was terminated with no safety-related equipment inoperable

#### 3-D Site Terrain Model

#### 3-D Plant Model

#### 3-D Simulation Model

### Impacts

- Dynamic methods provide a natural framework to represent spatial- and time-dependent flood events
- Simulation-based dynamic approach is increasing realism in flood risk modeling
- It could support traditional approach with various roles
- Future study:
  - Apply the approach to other flooding hazards
  - Couple the flooding-physics model to T-H codes
  - Expand to multiple flood mechanisms, coexistent hazards, and multiple units

---

3.3.7.2.9 Stratigraphic Records of Paleofloods, Geochronology and Hydraulic Modeling to Improve Flood Frequency Analysis Tessa Harden, U.S. Geological Survey, Oregon Water Science Center- Not submitted for proceedings
3.3.8 Day 2: Session 2A - Reliability of Flood Protection and Plant Response I

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

Development of guidance for assessing the reliability of flood protection and plant response to flooding events.

3.3.8.1 Performance of Flood-Rated Penetration Seals William (Mark) Cummings*, P.E., Fire Risk Management, Inc. (Session 2A-1; ADAMS Accession No. ML17355A095)

3.3.8.1.1 Abstract

Overall risk analyses of nuclear power plants (NPPs) include the need for protection against potential flooding events; both internal and external events. Typically, a primary means to mitigate the effects of a flooding event are to construct flood rated barriers to isolate areas of the plant to prevent the intrusion or spread of flood waters. Any penetrations through flood-rated barriers to facilitate piping, cabling, etc. must be properly protected to maintain the flood-resistance of the barrier. Numerous types and configurations of seal assemblies and materials are being used at NPPs to protect penetrations in flood-rated barriers. However, no standardized methods or testing protocols exist to evaluate, verify, or quantify the performance of these, or any newly installed, flood seal assemblies. In FY2016, the NRC implemented a research program to develop a set of standard testing procedures that will be used to evaluate and quantify the performance of any penetration seal assembly that is, or will be, installed in flood rated barriers. This presentation represents a project status update regarding the efforts completed since the previous PFHA Workshop. This includes completion of Phase I of the research effort, which culminated in the development of the draft Test Protocol. Additionally, information is provided regarding plans for Phase II research efforts, which will include actual performance testing of candidate flood-rated penetration seal assemblies using the draft Test Protocol.

3.3.8.1.2 Presentation

PERFORMANCE OF FLOOD RATED PENETRATION SEALS

W. Mark Cummings, P.E.
Fire Risk Management, Inc.
Flood Penetration Seal Performance Evaluation

NRC PROJECT TITLE: Flood Penetration Seal Performance at NPPs

Project Team: Fire Risk Management, Inc.
Nuvia US

Project Overview:
Project Objective: To establish Testing Standards and Protocols to evaluate the effectiveness and performance of seals for penetrations in flood rated barriers at NPPs.

Project Tasks:
Task 1: Development of Testing Standards, Acceptance Criteria, and Protocols
  Task 1.1: Identify and describe the various typical seal materials for FPSs used at NPPs
  Task 1.2: Develop standard testing procedures, acceptance criteria and protocols for testing effectiveness and performance of FPSs.
Task 2: Testing of Selected Flood Penetration Seal Types and Designs
Task 3: Final Technical Report

Flood Penetration Seal Performance Evaluation

TASK 1.1 OVERVIEW

- Researched publicly-available information regarding installed Flood-rated Penetration Seals
  - ADAMS database
  - NPP responses to NRC 50.54 Letter (54)
  - NRC Audit Reports
  - LERs, NUREGs, INs, IRs (relevant info noted in 28/f-15/13)
- Wide variety of seal assemblies and materials noted
  - Concrete, Mortar, Grout
  - Mechanical seals (such as boot or link)
  - Silicone foams (high & low densities)
  - Epoxy & Elastomers
  - Urethane
  - Caulking
- Combination of “fill” materials with exterior “damming” materials applied (waterproofing)
Flood Penetration Seal Performance Evaluation

TASK 1.1 OVERVIEW (Cont’d)

- Wide range of penetration configurations and types of penetrants
  - Rectangular & Circular
  - Slivered and Core Bore
  - Single & Multiple Penetrants and “Blanks”
  - Pipes, Cables, Conduit, etc.
  - Varying sizes / diameters
- Both interior and exterior applications
- FPS Assessments
  - “Formed in place” seals (foams, elastomers) appear to exhibit greatest variability in performance
  - Materials / Products (formulations) vary between Manufacturers
- Summary Report Developed: “Flood Penetration Seal Assemblies at Existing Nuclear Power Plants”
Flood Penetration Seal Performance Evaluation

TASK 1.2 OVERVIEW

- Review of NUVIA Flood Test Apparatus & Procedures
  - NUVIA is only entity currently testing FPSs; using standard procedures/protocols
- Review of UL 1479 – Fire Tests of Through-Penetration Firestops
  - Section 6A – Water Leakage Test (W rating)
- Review of FM Approval Standard for Flood Abatement Equipment
  - Does not address “penetrations” in flood barriers, primarily the barriers themselves, including dikes
  - Does provide some input regarding “impact” resistance
  - Used as a primary “template” for formatting Flood Test Procedure
  - Industry familiarity with formatting

Flood Penetration Seal Performance Evaluation

TASK 1.2 OVERVIEW (Cont’d)

- Development of draft Procedure complete – ready for use in Phase II
  - Provides “guidance” and standardized methodology for testing flood-rated penetration seals
  - Test apparatus design; including data acquisition
  - Performance-based approach to metrics (no specific pass/fail criteria)
  - Manufacturers will need to specify limitations of their products
  - Phase II testing may identify potential short-comings with the p-based approach
Flood Penetration Seal Performance Evaluation

TASK 2 OVERVIEW

- Development of Test Plan
  - Selection of candidate FPSs, types and numbers to be tested
  - Final design for Test Apparatus (completed)
  - Location for testing (completed)
- Test Objective(s)
  - Exercise & evaluate Flood Test Procedure (“test the test”)
  - Research/Evaluation of specific FPS assemblies/materials noted as installed at NPPs
- Test Matrix
  - Include all types of seal assemblies & materials
  - Greater emphasis on “formed in place” seals
  - Some evaluation of existing (non-standard) seal configurations noted during Task 1 document research
- Scheduled Test Results/Report due mid-2018
  - Test results used to modify Test Procedure as/if needed
  - Final Test Procedure submitted

Flood Penetration Seal Performance Evaluation

TASK 3 OVERVIEW

- Development of Final Technical Report
  - Summation of Task 1 & 2 results
  - Suitable for NUREG/CR
- Scheduled Project Completion; 3rd Qtr 2018

GOING FORWARD

- NUREG
  - Provide guidance to Industry for standardized process for evaluating/quantifying FPS performance
  - Support NRC oversight requirements
  - FPS pass/fail criteria will be function of Flood PRA requirements; NPP-specific
- Possible future development of commercial (industry) Test Standard
3.3.8.1.3 Questions and Answers

Question:

I'm very interested looking at in situ measurement as opposed to the laboratory… you talked about how you're going to test the seals in laboratory. Have you thought about in situ measurement and looking at performance surrogate indicators for instance moisture content using electric conductivity? Have you thought of how you would go about testing an existing penetration seal?

Answer:

The short answer is no we haven't. Ideally ultimately some particular seals, based on their configuration, their penetrants, may be more conducive to that type than others. If you've been in a lot of cable spreading rooms… trying to run a test like… I don't see how you would do it. Anytime you start introducing moisture, depending on the penetrant they're going to get real nervous about. It hasn't been anything that we've discussed at least not up to this point. It's not really the intent here.

Question:

One last question. At the Blayais site, they had failure with a lot of the penetration seals. Have you been able to talk to Électricité de France (EDF) and found that what kinds of lessons they learned from their failures?
Answer:

We have. A main customer obviously is EDF and so we have looked at that.

Question:

In the proof of the testing, do you intend to increase pressure until the seal fails? Or are you going to pick a design pressure and go to that?

Answer:

The fun part about the research is that you get to play a little bit. Depending on what you see and how things react. We may change but most likely you'll start for each one of the test decks, maybe a step type function. Are we going to go for many hours and days? Probably not. That again gets into the performance of the seals, not so much the test. We're going to play a little bit and look at different pressures.

Question:

I actually have two questions. I had one and then a follow-up to your comment about Blayais site. When you mentioned it was a large penetration… was that a large penetration with multiple penetrants going through it?

Answer:

Yes.

Question:

Then the other question. When you mentioned the exterior and interior seal applications, I was trying to remember back to that report, whether you saw any significant differences in either seal construction, seal types, or sealing material type between those two applications? I don't recall that there was but…

Answer:

No, there really wasn't and in some of the cases, it didn't actually identify what was an exterior barrier or interior.
3.3.8.2  *EPRI Flood Protection Project Status*  David Ziebell^ and John Weglian*, EPRI  
(Session 2A-2; ADAMS Accession No. ML17355A096)

3.3.8.2.1  Abstract

EPRI has collected information from member utilities on maintaining the licensing and design bases of flood protection barriers. EPRI and a technical advisory group of industry experts examined this data to determine the best practices in place in the industry. EPRI has recently published these best practices in a guide to EPRI members.

3.3.8.2.2  Presentation

![External Flood Protection Design/Licensing Management Best Practices Guide](image-url)

*John E. Weglian*  
Senior Technical Leader  
*David Ziebell*  
Senior Technical Leader  
3rd NRC External Flooding Research Workshop  
December 4-5, 2017
Topics

- EPRI Nuclear Maintenance Applications Center reports
- Technical Advisory Group Membership
- Best Practices Guide Overview

NMAC Reports

- Flood Protection Systems Guide - 3002005423
  - Published in 2015
  - Flood-protection components and the design, testing, inspection, and maintenance of these components

- External Flood Protection Design/License Basis Management Best Practices Guide - 3002010620
  - Published in 2017
  - Practices for owner/operators to assure the day-to-day operation of the plant complies with the design basis and licensing basis with respect to protection of safety functions from external flooding threats.
Technical Advisory Group

<table>
<thead>
<tr>
<th>Name</th>
<th>Organization</th>
</tr>
</thead>
<tbody>
<tr>
<td>Don Bentley</td>
<td>Entergy Operations, Inc.</td>
</tr>
<tr>
<td>Joshua Brewer</td>
<td>Duke Energy Carolinas</td>
</tr>
<tr>
<td>Karen Carboni</td>
<td>Tennessee Valley Authority</td>
</tr>
<tr>
<td>Raymond George</td>
<td>INPO</td>
</tr>
<tr>
<td>Jeff Greene</td>
<td>EPRI</td>
</tr>
<tr>
<td>Scott Groesbeck</td>
<td>DP Engineering, Ltd. Co.</td>
</tr>
<tr>
<td>Sam Harvey</td>
<td>EPRI</td>
</tr>
<tr>
<td>Chris Johnson</td>
<td>Entergy Operations, Inc.</td>
</tr>
<tr>
<td>John Johnson</td>
<td>Southern Nuclear Operating Co.</td>
</tr>
<tr>
<td>Bradley Langa</td>
<td>Exelon Generation, LLC</td>
</tr>
<tr>
<td>Matthew Mairinger</td>
<td>Ontario Power Generation, Inc.</td>
</tr>
<tr>
<td>Yasuyuki Moriyama</td>
<td>Chubu Electric Power Co., Inc.</td>
</tr>
<tr>
<td>Keita Naito</td>
<td>The Chugoku Electric Power Co., Inc.</td>
</tr>
<tr>
<td>Jeffrey Peacock</td>
<td>Exelon Corporation</td>
</tr>
<tr>
<td>Frances Pimentel</td>
<td>Nuclear Energy Institute</td>
</tr>
<tr>
<td>Swadesh Ramdeen</td>
<td>NextEra Energy, Inc.</td>
</tr>
<tr>
<td>Richard Rohrer</td>
<td>Xcel Energy Services, Inc.</td>
</tr>
<tr>
<td>Vincent Rougier</td>
<td>Electricite de France S.A.</td>
</tr>
<tr>
<td>Denis Shumaker</td>
<td>PSEG Nuclear, LLC</td>
</tr>
<tr>
<td>Mark Woodby</td>
<td>Entergy Nuclear Operations, Inc.</td>
</tr>
<tr>
<td>Paul Young</td>
<td>Dominion Generation, Inc.</td>
</tr>
<tr>
<td>David Ziebell</td>
<td>EPRI</td>
</tr>
</tbody>
</table>

Best Practices Guide – Section Outlines

- Purpose, Background, Approach and Implementation
- Design Documentation
  - Documenting the design basis external flood event
  - Documenting the flood protection features credited in the design
- Organizational and Procedural Methods
  - Roles and responsibilities
  - Monitoring and responding
- Inspections, Maintenance, and Demonstration of Manual Actions
  - Best practices for inspection for passive flood protection features
  - Best practices for maintenance for active flood protection features
  - Demonstration of manual action effectiveness for flood protection features that require manual action
  - Lessons learned from NEI 12-07 walkdowns
Best Practices Guide – Section Outlines continued

- Modifications and Work Control
  - Modification impacts
  - Work control
  - Compensatory measures
- Response to Imminent Flooding
  - Severe weather monitoring
  - Proceduralizing external flooding response
  - Recommended elements for external flooding response procedures
- Training and Communication
  - Skills and knowledge
  - Communication

Best Practices Guide – Section Outlines continued

- Management Oversight and Effectiveness Measurements
  - Assessing readiness
  - Assessing capability
  - Corrective action program trending
- References
- Appendix A: General Approach to Development of External Flooding Design and Licensing Bases
- Appendix B: External Flooding Survey Response Initial Analysis
- Appendix C: External Flood Protection Features List Examples
- Appendix D: Reasonable Simulation Timeline
3.3.8.2.3 Questions and Answers

Question:
I assume that by now you've applied this to a variety of sites? Have you? And if you have, what have you discovered, what lessons have you learned in applying these best practices?

Response:
So, the guidance document was just published maybe two or three weeks ago, and I don't know if there have been any lessons learned since it has been published in this short window. But the technical advisory group has been involved to decide what these best practices are and to help inform EPRI to develop this. I don't know if anybody's actually made changes to their plant yet based on this. I can look into that if you would like to know.

Question:
John this looks like a very valuable study here. I'm curious, when it comes to forecast information, for example riverine flood forecasts, you know they're not a high percent accurate. Has there been any discussion about how to deal with that uncertainty in terms of the response?

Response:
That's a good point, and local intense precipitation are quite varied. So, some sites have procedures that are more open to interpretation and others are very deterministic. In that if you get a weather forecast that says “this”, you will implement. I think that is a best practice because it removes the decision and the ability for the operator to make the wrong decision. It removes that possibility based on a judgment call, and so riverine flooding should be similar in that if you know that some sites have procedures that say upstream if you hit this level, you will implement the
procedure… as opposed to saying something like if the forecast looks like the site may be inundated, do this. That that would not be a best practice because it leaves room for operator error.

**Question:**

Is this report publicly available?

**Response:**

It is not available publicly. It's available to every member or for a price.

**Question:**

Could you describe a little more detail the forecast? What does the guide say about establishing durable reliable relationships with entities that provide forecasts? Either public entities like The Weather Service, National Hurricane Center, or perhaps a private entity that the licensee might hire? What does the guide say about developing that interface and how to convince yourself that it is durable, reliable?

**Response:**

Good question. I don't know the exact answer to that… but obviously sites need to establish relationships with the entities that provide this information. Some of it is published on a routine basis like from the national weather service, for example. I can I can look into that and get back to you.

**Question:**

On the forecast issue. In some cases, there are probabilistic forecasts… National Weather Service for example makes some use of forecasts for the floods. Do you know if there's any thinking about how to handle that kind of probabilistic forecast information?

**Response:**

I'm not sure if it's treated differently than another set of forecasts. I'd have to look into it and get back to you on that one.
3.3.8.3 A Conceptual Framework to Assess Impacts of Environmental Conditions on Manual Actions for Flood Protection and Mitigation at Nuclear Power Plants

Rajiv Prasad *, Ph.D., Garill Coles and Angela Dalton, Pacific Northwest National Laboratory; Kristi Branch and Alvah Bittner, Ph.D., CPE, Bittner and Associates; R. Scott Taylor; Ph.D., Battelle Columbus (Session 2A-3; ADAMS Accession No. ML17355A097)

3.3.8.3.1 Abstract

The U.S. NRC is currently pursuing a Probabilistic Flood Hazard Assessment Research Plan which is especially relevant following the Fukushima accident. One of NRC’s initiatives is to better understand the actions that licensees of nuclear power plants have planned to take outside of the control room to prepare for, protect against, and mitigate the effects of flooding events.

The Pacific Northwest National Laboratory (PNNL) conducted a comprehensive review of the literature about how the environmental conditions (ECs) associated with flooding events might affect performance of those actions. To support and inform the literature review, the research team identified and characterized the ECs that might accompany flooding events; these conditions included heat, cold, noise, vibration, lighting, humidity, wind, precipitation, standing and moving water, ice and snowpack, and lightning. Based on a review of (1) NRC Staff Assessments of Flooding Walkdown Reports from 60 nuclear power plant (NPP) sites, (2) available individual NPPs’ plant procedures (e.g., Abnormal Operating Procedures), and (3) descriptions of FLEX activities, the research team identified and characterized a set of manual actions (MAs). MAs would need to be performed at and around NPP sites (both inside and outside the main control room) in preparation for or response to a flooding event. The research team developed a method for decomposing the MAs into simpler hierarchical units—tasks, subtasks, generic actions (GAs), and performance demands (PDs)—to facilitate assessment of ECs’ impacts consistent with approaches in human performance literature. The first four levels in this hierarchy (i.e., MAs, tasks, subtasks, and GAs) are activity oriented while the last (i.e., PDs) describes the composition of human performance measures needed to accomplish the activities.

The literature review summarized the state of knowledge concerning the effects of the 11 ECs in terms of their mechanisms of action, effects on performance, and potential mitigation measures. A typology of PDs that includes detecting and noticing, understanding, decision-making, action, and teamwork provided a basis for applying research findings to estimate performance effects. PDs include both physical and cognitive aspects of human performance. The research team developed a conceptual framework to illustrate the relationships among ECs, MAs, and performance effects information. ECs can affect human performance by (1) affecting motor functions via a physical force (e.g., flowing water, wind), (2) affecting physiology (e.g., heat, cold), and (3) affecting cognition by interference of senses (e.g., darkness, vibration) and increasing workload. Research on ECs’ impacts on human performance in literature is available in four categories: Level 1, quantitative information that is directly applicable to an assessment of impact; Level 2, quantitative information that is less directly applicable; Level 3, qualitative information that may be used to inform expert judgments or sensitivity analyses; and Level 4, no information, i.e., a research gap. The research team demonstrated the applicability of Level 1 information using a simple example of a MA involving gross motor function (i.e., walking). The research team proposed a guideline for safe walking velocity based on experimental data reported in literature. The results show that time to walk a given distance can be significantly affected by the presence of standing and moving water. The research team notes that additional research, sensitivity analyses, and knowledge elicitation from experienced operators may be necessary to operationalize EC effects that fall in Levels 2-4.
Effects of Environmental Factors on Manual Actions for Flood Protection and Mitigation at Nuclear Power Plants

Rajiv Prasad, Garill Coles, Angela Dalton, Nancy Kohn (PNNL)
Scott Taylor (Battelle)
Kristi Branch, Alvah Bittner (Bittner & Associates)

The 3rd Annual Probabilistic Flood Hazard Assessment Workshop
December 4-5, 2017

Scope and Objectives

◆ Project scope
  - Review technical literature on effects of environmental conditions (ECs) on human performance
  - Consider environmental conditions that could occur during a flood and the manual actions (MAs) taken to prepare/respond

◆ Research objectives
  - Develop a framework for assessing the impact of ECs on human performance of manual actions for flood protection and mitigation
  - Develop a technical literature review on effects of ECs on human performance
  - Develop a proof-of-concept method for EC impact assessment
  - Identify approaches to using literature review results in the EC impact assessment method
Characterizing Manual Actions with Performance Demands

- Performance demands are the physical and/or cognitive exertions required by a human operator.
- We developed a taxonomy of performance demands by integrating performance capabilities from NUREG/CR-5680 (Echeverria et al. 1994), taxons (O'Brien et al. 1992), and cognitive functions in NUREG-2114 (Whaley et al. 2013).
- We used performance demands to characterize actions for assessing the impact of ECs on operator performance.

9 Performance Demands

- Detecting and Noticing
- Understanding
- Decision Making
- Action – fine motor
- Action – gross motor
- Action – other neurophysiological functions
- Teamwork – reading and writing
- Teamwork – oral communication
- Teamwork – crew interaction

Technical Literature Review on Environmental Conditions

- A key component of the project is the development of a comprehensive technical literature review on ECs pertinent to flood protection and mitigation.
- The literature review updated the information on ECs included in NUREG/CR-5680 and included additional ECs:
  1. Vibration
  2. Noise
  3. Heat
  4. Cold
  5. Lighting
  6. Humidity
  7. Wind
  8. Precipitation
  9. Standing and moving water
  10. Ice and snowpack
  11. Lightning

11 Environmental Conditions
Literature Review Approach: Example of Standing and Moving Water

<table>
<thead>
<tr>
<th>Factor</th>
<th>Standing and moving water</th>
</tr>
</thead>
<tbody>
<tr>
<td>Condition</td>
<td></td>
</tr>
<tr>
<td>Example</td>
<td>0 to 1.5 ft depth, 0 to 3 ft/s speed, 300-500 NTU turbidity, 40°F temperature, possible sewage contamination, light to dark yellow water</td>
</tr>
<tr>
<td>Attributes and Units</td>
<td></td>
</tr>
<tr>
<td>Depth (e.g., 1.5 ft)</td>
<td></td>
</tr>
<tr>
<td>Velocity (e.g., 3 ft/s lateral)</td>
<td></td>
</tr>
<tr>
<td>Chemical or biological contamination (e.g., sewage)</td>
<td></td>
</tr>
<tr>
<td>Duration (e.g., 6 h)</td>
<td></td>
</tr>
<tr>
<td>Turbidity (e.g., 500 NTU)</td>
<td></td>
</tr>
<tr>
<td>Color (e.g., yellow)</td>
<td></td>
</tr>
<tr>
<td>Precipitation (e.g., heavy rain)</td>
<td></td>
</tr>
<tr>
<td>Humidity (e.g., fog)</td>
<td></td>
</tr>
<tr>
<td>Temperature (e.g., 40°F)</td>
<td></td>
</tr>
<tr>
<td>Lighting (e.g., glare)</td>
<td></td>
</tr>
<tr>
<td>Wind (e.g., calm)</td>
<td></td>
</tr>
<tr>
<td>Mechanisms of Action</td>
<td></td>
</tr>
<tr>
<td>Loss of balance (tapping, sliding)</td>
<td></td>
</tr>
<tr>
<td>Oppositional force (drag)</td>
<td></td>
</tr>
<tr>
<td>Perception of risk</td>
<td></td>
</tr>
<tr>
<td>Slippery surfaces</td>
<td></td>
</tr>
<tr>
<td>Loss of vision</td>
<td></td>
</tr>
<tr>
<td>Effects on Performance</td>
<td></td>
</tr>
<tr>
<td>Gross motor skills (e.g., walking, standing)</td>
<td></td>
</tr>
<tr>
<td>Potential Mitigation</td>
<td></td>
</tr>
<tr>
<td>Protective gear: studded boots, waders, gloves</td>
<td></td>
</tr>
<tr>
<td>Protective gear required</td>
<td></td>
</tr>
<tr>
<td>Use a boat or high-wheeled vehicle for transportation</td>
<td></td>
</tr>
<tr>
<td>Quantifiable based on literature</td>
<td></td>
</tr>
<tr>
<td>Discussed in literature</td>
<td></td>
</tr>
<tr>
<td>Secondary ECs and secondary effects</td>
<td></td>
</tr>
<tr>
<td>Inferred by research team from literature</td>
<td></td>
</tr>
</tbody>
</table>

1 See cold, heat, precipitation, humidity, lighting, and wind EC figures

Leveraging Literature Review for Impact Assessment

Information identified from the literature review was classified into 4 categories in terms of what level of information is available and how it might be used in impact assessment.

Four Levels of Information

1. Quantitative information that is directly applicable to determining the quantitative impact of an EC on a performance demand and can be directly used to support the proof-of-concept approach.
2. Quantitative information that is of some applicability in determining the degree of impact of an EC on a performance demand (e.g., in some cases, EC severity limits may be available - below a lower limit, there is no discernible impact and above an upper limit, an operator cannot perform an activity at all). Under certain assumptions regarding the variation of impacts with changing severity between the two limits, this information might be used with the proof-of-concept model to provide useable information.
3. Qualitative information. General agreement exists that the EC affects a performance demand, but the measured impacts are not reported in literature, not even for limits. A performance demand may also be affected because a critical cognitive function is primarily impaired. This information might be used to inform a sensitivity analysis using the proof-of-concept model.
4. No information (i.e., a literature gap).
Example of Literature Review Summary

Table – Standing and Moving Water

- For each EC, the available literature was summarized by performance demands and coded based on the 4 levels of information.

<table>
<thead>
<tr>
<th>Performance Requirements for Standing/Moving Water</th>
<th>Level of Information Related to Impacts</th>
<th>Assumptions and Limitations on Applicability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Detection and Noticing</td>
<td>3 (b)</td>
<td></td>
</tr>
<tr>
<td>Attention, memory, vigilance, switching, saliency, perception and threshold perception</td>
<td>3 (b)</td>
<td></td>
</tr>
<tr>
<td>Sensation and Visual recognition</td>
<td>3 (b)</td>
<td></td>
</tr>
<tr>
<td>Understanding</td>
<td>3 (b)</td>
<td></td>
</tr>
<tr>
<td>Pattern recognition, discrimination, understanding, evaluating, hypothesizing, diagnosing, and integrating</td>
<td>3 (b)</td>
<td></td>
</tr>
<tr>
<td>Decision Making</td>
<td>3 (b)</td>
<td></td>
</tr>
<tr>
<td>Reasoning, computation, interpreting, classifying, goal setting, planning, adapting, and evaluating and selecting options</td>
<td>3 (b)</td>
<td></td>
</tr>
<tr>
<td>Action</td>
<td>3 (b)</td>
<td></td>
</tr>
<tr>
<td>Fine motor skills - discrete and motor continuous, and manual dexterity</td>
<td>3 (b)</td>
<td></td>
</tr>
<tr>
<td>Gross motor skills - heavy and light</td>
<td>1 (a)</td>
<td></td>
</tr>
<tr>
<td>Other neurophysiological functions</td>
<td>3 (b)</td>
<td></td>
</tr>
<tr>
<td>Teamwork</td>
<td>3 (b)</td>
<td></td>
</tr>
<tr>
<td>Reading and writing</td>
<td>3 (b)</td>
<td></td>
</tr>
<tr>
<td>Oral face-to-face and electronic communication</td>
<td>3 (b)</td>
<td></td>
</tr>
<tr>
<td>Cooperation, crew interaction, and command and control</td>
<td>3 (b)</td>
<td></td>
</tr>
</tbody>
</table>

- Information levels were not cleanly cut and expert judgment was used to make coding decisions.

1 = Quantitative information that is directly applicable to determining the quantitative impact of an EC on a performance demand and can be directly used to support the proof-of-concept approach.

2 = Qualitative information

Example of Level 2 EC Information in Literature – Heat

- Toppling risk is very quantifiable for models, but any individual’s toppling tendency may depend on additional factors including fitness, loose or form fitting clothing, shoe gripping abilities, etc.

(a) It can be assumed that once an individual topples in moving water, none of the other manual or cognitive tasks will be possible.
Example of Level 1 Information in Literature – Standing and Moving Water on Human Performance

\[ U_c = \alpha \left( \frac{h_f}{h_p} \right)^\beta \sqrt{\frac{m_p}{\rho_f h_f^2} - \left( \frac{a_1}{h_p^2} + \frac{b_1}{h_f h_p} \right) (a_2 m_p + b_2)} \]

- \( h_f \) is depth of water
- \( h_p \) is responder height
- \( m_p \) is responder mass
- \( \rho_f \) is density of water
- \( a, \beta, a_1, b_1, a_2, b_2 \) are constants
- Critical flow velocity for toppling, \( U_c \)
- Safe flow velocity for toppling, \( U_{ct} = 0.5 U_c \)
- Safe walking velocity \( SWV = \max(U_{ct} V, 0) \)

Example of the Effect of Standing and Moving Water on Human Performance

Flood water surface elevation: 204.8 m
Distance from Point A to Point B = 1,000 m
ER is triggered when river reaches 205.4 m. Responder’s task is to retrieve a piece of equipment from Point B to Point A. The responder is initially at Point A.

Flood water surface elevation: 207.8 m
Example of the Effect of Standing and Moving Water on Human Performance

\[ T_{B-A} = \int_{x_B}^{x_A} \frac{dx}{SWV_x} = \int_{x_B}^{x_A} \frac{dx}{\max(U_{ctl} - V_x, 0)} \]

Timeline of the Example Emergency Action

- **Baseline walking time**: 0:20:00
- 0:00:00: ER action is triggered when river reaches 205.4 m (673.8 ft) NAVD88; Responder is at Point A
- 0:20:00: Responder starts walking from Point A to Point B
- 0:32:11: Responder walks on dry path
- 1:12:21: Responder reaches Point B
- 1:12:21: Responder isolates and disconnects the equipment
- 1:55:07: Responder walks on inundated path
- 1:58:41: 1:51:48: ER action is completed

Pacific Northwest National Laboratory
Insights from Reported Experimental Data to Develop a Simple Metric

Product Number
PN = \( U_c \times h_f \)

Conclusion

✦ Existing research findings can be leveraged to provide the technical basis for detailed impact quantification for some ECs based on the research literature

✦ For walking under flowing water, research suggests that both
  - a rapid evaluation approach (i.e., PN < 0.3) may be used as a simple metric to assess responders’ safety
  - a detailed quantitative evaluation on the effect of transit time can be performed using dynamic flood characteristics
Directions for Future Research

- Adapting the model to account for both primary and secondary EC impacts on performance
- Modeling complexity in task sequence and crew performance
- Expanding the approach to model the time it takes to recover from critical operator errors
- Modeling effects of multiple, simultaneously-occurring ECs
- Modeling the effects of dynamic ECs
- Addressing uncertainties in model parameters
- Addressing additional factors (e.g., fatigue, stress, and learning) that might influence performance

Questions?
3.3.8.3.3 Questions and Answers

Question:

You mentioned FLEX equipment as part of the consideration, but among the three types of action... I do not find a good match of the FLEX equipment. In particular...the FLEX equipment is portable. What type of action in your design covers this?

Response:

I didn't show you the details of it but the way we think about these manual actions is that we have to do a task analysis to look at what the basic actions might be. And there are these generalized actions that we test... that I talked about... which do involve things like operating a vehicle or moving things from one location to another location that might involve machinery. And using machinery to perform certain tasks, so if you're monitoring things, for example, one of the things that you'll find in the report is an action we described about electrical equipment that needed jumper connections so that is one part of the actions that we're also describing. But when we describe that action, it doesn't really matter what that action is... that is we assume that the personnel that are going to perform these actions are trained in those actions. The only thing that matters is that the human performance itself.
3.3.8.4 External Flooding Walkdown Guidance John Weglian*, EPRI (Session 2A-4; ADAMS Accession No. ML17355A072)

3.3.8.4.1 Abstract

Utilities have performed walkdowns in support of internal flooding PRAs and in response to the 50.54(f) letters from the NRC, they have performed deterministic external flooding walkdowns. However, an external flooding PRA may require something in addition to those two walkdowns. EPRI is conducting research into the requirements for a walkdown to support an External Flooding PRA.

3.3.8.4.2 Presentation
EPRI Research – XFPRA Walkdown Guidance

- External Flooding is a credible hazard to many sites
- An external flooding PRA model can be used to help identify the risks associated with these hazards
- EPRI is conducting research on performing a walkdown to support an external flooding PRA
- A draft guidance report will be available in 2018
- EPRI plans to pilot the guidance prior to publishing the final guidance with lessons learned from the pilot(s)

External Flooding PRA

- An External Flooding PRA (XFPRA) relies on a number of parts
  - Determine the applicable external flooding hazards to the site
  - Determine the flood parameters for each applicable flood mechanism
  - Develop a flood hazard curve to determine the frequency of the flood parameters
  - Create one or more scenarios that describe relevant portions of the flood hazard curve for each hazard
  - Evaluate the plant response for each scenario with a PRA model and quantify risks associated with each scenario
- For spatially-relevant hazards, plant walkdowns are an important part of a PRA
  - Walkdowns support the determination of the scenarios and evaluation of the plant response
Flood Parameters of Interest

- Stillwater elevation
- Wave run-up elevation
- Hydrodynamic/debris loading
- Sediment deposition or erosion
- Groundwater
- Warning time
- Period of inundation
- Period of recession

Walkdown Focus

- External flooding equipment list (XFEL)
  - A list of the components that could be required to mitigate the event
- External flood operator actions list (XFOAL)
  - Actions personnel take to provide flood protection prior to the arrival of the flood
  - Actions the personnel take after the flood arrives to mitigate the event that may be impacted by the flood
- External flood protection features
  - Barriers to prevent flood waters from affecting plant equipment
  - Sumps or basements that may provide water retention
  - Drainage systems
Leverage Existing Information

- Internal Flooding PRA model
  - SSCs for inclusion in the XFEL including height above the floor
  - Propagation paths for flooding
- Individual Plant Examination of External Events (IPEEEE)
  - May provide expected sequence of events for applicable flood mechanisms
  - SSCs for inclusion in XFEL and operator actions in the XFOAL
- Deterministic walkdowns performed for Recommendation 2.3 of the NRC’s 50.54(f) letter to utilities
  - Evaluated the site based on deterministic flood parameters for the applicable floods

Leverage Existing Information (cont.)

- Flood Hazard Reevaluation Report (FHRR)
  - Per the NRC 50.54(f) letter under Recommendation 2.1, sites reevaluated their flooding hazards using the current guidance for new reactor sites
  - Includes site topography, important SSCs, and spatial and temporal data relevant to flooding
  - Includes current design and licensing bases flood protection features
- Mitigating Strategies Assessment (MSA)
  - FLEX strategies may have been based on a plant’s design/licensing basis flood requirements rather than using the current guidance as was used in the FHRR
  - MSAs demonstrated how the FLEX mitigating strategies could be employed during flooding based on the events evaluated in the FHRR.
Leverage Existing Information (cont.)

- Focused Evaluations or Integrated Assessments
  - Sites with a reevaluated hazard that exceeds the current license bases or design basis were required to submit an integrated assessment to evaluate the plant response to the unbounded flood parameters
  - Following guidance in NEI 16-05, this can take the form of a focused assessment or integrated assessment
  - This report will contain an assessment of flood protection and may include (for the integrated assessments) an analysis of flood hazard frequency

External Flooding Equipment List (XFEL)

- Walkdown team requires certain information on SSCs in the XFEL including:
  - Applicable flood mechanisms that could impact the SSC
  - Location and elevation
  - Normal position and PRA-desired position
- The walkdown would confirm the location and evaluate the SSC’s susceptibility to failure from external flooding
External Flood Operator Actions List

- Warning time may provide the ability for operators to take measures to protect against the flood
  - Install flood barriers
  - Build sandbag barriers
  - Movement of portable equipment
- Other actions may be impacted by the flood
  - Increased travel time due to flooding or flood propagation
- The walkdown should confirm that human actions are feasible and determine an appropriate adjustment to timing to perform actions
  - Identify primary and alternate travel paths
  - Confirm materials are available to perform actions
  - Identify any dangers the flooding could present

External Flood Protection Features

- Identify plant features that would protect against flooding including active and passive items such as:
  - Levees
  - Temporary or permanent flood barriers
  - Sump pumps and portable pumps
  - Watertight doors
- Identify features that could retain water
  - Sumps
  - Basements or building levels without important SSCs
- The walkdown should identify important information on the barriers such as:
  - Flood parameters that could defeat the barrier
  - Actions required for active features
  - Retention capability
Next Steps

- Use the Corrective Action Process to address any deficiencies noted during the walkdown
- Create the external flooding scenarios (for example, based on flood height that overtops a levee or other flood barrier)
- Develop propagation of water in the external flooding scenarios to determine which equipment is directly failed by the flood and the time available for human action
- Perform the human reliability analysis to assess the probability of failure of human actions
- Model the external flooding scenarios in a PRA model and assess the risk to the site from the applicable hazards
- Identify any vulnerabilities and determine actions the site can take to reduce those vulnerabilities

Together...Shaping the Future of Electricity

John E. Weglian  
Senior Technical Leader  
jweglian@epri.com  
704-595-2763

Hasan Charkas  
Senior Technical Leader  
hcharkas@epri.com  
704-595-2645
3.3.8.4.3 Questions and Answers

Question:

Can you talk about to what degree you're coordinating the development of this guidance with modifications and revisions to the external flooding PRA standards that are currently underway?

Response:

So, we'll be looking at the external flooding PRA standard. This effort is still in draft and we've got like three chapters written so far, but we'll make sure that we're in tune with what's in the standard.

Question:

Do you guys have a library of case histories that can be used for practitioners such that you can learn and describe effects from particular incidents? Say the duration of Fort Calhoun flood and frequency of those events.

Response:

I don't know that we were planning to include that in this document. That sounds more like on the hazard assessment side. To me there's a difference prior to doing the walk down, you do a hazardous assessment, and there's multiple EPRI guidance documents that tell you how to do that. That sets the stage if you will for what the site will look like and those should include certainly those lessons learned. Then you would incorporate that into your information when doing the walk down.

Question:

Let me rephrase. Were there lessons learned on the walk down post-event for Fort Calhoun that could be used to inform that guidance?

Response:

Obviously, their duration was three months or so…

Other Response:

Their assumptions on the PMF and dam failures are on the order two to seven days so there's a disconnect between the frequency of events and what can happen and vulnerabilities for the response. That's what I'm highlighting here, so this could be a neat opportunity to synthesize those case histories to improve the lockdowns and responses.

Response:

That's a good point. I'll take that into consideration.

Question:

Nathan Siu, [NRC] Office of Research. The IPEEE's are really old studies…your last slide talked about updating the plant PRA to include external flooding. If you're going to update your analysis to include external flooding, it states: here's what we would suggest you do?
Response:

No. I'm assuming that you're not going to do a walk down unless you're building a PRA. If you've decided that you're screening out all the hazards or your hazard risk is low enough through some analysis that you don't require an actual PRA model, then you wouldn't be in this step. Now to the last point... these next steps are after you've done the walk down so this is after the guidance.

3.3.8.5 Erosion Testing of Zoned Rockfill Embankments  Tony Wahl\(^\text{\textregistered}\), Hydraulics Laboratory, Denver, Colorado, U.S. Bureau of Reclamation (Session 2A-5; ADAMS Accession No. ML17355A073)

3.3.8.5.1 Abstract

Three medium-scale embankment dam breach experiments (3-ft dam height) were recently performed by the Bureau of Reclamation. The first test was of a homogeneous silty clay embankment failed by internal erosion through an intentionally created concentrated leak. Two subsequent tests funded by NRC considered zoned embankments with a silty clay core sandwiched between upstream and downstream rockfill zones modeled with a well graded road base soil having 12% fines. One of these embankments was failed by overtopping flow and the second was subjected to internal erosion in a manner similar to the test of the homogeneous silty clay embankment.

In the overtopping test of the zoned embankment, the downstream rockfill zone demonstrated significant erosion resistance. The pattern of breach development was characterized by surface erosion of the downstream slope and the top of the exposed silty clay core, which is in contrast with the headcut erosion that is often observed in cohesive soils. Photographic records were used to evaluate rates of erosion and to estimate applied stresses and erodibility parameters for the rockfill zone, which seemed to be the primary control on the rate of breach development. Estimates of erodibility parameters were compared to results of submerged jet erosion tests. The contribution of gravel to the erosion resistance of the well graded soil was very significant.

The internal erosion tests demonstrated the dramatic influence of upstream and downstream gravel zones on the internal erosion breach development process. Initially, the gravel zone acted as a filter and was able to heal the concentrated leak through the core. After the concentrated leak was enlarged, the gravel zones acted to limit the flow, which significantly slowed the development of internal erosion. Observations from the tests are discussed and compared to available numerical and empirical models that can be used to evaluate the risk of internal erosion.
Overview

- Three dam breach tests 2015-2017
  - First test funded by Reclamation Dam Safety
    - Homogeneous silty clay soil (CL-ML), internal erosion
    - Baseline for subsequent tests, same soil later used as core of zoned embankments
  - NRC-funded tests
    - Zoned embankment – overtopping
    - Zoned embankment – internal erosion
Dam Breach Test Facility
Denver, Colorado

- 13-ft wide, 3-ft high embankment
- Inclined abutment (1:10), acrylic for viewing
- Large tailbox to contain breach outflow
- Headbox spillway with adjustable crest to maintain steady reservoir level

Imaging Equipment
Objectives

Observe erosion and breach development mechanics, compare to numerical models

Materials

Establish erodibility parameters of soils

Demonstrate consistent relationships between applied stress, erosion resistance, and observed erosion

\[ \varepsilon_r = k \cdot d \left( \tau - \tau_c \right) \]

Submerged Jet Test - Erodibility
Erodibility varies widely

- Hanson and Simon (2001) study of streambed soils
- USBR studies of remolded soils

Jet test was developed primarily for cohesive soils

Test 1

- Homogeneous embankment of Silty Clay (CL-ML), internal erosion triggered at mid-depth by withdrawing 0.5-inch rebar

- $k_e = 5.5 \text{ ft/hr/psf}$, $\tau_c = 0.0015 \text{ psf}$ (from pre-test JETs) (Very erodible)

Total elapsed time = 48 minutes
Post-test modeling: WinDAM C

- WinDAM C is a dam breach model developed by USDA to simulate overtopping and internal erosion failures of homogeneous cohesive embankments

Post-test modeling: WinDAM C

- Good match of predicted breach outflows and internal erosion conduit sizes when we used $k_d = 2 \text{ ft/hr/psf}$ and initial conduit size of 1 inch
- Close to actual conditions:
  - 0.5-inch rebar could have disturbed a larger area
  - $k_d = 5.5 \text{ ft/hr/psf}$ measured with JET
Zoned Embankment Objectives

- Not much experience with failure of rockfill dams
- Rockfill dams are difficult to evaluate
  - What are erodibility parameters (especially $k_d$) for gravelly soils?
  - How do different zones interact and affect one another?
- There are rockfill dams upstream from several U.S. nuclear facilities

What is rockfill?

- Consultations with embankment designers at USBR, USACE, etc.
  - Materials in rockfill dams vary widely
  - Usually broadly graded
  - Often “dirtier” than expected
  - Variability of behavior is common because segregation and layering often occur during construction
Zoned Embankments

- Modeled a relatively simple embankment design
  - Did not include modern features such as filters,

![Diagram](image1)

*Note overfall immediately below embankment*

Soils

- Rockfill zones represented by a Class 6 road base soil from local aggregate supplier
  - GW-GC (Well-Graded Gravel with Clay and Sand)
  - 12% fines (passing #200 sieve) with CL-ML (Silty Clay) classification
    - LL=25, PI=6
- Core is also CL-ML (Silty Clay)
  - 86% fines
    - LL=27, PI=6
GW-GC Rockfill

D(15)=5 mm, D(30)=0.7 mm, D(60)=2.05 mm
Cu = D(60)/D(10) = 180
Cc = D(399)/D(107/D(10)) = 1.09
Sample qualifies as well-graded gravel (Cu > 4 and 1 < Cc < 5)

<table>
<thead>
<tr>
<th>Coarse (%)</th>
<th>Gravel (%)</th>
<th>Sand (%)</th>
<th>Fines (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>14.2</td>
<td>5.7</td>
<td>12.4</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Color</th>
<th>Fine</th>
<th>Coarse</th>
<th>Medium</th>
<th>Fine</th>
</tr>
</thead>
<tbody>
<tr>
<td>56.3</td>
<td>0.1</td>
<td>11.0</td>
<td>11.6</td>
<td>9.2</td>
</tr>
</tbody>
</table>

CL-ML Core

D(15)=5 mm, D(30)=0.7 mm, D(60)=2.05 mm
Cu = D(60)/D(10) = 180
Cc = D(399)/D(107/D(10)) = 1.09
Sample qualifies as well-graded gravel (Cu > 4 and 1 < Cc < 5)

<table>
<thead>
<tr>
<th>Coarse (%)</th>
<th>Gravel (%)</th>
<th>Sand (%)</th>
<th>Fines (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>13.3</td>
<td>96.3</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Color</th>
<th>Fine</th>
<th>Coarse</th>
<th>Medium</th>
<th>Fine</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.5</td>
<td>6.5</td>
<td>14.0</td>
<td>14.0</td>
<td>18.0</td>
</tr>
</tbody>
</table>
Embankment Construction

JET test of core

Sand cone tests also performed to measure density of core and gravel zones

Approx. 100% of standard Proctor for all zones
Overtopping Test – 3 minutes

Overtopping Test – 5 minutes
Overtopping Test – 19 minutes

Overtopping Test – 26 minutes
Overtopping Test – 120 minutes

End of Test

Overtopping Test – 180 minutes
End of Test

Material Behavior - cohesive
Observations

- Although core and gravel zones both showed cohesive behavior (near-vertical sidewalls), erosion did not adopt a headcut pattern
- Surface erosion was dominant
  - Lack of tailwater pool to provide recirculation and accelerate erosion at toe

Post-Test Analysis

- Estimate erosion rates and hydraulic stresses from photo records and use to estimate values of \( k_d \)

\[
\varepsilon_r = k_d (\tau - \tau_c)
\]

- Compare to Jet Erosion Tests (JETs) of soil in downstream rockfill zone
### Estimate $k_d$ from photos

**Table 1.** — Flow and breach channel properties used to estimate value of $k_d$ for gravel zone.

<table>
<thead>
<tr>
<th>Elapsed time</th>
<th>Channel width</th>
<th>Flow depth</th>
<th>Discharge</th>
<th>Velocity</th>
<th>Channel slope</th>
<th>Manning’s $n$</th>
<th>Shear stress, $\tau = \gamma RS(n/m)^{1/2}$</th>
<th>Bed position normal to slope, ft</th>
<th>$k_d$</th>
</tr>
</thead>
<tbody>
<tr>
<td>hh:mm:ss</td>
<td>ft</td>
<td>ft</td>
<td>ft$/s$</td>
<td>ft$/s$</td>
<td>ft/ft</td>
<td>ft/ft</td>
<td>lb/ft$^2$</td>
<td>ft/hr/ft$^2$</td>
<td></td>
</tr>
<tr>
<td>0:03:20</td>
<td>1.10</td>
<td>0.23</td>
<td>0.61</td>
<td>2.42</td>
<td>0.51</td>
<td>0.130</td>
<td>0.158</td>
<td>0.34</td>
<td>---</td>
</tr>
<tr>
<td>0:05:20</td>
<td>1.16</td>
<td>0.23</td>
<td>0.73</td>
<td>2.69</td>
<td>0.53</td>
<td>0.122</td>
<td>0.193</td>
<td>0.45</td>
<td>19.59</td>
</tr>
<tr>
<td>0:07:20</td>
<td>1.22</td>
<td>0.24</td>
<td>0.84</td>
<td>2.92</td>
<td>0.57</td>
<td>0.118</td>
<td>0.225</td>
<td>0.47</td>
<td>2.31</td>
</tr>
<tr>
<td>0:14:20</td>
<td>1.42</td>
<td>0.24</td>
<td>1.17</td>
<td>3.43</td>
<td>0.58</td>
<td>0.105</td>
<td>0.305</td>
<td>0.51</td>
<td>1.16</td>
</tr>
<tr>
<td>0:19:20</td>
<td>1.57</td>
<td>0.24</td>
<td>1.50</td>
<td>3.94</td>
<td>0.60</td>
<td>0.095</td>
<td>0.398</td>
<td>0.54</td>
<td>0.93</td>
</tr>
<tr>
<td>0:26:20</td>
<td>1.77</td>
<td>0.25</td>
<td>1.81</td>
<td>4.13</td>
<td>0.60</td>
<td>0.093</td>
<td>0.432</td>
<td>0.59</td>
<td>1.04</td>
</tr>
<tr>
<td>0:34:28</td>
<td>2.07</td>
<td>0.25</td>
<td>2.01</td>
<td>3.88</td>
<td>0.62</td>
<td>0.104</td>
<td>0.376</td>
<td>0.64</td>
<td>1.17</td>
</tr>
<tr>
<td>0:37:00</td>
<td>2.08</td>
<td>0.26</td>
<td>2.01</td>
<td>3.79</td>
<td>0.58</td>
<td>0.103</td>
<td>0.357</td>
<td>0.67</td>
<td>1.70</td>
</tr>
<tr>
<td>0:47:00</td>
<td>2.10</td>
<td>0.29</td>
<td>2.21</td>
<td>3.61</td>
<td>0.53</td>
<td>0.112</td>
<td>0.313</td>
<td>0.71</td>
<td>0.82</td>
</tr>
<tr>
<td>1:17:00</td>
<td>2.16</td>
<td>0.38</td>
<td>2.5</td>
<td>3.02</td>
<td>0.49</td>
<td>0.148</td>
<td>0.204</td>
<td>0.82</td>
<td>1.21</td>
</tr>
<tr>
<td>2:00:00</td>
<td>2.25</td>
<td>0.61</td>
<td>3.63</td>
<td>2.66</td>
<td>0.45</td>
<td>0.201</td>
<td>0.141</td>
<td>0.88</td>
<td>0.73</td>
</tr>
<tr>
<td>3:00:00</td>
<td>2.38</td>
<td>0.64</td>
<td>4.55</td>
<td>3.00</td>
<td>0.32</td>
<td>0.157</td>
<td>0.177</td>
<td>0.95</td>
<td>0.41</td>
</tr>
</tbody>
</table>

### Estimates of $k_d$ from photos

![Graph showing estimates of $k_d$ from photos]
Jet Erosion Tests

- Hypothesis is that erodibility of mixed soils (granular & cohesive) is primarily determined by the cohesive fraction
  - Presence of gravel may also add marginally to erosion resistance (armoring, shielding)
- Used ASTM D4718 procedure to calculate a gravel correction to determine effective density and water content of the finer fractions of the well-graded gravel
  - Minus No. 4 and minus 3/8” fractions

JET specimens

- Two minus No. 4’s compacted by hand to achieve calculated target densities (comparable to 100% standard Proctor)
- Two minus No. 4’s using modified Proctor (4.5 times more energy) (109-114%)
- One minus 3/8” at standard Proctor
- One minus 3/8” at modified Proctor
- One whole gravel specimen at standard Proctor
**JET results**

Minus No.4, standard compaction specimens were a little more erodible than gravel zone in embankment, but in same order of magnitude.

<table>
<thead>
<tr>
<th>ID</th>
<th>Specimen</th>
<th>Water content, w, %</th>
<th>Dry density, γ_s, lb/ft^3</th>
<th>Water content of minus No. 4, w_4, %</th>
<th>Dry density of minus No. 4, γ_4, lb/ft^3</th>
<th>Compaction method</th>
<th>Detachment rate coefficient, F_e, lb/sec/ft^2</th>
<th>Critical shear stress, τ_s, lb/ft^2</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Minus No. 4 fraction</td>
<td>12.4</td>
<td>113.2</td>
<td>12.4</td>
<td>113.2</td>
<td>5-layers, target γ_s = 114 lb/ft^3, w = 12.5%</td>
<td>5.1</td>
<td>0.00024</td>
</tr>
<tr>
<td>2</td>
<td>Minus No. 4 fraction</td>
<td>12.8</td>
<td>112.9</td>
<td>12.8</td>
<td>112.9</td>
<td>5-layers, target γ_s = 114 lb/ft^3, w = 12.5%</td>
<td>4.9</td>
<td>0.00029</td>
</tr>
<tr>
<td>3</td>
<td>Minus No. 4 fraction</td>
<td>13.0</td>
<td>124.8</td>
<td>13.0</td>
<td>124.8</td>
<td>modified Proctor, 56,250 ft-lb/ft^3</td>
<td>0.63</td>
<td>0.025</td>
</tr>
<tr>
<td>4</td>
<td>Minus No. 4 fraction</td>
<td>11.4</td>
<td>130.3</td>
<td>11.4</td>
<td>130.3</td>
<td>modified Proctor</td>
<td>0.45</td>
<td>0.046</td>
</tr>
<tr>
<td>5</td>
<td>Minus 3/8-inch</td>
<td>11.0</td>
<td>132.3</td>
<td>14.2</td>
<td>121.7</td>
<td>standard Proctor, 12,375 ft-lb/ft^3</td>
<td>1.01</td>
<td>0.0056</td>
</tr>
<tr>
<td>6</td>
<td>Minus 3/8-inch</td>
<td>10.3</td>
<td>133.7</td>
<td>13.2</td>
<td>123.3</td>
<td>modified Proctor</td>
<td>0.31</td>
<td>0.044</td>
</tr>
<tr>
<td>7</td>
<td>Full sample</td>
<td>8.4</td>
<td>140.3</td>
<td>15.5</td>
<td>114.8</td>
<td>standard Proctor</td>
<td>3.1</td>
<td>0.07</td>
</tr>
</tbody>
</table>

• Minus No.4, modified compaction showed increased erosion resistance.
• Lower layers of embankment may have been overcompacted when upper layers were added.
JET results

- Minus 3/8" specimens both showed more erosion resistance than comparable minus No. 4 specimens.
- Could be due to other factors. More testing needed to confirm trend.

<table>
<thead>
<tr>
<th>ID</th>
<th>Specimen</th>
<th>Water content, w, %</th>
<th>Dry density, ( \gamma_d ), lb/ft(^2)</th>
<th>Water content of minus No. 4, w, %</th>
<th>Dry density of minus No. 4, ( \gamma_d ), lb/ft(^3)</th>
<th>Compaction method</th>
<th>Detachment rate coefficient, ( f_{dc} ), lb/hr/ft(^2)</th>
<th>Critical shear stress, ( \tau_c ), lb/ft(^2)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Reference</td>
<td>7.0</td>
<td>140.0</td>
<td>12.4</td>
<td>114.3</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>1</td>
<td>Minus No. 4 fraction</td>
<td>12.4</td>
<td>113.2</td>
<td>12.4</td>
<td>113.2</td>
<td>5-layers, target ( \gamma_d = 114 \text{ lb/ft}^3 ) ( w = 12.5% )</td>
<td>5.1</td>
<td>0.00024</td>
</tr>
<tr>
<td>2</td>
<td>Minus No. 4 fraction</td>
<td>12.8</td>
<td>112.9</td>
<td>12.8</td>
<td>112.9</td>
<td>5-layers, target ( \gamma_d = 114 \text{ lb/ft}^3 ) ( w = 12.5% )</td>
<td>4.9</td>
<td>0.00029</td>
</tr>
<tr>
<td>3</td>
<td>Minus No. 4 fraction</td>
<td>13.0</td>
<td>124.8</td>
<td>13.0</td>
<td>124.8</td>
<td>modified Proctor, 56,250 ft-lb/ft(^3)</td>
<td>0.63</td>
<td>0.025</td>
</tr>
<tr>
<td>4</td>
<td>Minus No. 4 fraction</td>
<td>11.4</td>
<td>130.3</td>
<td>11.4</td>
<td>130.3</td>
<td>modified Proctor</td>
<td>0.45</td>
<td>0.046</td>
</tr>
<tr>
<td>5</td>
<td>Minus 3/8-inch</td>
<td>11.0</td>
<td>132.3</td>
<td>14.2</td>
<td>121.7</td>
<td>standard Proctor, 12,375 ft-lb/ft(^3)</td>
<td>1.01</td>
<td>0.0056</td>
</tr>
<tr>
<td>6</td>
<td>Minus 3/8-inch</td>
<td>10.3</td>
<td>133.7</td>
<td>13.2</td>
<td>123.3</td>
<td>modified Proctor</td>
<td>0.31</td>
<td>0.044</td>
</tr>
<tr>
<td>7</td>
<td>Full sample</td>
<td>8.4</td>
<td>140.3</td>
<td>15.5</td>
<td>114.8</td>
<td>standard Proctor</td>
<td>3.1</td>
<td>0.07</td>
</tr>
</tbody>
</table>

Full gravel specimen was more erodible again, but still close to range of estimates for embankment rockfill zone. This specimen is probably pushing the limits for doing a valid JET test (too much gravel, too big).
JETs

- Minus No. 4 (3/16”)
- minus 3/8”
- full gravel up to ¼”

Piping Test (Internal Erosion)

- Embankment was reconstructed only in the area affected by first test (near abutment)

- ½” rebar
- 18 inches below crest
Piping Test

- Took place over four days (48 hours of flow)
  - Day 1
    - Reservoir was filled and rebar withdrawn
    - Initial flow through “pipe” probably less than 5 gpm
    - Initially turbid, but gradually cleared
    - Within 90 minutes, flow stopped completely

- Pipe healed itself
- No erosion was ever visible through the acrylic left abutment wall

Healing of Pipe

- Gravel zone met basic criteria to serve as a filter for the core

\[
\frac{D_{15,\text{filter}}}{D_{15,\text{base}}} \geq 5
\]

\[
\frac{D_{15,\text{filter}}}{D_{85,\text{base}}} \leq 5
\]

\[
\frac{0.12 \text{ mm}}{0.015 \text{ mm}} = 8.0
\]

\[
\frac{0.12 \text{ mm}}{0.07 \text{ mm}} = 1.7
\]
Day 2

- Interventions to try to initiate a failure and then observe erosion processes
  - Reinserted rebar and withdrew again

Day 2

- Flow was again initially turbid, then cleared
- Flow rate remained steady (about 5 gpm)
- Hole through downstream gravel zone gradually became more distinct as fines and fine sand were carried away
  - Further growth of hole was limited by medium to coarse sand and fine gravel left behind
  - Enlargement of hole through core zone became visible after 19 minutes
Internal Erosion – 1 minute

Internal Erosion – 5 minutes
Internal Erosion – 10 minutes

Internal Erosion – 20 minutes
Internal Erosion – 30 minutes

Internal Erosion – 60 minutes
Internal Erosion – 90 minutes

Internal Erosion – 2 hours
Internal Erosion – 3 hours

Internal Erosion – 4 hours
Internal Erosion – 12 hours

Internal Erosion – 15 hours
Failure Modes

- Erosion process is leading to a slow “stoping” failure
  - Upward migration of erosion channel as roof slowly collapses and void increases in size
  - As stope rises, this could eventually cause a collapse of the crest that could produce...
    - Overtopping
    - Shortened seepage path -- increased hydraulic gradient
- Downstream and upstream gravel zones limiting flow, keeping process slow

Internal Erosion – 24 hours

Tried opening channels thru gravel
Internal Erosion – 36 hours

Opening downstream zone allowed much of the deposited soil in the bottom of the void to be transported out, but did not otherwise accelerate process.

Opening upstream zone had little effect, as gravel simply collapsed back into the hole, continuing to limit flow.

Test stopped after a total of 48 hours of flow.

Takeaways from Piping Test

- Numerical models of embankment breach by internal erosion assume a concentrated leak and model only the detachment and removal of soil to enlarge that leak
  - Re-deposition of material collapsing from roof is not modeled
  - Simulating the “stoping” mechanism is beyond capabilities of current models
- Limitation of flow by upstream/downstream gravel zones is also not well represented in numerical models
Internal Erosion “Toolbox”

- USBR and US Army Corps of Engineers (USACE)
  - Best Practices in Dam and Levee Safety Risk Analysis

- Set of empirical and experienced-based procedures for analyzing the sequence of events (event-tree) needed for internal erosion failure modes
Typical Internal Erosion Event Tree

- Water level at or above threshold level
- Initiation – Erosion starts
  - Continuation – Unfiltered or inadequately filtered exit exists
  - Progression – Continuous stable roof and/or sidewalls
  - Progression – Constriction or upstream zone fails to limit flows
  - Progression – No self-healing by upstream zone
  - Unsuccessful detection and intervention
  - Breach (uncontrolled release of impounded water)

For this embankment, projected breach rate is Rapid to Medium, 1 to 7 days

Summary

- Overtopping test
  - Erodibility ($k_d$) of gravel zone estimated from embankment test observations matches well with JET tests
  - Understanding erodibility of mixed gravel & cohesive soils is a big challenge as ratio of coarse-to-fine soil changes
  - This gravel had enough fines to behave like a cohesive soil, but what about…
    - Cleaner rockfills ???
    - Cobbles and boulders ???
  - There is still uncertainty predicting when headcut erosion or surface erosion will take place
Summary

- Internal erosion
  - Complex interactions of different zones are possible
  - Available numerical models are not equipped for all of the possibilities
  - Empirical internal erosion toolbox provides best approach for understanding event trees for internal erosion failure of zoned embankments

3.3.8.5.3 Questions and Answers

None.
3.3.9 Day 2: Session 2B - Frameworks I

Session Chair: John Weglian, EPRI

Development and demonstration of a PFHA framework for flood hazard curve estimation.

3.3.9.1 A Framework for Inland Probabilistic Flood Hazard Assessments: Analysis of Extreme Snow Water Equivalent in Central New Hampshire  
Brian Skahill*, Ph.D. and Carrie Vuyovich, Ph.D., U.S. Army Corps of Engineers, Engineer Research and Development Center (Session 2B-1; ADAMS Accession No. ML17355A074)

3.3.9.1.1 Abstract

The NRC Probabilistic Flood Hazard Assessment (PFHA) research plan aims to build upon recent advances in deterministic, probabilistic, and statistical modeling of extreme events to develop regulatory tools and guidance for NRC staff with regard to PFHA for nuclear facilities. For inland nuclear facility sites (i.e., non-coastal sites), a PFHA must be able to incorporate probabilistic models for a variety of processes, allow for characterization and quantification of aleatory and epistemic sources of uncertainty, and facilitate propagation of uncertainties and sensitivity analysis. Moreover, the PFHA framework should be capable of modeling spatial and temporal correlation between and within events. The bases for the framework are two distinct spatial analysis methodologies for characterizing hazard curves that each in their own right are recent advances in the modeling of extreme events. The two spatial methods were selected as the basis given that most relevant flood hazard phenomena naturally occur as spatial processes and regionalization is likely a minimum requirement toward improved accuracy and precision of estimates. Related, the two methods are each designed in a manner such that they, or their respective adaptations, can be readily applied to leverage any and all available relevant information for a given hazard analysis. The first method is spatial or spatiotemporal Bayesian Hierarchical Modeling (BHM); whereas, the second approach employs max-stable processes. The application of either approach involves the use of spatial and temporal covariate data to distribute model parameters in space and also account for temporal trends. The spatial/spatiotemporal BHM methodology is simple and flexible and leverages the multiple merits of Bayesian inference to support probabilistic flood hazard analyses to readily develop spatially coherent pointwise return level maps. However, its likelihood formulation assumes conditional independence among the extremes, which can be difficult to ignore for flood hazard phenomenon, and its use of a Gaussian process for the latent variable model results in a lack of conformance with extreme value theory (EVT). The second framework approach; viz., max-stable processes, when applied does account for the dependence among the extremes, conforms with EVT which is highly notable as framework applications require credible extrapolation well beyond the observed record, and moreover, supports the capacity for more complex areal assessments of risk beyond the simple generation of pointwise return levels. For extreme rainfall and SWE analyses; for example, it is particularly noteworthy that max-stable process applications can develop areal based exceedance probabilities. PFHA framework method choice is dependent upon an initial assessment of dependence among the extreme data. The framework also involves a multi-model averaging step in attempts to account for the uncertainty associated with model choice. We profile a complete application of the framework for the analysis of extreme snow water equivalent data in central New Hampshire which leverages regionalization, additional data derived from process-based hydrologic simulation, climate index data, max-stable process selection, and trend surface modeling analysis to develop individual model and multi-model averaged pointwise return level maps and areal-based exceedance probability estimates.
A Framework for Inland Probabilistic Flood Hazard Assessments: Analysis of Extreme Snow Water Equivalent in Central New Hampshire

Brian Skahill\textsuperscript{1}
Carrie Vuyovich\textsuperscript{2}
US Army Corps of Engineers Engineer R&D Center
\textsuperscript{1}Coastal and Hydraulics Laboratory
Hydrologic Systems Branch
\textsuperscript{2}Cold Regions Research and Engineering Laboratory
Remote Sensing, GIS and Water Resources Branch
December 05, 2017

Objective

Construct site-specific flood hazard curves for the full range of return periods of interest for nuclear power plants.

Must be able to incorporate probabilistic models, allow for characterization and quantification of aleatory and epistemic sources of uncertainty, and facilitate propagation of uncertainties and sensitivity analysis.

Build on recent advances in modeling extremes

Focus areas:
- Literature review
- Rainfall and Local Intense Precipitation
- Cool Season Processes
- Site-scale Flooding from Local Intense Precipitation
- Riverine Flooding - Rainfall or Rainfall and Snowmelt
- Riverine Flooding - Hydrologic Dam/Levee Failure
- Knowledge transfer

Should be capable of modeling spatial and temporal correlation between and within events.
### PFHA Framework

**Step 1 (Repeat K times)**

- **Data Analysis**
- **Causal Information Expansion**
- **Spatial Information Expansion**
- **Temporal Information Expansion**

**Available tools**: R packages SpatialExtremes, Spatio-temporal BHM / Spatial Extremes

**Step 2 Apply a multi-model averaging technique**

Bayesian Model Averaging

\[
p(\Delta | M_1, ..., M_K) = \sum_{k=1}^{K} w_k g_k(\Delta | M_k)
\]

For example or

Information Criterion Averaging

\[
\beta_k = \frac{\exp\left(-\frac{1}{2} I_k\right)}{\sum_{k=1}^{K} \exp\left(-\frac{1}{2} I_k\right)}
\]

**Demonstration Site & Data**

**New Hampshire Department of Environmental Services (NHDES)**

The NHDES conducts bi-weekly snow surveys throughout the winter season in several basins in central New Hampshire where the agency manages reservoir water supply and releases.

**Snow Survey, 3 Jan 2017, USACE New England District**

**Historical data is available for the period of record on their website:**

[http://www4.des.state.nh.us/fli_home/snow_sampling_stations.asp](http://www4.des.state.nh.us/fli_home/snow_sampling_stations.asp)
The VIC model is a large-scale, semi-distributed hydrologic model.

Brief Description:
- VIC CONUS daily data from 1915 to 2011 at 115 resolution. The dataset variables have been generated using the Variable Infiltration Capacity VIC hydrologic model v4.12. It is driven with the corresponding meteorological data.

Temporal Coverage:
- Daily means from 1915 to 2011
- Monthly means from 1915 to 2011
- Yearly means from 1915 to 2011
- Monthly long-term means from 1915 to 2011

Spatial Coverage:
- 0.0625 degree latitude x 0.0625 degree longitude CONUS grid
- 21.2305 x 23.5696 x 25.6486 x 23.0312 NE

Levels:
- Surface
- Soil

Update Schedule:
- None

Variables:
- Meteorological Variables (station variables input)
- Flux Variables (model generated)

VIC Snow Algorithm
VIC uses an energy balance approach to represent snow accumulation and ablation on the ground.

The land surface is modeled as a grid of large (>>1km), flat, uniform cells

Sub-grid heterogeneity (e.g. elevation, land cover) is handled via statistical distributions

Inputs are time series of sub-daily meteorological drivers (e.g. precipitation, air temperature, wind speed, radiation, etc.)

Land-atmosphere fluxes, and the water and energy balances at the land surface, are simulated at a daily or sub-daily time step

Water can only enter a grid cell via the atmosphere
Causal Information Expansion Data

<table>
<thead>
<tr>
<th>Site</th>
<th>Observed NHDES data record</th>
<th>Observed NHDES data record length</th>
<th>Remaining record using adjusted Linneh SWE data</th>
<th>Adjusted Linneh SWE data record length</th>
</tr>
</thead>
<tbody>
<tr>
<td>GULFORD</td>
<td>1980 - 2013</td>
<td>60</td>
<td>1982 - 1994</td>
<td>35</td>
</tr>
<tr>
<td>MEREDITH</td>
<td>1980 - 2013</td>
<td>60</td>
<td>1982 - 1994</td>
<td>35</td>
</tr>
<tr>
<td>CENTERHURST</td>
<td>1980 - 2013</td>
<td>60</td>
<td>1982 - 1994</td>
<td>35</td>
</tr>
<tr>
<td>MERIDIAN</td>
<td>1980 - 2013</td>
<td>60</td>
<td>1982 - 1994</td>
<td>35</td>
</tr>
<tr>
<td>OAK BROOK</td>
<td>1980 - 2013</td>
<td>60</td>
<td>1982 - 1994</td>
<td>35</td>
</tr>
<tr>
<td>HEMENWAY</td>
<td>1980 - 2013</td>
<td>60</td>
<td>1982 - 1994</td>
<td>35</td>
</tr>
<tr>
<td>SCRIBNER BROOK</td>
<td>1980 - 2013</td>
<td>60</td>
<td>1982 - 1994</td>
<td>35</td>
</tr>
<tr>
<td>NORTH WOLFORD</td>
<td>1980 - 2013</td>
<td>60</td>
<td>1982 - 1994</td>
<td>35</td>
</tr>
<tr>
<td>GRAIN BEND</td>
<td>1980 - 2013</td>
<td>60</td>
<td>1982 - 1994</td>
<td>35</td>
</tr>
<tr>
<td>SCRIBNER BROOK</td>
<td>1980 - 2013</td>
<td>60</td>
<td>1982 - 1994</td>
<td>35</td>
</tr>
<tr>
<td>NEWBURY</td>
<td>1980 - 2013</td>
<td>60</td>
<td>1982 - 1994</td>
<td>35</td>
</tr>
<tr>
<td>HUDSON LAKE</td>
<td>1980 - 2013</td>
<td>60</td>
<td>1982 - 1994</td>
<td>35</td>
</tr>
<tr>
<td>AVAUS LAKE</td>
<td>1980 - 2013</td>
<td>60</td>
<td>1982 - 1994</td>
<td>35</td>
</tr>
<tr>
<td>NISBON BROOK</td>
<td>1980 - 2013</td>
<td>60</td>
<td>1982 - 1994</td>
<td>35</td>
</tr>
</tbody>
</table>

Model Dependence & Marginals

\[ P_A = \text{mean annual precipitation}; \quad T_A = \text{mean annual temperature}; \]
\[ P^w = \text{mean winter precipitation}; \quad T^w = \text{mean winter temperature}; \quad a = \text{parsimonized version of model}; \quad \text{NAO} = \text{use of North Atlantic Oscillation climate index temporal covariate data} \]

\[ = \text{gridded covariate dataset of mean annual temperature} \]
Roughly speaking, the NAO is an atmospheric process with two different phases, positive and negative, which relate to how the atmospheric mass is distributed. The gradient between two large-scale pressure cells over the Atlantic Ocean, a low located near Iceland and a high over the Azores, affects the strength of westerlies and storm track direction.

35 models considered; viz., 3a – 9a, all including use of NAO, and 5 max-stable model configurations.
Pointwise Return Levels

1000-year Return Level - NEWBURY

Estimate including lower and upper 95% uncertainty bounds

Model Choice

Top 6 models
Generalize Model Selection

Areal-based Exceedances

With max-stable process applications, additional more complex assessments of risk can also be evaluated. For example, the joint spatial modeling of observations (e.g., precipitation, snow water equivalent (SWE), snowmelt rate, or temperature), denoted for generality by $Y(x)$, over a basin $B$, supports the capacity to compute, via simulation, an integral such as

$$\Pr \left\{ \int_B Y(x)\,dx > z_{crit} \right\}$$

"By spatially modelling rare events, one can simulate unusual episodes rather than merely produce pointwise maps of high quantiles, and thus allowing a more powerful risk analysis."

Areal SWE in Winnpesaukes
Summary

Recent advances in the modeling of extreme events

Max-stable models

Account for dependence

Credible extrapolation (conforms with EVT)

Areal based exceedance calculations

Spatial Information
Regionalization

Casual Information
Livneh Data Process Layer

Temporal Information
NAO Climate Index

Multiple distributions
Generalize Model Choice

Process layer
Multiple max-stable model permutations

Future Related Work

Further develop and demonstrate cool season design scenarios via max-stable areal exceedance simulation and comparison with years with high SWE AM

Adapt Spatial/Spatio-temporal BHM and max-stable model likelihoods

\[ p(y | \mu_s, \kappa_s, \xi_s) \mid \gamma = \prod_{s \in \mathcal{S}_0} \prod_{t=1}^{T_s} p(y_{t,s} | \mu_s, \kappa_s, \xi_s) \]


https://www.nohrsc.noaa.gov
3.3.9.1.3 Questions and Answers

None.

3.3.9.2 Structured Hazard Assessment Committee Process for Flooding (SHAC-F) for Riverine Flooding  Rajiv Prasad*, Ph.D.; Pacific Northwest National Laboratory; Kevin Coppersmith*, Ph.D.; Coppersmith Consulting (Session 2B-2; ADAMS Accession No. ML17355A075)

3.3.9.2.1 Abstract

This research project is part of the U.S. NRC’s Probabilistic Flood Hazard Assessment (PFHA) Research plan in support of development of a risk-informed analytical approach for flood hazards. The approach is expected to support reviews of license applications, license amendment requests, and reactor oversight activities. Pacific Northwest National Laboratory is leading the development of a structured hazard assessment committee process for flooding (SHAC-F). In previous years, we described the virtual study following a Senior Seismic Hazard Analysis Committee (SSHAC Level 3 process for local intense precipitation (LIP)-generated flood.

The objective of the current effort is to develop the SHAC- process for riverine flooding (with and without snowmelt but excluding dam breaches) and to provide confidence that all data sets, models, and interpretations proposed by the larger technical community have been given appropriate consideration and that the inputs to the PFHA reflect the center, body, and range of technically defensible interpretations. Several of the issues identified and solutions proposed
during the LIP PFHA SHAC-F virtual study informed the development of riverine SHAC-F process. These issues included precise definition of data and models, compilation of data related to riverine flood characterization, compilation of previous hydrologic and hydraulic models applied to the river basin, and previous characterization of uncertainties in the river basin.

SHAC-F studies can be carried out at three levels which are defined in terms of the purpose of the assessment. Level 1 and Level 2 SHAC-F studies are expected to support NRC’s significance determination process. The purpose of a Level 1 study is primarily screening (e.g., binning of flood hazards into high or low risk categories). Level 2 studies would be appropriate to (1) perform a more refined screening analysis (e.g., where a Level 1 study could not adequately support binning of flood hazards) and (2) update an existing Level 3 assessment. The purpose of a Level 3 assessment is to support design reviews and to support probabilistic risk assessment (PRA) for new and existing power reactors. For all three SHAC-F levels, the expected outcome of the study is generation of a family of flood hazard curves appropriate for the purpose of the assessment.

Data and methods used for the three SHAC-F levels are also defined to be commensurate with the purpose of the study. A Level 1 SHAC-F study would use existing data, possibly within an at-site flood-frequency study. The study may use alternative conceptual models (ACMs, various parametric or non-parametric distributions in the case of flood-frequency studies) to represent epistemic uncertainty coupled with regionalization and accounting for nonstationarities. A SHAC-F Level 2 study could supplement flood-frequency analyses with existing simulation model studies. ACMs would include alternative simulation models that can reasonably represent the flood behavior at the site. A SHAC-F Level 3 study would need to account for spatiotemporal resolution of flood hazard predictions that can support licensing and PRA needs. Existing data can be used in a Level 3 study, but a site-specific, detailed analysis would be needed. At all levels of SHAC-F studies, explicit characterization of uncertainty is needed.

3.3.9.2.2 Presentation
SHAC-F Project: Purpose and Approach

◆ Purpose
  ● Adapt the well-established Senior Seismic Hazard Assessment Committee (SSHAC) approach to Probabilistic Flood Hazard Assessment (PFHA)
  ● Refer to as the “Structured Hazard Assessment Committee Process for Flooding” (SHAC-F)
  ● Develop SHAC-F framework and guidance

◆ SSHAC process
  ● Provides assurance that all data, models, and methods have been evaluated and that full range of knowledge and uncertainties is captured in the hazard analysis

◆ Approach for development of the SHAC-F framework
  ● Based on virtual implementation of the SSHAC process to PFHA for selected flood mechanisms
  ● Development of a Template Project Plan for selected flood mechanisms

SHAC-F Project: Purpose and Approach

◆ Selected flood mechanisms
  ● Local intense precipitation (LIP) flooding
  ● Riverine flooding (RF) without snowmelt
  ● Riverine flooding from combined rainfall and snowmelt

◆ Project adapts and tailors elements of SSHAC process
  ● Implementing typical steps of SSHAC to PFHA in virtual studies
  ● Documenting lessons learned
  ● Refining Template Project Plan

◆ Activities and Products
  ● SHAC-F Work Plan: defines the activities associated with the virtual studies for the SHAC-F project
  ● PFHA Template Project Plan: defines all elements of an actual SHAC-F study for a selected flood mechanism
    ● Goal is to produce PFHA Template Project Plans
    ● Guidance for SHAC-F PFHA studies
Lessons Learned from the LIP SHAC-F Virtual Study and Path Forward for Riverine PFHA

◆ Logistics issues
  - Structured workflow for a Level 3 project; large number of participants
  - Highly site-specific nature of flooding processes
  - Both of these issues raise costs of a SHAC-F study

◆ September 2017 Project Meeting at Richland
  - SHAC-F Levels are now defined in terms of the purpose of the assessment
    - SHAC-F Levels 1 and 2: support NRC’s Significance Determination Process (SDPs)
    - SHAC-F Level 1 to support screening
    - SHAC-F Level 2 to support a more refined screening assessment
    - SHAC-F Level 2 to support update of an existing SHAC-F Level 3 assessment
    - SHAC-F Level 3 to support design reviews and PRAs for new and existing power reactors

NUREG-2213
SSHAC Guidelines and Guidance

Goal of a SSHAC Process

- The fundamental goal of a SSHAC 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 the 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)."
SHAC-F Levels – Redefined with Purpose of Assessment (After NUREG-2213 Table 3-1)

<table>
<thead>
<tr>
<th>Riverine Floods</th>
<th>SHAC-F Level 1</th>
<th>SHAC-F Level 2</th>
<th>SHAC-F Level 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Purpose</td>
<td>Screening (e.g., listing flood hazards in high or low risk categories)</td>
<td>Update existing Level 3 or refined analysis for screening</td>
<td>Support design PRA for licensing new and existing plants</td>
</tr>
<tr>
<td>Expected Outcome</td>
<td>Family of Discharge/Elevation Hazard Curves relevant to the system you are analyzing (need to revisit)</td>
<td>Family of Hazard Curves plus associated effects</td>
<td>Family of Hazard Curves plus associated effects</td>
</tr>
<tr>
<td>Data</td>
<td>Stage Discharge Data</td>
<td>Discharge Data</td>
<td>Discharge Data</td>
</tr>
<tr>
<td></td>
<td>(systematic site data including historic information)</td>
<td>Regional Data</td>
<td>Regional Data</td>
</tr>
<tr>
<td></td>
<td>Regional and Paleo data if available</td>
<td>Historic and Paleo data</td>
<td>Historic and Paleo data</td>
</tr>
<tr>
<td></td>
<td>(flood frequency)</td>
<td>(flood frequency)</td>
<td>(flood frequency)</td>
</tr>
<tr>
<td></td>
<td>Use what you have</td>
<td>Use what you have</td>
<td>Use what you have</td>
</tr>
<tr>
<td></td>
<td>• More extensive effort to find and assemble existing data</td>
<td>• More extensive effort to find and assemble existing data</td>
<td>• More extensive effort to find and assemble existing data</td>
</tr>
<tr>
<td></td>
<td>• Contact resource experts for simulation model data</td>
<td>• Contact resource experts for simulation model data</td>
<td>• Contact resource experts for simulation model data</td>
</tr>
<tr>
<td>Models</td>
<td>Screening flood frequency model</td>
<td>ACM – L2</td>
<td>Conceptual Model</td>
</tr>
<tr>
<td></td>
<td>• Conceptual Model</td>
<td>Consider spatial variation</td>
<td>ACM – L3</td>
</tr>
<tr>
<td></td>
<td>• ACM – L1</td>
<td>Simulation models</td>
<td>Statistical plus simulation</td>
</tr>
<tr>
<td></td>
<td>• Statistical Models</td>
<td></td>
<td>Spatiotemporal resolution of model</td>
</tr>
<tr>
<td></td>
<td>• Process understanding influencing data</td>
<td></td>
<td>predictions to support PRA</td>
</tr>
<tr>
<td></td>
<td>• Single population</td>
<td></td>
<td>Locations of SSSs</td>
</tr>
<tr>
<td></td>
<td>• Regionalization</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Nonstationarity</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Principal Sources of Sensitivity</td>
<td>Streamflow</td>
<td>Streamflow (possibly precipitation, basin initial conditions)</td>
<td>Streamflow, precipitation, basin initial conditions</td>
</tr>
<tr>
<td>Principal Sources of Uncertainty</td>
<td>Measurement uncertainty in discharge data, alternative statistical models, parameter uncertainty</td>
<td>Measurement uncertainty in discharge data, alternative statistical models, parameter uncertainty</td>
<td>Measurement uncertainty in discharge data, alternative statistical models, parameter uncertainty</td>
</tr>
</tbody>
</table>

3-311
### SHAC-F Levels – Redefined with Purpose of Assessment (After NUREG-2117 Rev. 2 Table 3-1) (cont.)

<table>
<thead>
<tr>
<th>Riverine Floods</th>
<th>SHAC-F Level 1</th>
<th>SHAC-F Level 2</th>
<th>SHAC-F Level 3</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>TI Team Makeup</strong></td>
<td>Small TI Team (e.g., two-one in flood frequency modeling, one in regional hydrologic modeling)</td>
<td>Small TI Team; possibly multiple teams (e.g., probabilistic modeler, precipitation frequency analyst, and runoff/hydraulic modeler)</td>
<td>Larger TI Team members (alternative models may require additional TI team members, e.g., probabilistic modeler, precipitation frequency analyst, and runoff/hydraulic modelers)</td>
</tr>
<tr>
<td><strong>PPRP</strong></td>
<td>Small PPRP Team (e.g., two-one for flood frequency modeling review and one for regional hydrologic modeling review)</td>
<td>Two or more reviewers (e.g., one/more for flood frequency, one/more for simulation modeling, one/more for regional hydrologic modeling); Feedback on preliminary models; Communication with PPRP during evaluation and integration</td>
<td>Larger team of reviewers (e.g., precipitation and runoff experts, experts in use of potential runoff/hydraulic models, PRA expert); Feedback on preliminary models; Engagement during evaluation and integration process; PPRP briefing of final model</td>
</tr>
<tr>
<td><strong>Others from Table 3-1 in NUREG-2113</strong></td>
<td>****</td>
<td>****</td>
<td>****</td>
</tr>
</tbody>
</table>

---

### Riverine PFHA Project Structure – SHAC-F Level 1

```
Project Sponsor

                      ↘
                      │
                      ▼
Project Team

                       ↘
                       │
                       ▼
Flood Frequency Modeler  Regional Hydrology Expert  PPRP
```

---

Pacific Northwest NATIONAL LABORATORY

3-312
Riverine PFHA Project Structure – SHAC-F Level 2

Project Sponsor

Project Technical Integrator (PTI)

Flood Frequency Modeler  Regional Hydrology Expert  Flood Simulation Modeler

PPRP

Riverine PFHA Project Structure – SHAC-F Level 3

Project Sponsor

Project Quality Engineer

Project Manager

Project Technical Integrator (PTI)

Project Technical Resources  Hazard Analyst  Database Manager

Specialty Contractors

Resource Experts

Proponent Experts

MMC TI Lead  HOMC TI Lead  HAMC TI Lead

MMC TI Team  HOMC TI Team  HAMC TI Team
Conclusions

- LIP PFHA Virtual Study provided insights that are unique to the flooding problem
- Site-specific nature of flooding requires careful consideration of level of effort for PFHA
- Tying SHAC-F levels to purpose of the assessment is needed
  - Proposed SHAC-F Levels now align with NRC regulatory needs and are consistent with updated SSHAC guidance
  - Proposed riverine PFHA project structures for the three SHAC-F levels are being developed

Questions?
Questions and Answers

Question:

This is Fernando Ferrante with EPRI. You had a suggestion to redefine the level one in SHAC-F to be used for significance determination processes and I think that some interesting insight into the potential benefits and challenges this process can have. SDPs are fast and furious risk assessment types of things and unless data is available, and we say for particular issue, you have paleoflood, you have the availability of complicated models… one of the conclusions may be: if the driver is the one-million-year flood, you don’t have any insights that are very explicit qualitative in size. And maybe that’s one insight of the process: we’ve got the kind of thinking that you guys are applying in terms of the SDP or is that kind of preliminary at this point?

Response (Prasad):

It is slightly preliminary at this point. But the assumption is that you would have data that you can quickly collect, and you would be able to do at least the flood frequency analysis relatively easily and quickly. There are methods available now with the Bulletin 17 C and related tools available that could be quickly operationalized and used. But I do think that there is a need to have some of this data centrally compiled and some of the database stuff that we were talking about, that INL was talking about, I think there is a potential for linking through that or an NRC analyst or even an industry analyst to go there quickly get that data which has already been compiled and you don’t have to go and dig in into research papers and contact people to get that data. That would speed up the process.

Response (Ferrante):

Well, I think my suggestion would be looking at some of the past SDPs that happened and see how this expert panel, you know ‘tiger team’, will be able to gather information and have helped some of them.

Question:

I have some experience designing a SHAC study and when the project sponsor got the estimate, they ran a million miles away and it never happened. But, in putting this proposal together it struck me that if others have done a similar project in the flood area and multiple projects have been done, to some extent we’d be going down the same pathways. Each site is different, I agree, but there’s only so many models and so many ways of looking at different hydrologic processes and so on. So that leads me to the idea: is there a way of somehow streamlining things? Benefiting from other similar studies that have been done?

Response:

Yes. Definitely. If you look at the lower level SHAC and it says use what you have so the idea being that if you have existing studies and people have done some of those studies, you need to bring them in and you don’t need to re-perform them. One of the central things about SHAC is when you get in and do a modeling study that shows your bias: What are your experiences? How do you use models? How do you use data to come up with an answer? The SHAC process says that you are not acting as yourself, but you are acting to represent the whole community: all different viewpoints that might be brought together. So, in level one, what would happen is that you would go through and doing the review of every study that has been done for that site: is it relevant for
that particular site? You would compile them, and you would appropriately rate them. But in cases where models have not been done or you feel that epistemic uncertainty has not been carried out to the extent that it captures the center and the body of the range, then you would have to go out and do that. So, yes, streamlining as far as possible, you would definitely use that

**Question:**

I'm interested in clarification on expert elicitation and level two and where that comes in between levels 2 & 3. How do you start weighting parameters and models at the level two process with expert elicitation either internally or externally?

**Response:**

My understanding is that when you weight these models, the committee goes through an appropriately weighted phase and one thing that can help there is that if we can have Bayesian model averaging to show that there are some models which perform better under certain circumstances that could be one way of doing it. Traditionally, model weighting has been done as part of this committee.

### 3.3.10 Day 2: Session 2C - Panel Discussions

#### 3.3.10.1 Flood Hazard Assessment Research and Guidance Activities in Partner Agencies

(Session 2C-1, ADAMS Accession No. ML17355A076)

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

3.3.10.1.1 US Army Corps of Engineers, Engineer Research and Development Center, Coastal Hazards Laboratory(CHL), Coastal Hazards Group, Norberto Nadal-Caraballo, Ph.D., and Victor Gonzalez, P.E.
Coastal hazards group
Harbors entrances and structures

Development of probabilistic coastal hazard assessment (PCHA) studies and tools

\[ \text{Risk} = \text{Hazard} \times \text{Exposure} \times \text{Vulnerability} \]

\[ \text{Hazard} = \text{Intensity} \times \text{Probability of Occurrence} \]

Tools
- StormSim: suite of computer scripts for advanced stochastic analyses.
  - PCHA
  - Coastal Hazards Prediction System
  - Monte Carlo Simulation
  - Extreme Value Analysis
  - Stochastic Simulation Technique
  - Coastal Structure Reliability

Results:
- Surge
- Waves
- Wind
- Currents

Statistics:
- Hazard curves
- Storm Recurrence Rate
- Storm Relative Probabilities

- CHS: only national resource for PCHA results and statistics. Supports probabilistic design and risk assessment.
  - Based on regional high-resolution numerical modeling of coastal storms

Coastal hazards group
Harbors entrances and structures

StormSim-CHRP
Coastal Hazards Rapid Prediction

- Provides rapid prediction of coastal hazards for operations and emergency management.
- Uses Gaussian Process Metamodels (GPM) constructed on:
  - CHS high fidelity hurricane-response data
  - Hurricane parameters (latitude, longitude, central pressure deficit, radius of maximum winds, forward speed, heaving)
- Hurricane parameters (for an active storm) are read from NOAA 6-hour update web service and used to predict waves and water levels in seconds.

Example simulation for Hurricane Harvey

Peak water level output
Zoom in and select a point
Get a plot of time series of surge+tide with landfill indicated

Validation:
- Hurricane Harvey
- Advisory 16

Innovative solutions for a safer, better world
StormSim-CHRP
Models and Domain

• Predicts surge or surge+tide for 6427 locations in TX, 829 in LA/MS in 0.1 sec, 1100 in AL/Panhandle

Ongoing Studies

Comprehensive
• Coastal Texas Study (CTXS)
• South Atlantic Study (SACCS)
  ➢ Includes Puerto Rico & USVI

Region Specific
• 1) Metropolitan Washington, DC Coastal Storm Risk Management Feasibility Study
• 2) New Jersey Back Bays Coastal Storm Risk Management Feasibility Study
• 3) Nassau County Back Bays Study
• 4) Passaic River Levee System Tidal Flooding Study
• 5) Mississippi and Atchafalaya Rivers Flood Event and Structure Operations Assessment
• 6) ACCP Vulnerability Mapping Data (Alabama)
3.3.10.1.2 US Army Corps of Engineers, Risk Management Center, John England, Ph.D., P.E., P.H., D.WRE

Hydrologic Hazards for Risk-Informed Dam and Levee Safety
Some Concepts and Progress

John England, Ph.D., P.E., P.H., D.WRE
Hydrologic Hazards Lead Civil Engineer
USACE Risk Management Center

U.S.NRC 3rd PFHA Workshop
05 Dec 2017

Risk-Informed Decision Making (RIDM) for Dam Safety and Hydrologic Hazards

Example Overtopping Portfolio

Hazard curves: reservoir and river stages
Full distributions (unbounded) with uncertainty and expected probability
Data and methods depend on level of study
Hydrologic Hazards for Periodic Assessments: RMC-RFA

- Inflow
  - Volume-based stochastic modeling approach
- Streamflow, historical flood, paleoflood data (inputs from Bulletin 17C)
- Hydrograph shapes
- Flood season
- Initial reservoir level

- Natural Variability
  - Irreducible, function of the natural system
- Knowledge Uncertainty
  - Reducible through further study & measurement
  - Focus in RMC-RFA is on sampling error

Contact: Haden Smith, RMC

Paleoflood Studies for SQRA/IES/DSMS

- Ball Mountain Dam
  - West River, VT
- Garrison Dam
  - Missouri River, ND
- Lookout Point Dam
  - Middle Fork Willamette River, OR
- Stillhouse Hollow Dam
  - Lampasas River, TX

Studies led by Keith Kelson, Justin Pearce
Hydrologic Hazard Analysis IES/DSMS System of Reservoirs: Ingredients

- Extreme Storm Data Collection
  - Spatial/temporal patterns
- Regional Precipitation Frequency Analysis
  - Seasonality
  - Storm typing
  - Stochastic Weather Generation
- Stochastic Rainfall-Runoff Modeling (HEC-WAT)
- Combine with Flow Frequency Curves (HEC-SSP)
- Uncertainty with Expected Probability Curves
3.3.10.1.3 Federal Energy Regulatory Commission (FERC), Office of Energy Projects, Division of Dam Safety & Inspections, Kenneth Fearon, P.E.
SSHAC Seismic Fragility Analysis

- Wanapum Dam on the Mid-Columbia River has a river closure embankment with liquefaction issues.

- A SSHAC fragility analysis is being conducted to evaluate the risk and uncertainty of failure of this dam section.

- Currently the second SSHAC workshop has been held and second Technical Integration team meeting is schedule for early January.

Risk-Informed Decision-Making Program

- Draft Guidelines issued March 2016
  - 4 Policy Guidance Chapters
  - 6 Technical Methodology Chapters

- Two additional RIDM pilots are being conducted in Michigan and California

- Both have hydrology and hydraulics issues.
Risk-Informed Decision-Making Program

- Working on a simplified hydrologic model for our Semi-Quantitative Risk Analysis (Level 2) program.

- This program (still in draft) is intended to provide a somewhat conservative result for flood frequencies out to 0.00001 and greater AEPs.

RIDM Evaluations

- In both pilots, the uncertainties associated with the structures are more likely to influence decisions about the dams than those associated with the hydrologic loading.

- For this reason, further calculation of hydrologic uncertainties are not likely to be useful.

- Each FERC regulated dam is unique, so other situations could require a more rigorous evaluation of uncertainty.
Spillway Flow: 100,000 cfs
Emergency spillway erosion as the result of 12,600 cfs discharge

The Work

- Spillways contract awarded to Kiewit Construction on April 17, 2017
- Interim requirement was to be able to pass service spillway flows by November 1, 2017
- Final completion by November 1, 2018
- Bid amount = $274 million
By November 1, 2017

Replace Service Spillway Chute
Service Spillway Progress

MAY 20: 165 DAYS
JUN 30: 124 DAYS
JUL 30: 94 DAYS
AUG 30: 63 DAYS
SEP 30: 32 DAYS
NOV 1: 0 DAYS

Emergency Spillway

Underground Cut-off Wall
(Secant pile wall)
1,450 ft long
35 - 65 ft deep

A secant pile wall is an underground wall constructed of overlapping structural concrete shafts that are embedded into bedrock at depths of 30 to 50 feet, which will prevent the kind of uphill, or head-cutting, erosion that occurred before the emergency spillway in February.
Summary of Significant Work Items

- 50,000 cy foundation concrete
- 30,000 cy structural concrete
  - 264 concrete slabs
  - 78 wall panels
- 3,000 sy shotcrete
- 340,000 cy RCC
- 220,000 cy rock excavation
- 605 secant piles (still in progress)
Enough concrete to place a 4-foot-wide sidewalk 4 inches deep from Washington, DC to Cheyenne, WY

Summary of Work Effort

- 5 months duration
- Over 1000 construction workers a day at the peak
- Almost $3 million dollars a day over the last 2 months
- $220 to $235 million construction in costs so far
  - That’s a 3-year project anywhere else!
Natural Phenomena Hazards Analysis and Design Criteria for DOE Facilities

Sharon Jasim-Hanif, Ph.D.
U.S. Department of Energy
Office of Nuclear Safety Basis & Facility Design (AU-31)
December 2017

Overview

• DOE NPH Program Summary
• DOE Standard NPH Requirements
• DOE Flood Design Criteria & Guidelines
NPH Program Summary

- **DOE Office:** Office of Nuclear Safety (AU-30)
- **Mission:** Develop & maintain requirements, standards and guidance for DOE facilities (new/existing/owned/leased) exposed to NPHs
- **Driver:** Established through DOE Order (O) 420.1C, Facility Safety
- **Direction & Guidance:** Ensure that SSCs will perform assigned safety functions during and after design basis NPH events; provide requirements and guidance in the use of building codes and voluntary consensus standards
- **How:** Provides assistance, training, communications & support to facilitate effective implementation of DOE’s NPH Requirements to assure public & worker health & safety

DOE NPH Requirements

- **DOE Standard 1020**
- **DOE Handbook 1220**
DOE STD 1020/DOE HDBK 1220
Overview

Section 1. Introduction
Section 2. General Criteria for NPH Design
Section 3. Seismic Design
Section 4. Wind, Tornado, and Hurricane Design
Section 5. Flood, Seiche, and Tsunami Design
Section 6. Lightning Design
Section 7. Precipitation Design
Section 8. Volcanic Eruption Design
Section 9. Evaluation and Modification of SSCs in Existing Facilities
Section 10. Quality Assurance and Peer Review

NPH Analysis & Design
Overview

Non-Nuclear Requirements

Step 1
New Facility: Select Site

Step 2
Establish regulatory requirements for site

Nuclear Hazard Category 1,2,3 Requirements

Step 3
Safety Analyses (DSA)
To identify safety SSCs

Step 4
Common-cause failure & system interaction

Step 5
NPH categorization
Establish performance criteria

Step 6
Design/evaluate identified SSCs ensuring functionality
Flood Design
Criteria & Guidelines

Section 5:
- 5.1 Determine Flood Design Categorization
  - General Approach
  - Return Periods for Design Basis Floods
- 5.2 Perform Site Characterization for Flood-Related Design
  - General Requirements
  - Characterization of Site Hydrological/Meteorological Data
- 5.3 Determine Flood-Related Hazards
- 5.4 Perform Probabilistic Flood Hazard Assessment & Determine Flood Design Parameters
  - Design Basis Flood Level FDC1-2
    - IBC-2015 (II/IV) Requirements
  - Design Basis Flood Level FDC3-5
    - Flood Screening Analysis/Comprehensive Flood Hazard Assessment
    - “Extreme Load” category ACI 349-13 & ANSI/AISC N690-12 criteria
- 5.5 SSC Design & Evaluate of SSCs to Mitigate Flood-Related Hazards

DOE HDBK 1220
(Appendix B)
Probabilistic Flood Hazard Analysis

- B.1 Flood Hazards Overview
- B.2 Probabilistic Framework
  - (Overview, taxonomy of Uncertainties, PFHA Results, Flood Hazard Characterization)
- B.3 Probable Maximum Methods
- B.4 PFHA Goals, Elements and Models
- B.5 PFHA for Riverine Flooding
  - (probabilistic aleatory uncertainty model & probabilistic epistemic uncertainty model)
- B.6 PFHA for Flood Associated with Controlled & Uncontrolled Releases from Dams
  - (events & effects of Dam Failures on downstream releases, hydrologic events-extreme precipitation and dam failure, dam failures caused by seismic events, sunny day failures, evaluation of dam break flooding, probabilistic aleatory uncertainty model & probabilistic epistemic uncertainty model)
- B.7 PFHA for Storm Surge Due to Hurricanes, Tropical Storms & Tropical Depressions
  - (analysis, models, probabilistic aleatory uncertainty model & probabilistic epistemic uncertainty model)
- B.8 PFHA for Flooding Induced by Seiches
  - (models, probabilistic epistemic uncertainty model)
- B.9 PFHA for Flooding Due to Tsunamis
  - (model, probabilistic aleatory uncertainty model, probabilistic epistemic uncertainty model)
- B.10 Potential Flood Damage to SSCs
  - (submergence, hydrostatic loads & hydrodynamic loads)
3.3.10.1.5 Tennessee Valley Authority, Gabriel Miller

Flood Hazard Analyses Update

Gabriel Miller
Hydrologist
Why should we care about flood hazards?

- Risk consists of
  - Loading (Hydrologic hazard curves)
  - System response (Does a dam fail?)
  - Consequences (Life loss, economic, other)

Let’s use Watauga as an example

- PMF overtops dam by 8’
- However, morning glory has never even been used
- What decisions would a 1:1,000-yr overtopping trigger?
- What decisions would a 1:1,000,000,000-yr overtopping trigger?
AEP curve for Watauga @ Elizabethton

- AEP Curve developed using annual maximum streamflow
- Done with HEC-SSP

Large uncertainty at the extremes
Historical observations are highly impactful

Statistics for only controlled years
TVA PFHA System

- For each storm type:
  - Sample a date
  - Sample starting states from the long-term simulation
  - Sample storm depth from rainfall frequency maps/stats
  - Sample a storm template, scale to depth and place randomly
  - Calculate runoff
  - Route flow
  - Capture statistics

Precipitation Inputs

- Observed storms transposed, scaled and placed randomly over the basin.
- Storm split into types
  - Big winter frontal storms (MLC)
  - Summer thunderstorm complexes (MEC)
  - Tropical storm remnants (TSRs)
Bonus of storm Typing

- We are extrapolating to very extreme levels, so reducing uncertainty is very important.
- Separating storm types helps reduce uncertainty a lot, because each storm type is very different.
- At right, is the example of a farmyard. Storms behave in a similar manner.

Our Results

- Likelihood of PMF is REMOTE
- Likelihood of overtopping is REMOTE
- Raising the dam would be a poor risk-reduction measure ($$$$
- Investing elsewhere would reduce more risk (lives)
Boone doesn’t lose control until at least 10" of rainfall

Boone only loses control if Watauga loses control

Framework Documentation

- Our documentation (available upon request)
  - Overview Calculation
  - SOP and User Manual
  - Point Precipitation Frequency Calculation
  - Methods for Preparation of Rainfall Inputs Calculation
  - Technical Documentation Calculation
  - RiverWare Model Calculation

- Peer Review
  - John England: Main driver behind USBR and national flood hazard methods
  - Dr. Jery Steding: Internationally-recognized water statistics expert
  - Review was extremely positive
3.3.10.1.6 Discussion

Question:
I'm very interested in what TVA is doing. You said you're doing very intense precipitation analysis for each watershed. Are you making estimates of the problem maximum precipitation for those, and if so, do you have sufficient data and who's doing that analyses?

Response (Gabe Miller, TVA):
Yes, we have done probable maximum precipitation for all of those. I haven't been involved so much in that part of the project. I know that we've worked with MetStat and MGS a lot for the precipitation part of this work. You might talk to Sean. He has been involved in that a lot, but I haven't I wasn't actually involved in that part of the analysis. [Sean: AWA - Applied Weather Associates].

Question:
Joe Wright here with Reclamation and I have a few questions but the sake of time I'll start with Gabe I've heard a few talks yesterday on paleo flood estimates in the Tennessee Valley and I'm just curious to know how your stochastic event flood model, how the results that you're getting from that compared to those paleo flood numbers. Now I realize you have to run it unregulated but…

Response (Gabe Miller, TVA):
Yes, so that question I can answer. That's something that we still are hoping to analyze. So, we have a lot of that paleo flood information. We have a Naturals model for the Tennessee River. So, the idea is that we will be able to run a lot of our storms through the Naturals model to hopefully
match some of the stages and information from those paleo floods and hopefully that should give us a better sense of how our system is performing and also look at some of those paleo floods. So that's still pending analysis for us but something that we have on the docks to do.

**Question:**

Steve Breithaupt with the NRC. I'm curious: this is again for Gabe. What you're doing is really interesting. So, the question is about your storm templates. Can you describe that a little bit more - about what that includes? Like, I'm particularly interested in multiple peaks, durations… how you included that?

**Response (Gabe Miller, TVA):**

So, we've taken a lot of storms of different durations for the region and we've come up with gridded precipitation sets for those storms and there are some durations… I'm not sure if we're using multiple peaks on some of them, although we are getting the antecedent conditions before that, so those storms that we've looked at are historical maximum storms from those areas and are then transposed and scaled based on kind of the region and the topography over the locations that were interested in.

**Follow-up (Breithaupt):**

So, it's your understanding that it's basically a single peak storm? Is that what you're saying or…

**Response (Gabe Miller, TVA):**

I'm going to let Shaun answer that.

**Response (Shaun Carney, RTI International):**

The basic idea is the largest historical storms that have been run, we took those and analyzed the entire period of the storm. So, some of those are multi peak events that actually occurred historically, or they may be a one bump storm. But the idea is to try to capture the actual variability that's happened historically and in these extreme storms and represent that in the simulation. So, we have a suite of forty different storm templates or something that we can draw from to capture the variability that's happening.

**Follow-up (Breithaupt):**

Is this information going to be when this is going to be released? A website or something…

**Response (Gabe Miller, TVA):**

So, we have a lot of documentation. I don't think we're going to put it on a website, but we do have a lot of documentation and information that we can and are willing to share about it. So, if you want to contact or talk to me or one of us at TVA afterwards we’d be happy to share that information.

**Question (Joe Wright, Reclamation):**

This time I have a question for Ken, but it could be directed to all of you. This involves construction risks and it's something that we wrestle with that at Reclamation and I'm just curious how you
might deal with interim construction risks, in reference to some of the large floods that can occur while the construction site is, so to speak, vulnerable to the more frequent floods?

Response (Ken Fearon, FERC):

I found at Oroville that a lot of effort went into looking at start data for rainfall events and, pretty much, the target was June 1 to November 1. Because historically California doesn’t get rain June 1st to November 1st. So, for this one, and, you know, like it or not, things had to be fixed. And so, we didn't have an option to spend a lot of time and say we're going to do analyses after analysis. I mean it was looked at. Everything was done fast. But that's why it was built the way it was. There was no way you're going to rebuild this entire structure in a couple months. So, you know you have sections that are final you have sections that are going to be replaced.

Response Question (Joe Wright, Reclamation):

Orville might be a bad example or an extreme example there. But what if you have something that spans a three or five-year construction period.

Response (John England, USACE/ Risk Management Center (RMC)):

Now we have those in the Corps of Engineers and, as Joe knows, in Reclamation so I will point to interested folks to the joint publication by Reclamation and the Corps of Engineers Best Practices in Dam and Levee Safety Risk analysis. We have a course that's usually every year with documentation that's periodically updated and one of the sections in that is on construction risk. So, you'll find out if you look on the web and do some searching that one of our facilities in Houston had an embankment exposed; working on essentially a filter blanket during [Hurricane] Harvey. So, the choice in the risk analysis is focusing on what level of cofferdams do you design to protect the particular area of interest. So, there are procedures to do construction risks when you're doing structural modifications for existing dams. It's not a straightforward and there's lots of areas or improvements.

Question (Tom Nicholson, U.S. NRC):

I have a quick question for Victor. I'm very fascinated. You were talking about the probabilistic coastal hazard assessment and you said that you had looked because of Hurricane Harvey at the Galveston district. One of the questions we had of the weather district (we went and actually met with them about a month before that) and the things we were concerned about is that not only do you worry about storm surge, but the accumulation of rainfall. So, the areas in the interior: they referred to it as fresh water flooding as opposed to saltwater flooding. I'm interested in what kind of insights you got before and after that storm with regard to rainfall amounts and flooding due to that, especially the long duration of that hurricane over Houston. What kind of information you have for us on that?

Response (Victor Gonzalez, USACE/CHL):

Well, for the lab it was a big eye-opener and, I know for a fact, that now other branches in the lab, the ones involved in hydrology, are actively engaging in research in this area. That's one of the research areas we want to expand because at some point we need to somehow include precipitation on our hurricane models, but as of now, it's not included.
Question:
Not to pick on you, Victor, but I think you're talking about synthetic storm generation as part of this East Coast risk assessment / risk management process. My recollection is a few years ago people were talking about East Coast tsunamis and I was wondering how tsunamis fit into this risk management picture, if at all.

Response (Victor Gonzalez, USACE/CHL):
No, it's separate. I mean, the forcing, the response that we're looking at is completely different.

Response Question:
I understand the different mechanism. I'm talking more programmatically: who's got the ball? I

Response (Joseph Kanney, U.S. NRC):
NOAA and USGS collaborate to have a tsunami warning system. And then NOAA has developed several tsunami modeling systems.

Question (Joseph Kanney, U.S. NRC):
I have a question for Sharon. You mentioned that your guidance has developed over several years: you're in version 5. As that handbook has evolved and, you group has several projects, like the waste treatment plant, which has been under construction for many years. What happens when you revise your guide to facilities like that that are they're still under construction? At NRC we have this concept of back fit with our licensees: we have to do a cost-benefit analysis to show that changing the standard will have a significant safety benefit before one would go back and look at older facilities or facility you've already made a decision about. How do you handle that?

Response (Sharon Jasim-Hanif, DOE):
So, we have a similar process except that it depends on the contract. So, if a site has a contract: it depends on the year of the design. For example, with this 2016 update, most of our sites have not incorporated the 2016 and they still they have to work within the policy document that are within their contract. So, it is in their interest to use the most updated information out there and I get calls about that. And I provide training on the differences between the previous version of the standard and the updated: what changed. But if it's in their contract to use a 2012 version of the standard they are about to use that.

Question (Joseph Kanney, U.S. NRC):
John one question for you. In the paleo-flood studies that the Corps has done have you guys looked at any other methods other than slack water deposits to determine paleo-stages?

Response (John England, USACE/RMC):
So, the questions are on slackwater. I neglected to highlight that issue. I was relying on some of the talks from yesterday. So, we actually are focusing on non-exceedance: both [non-exceedance and slack water]. The same thing that would happen at Reclamation. Where if you have a strap terrace in Vermont you have a nice stable surface that's of a certain age and you can tell that it
hasn't been exceeded. And then the record between that and, say, some positive evidence of flood is incomplete. So, we try to use both pieces of information. So, it's not just the slack water, but it's those evidence of terraces and longer-term features, maybe eight thousand years in the Ball Mountain case and in the Garrison case a couple thousand years, that the floods haven't reach that. So, there is a limit on the magnitude-frequency relationship.

**Question (Joseph Kanney, U.S. NRC):**

Victor. One question I had for you is with regard to the storm sim tool. Have you thought about getting results from other people's models to enhance what you all have done (thousands of simulations)? But there's also been collectively thousands of simulations done for FEMA studies, for example. Have you contemplated actually going out and getting other people's results to add to yours to give it more statistical power?

**Response (Victor Gonzalez, USACE/CHL):**

Yes, and the coastal hazard system has some results from FEMA studies and wherever we can get those results for further modeling we incorporate them in our database. So, yes, we do actively search for that information for other studies.

**Question:**

Is it available?

**Response (Victor Gonzalez, USACE/CHL):**

It's online so you're free to access the webpage of the coastal hazard systems and you can download the information.

**Comment (Joseph Kanney, U.S. NRC):**

Yes, actually here at NRC we've leveraged some of the information from that database to help in some of some of our reviews.

**Question (Tom Nicholson, U.S. NRC):**

John you had mentioned the extreme storm database collection. Could you tell us the status of that? We know something about it - we actually had a demo about a year ago. The question is what are you doing now with regard to creating the portal and the database so that we can interact with it and then look at a variety of storms? As I understand it, you look at some severe storms and then you ask the question: what is the precipitation distribution associated with that storm and then what was the river responds to that storm? So, if you could give us some insights of where that project is now and how soon that could become available to other federal agencies?

**Response (John England, USACE/RMC):**

The status is easy. The schedule is a challenge. For background I think on my website if you go search there's probably a presentation I gave last year on this. Chuck McWilliams in Omaha district is a meteorologist in charge of our extreme storm database project with folks spread throughout the Corps and they're working now on upload capability. The database has been restructured to look like the National Levee Database. So, for those of you who are familiar with
that you can go online and look at essentially static Maps and download some information. They're essentially grid points - so we'll have essentially this space-time of individual events - like what Gabe was talking about - we're doing the same sort of things and I believe Reclamation has done some similar things with storm patterns and since you store those in a library of the largest ones. Currently, though, the limitation is that it’s internal only, so we've just got the protocol and CAC authentication, so people have the capability to upload that information. I would hazard a guess maybe in 18 months we could hopefully open it up to sharing for others to contribute. So hopefully between then, now and then, we could hopefully have it as an open website, just like the National Levee Database, so people can get the information. Resource issues are always a challenge with that one, sorry to say.

**Question (Ray Schneider, Westinghouse):**

I have a question for Victor. Given the amount of synthetic storms that you can create or have created and the large expanse of areas that you have the ability to basically model storm surge and the various tracking and your ability to do this: Is the intent to develop statistical models to basically come up with the probability of flood surge at various point locations if you need to? To just basically sample all your data - could you put your data with, basically, some kind of a sampling structure with reasonable paths and reasonable locations and at various probabilities of getting certain storm sizes of various types to create something that resembles a synthetic way of creating a probabilistic hazard curve for the coast?

**Response (Victor Gonzalez, USACE/CHL):**

Yes, the answer is just that the selection of storms is done per study and typically those studies get output set at save-points. So, obviously, as we do more areas of the coast we will get coverage over most of the coast of the United States. We will have the ability to do that throughout the Coastline. But, right now, yes you have the ability to create a probabilistic hazard curve based on the probabilities of the synthetic storms for a particular location.

**Follow-up Question:**

And that could just be done basically by sampling using your data in your systems and basically moving stuff around?

**Response (Victor Gonzalez, USACE/CHL):**

And you have to download the data. We're working towards making this a little bit more user friendly and in order to better distribute this. But, yes, you can download the storm and you can download the relative probabilities of the storms and you can download the corresponding response for these storms. So, you have what you need to do sampling.
3.10.2 External Flooding Probabilistic Risk Assessment (PRA): Perspectives on Gaps and Challenges (Session 2C-2, ADAMS Accession No. ML17355A077)

Session Chair: Fernando Ferrante, EPRI

3.10.2.1 US NRC, Office of New Reactors, Division of Site Safety & Environmental Analysis, Chief, Hydrology and Meteorology, Christopher Cook, P.E.

---

**PFHA Panel Discussion on Gaps and Challenges**

Christopher Cook  
Chief, Hydrology & Meteorology  
Office of New Reactors

---

**New Considerations: Presentation of Results at Site**

- Future is certain:
  - 2D hydraulic modeling and inundation mapping is a common technology for non-screened hazards.
  - There are multiple entities with capabilities to perform these rapid assessments.
  - Inundation maps are FEMA standard for communication of flood hazard information (warning time, inundation depth/duration, and recession time).
- Next section: Example from USACE & Hurricane Harvey
  - During a flood event, information gaps will be filled regardless of root cause
  - Info gaps will be filled by media outlets, emergency management agencies, other agencies.
  - Incident modeling & mapping can be done *by you*, *with you*, *for you* or *to you*. 

---

12/05/2017  
2017 PFHA Workshop
Hurricane Harvey: 10-Day Forecast of Inundation from Barker and Addicks Dams

27 Aug 2017 - Hurricane Harvey Inundation

Event Timeline
25 Aug 17 - Reservoirs are empty prior to Hurricane Harvey
28 Aug 17 - Surcharge releases from Addicks and Barker begin
29 Aug 17 - Water begins flowing around north end of Addicks
29 Aug 17 - Releases increase from Addicks and Barker
30 Aug 17 - Addicks and Barker reach peak elevations
03 Sep 17 - Releases decrease from Barker
09 Sep 17 - Releases decrease from Addicks
15 Sep 17 - Surcharge releases end

Presentation released on Sept 4

PFHA Gap/Challenge #1

- Static vs dynamic flood hazard information
  - Previously, CDB was reported as a maximum elevation reported to 0.1 ft.
  - Going forward, flood hazards represented as dynamic inundation maps. These show progression of inundation and key associated effects (e.g., water velocity) over time.
  - How can dynamic inundation maps be used to feed PRA models?
  - What does the nuclear PRA community need and is it what the Civil Eng community is producing?

PFHA Gap/Challenge #2

**BACKGROUND:**
Guidance for screening of upstream dams developed as part of JLD-ISG-2013-01.

- **Figure:** 18,286 dams upstream. Eight of these have a height greater than 250 ft with a max of 491 ft.
- **Figure:** within 500 miles of one NPP (straight line) there are 5,616 dams with a height equal to or greater than 25 ft.
PFHA Gaps and Challenge #2

- Enhanced Screening of Flood Mechanisms
  - LIP impacts every NPP site (e.g. rain falls on every site). Can it be screened?
  - Regardless, other flood mechanisms can safely be screened given site conditions.
  - Active topic in the PRA Standard-Part 8 (flooding) update group.
  - What guidance should be updated or included in SRP updates and related documents?
Regulatory Application of External Flooding PRAs

- To date, external flooding has generally been addressed in risk informed licensing actions by using bounding assessments
  - Sufficiently supports decision making needs for vast majority of licensing actions
  - Provides assurance that risk estimates are bounded
- While full External Flooding PRAs can provide more realistic treatment, the methods must be sufficiently developed to support this realism

Fire PRA Lessons Learned

- Modern Fire PRA process developed and piloted in 2005-2008 timeframe
  - Piloting process was piecemeal
  - Framework for Fire PRA development was sound, but individual components retained substantial conservatism
  - Net effect of individual conservatism resulted in large, unrealistic results
- Regulatory application of Fire PRAs began prior to addressing issues revealed in pilot process, or full understanding of scope and scale of issues
  - Led to inability to support robust decision making process
Key Sources of Conservatism to Address Prior to Widespread Regulatory Application

- Lack of information regarding initiating event frequencies for the ranges of interest in external flooding PRAs
- Physical behavior of flooding phenomena for extreme events
- Treatment of dam failures, including combinations
- Consideration of warning time for some hazards
- Fragility of SSCs during flooding event

How Do We Know We Are Ready?

- Completion of pilot process
  - More than one pilot, addressing all aspects of External Flooding PRA
  - Ability of framework to support development of realistic results in a variety of scenarios
- Alignment of results with operating experience
  - Review accident sequence precursors and compare External Flooding PRA results
  - Comparison of relative risk from other hazards
External Flooding PRA

- Recall, an External Flooding PRA (XFPRA) relies on a number of parts
  - Determine the applicable external flooding hazards to the site
  - Determine the flood parameters for each applicable flood mechanism
  - Develop a flood hazard curve to determine the frequency of the flood parameters
  - Create one or more scenarios that describe relevant portions of the flood hazard curve for each hazard
  - Evaluate the plant response for each scenario with a PRA model and quantify risks associated with each scenario
- So, what gaps and challenges can be found in these steps?
Uncertainty

- Wide uncertainties exist when estimating very low hazard frequencies
  - Paleo data may be helpful in reducing the uncertainty, especially in the $10^{-2}$/yr to $10^{-4}$/yr range
  - Uncertainties below $10^{-4}$/yr will still be large

- Uncertainty combined with cliff-edge effects has the potential to hide significant risk
  - Sensitivity studies can be used to determine if the model results are sensitive to particular aspects of the model, including cliff-edge effects
  - Careful use of scenarios can be used to ensure cliff-edge effects are considered

Hazard Assessment – Dam Failure

- Most dams of interest are regulated by the U.S. Army Corps of Engineers, FERC, or the Bureau of Reclamation
- Up to now, utilities have requested deterministic information from the regulator via the NRC
- Performing a risk assessment for dams not under the control of the utility is challenging
  - The relevant information is not available
  - The government agencies that regulate dams have an agreement that only they will assess the risk of their dams
- A PRA is not treated as security-related information and any risk information from a dam regulator needs to be provided in a form that isn’t tightly controlled
- Potential Solution: partnership with NRC and dam regulators to decide what data can be shared, how to generate it, and how to share it
Human Reliability Analysis (HRA) for XFPRA

- We have an existing framework for HRA for external events, and, in general, this can be applied to external flooding
- External flooding has specific challenges that still need to be addressed (e.g., for actions that take place prior to the arrival of the floodwaters during the warning time)
  - How is the decision made to initiate actions to prepare for the flood (e.g., are the cues subject to interpretation)?
  - What are the failure modes involved in performing the actions (e.g., what are the failure modes of building a sandbag wall)?
  - Under what conditions would Operations not allow personnel to work outside due to personal safety concerns?
- Need to collect operating experience to inform our methods and identify gaps
- Need to understand how the HRA picture might change with correlated hazards (e.g., concurrent high winds and flooding)
External Flood Risk Analysis -- From Probabilistic to Computational Risk Assessment

Zhegang Ma, Ph.D., P.E.

3rd Annual NRC PFHA Research Workshop
Washington DC, December 4-5, 2017

External Flood Risk Analysis – the Need

• External flooding risks are real and could be significant
  – Interrupt offsite power
  – Threaten plant structures and mitigating components
  – Limit plant access
  – Potential for either safety or economic impacts

• External flood risk analysis could be used to
  – Identify plant flood vulnerabilities
  – Provide inputs to risk-informed decision making
  – Evaluate event/condition significance
    AND
  – Protect Public Health and Safety
External Flood Risk Analysis – What We Have and What are Challenges

- What Do We Have?
  - Revised ASME/ANS external flooding PRA standard
  - Existing PRA methodologies (classical ET/FT but adequate)
  - Existing PRA models (internal event, internal flooding...)

- What are Challenges?
  - Hazard analysis: IE frequency, concurrent hazards...
  - Fragility analysis: component failure probabilities with different flood height
  - Plant response modeling:
    - Spatial: location, location, location...
    - Temporal: sequence/human action are time-dependent...
    - Mechanics: flooding effect, multi-physics phenomena...
    - Topology: multi-state vs yes/no, causal links...

External Flood Risk Analysis – From Probabilistic to Computational

- Advancing Probabilistic RA to Computational RA
  - Improve state-of-art PRA model from classic ET/FT model to integrated simulation-based dynamic PRA (or CRA)
  - Enhanced computation capabilities
  - Static -> Dynamic: by adding time element into PRA explicitly
  - Integrated PRA: through simulations
    - Monte Carlo simulation
    - 3-D physical simulations
    - Mechanical simulations

- Potential Roles
  - Stand along analysis tool
  - Supplemental role to support traditional approach
External Flood Risk Analysis – the Path Forward

- Challenges
  - Methodologies (site simulation, 3-D flood simulation, "smart" Monte Carlo simulation for extremely low probability...)
  - Resource (3-D plant modeling and beyond)
  - Uncertainties

- The Road
  - NRC project: local intense precipitation case study
  - DOE/RISMC projects: case studies on external flood, dam, high wind, seismic hazards
  - Selected scenarios -> full PRA model
  - Other external flood mechanisms
  - Concurrent external hazards
  - Able to address multi-unit risks in one integrated analysis

3.3.10.2.5 Westinghouse, Ray Schneider

Perspectives on External Flooding Probabilistic Risk Assessment: Gaps and Challenges
Risk Analyst Perspective

Ray Schneider
Fellow
Westinghouse Electric Company

NRC 3rd Annual Flood Workshop (2017)
Considerations for Constructing an External Flood PRA

- Characterizing the Initiating Event
- Fragility of Flood Protection SSCs/Barriers
- Treatment of Preventive actions and organizational behaviors
- Characterizing the Plant Initial State

Characterizing the Initiating Event

- A single flood hazard curve may mask PRA important parameters
- Flood Hazard Curve is typically considered a singular relationship relating the frequency of exceedance per year that a site can experience a flood > height/elevation, H.
- Hazard Curve is reasonable simplification for design applications but reflect only one dimension of the cumulative impact of multiple similar but independent hazards if they occur
- Lacks information needed to develop an external flood PRA and to evaluate associated hazard risks
Combined Dam Failure / Precipitation Hazard Curve
Developed from Multiple Related Mechanisms

Single curve masks impact of:
- Presence of Pre-Existing Flood Challenges
- Warning Time
- Coexistent Hazards

Impact of Co-existent/correlated Hazards:
- Flood elevation may be impacted by wind induced wave “run-up”:
  - Wind effects may impact human performance.
  - Elevation / run-up effect typically not significant unless associated with hurricane type winds or hazard has cliff edge in vicinity of still water levels.
- Seismic dam failures can have accompanying seismic impact at site:
  - Limit access paths.
  - May impact communication.
  - Reduce equipment availability.
  - Local/on site impact can create distractions.
  - Potential floodwater ingestion into structures through damaged penetrations, structural deformations, etc.

Need for Disaggregated curves can capture the key characteristics of the hazard event
Fragility of Flood Protection SSCs

Fragility understanding generally limited to operating equipment and traditional structures
Flood Risk may be dependent on failure/degradation/leakage of atypically analyzed items (e.g.):

- Penetration seals
- Temporary walls/barriers (inflatable barriers, sand bag walls, etc.) (Quality of barrier installation)
- Small portable, commercial equipment (e.g., sump pumps)
- Seismically induced structural degradation (cracks)

Treatment of Preventive actions and organizational behaviors

Traditional treatment of trained human actions focus on procedural responses with defined cues in an anticipated environment
Plant flood responses can include:

- Organizationally driven flood actions with uncertain trigger points and uncertain resource loads, uncertain flood levels, etc.
- Potential for flood induced “cliff edge” dominated actions
- Consideration of actions within complex environments and unique personnel hazards
- Overall actions that look more like complex PERT diagrams resulting with multiple varying probability end states
Considerations in Characterizing the Plant Initial State

Typical plant PRAs occur with a single plant state and defined plant condition. Success is establishing a defined safe shutdown condition.

Initial plant state is known prior to external flood but, flood may dictate alternate shutdown/operational states

- Success of actions to shutdown and re-configure plant for hazard not guaranteed. Leads to multiple shutdown states with differing degrees of flood protection and possible recovery actions

- Duration considerations may complicate definition of mission time.
  • Time to shutdown and re-configure?
  • Time for flood to recede from site
  • Something else?

- Multi-Unit considerations generally apply

Adds complexity and may require additional guidance

Questions?

Westinghouse
External Flooding PRA: Looking to the Future*

N. Siu
Office of Nuclear Regulatory Research
U.S. Nuclear Regulatory Commission

Panel Discussion:
Integrating Flooding Hazard Information Into NPP PRAs

3rd Annual NRC Probabilistic Flood Hazard Assessment (PFHA) Research Workshop
Rockville, MD; December 4-5, 2017

*The views expressed in this presentation are not necessarily those of the U.S. Nuclear Regulatory Commission

Some Technical Challenges

• Discussed
  – Different approaches for spectrum of contributors
    • “Unlikely confluence of likely events”
    • Mega-events
  – Searching for problem scenarios
  – Mechanistic analysis
    • Human and organizational behavior
    • Dynamics
      – Long-term changes in hazard
      – Macro-scenario (warning, plant response, hazard buildup, ...)
      – On-site effects (2D time series for elevation)
    • Additional hazards (beyond inundation, beyond flooding)

• In addition...
  – Improved screening
  – Multi-unit, multi-site
An Improving Situation

- Recognition of potential importance
  - “Other” external hazards => full attention
  - PRA standard update
- Broad interest
  - Multiple agencies, international working groups (e.g., OECD/NEA/CSNI Working Group on External Events)
  - Potentially useful methods, models, tools, data, solutions
- Computational technology
  - Scientific simulations including uncertainty: natural language for multidisciplinary analysis, addressing dependencies
  - Knowledge engineering

Cautions/Reminders

- R&D prioritization considerations
  - Need to be purposeful (limited resources) vs. the “Easy Button”
  - Precision of entire risk assessment
  - Balanced use of video
- Limitations of “repurposed” analyses
- PRA uncertainty analysis amplifies typical simulation challenges
  - Input data validity (distributions, correlations)
  - Simulation validity for combinations of parameters
  - Extracting meaning from massive output
  - Treatment of model uncertainty
- “Risk” includes qualitative as well as quantitative information
3.3.10.2.7 Discussion

Question (Tom Nicholson, U.S. NRC):

I'm fascinated to hear from NEI that you are welcoming the concept of a pilot study: you want more than one. So, the question really comes down to: what would be the attributes of the pilot studies chosen? What are you looking specifically for? What would be the objective? For instance, would you want to do a PRA in which you looked at combined events, that Ray brought up and others have brought up? The argument is that it's a systematic disciplined way of looking at events combined events and what is risk significant and what isn't was significant? So, if you can answer that, Victoria and Frances, and other people might want to chime in as well.

Response:

Sure. I think what we want to be doing is doing a pilot with a plant that could represent the full spectrum of events and I think also part of the methodology that we would pilot would need to be some sort of screening process and I think that has to be part of any kind of PRA methodology process and so we'd have to pilot that screening process and make sure that that was robust and practical as well.

Response (John Weglian, EPRI)

I think from my perspective even though we're here at the NRC, we would probably want international participation in pilots to make sure that it's not US-centric. Any guidance that WPRI produces: we are going to be focused internationally as well as domestically.

Question (Joseph Kanney, U.S. NRC):

Since you mentioned the phased mission concept: what I was wondering is how does - when you mentioned that I immediately thought back to Victoria's comment about sort of doing things piecemeal and I was wondering - how do we do phased mission approaches without stepping into the trap of having conservatisms built into each of the different phases that we didn't really notice until we put everything back together?

Response (Nathan Siu, U.S. NRC):

I think those are kind of different issues but the issue with piecemeal had to do with specific phenomena. So, for example heat release rate for a fire or let's say the treatment of detection of fires. There are different pieces that are all the things that need to go into a PRA. And, yes, if you are conservative in each of these pieces you will get a conservative answer unless you've missed something that you haven't included in your model at all. Phased mission simply says I'm going to discretize the scenario into pieces (and of course not to pay attention to the handoffs) so I lead from this part of the scenario to this part of the scenario. There's nothing that forces me to be conservative about that. I may, as a business decision, choose to do that if I don't want to take the time to analyze things to the level of detail that maybe could be done and maybe I want to take a conservative shortcut. But these are things that are done in regular PRAs. It's I think the question of degree and extent, but I really think those are two separate issues. And, Victoria, of course…
Response (Victoria Anderson, NEI):

I think he may be a little closer than that. I mean, when we talked about in fire PRA and the piecemeal approach and the different phenomena: the issue was that they all stacked up on each other as different steps and I think if you take the phased approach you could run into the same kind of danger.

Response: (Nathan Siu, U.S. NRC):

Obviously, your intent would be a realistic analysis and given the resource constraints that you’ve got. But, yes, if you have conservatism at one level of the one phase, it could propagate. In fact, this is one of the problems with the dynamic analyses is when you start getting into the details. If you start making simplifications in part of the analysis you can end up with things that just make no sense whatsoever by the time you get to the end of the analysis. You have operators responding to cues that they aren’t going to see in practice because of the simplifications made earlier. So, there’s a certain degree of detail that has to be taken care of if you’re going to do that kind of analysis.

Question (Moderator Fernando Ferrante, EPRI):

Let me ask the question to Chris. You had an interesting bullet where you said, from the civil engineering community, what does the nuclear engineering community expect to get? And so, we had discussions during this workshop on essentially paleo-flood, how to do coastal surge, what are the different numerical models – L-moments, Bayesian Inference… let me ask, maybe Ray or John or anybody else the question that Chris posed. I mean, we are looking at a different world and different communities here. I think we all do risk assessment, at the end of the day. I haven’t seen anything new under the sun in risk since we said hazard: risk triplets hazards, impacts, consequences and so forth. And so, from somebody who is doing plant analysis and we have several that have done this before, what have you guys heard and what you are looking to see forward to be able to have something useful. You know I always was the person, at some point, until I got more educated, to say just give me that number and tell me what the flood frequency is until I realized it’s not that easy. But what do you guys see moving forward? Ray John, do you want to take a stab at that?

Response (John Weglian, EPRI)

Can you rephrase that in a simple question?

Follow-up:

If you had all the money in the world and all the time in the world and you were going to do a pilot and you have a plan and he said, to the community, to the hydrologic community, tell me something I can use? Given your experience in having seen some of this, what would you hope to see; more than that, are you going to use?

Response (John Weglian, EPRI)

I see multiple parts that need to feed in to get to the end goal and the end goal is to assess the risk. The end goal is not to get a CDF number – right. It's to evaluate a plant and understand the risks to the plant so pieces of that are the hazard and different hazards have different
uncertainties. They have different modeling techniques. Simulation may be extremely useful for some and may be less useful for others. So that's the piece: you've got how do you do the assessment of the plant responses? And so, I mentioned the plant walk down. But that's one way to assess that. Right now, for barrier fragilities for example, typically we assume kind of a go/no-go - the water level gets to this high on the door and we assume the door fails. There's a there's a more nuanced approach to that that may or may not change your risk insights. So, you don't want to just put in a fragility which greatly complicates your analysis just to have it in there when the risk insights would be the same otherwise. Then once you've got your model for all your different hazards - I envision if you're at a site and you have three applicable hazards that didn't screen, you would effectively have three separate external flooding models that you could run independently of each other because they may have completely different site impacts. That's how I see it being put together. You might get risk insights from one floating mechanism and not another. So, at the end of the day you have to look at your total package and what do you learn from it? One thing I want to address: so, I mentioned before - do the risk insights change and one of the concerns that that I have with the SHAC-F process is – is it going to give you a different answer? If it cost five million dollars to do a site-specific SHAC-F and it costs a hundred thousand dollars to do the equivalent of a level one that you just do in-house with you someone else doing a peer review for you and you don't get a different risk insight at the end of the day. If it doesn't change any of your decisions that you would make - you wasted the money if you did the five million dollars thing. So, we need to understand what's the benefit of doing all these extra things? And that might also be site-specific. It might be that at this site it's not going to change the answer enough to make further refinement of the analysis worthwhile and at another site it might be completely worthwhile because cliff-edge effects, or whatever. That it's extremely important that we understand the cascade of events that happen there.

Response (Ray Schneider, Westinghouse):

I'd like to take it from you. I think the question you were kind of asking is: what are we getting from the hydrologic community in terms of what we need? I think that the thing is that when you develop the hazard curves in a number of instances you're actually developing a series of curves that you basically are putting this on one another which have different characteristics. And so, for the events I have, again, different levels of run-up because you have different wind velocities or wind speeds. You may have different accumulation rates or information like that that may be relevant in, basically, dealing with downstream work and PRA, like human factors or something. So, if there's assumptions you're making that that would likely affect how that event is actually proceeding, not so much just this total elevation. And, say, well, I have a 10^5 110 foot flood, or something like that, but there's information that goes along with that that created that that may be made up of five or six different types of floods and have different characteristics. That would be of used in developing the initiating event that basically drives the rest of the model because without that it's really hard to really understand the pieces that are going to follow. And this mainly comes, in my instance, from dam breaks, dam events: you can have early releases, you could have random failures of the dam, or you could have catastrophic failures: I mean with the full-on, totally catastrophic overtopping kind of failures and as a result of that they all go into the same curve: but every one of those is a different event. And so, we just have to be careful that if you want us to view it as one event, where one kind of event with all of the same characteristics, then that's fine. But if there really are multiple different events in it: somehow you have to figure out a way of communicating that information to the people downstream.
Response (Nathan Siu, U.S. NRC):

I know John has a question but I'm going to jump in. The part about insights - of course who would argue about the importance of insights. But I also want to say that insights aren't necessary the only metric and the only reason why one does something. You obviously have to have confidence in the results of the study. You have to believe the insights have sufficient basis and if this expensive process gives you that increased confidence, and that's an if, then you could say that might be worth doing even if in the end you don't get the a very different answer. And of course, the classic example people have these jokes about HRA and the various calculator used for HRA which are totally random. But would you indeed base a safety decision on that - even if you had some belief that you were going to end up with a number that kind of was similar to what the HRA might produce - I don't think so. The other thing of course is that insights are very dependent on the purpose of the analysis. So, a level one study you get certain kind of insights, a level two study may give different insights. I think a lot of times in PRA we do these game-over modeling assumptions and say, look, I know this is going to failure so I'm not going to model it anymore and that's fine for the purpose of analysis. But you're not going to gain any insights, perhaps, about what people might do after you reach that particular point. So, helping operators, perhaps, respond to the event in this extreme situation- you're not going to get that insight. So, it might be worthwhile pursuing with a more detailed model. But again, it depends on the purpose of the study.

Comments (John England, USACE):

I don't have a question. I just have a whole page full of comments, so I'll keep it brief. For those who haven't - who missed my presentation 2013, we started flood hazard analysis at Reclamation when I walked in there in 1997 and we've gone through an inventory of 350 dams and made major decisions on those facilities. So that one key difference I came up with earlier was Reclamation, which I can't speak for, but I can speak for the Corps of Engineers: we're self-regulating. So, we use risk to prioritize limited funds across portfolios. So, you can rack and stack when you only have 40 plants, all potential failure modes (PFMs), for those individual plants which may add up to our matrix of the number of facilities we have. But we've made structural decision modifications on those facilities based on these hazard curves, so I encourage you to look at some of those reports and what's behind them because besides water levels we have durations, which are the key triggers for things like Orville, which Ken Fearon presented. I think one of the barriers: two of them. One is the industry's lack of moving toward PRA in the first place for floods - which I think Reclamation led 20 years ago - is now upon us. You've seen all the things talking about that. But the pieces you've been missing with this panel and that we've experienced over the years is the integration of the hazard folks with response folks - so you can target specific hazard curves for those things like duration for the spillage of the cracks in that joint in Orville which drives - that is totally duration driven issue - and you can quantify that. It's very easily done. And as far as uncertainty is concerned we've provided - I think Joe Wright mentioned this earlier - what uncertainties do you or what level of confidence do you want? So, for various water levels we have full uncertainty but they're full uncertainty. So, if you want to choose conditional non-exceedance probability at 97 a half % or 84% we have that information in there. So, I think there's a disconnect in terms of at least what I'm hearing here is the usage of that information in the PRA process and structuring of individual decisions on event trees.

Comments (Moderator Fernando Ferrante, EPRI):

John can I comment on that before you continue. So, I think one of the things that it's interesting that you bring up is and this is the kind of the different communities coming together. I mean I
can't speak for the NRC, of course, anymore, but risk is tremendously used within the NRC or risk management. So, I understand your point. I mean it is used right now in terms of if a piece of equipment is out of service, how you rank whatever actions you might need to take with that. It's used for risk ranking on all the important components. It is used for risk ranking on fire protection. So, I think there is a framework in the nuclear world. When it comes to flooding is where we're kind of... I can speak because I took the training at the Bureau when you were there, and I was very impressed with a framework insight. I can see putting aside the two frameworks and then saying okay how do we come together when flooding is the topic? And what is it that can be cross-pollinated given the requirements that you need to have for a nuclear grade PRA with flooding hazard within that. So, I fully hear you. I think nuclear risk has gone very far. I think the consequence is there. I think there's a gap presented here. I mean we do go to consequence analysis, radiological consequence analysis. Our models are – they tend to become surrogates because they stop a core damage. NRC is doing a level three which is when you take it all the way from the beginning to the end. I think your point is fully well taken. I think the question is for flooding is where some gaps are. And then how do we bring this community. For example, if somebody were to do a very detailed NPRA and they get all the sequences, now how do we give it to Ray or somebody within the utility who have millions of cutsets coming up of other things and now they have to prioritize that information and put it... so I ask the question because I had a question in hidden in my mind which was the narrowing of the information so somebody within the nuclear plant response (let me put it that way so we don't divide people in PRA bends) uses that in some manner. I don't know if that aligns with your comment in a way.

Comments (John England, USACE):

I'm looking at my former coworker here. If the integration, so when the report is producing you get that report. It's like back to Chris's point about visualization – we completely agree on that. I don't have anything profound standard for visualization which we need more of. Because we have found over the years that we produce a report. Then engineers in response get it two years or five years later and they don't have questions about it. So, then it's an integration and part of the PRA process, as you probably already have facilitated, to integrate that information collectively and then ask for additional key information when you need it because there's gaps all along the way. The other thing I could comment on - back to case histories - I'll put Joe Wright on the spot here because, at least when I was at Reclamation, we modified facilities. Meaning we use taxpayer money to improve them and reduce risk (structural). Some cases in the Corps now we're doing non-structural solutions. So, having a library of which facilities you've gone through on fire hazard protection or maybe some seismic retrofit and gone through, so you can holistically start to use that as a screening process to gain information might be useful.

Question (Joe Wright, Reclamation):

My question is a little unrelated, a little different. My question kind of goes back to John Weglian. I heard you mentioned a couple of times dealing with non-stationarity and this was something that we wrestled with quite a bit in Reclamation. I just thought since everyone's here I might open this up for some discussion on how we might deal with non-stationarity. One method that we have at Reclamation and are comfortable using is the fact that we review our facilities every eight years, we see the non-stationarity problem kind of taking care of itself within that process. But that doesn't address any kind of final design or corrective action type fixes where we’re going to make a decision based on the non-stationarity of a project. I'm just worried that sometimes when I hear of these decisions. Are we taking a step backwards from risk-based decision making and going back to the old deterministic PMF type problem? Any thoughts?
Response (Victoria Anderson, NEI):

I'm actually going to break in before John. We don't do risk-based regulation at all. It's all risk-informed meaning that we're never abandoning the first deterministic principles in the first place so that's something that shouldn't be an issue.

Response (John Weglian, EPRI):

In terms of how you update there's kind of two pieces of that. So, PRA models typically get updated every two fuel cycles. So, every three to four years you do a re-evaluation of your data and I would imagine with external flooding you would be looking at that. I know EPRI has activity underway that looks at new information for external hazards and see does that fundamentally challenge the existing base of information. Hurricane Harvey was an example. They looked at that event and said does this challenge our PMP analyses and things like that right. So, there's this process in place that looks to see is there new information that we need to consider right now, is it information that we add to the database that you include over time. As an industry we are looking for those kinds of things. I would say the potential problem with relying on the recent change in data: you're getting what is the non-stationarity of the one in ten-year type events. Maybe you have no idea how that's affecting the one in a million which you really had no idea anyway because your uncertainties were so large. I think when you're looking at that range the only way to really handle it, with these uncertainties, is with sensitivity studies. You do a sensitivity study and say: what if I was wrong by a lot? I don't know what a lot is: is a lot 20%, is a lot 50%? I don’t know. But you do an assessment there and you know if I was off by a lot does the answer fundamentally change or not and if it's effectively the same risk insights. Then you feel confident that your model is giving you good risk insights. If it is fundamentally different now you might want to look at why is it different. Where does that come from? Is it a particular cliff edge effect and if it is maybe I want to focus on that and try to understand what I can do to reduce that impact on my client.

Question:

If you have limited resources, what problem will you tackle first? Which problems are really bugging you as other industry, NRC or NEI or EPRI?

Response (John Weglian, EPRI):

Everybody's got limited resources right, so everybody has that problem. I think it's probably site-specific. I think we have in most cases a decent path forward on the hazard risk assessment. We saw a lot of work today on that, so I think we have a good path forward there. I would focus the efforts on how to build the PRA model with what we have and identify is there something out there that's missing that we need to invest in more research to address that issue.

Response (Christopher Cook, U.S. NRC)

I guess from my standpoint at the NRC about 10 years and I was working for about five years before as a contractor. I think if I look at that 15-year period and I look at where we are today both of my gaps are more: how do we bring these roles together? That's what John was getting at with Joe; in some ways, as Victoria mentioned, getting on with pilots. It's taking what we have: it's what this workshop is about, what everyone has been doing for the past several years on this and now looking to the future. We're looking at how we direct it going forward taking what we have and then actually using it to keep it going then those studies.
3.3.11 Day 2: Session 2D - Future Work in PFHA

Session Chair: Mark Fuhrmann, NRC/RES/DRA/FXHAB

3.3.11.1 Future Work in PFHA at EPRI John Weglian*, EPRI (Session 2D-1; ADAMS Accession No. ML17355A078)

3.3.11.1.1 Presentation

Future Work in PFHA at EPRI

John E. Weglian
Senior Technical Leader
3rd NRC External Flooding Research Workshop
December 4-5, 2017

Near-Term EPRI External Flooding Research

- Collection of paleoflood evidence
  - Report at end of 2017
- Use of paleoflood data in risk-informed approaches
  - Research in 2017-2018
- Estimation of frequency of hurricane-driven storm surge
  - Research in 2017
- Guidance on conducting PRA external flooding walkdowns
  - Research in 2017
External Flooding PRA Walkdown Guidance

- External flooding walkdowns for deterministic flood analyses (such as for answering the 50.54(f) letter) may not be sufficient for an external flooding PRA
- EPRI will develop a guidance document for conducting a walkdown to support an external flooding PRA
- This guidance will help utilities use the results of a PFHA to assess the impact on the site from the external flooding hazards

Paleoflood Data

- Paleoflood data has the potential to inform the flood-frequency curve in the $10^{-2}$/yr to $10^{-4}$/yr range
- Process involves:
  - Finding paleoflood evidence
  - Interpreting the evidence to estimate flood stage or discharge and date for each flood
  - Confirming that the conditions at the time of the floods were applicable to the current conditions
  - Estimate the flood parameters of interest at the site
  - Adjusting the flood-frequency curve based on the applicable data
- EPRI is publishing a report on the paleoflood evidence in 2017 – EPRI ID: 3002010667
- EPRI is prioritizing research on the other aspects of using paleoflood data
Hurricane-Driven Storm Surge

- EPRI is conducting research on the use of simulations of hurricane parameters to estimate the storm surge at a given site
- Research on this topic is expected to be complete in 2018

External Flooding PRA Walkdown Guidance

- EPRI is developing draft guidance for performing external flooding PRA walkdowns
- EPRI plans to pilot the guidance at one or more sites in 2018
- EPRI would then incorporate the lessons learned from the pilot site(s) before issuing the final guidance as a Technical Report
Potential Long-Term External Flooding Research

- Seiche and tsunami frequency estimation
  - Leverage existing international research
- Dam failure
  - Possible coordination with NRC working with dam regulators
- Correlated hazards (e.g., storm surge and wind)
  - Research would investigate whether a simple correlation (e.g., match the $10^{-4}$/yr winds with the $10^{-4}$/yr storm surge) is sufficient
- Flood barrier fragility
  - Current flooding PRAs treat flood barrier success deterministically (e.g., a door fails at a particular height)
  - Additional methods and data may provide a better estimation for barrier fragilities

Together...Shaping the Future of Electricity

John E. Weglian  
Senior Technical Leader  
jweglian@epri.com  
704-595-2763

Hasan Charkas  
Senior Technical Leader  
hcharkas@epri.com  
704-595-2645
3.3.11.1.2 Questions and Answers

Question:
I think a side benefit of doing a fragility analysis will be bringing this into the PRA model and as a parameter that can then be addressed with importance measures.

Response:
There’re additional benefits to including that: you can make it an element in your online risk assessment and when you do maintenance and you've got the door propped open you can actually fail that directly and see exactly what that impact is. If you do that for every door in the plant, you've greatly complicated the model, and you may have made it unquantifiable in a reasonable amount of time. So, you need to look at the balance: where does it make sense to do that… where does it not make sense. And I would imagine that you probably wind up with a mixture. Here are my most important doors and I'm going to treat those with the fragility and the others I'm going to treat deterministically.

Question:
You mentioned tsunamis. This workshop didn't focus on tsunamis but I'm sure you're aware the NRC's produced some recent NUREG reports on tsunamis especially for the East Coast of the United States. Are you guys reviewing those?

Response:
I'll have to look at that. I've been a little busy.

Question:
On your storm surge research, is the work that you're doing now for a single site or is it regional?

Response:
It's based on work that was done for a particular site, but the guidance should be general.
3.3.11.2 *Future Work in PFHA at NRC* Joseph Kanney, Ph.D., Meredith Carr*, Ph.D., P.E., Thomas Aird, Elena Yegorova, Ph.D., and Mark Fuhrmann, Ph.D., Fire and External Hazards Analysis Branch, Division of Risk Analysis; and Jacob Philip, P.E., Division of Engineering, Structural, Geotechnical and Seismic Engineering Branch, Office of Regulatory Research, U.S. NRC (Session 2D-2; ADAMS Accession No. ML17355A079)

3.3.11.2.1 *Presentation*
Expected NUREG/CR Completions in FY18

- Guidance on Application of State-of-Practice Flood Frequency Analysis Methods and Tools (USGS)
- Technical Basis for Extending Frequency Analysis Beyond Current Consensus Limits (USBR)
- Research to Develop Guidance on Extreme Precipitation Frequency in Orographic Regions (USBR)
- Technical Basis for Probabilistic Flood Hazard Assessment – Riverine Flooding (PNNL)
- Quantifying Uncertainties in Probabilistic Storm Surge Models (USACE)
- Effects of Environmental Factors on Manual Actions for Flood Protection and Mitigation at NPPs (PNNL)
- Modeling Plant Response to Flooding Events (INL)
- Regional Climate Change Projections: Potential Impacts to Nuclear Facilities (PNNL)

External Hazard Information Digest (INL)

- Flood hazard population expected complete FY18-Q2
- Expansion to support Process for Ongoing Assessment of Natural Hazard Information (SECY-16-0144; SRM-SECY-16-0144):
  - Tool for collecting, aggregating, reviewing, and assessing information on an ongoing basis
  - Other Hazards
    - Expanded flooding content
    - High Winds
    - Extreme Temp/humidity
    - Seismic
FY18 – New External Projects and Internal Initiatives

Critical Review of Dam Risk Assessment State of Practice

- David Watson, Scott DeNeale, Brennan Smith & Shih-Chieh Kao (ORNL)
- Gregory Baecher (University of Maryland)
  - NRC PM: Carr
  - Project Timeline: Sept 2017 to Apr 2019

Objective
Develop technical basis for guidance on application of state-of-the-practice approaches, methods and tools for dam risk analysis to inform assessment of flood hazards due to dam failure.

Scope
Assess methods for characterizing and quantifying key uncertainties, as well as propagating these uncertainties through the risk analysis procedure to support risk-informed decision-making.
Critical Review of Dam Risk Assessment State of Practice

Key Tasks

- Conduct workshop with federal agencies, academic researchers and private industry to review current state of practice in dam risk analysis.
- Summarize current state of practice with focus on development of fragility information for:
  - key components
  - control systems
  - operational procedures
- Review key process uncertainties, their characterization, and the degree to which they are propagated in state of practice approaches.

Application of Point Precipitation Frequency Estimates to Watersheds

- Shih-Chieh Kao, Scott DeNeale (ORNL)
  - NRC PM: Yegorova

- Project Timeline: Oct 2017 to May 2019
- Current precipitation frequency products (e.g., NOAA Atlas 14) are mostly developed for point rainfall
- Areal reduction factors (ARFs) are needed to convert these point precipitation estimates to watershed estimates for H&H modeling
- ARFs in common use suffer from several key deficiencies:
  - Limited/obtained data
  - Small area sizes (up to 400-mi²)
  - Do not vary with location, return period, or season
Application of Point Precipitation Frequency Estimates to Watersheds

Project Objectives

- Provide a summary of available precipitation products that can be used to develop point to area conversions of precipitation frequency estimates.
- Provide a critical review of available point to area conversion methods with a view to addressing the deficiencies in the commonly used empirical methods.
- Demonstrate use of the most promising method/dataset combinations through selected test cases.
- Support the development of future PFHA guidance on ARF

Interfacing Flood Hazard Modeling Outputs with HRA and PRA Models

- Integrate flood hazard into existing models
- Determine important scenarios
- Handle time dependencies (phasing)
- Internal Collaboration
Projected FY19-20 Work*

* Subject to availability of funding

Probabilistic Treatment of Coincident and Correlated Hazards and Their Effects
Application of SHAC-F to Coastal Flooding Hazard Assessments

Quantifying Uncertainties in Probabilistic Riverine Flood Models

Contributions to model parameters to uncertainty in model predictions: Fan et al. 2015
Draft Regulatory Guidance

Pilot Studies

[Diagram showing flowchart and data analysis]

3-387
3.3.11.2.2 Questions and Answers

Question:

The interface between the hazard and the PRA model... are you working on this in 2017-2018 or I couldn't catch?

Response:

We've started internal discussions within our office to try to get an idea what's going on and we're starting to spread that out to other offices. We'd like to get collaboration because it's such an issue that we want to make sure people from all the different fields get involved before we come out with some sort of hazard guidance that doesn't fill the needs of PRA.

Question:

So, this is budgeted basically?

Response:

Yes. But there's no specific external funding

3.3.12 Day 2: Final Wrap-up Session / Public Comment

Question:

I've mentioned to a couple people this idea: the nuclear industry has a database of component failures and I've noticed the dam industry does not have such a system but a lot of dams, independently, keep track of component issues that they have... is there a way we could leverage the nuclear industry's set-up for the dam industry as well?

Response

(Joe Kanney, NRC): I actually had an inquiry from Marty McCann about this probably at least two years ago. I told him about what the structure is in the nuclear industry, how their organizations, like INPO, collect this information and have databases. I'm not sure where it went after that.
3.4 Summary

This report documents the 3rd Annual NRC Probabilistic Flood Hazard Assessment Research Workshop held at NRC Headquarters in Rockville, MD, on December 4-5, 2017. These proceedings included the following:

• Section 4.2: Workshop Agenda (in the program (ADAMS Accession No. ML17355A081)
• Section 4.3: Proceedings (abstracts at ADAMS Accession No. ML17355A081 and complete workshop presentation package including slides and questions and answers at ADAMS Accession No. ML17355A071)
• Section 4.4: Summary
• Section 4.5: Workshop Participants
3.5 Workshop Participants

Thomas Aird\textsuperscript{SC, C}
General Engineer
U.S. NRC/RES/DRA/FXHAB
thomas.aird@nrc.gov

Victoria Anderson\textsuperscript{P}
Technical Advisor
NEI
vka@nei.org

John Antignano\textsuperscript{R}
Managing Director
Nuvia USA
john.antignano@nuvia-usa.com

William Asquith\textsuperscript{R}
Research Hydrologist
U.S. Geological Survey
wasquith@usgs.gov

Greg Baecher
Professor of Engineering
University of Maryland
gbaecher@mac.com

Victoria Sankovich Bahls\textsuperscript{R}
Project Manager and Senior Hydrometeorologist
MetStat, Inc.
vbahls@metstat.com

James Barbis
Senior Water Resource Engineer
Wood
James.barbis@woodplc.com

Joseph Bellini\textsuperscript{R}
Vice President - Principal Water Resources Eng.
Aterra Solutions
joe.bellini@aterrasolutions.com

Christopher Bender
Senior Coastal Engineer
Taylor Engineering
cbender@tayloengineering.com

Michelle Bensi
Assistant Professor
University of Maryland
mbensi@umd.edu

Paul Boulden\textsuperscript{R}
President
Appendix R Solutions, Inc.
paulboulden@ars-corp.net

David Bowles
Managing Principal & Professor Emeritus
RAC Engineers and Economists, LLC & Utah State University
David.S.Bowles@hotmail.com

Stephen Breithaupt
Hydrologist
U.S. NRC/NRO/DSEA
Stephen.Breithaupt@nrc.gov

Robert Budnitz\textsuperscript{R}
Scientist
Lawrence Berkeley National Laboratory
RJBudnitz@lbl.gov

Andy Campbell
Deputy Director, DSEA
U.S. NRC/NRO/DSEA
Andy.Campbell@nrc.gov

Karen Carboni\textsuperscript{R}
Program Manager
Tennessee Valley Authority
kcarboni@tva.gov

Shaun Carney
Senior Water Resources Engineer
RTI International
scarney@rti.org

Meredith Carr\textsuperscript{S, SC, C}
Hydrologist
U.S. NRC/RES/DRA/FXHAB
meredith.carr@nrc.gov

---

\textsuperscript{S – Speaker; P – Panelist, SC – Session Chair, C – Organizing Committee, R – Remote, RS – Remote Speaker}
Yung Hsien Chang
Human Reliability Engineer
U.S. NRC/RES/DRA/HFRB
James.Chang@nrc.gov

Laura Chap
Senior Engineer
Atkins
laura.chap@atkinsglobal.com

Hasan Charkas
Senior Technical Leader
EPRI
hcharkas@epri.com

Yuan Cheng
Hydrologist
U.S. NRC/NRO/DSEA/RHM
yuan.cheng@nrc.gov

Nilesh Chokshi
Consultant
U.S. NRC/NRO/DSEA
nilesh.chokshi@nrc.gov

Young-Sun Choun
Principal Research Engineer
Korea Atomic Energy Research Institute
sunchun@kaeri.re.kr

Jon Clark
Project Manager
Amec Foster Wheeler
jon.clark@amecfw.com

Leremy Colf
Director of Disaster Science
Department of Health and Human Services
Assistant Secretary for Preparedness and Response
leremy.colf@hhs.gov

Christopher Cook
Chief, Hydrology and Meteorology Branch
U.S. NRC/NRO/DSEA/RHM
christopher.cook@nrc.gov

Kevin Coppersmith
President
Coppersmith Consulting
kevin@coppersmithconsulting.com

William Cummings
Principal Engineer
Fire Risk Management
wmark@fireriskmgmt.com

Biswajit Dasgupta
Staff Engineer
Center for Nuclear Waste Regulatory Analyses / SwRI
biswajit.dagupta@swri.org

Mary Alice Lisa Davis
Associate Professor
University of Alabama, Dept. of Geography
lisa.davis@ua.edu

Gerald (Jay) Day
Senior Director
Water Resources Management Division, RTI International
gday@rti.org

Scott DeNeale
Water Resources Engineer
Oak Ridge National Laboratory
denealest@ornl.gov

Stephanie Devlin-Gill
DSEA Technical Assistant
U.S. NRC/NRO/DSEA
Stephanie.Devlin-Gill@nrc.gov

Alain Dib
Postdoctoral Scholar
University of California, Davis
aedib@ucdavis.edu

Kevin Dobbs
Visiting Scientist
NGA
kevindobbsfr@gmail.com

Adrienne Driver
Reliability and Risk Analyst
U.S. NRC/NRR/DRA
Adrienne.Driver@nrc.gov
John England, Jr.  
Lead Civil Engineer  
U.S. Army Corps of Engineers, Risk Management Center  
john.f.england@usace.army.mil

J. Christopher Ey  
Senior Professional Associate  
HDR  
chris.ey@hdrinc.com

Kenneth Fearon  
Deputy Director, Division of Dam Safety and Inspections  
Federal Energy Regulatory Commission  
kenneth.fearon@ferc.gov

Fernando Ferrante  
Principal Technical Leader  
Electric Power Research Institute  
FFerrante@EPRI.com

Mark Fuhrmann  
Geochemist  
U.S. NRC/RES/DRA/FXHAB  
mark.fuhrmann@nrc.gov

Amitava Ghosh  
Geotechnical Engineer  
U.S. NRC/NRO/DSEA/RPAC  
amitava.ghosh@nrc.gov

Joseph Giacinto  
Hydrologist  
U.S. NRC/NRO  
joseph.giacinto@nrc.gov

Jason Giovannettone  
President  
HydroMetriks  
jpgiovannettone@hydrometriks.com

Jeanne Godaire  
Supervisory Geologist  
U.S. Bureau of Reclamation  
jgodaire@usbr.gov

Felix Gonzalez  
Reliability and Risk Engineer  
U.S. NRC/RES/DRA/FXHAB  
felix.gonzalez@nrc.gov

Victor Gonzalez  
Research Civil Engineer  
U.S. Army Engineer Research and Development Center Coastal and Hydraulics Laboratory  
victor.m.gonzalez@usace.army.mil

Orli Gottlieb  
Engineer II  
Alden Research Laboratory  
ogottlieb@aldenlab.com

Kevin Griebenow  
Civil Engineer  
FERC  
kevin.griebenow@ferc.gov

Eric Gross  
Senior Civil Engineer  
FERC  
eric.gross@ferc.gov

Justin Habit  
Intern  
USDA - NRCS  
justin.habit@wdc.usda.gov

Kenneth Hamburger  
Fire Engineer  
U.S. NRC/RES/DRA/FXHAB  
Kenneth.Hamburger@nrc.gov

Tess Harden  
Hydrologist  
U.S. Geological Survey  
tharden@usgs.gov

Donnie Harrison  
Senior Level Advisor for Risk Assessment  
U.S. NRC/NMSS  
Donnie.Harrison@nrc.gov

Brad Harvey  
Team Lead, Meteorology Team  
U.S. NRC/NRO/DSEA/RHM/RMET  
brad.harvey@nrc.gov

Lyle Hibler  
Hydrologist  
U.S. NRC/NRO/DSEA  
lyle.hibler@nrc.gov
L. Ruby Leung\[^S\]
Battelle Fellow
Pacific Northwest National Laboratory
ruby.leung@pnnl.gov

Marc Levitan\[^R\]
Acting Director, NWIRP
NIST
marc.levitan@nist.gov

Rachel Lombardi
Graduate Research Assistant
University of Alabama
rlombardi@crimson.ua.edu

David Lord\[^R\]
Senior Civil Engineer
FERC
dwlord101@gmail.com

Zhegang Ma\[^P\]
Lead Risk Analysis Engineer
Idaho National Laboratory
zhegang.ma@inl.gov

Pathmathevan Mahadevan
Civil Engineer
FERC - Dam Safety Division
devan.mahadevan@ferc.gov

Kelly Mahoney\[^R\]
Meteorologist
NOAA Earth System Research Lab Physical Sciences Division
kelly.mahoney@noaa.gov

Debbie Martin\[^R\]
Project Manager and Senior Hydro meteorologist
MetStat, Inc.
dmartin@metstat.com

Robert Mason\[^R\]
Extreme Hydrological Events Coordinator
U.S. Geological Survey
rmason@usgs.gov

Michael Mazaika\[^R\]
Physical Scientist (Meteorologist)
U.S. NRC/NRO/DSEA/RHM/RMET
michael.mazaika@nrc.gov

Stephen McDuffie
Seismic Engineer
U.S. Department of Energy
stephen.mcduffie@rl.doe.gov

Fehmida Mesania\[^R\]
Flooding Engineer
Duke Energy
Fehmidakhatun.Mesania@duke-energy.com

Andrew Miller
Senior Engineer
Jensen Hughes
amiller@jensenhughes.com

Gabriel Miller\[^P\]
Hydrologist
Tennessee Valley Authority
gamiller0@tva.gov

Jeffery Mitman
Senior Reliability and Risk Analyst
U.S. NRC/NRR/DRA/APOB
Jeffrey.Mitman@nrc.gov

Michael Mobile\[^R\]
Senior Technical Specialist
GZA.
michael.mobile@gza.com

Mathieu Mure-Ravaud\[^S\]
PhD student
UC-Davis
mmureravaud@ucdavis.edu

Norberto Nadal-Caraballo\[^S, P, R\]
Leader, Coastal Hazards Group
U.S. Army Engineer R&D Center, Coastal and Hydraulics Laboratory
Norberto.C.Nadal-Caraballo@usace.army.mil

Keil Neff\[^S\]
Hydrologic Engineer
Bureau of Reclamation, Technical Service Center, Flood Hydrology & Meteorology
kneff@usbr.gov
Kit Yin Ng  
Chief Engineer  
Bechtel Infrastructure and Power LLC  
kyng@bechtel.com

Thomas Nicholson  
Senior Technical Advisor  
U.S. NRC/RES/DRA  
thomas.nicholson@nrc.gov

Lauren Ning  
Reliability And Risk Engineer  
U.S. NRC/RES/DRA/PRAB  
lauren.ning@nrc.gov

Nicole Novembre  
Chief Hydrologic Engineer  
MetStat, Inc.  
nnovembre@metstat.com

Desta O'Connor  
U.S. Department of Homeland Security  
Desta.OConnor@HQ.DHS.GOV

Tye Parzybok  
President/CEO and Chief Meteorologist  
MetStat, Inc.  
tyep@metstat.com

Sanja Perica  
HDSC Chief  
NOAA/NWS/OWP  
sanja.perica@noaa.gov

Jacob Philip  
Sr. Geotechnical Engineer  
U.S. NRC/RES/DE/SGSEB  
jacob.philip@nrc.gov

Frances Pimentel  
Sr. Project Manager, Risk and Technical Support  
NEI  
fap@nei.org

Rajiv Prasad  
Senior Research Scientist  
Pacific Northwest National Laboratory  
rajiv.prasad@pnnl.gov

Steven Prescott  
PRA Software Engineer  
Idaho National Lab  
Steven.Prescott@inl.gov

Kevin Quinlan  
Physical Scientist  
U.S. NRC/NRO/DSEA  
kevin.quinlan@nrc.gov

John Randall  
U.S. NRC/RES Retired  
JohnRandall2@comcast.net

Mehdi Reisi-Fard  
Reliability and Risk Analyst  
U.S. NRC/NRR/DRA/APLB/RILI  
mehdi.reisifard@nrc.gov

Tammie Rivera  
Reliability And Risk Engineer  
U.S. NRC/RES/DRA/FXHAB  
Tammie.Rivera@nrc.gov

Christina Roy  
NGA Liaison to DHS - FEMA  
National Geospatial-Intelligence Agency  
christina.c.roy.us@gmail.com

Karen Ryberg  
Research Statistician  
U.S. Geological Survey  
kryberg@usgs.gov

MarkHenry Salley  
Branch Chief  
U.S. NRC/RES/DRA/FXHAB  
MarkHenry.Salley@nrc.gov

Periandros Samothrakis  
Engineering Specialist - Hydraulics & Hydrology  
Bechtel Corporation  
psamothr@bechtel.com

Selim Sancaktar  
Reliability and Risk Analyst  
U.S. NRC/RES  
selim.sancaktar@nrc.gov
Raymond Schneider
Fellow
Westinghouse Electric Company
schneire@westinghouse.com

Penny Selman
Sr. Program Manager, Seismic
Tennessee Valley Authority
pbselman@tva.gov

Ken Shelley
Southern Nuclear
klshelly@southernco.com

Nathan Siu
Sr Technical Adviser in PRA
U.S. NRC/RES/DRA
Nathan.Siu@nrc.gov

Brian Skahill
Engineer
USACE Coastal and Hydraulics Laboratory
Hydrologic Systems Branch
Brian.E.Skahill@usace.army.mil

Brennan Smith
Senior Research Scientist/Group Leader
Oak Ridge National Laboratory /Energy-
Water Resources Systems Group
smithbt@ornl.gov

C. Lance Stewart
Graduate Assistant
Murray State University Dept. of
Geosciences
cstewart19@murraystate.edu

Gary Stinchcomb
Assistant Professor
Murray State University Dept. of
Geosciences
gstinchcomb@murraystate.edu

Craig Talbot
Principal Engineering Specialist
Bechtel Corporation
ctalbot@bechtel.com

Robert Taylor
Director, DSEA
U.S. NRC/NRO/DSEA
Robert.Taylor@nrc.gov

Stewart Taylor
Bechtel Fellow
Bechtel Global Corporation
swtaylor@bechtel.com

Keith Tetter
Reliability and Risk Engineer
U.S. NRC
Keith.Tetter@nrc.gov

Jenise Thompson
Geologist
U.S. NRC/NRO/DSEA/RGS
jenise.thompson@nrc.gov

Nebiyu Tiruneh
Hydrologist
U.S. NRC/NRO
nebiyu.tiruneh@nrc.gov

Nicholas Valos
Region 3 Senior Reactor Analyst
U.S. NRC/R-III
nicholas.valos@nrc.gov

Andrew Verdin
Hydrologic Engineer
Bureau of Reclamation
averdin@usbr.gov
Carrie Vuyovich
Engineer
Error! Bookmark not defined. Cold Regions Research and Engineering Laboratory
Carrie.m.vuyovich@usace.army.mil

Tony Wahl
Hydraulic Engineer
USBR
twahl@usbr.gov

Bin Wang
Senior Technical Specialist
GZA GeoEnvironmental, Inc.
bin.wang@gza.com

Weijun Wang
Geotechnical Engineer
U.S. NRC/NRO
weijun.wang@nrc.gov

Z. Gary Wang
Reliability and Risk Engineer
U.S. NRC/RES/DRA/PRB
Zeechung.Wang@nrc.gov

David Watson
Senior Research Scientist
Oak Ridge National Laboratory
watsondb@ornl.gov

David Watson
Project Manager/Flood Engineer
Duke Energy
David-Watson3@duke-energy.com

Michael Weber
Director, Office of Nuclear Regulatory Research
U.S. NRC/RES
Michael.Weber@nrc.gov

John Weglian
Senior Technical Leader
EPRI
jweglian@epri.com

Jason White
Physical Scientist
U.S. NRC/NRO/DSEA/RHM/RMET
Jason.White@nrc.gov

Gordon Wittmeyer
Director of Technical Resources
Center for Nuclear Waste Regulatory Analyses, Southwest Research Institute
gordon.wittmeyer@swri.org

Jeff Wood
Reliability and Risk Analyst
U.S. NRC/RES/DRA/PRAB
jeffery.wood@nrc.gov

Joseph Wright
Supervisory Hydraulic Engineer
U.S. Bureau of Reclamation
jmwright@usbr.gov

David Ziebell
Senior Technical Leader
EPRI
dziebell@epri.com
5 SUMMARY AND CONCLUSIONS

5.1 Summary

This report has presented agendas, presentations and discussion summaries for the first four NRC Annual PFHA Research Workshops (2015-2019). These proceedings include presentation abstracts and slides and a summary of the question and answer sessions. The first workshop was limited to NRC technical staff and management, NRC contractors, and staff from other Federal agencies. The three workshops that followed were meetings attended by members of the public; NRC technical staff, management, and contractors; and staff from other Federal agencies. Public attendees over the course of the workshops included industry groups, industry members, consultants, independent laboratories, academic institutions, and the press. Members of the public were invited to speak at the workshops. The fourth workshop included more invited speakers from the public than from the NRC and the NRC’s contractors.

The proceedings for the second through fourth workshops include all presentation abstracts and slides and submitted posters and panelists’ slides. Workshop organizers took notes and audio recorded the question and answer sessions following each talk, during group panels, and during end of day question and answer session. Responses are not reproduced here verbatim and were generally from the presenter or co-authors. Descriptions of the panel discussions identify the speaker when possible. Questions were taken orally from attendees, on question cards, and over the telephone.

5.2 Conclusions

As reflected in these proceedings PFHA is a very active area of research at NRC and its international counterparts, as well as 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 NRC’s PFHA Research Program. This technical-basis phase is nearly complete, and the NRC has initiated a second phase (pilot project phase) that is a syntheses of 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. NRC staff looks forward to further public engagement regarding the second and third phases of the PFHA research program in future PFHA Research Workshops.
ACKNOWLEDGEMENTS

These workshops were planned and executed by an organizing committee in the U.S. Nuclear Regulatory Commission’s (NRC’s) Office of Nuclear Regulatory Research (RES), Division of Risk Analysis, Fire and External Hazards Analysis Branch, and with the assistance of many NRC staff.

Organizing Committees


2nd Workshop, January 23–25, 2017: Co-Chairs: Meredith Carr, Joseph Kanney; Members: Thomas Aird, Thomas Nicholson, Mark Henry Salley; Workshop Facilitator: Kenneth Hamburger


4th Workshop, April 30–May 2, 2019: Co-Chairs: Meredith Carr, Elena Yegorova; Members: Joseph Kanney, Thomas Aird, Mark Fuhrmann, Mark Henry Salley; Workshop Facilitator: Kenneth Hamburger

Many NRC support offices contributed to all of the workshops and these proceedings. The organizing committee would like to highlight the efforts of the RES administrative staff; the RES Program Management, Policy Development and Analysis Branch; and the audiovisual, security, print shop, and editorial staff. The organizers appreciated office and division direction and support from Jennene Littlejohn, William Ott, Mark Henry Salley, Mark Thaggard, Michael Cheok, Richard Correia, Mike Weber, and Ray Furstenau. Michelle Bensi, Mehdi Reisi-Fard, Christopher Cook, and Andrew Campbell provided guidance and support from the NRC Office of New Reactors and the Office of Nuclear Reactor Regulation. The organizers thank the Electric Power Research Institute (EPRI) for assisting with planning, contributions, and organizing several speakers. EPRI personnel who participated in the organization of the workshops include John Weglian, Hasan Charkas, and Marko Randelovic.

During the workshops, Tammie Rivera assisted with planning and organized the registration area during the conference. David Stroup and Don Algama assisted with room organization. Notes were studiously scribed by Mark Fuhrmann, David Stroup, Nebiyu Tiruneh, Michelle Bensi, Hosung Ahn, Gabriel Taylor, Brad Harvey, Kevin Quinlan, Steve Breithaupt, Mike Lee, Jeff Wood, and organizing committee members. The organizers appreciate the assistance during the conference of audiovisual, security, and other support staff. The organizers thank the panelists, the technical presenters, and poster presenters for their contributions; Thomas Aird and Mark Fuhrmann for performing a colleague review of this document; and the Probabilistic Flood Hazard Assessment Research Group for transcript reviews.

Members of the Probabilistic Flood Hazard Assessment Research Group:
Mark Henry Salley (Branch Chief), Joseph Kanney (Technical Lead), Thomas Aird, Meredith Carr, Mark Fuhrmann, Jacob Philip, Elena Yegorova, and Thomas Nicholson (Senior Technical Advisor)
## APPENDIX A: SUBJECT INDEX

17B, Bulletin, 1-48, 1-178, 1-189, 2-36, 2-187, 2-200, 4-215, 4-262, 4-265
17C, Bulletin, 2-36, 2-187, 2-194, 2-244, 3-121, 3-332, 4-163, 4-208, 4-214, 4-220, 4-230, 4-232, 4-236, 4-252, 4-257, 4-261, 4-265, 4-289
2D, 1-34, 3-385, 4-314
model, 1-183, 1-186, 2-52, 2-211, 2-362, 2-367, 2-377, 3-367, 4-202, 4-313, 4-326
CASC2D, 1-151
HEC-RAS. See HEC-RAS
TELEMAC, 4-203, 4-206, 4-328
3D, 4-314
coastal, 4-123
model, 1-252, 1-261, 2-288, 2-295, 2-302, 2-306, 2-393, 3-22, 3-25, 3-199, 3-378, 4-24, 4-126, 4-291
terrain mapping, 1-252
accumulated cyclone energy, ACE, 4-372
ADCIRC, 1-196, 2-78, 2-334, 2-379, 2-403, 4-57, 4-94
AEP, xxxvii, 1-12, 1-17, 1-36, 1-50, 1-54, 1-69, 1-149, 1-166, 1-191, 1-198, 2-22, 2-43, 2-54, 2-154, 2-187, 2-201, 2-204, 2-219, 2-225, 2-270, 2-307, 2-340, 3-15, 3-21, 3-74, 3-97, 3-116, 3-117, 3-132, 3-135, 3-138, 3-337, 3-355, 4-15, 4-60, 4-74, 4-94, 4-120, 4-127, 4-132, 4-194, 4-209, 4-214, 4-253, 4-286, 4-381
drainage area based estimate, 1-69
low AEP, 2-187, 3-117, 3-135
neutral, 1-185
return periods, 1-51
very low AEP, 1-166, 2-187, 3-117, 4-158
AEP4. See distribution: Asymmetric Exponential Power
aleatory uncertainty. See uncertainty, aleatory
American Nuclear Society. See ANS
AMM. See Multi-decadal: Atlantic Meridional Mode
AMO. See Multi-decadal: Atlantic Multi-Decadal Oscillation
AMS. See annual maximum series
ANalysis Of VAriance, ANOVA, 4-201
annual exceedance probability. See AEP
annual maximum series, 1-72, 1-165, 2-155, 2-201, 2-373, 3-75
searching, 4-149
ANS, 3-377, 4-442, 4-452, 4-461, 4-471
areal reduction factor. See ARF
ARF, 1-84, 2-374, 2-383, 2-417, 3-224, 3-401, 4-18, 4-120, 4-133, 4-142, 4-144, 4-149, 4-152, 4-162
averaging, temporal and spatial, 4-148
dynamic scaling model, 4-151
methods, 4-147
empirical, 4-151
test cases, 4-147
arid, 1-61, 2-217, 2-223, 3-163, 3-200, 4-132
semi-, 4-131
ARR. See rainfall-runoff: model: Australian Rainfall and Runoff Model
ASME, American Society of Mechanical Engineers, 4-442
associated effects, 1-12, 1-31, 1-34, 2-43, 3-15, 4-15, 4-31
atmospheric conditions, 1-90
dispersion, 2-16
environment, 2-71
instability, 4-377
interactions, 4-98
moisture, 3-28, 4-125, 4-346, 4-353
parameters, 2-81, 3-111
patterns, 2-85
processes, 3-310
rivers, 1-56, 1-59, 1-162
stability, 4-163
variables, 4-122
at-site, 1-84, 1-180, 2-31, 2-152, 2-155, 2-160, 2-163, 2-188, 2-206, 2-209, 3-70, 3-75, 3-79, 3-84, 3-132, 3-139, 3-310, 3-315, 4-125, 4-137, 4-208, 4-214, 4-264
Australian Rainfall and Runoff Model. See rainfall-runoff: model: Australian Rainfall and Runoff Model
autocorrelation, 3-126
BATEA. See error: Bayesian Total Error Analysis
Bayesian, 2-151, 2-162, 2-165, 2-313, 2-400, 2-402, 3-70, 3-88, 3-93, 3-140, 3-304, 4-163, 4-220, 4-223, 4-229, 4-257, 4-294
analysis, 1-171, 4-308
approach, 1-167, 2-168, 2-308, 4-257, 4-366
BHM, 1-86, 1-175, 2-338, 2-345, 3-304
estimation, 1-156
framework, 1-161, 1-163, 2-321, 2-369, 2-400, 4-257
gridded, 3-90
hazard curve combination, 4-220
inference, 2-338, 2-342, 2-347, 3-70, 3-78, 3-93, 3-304, 3-313, 3-387, 4-223
maximum likelihood, 1-186
model, 2-321, 2-345, 2-353, 2-402, 3-307, 3-326
posterior distribution, 1-161, 1-163, 1-171, 2-163, 2-321, 2-338, 2-342, 3-78, 3-79, 3-88, 3-93, 4-223
prior distribution, 1-161, 1-171, 2-163, 3-78
Quadrature, 1-196, 2-68, 4-69
regional, 2-163, 3-79
Bayesian Hierarchical Model. See Bayesian:BHM
best practice, 1-15, 1-151, 2-34, 2-45, 2-248, 2-354, 2-359, 3-94, 3-314, 3-320, 4-266, 4-305, 4-312, 4-404, 4-405, 4-425
Blayais, 2-9, 2-266, 3-27, 3-240, 4-390, 4-472
bootstrap
1000 year simulation, 3-359
resampling, 4-64
boundary condition, 1-90, 1-95, 1-196, 2-102, 2-113, 2-150, 2-312, 2-320, 2-326, 2-354, 2-366, 2-413, 3-43, 3-47, 3-68, 4-30, 4-39, 4-203, 4-266, 4-271, 4-298
bounding, 2-323, 2-337, 3-28, 4-457, 4-470, 4-478
analyses, 2-268, 2-322, 3-28, 4-470
assessments, 3-370
assumptions, 2-322
estimates, 2-37
tests, 2-268
BQ. See Bayesian:Quadrature
breach, dam/levee, 1-21, 1-148, 1-209, 1-214, 1-220, 2-34, 2-322, 2-325, 2-329, 3-267, 3-268, 3-314, 4-198, 4-204, 4-262, 4-312, 4-404, 4-405, 4-425
computational model, 4-415, 4-417
development, 3-267
initiation, 3-198
location, 4-262, 4-313
mass wasting, 4-419
models, 3-301, 4-425
tests, 3-269, 4-406
Bulletin 17B. See 17B, Bulletin
Bulletin 17C. See 17C, Bulletin
calibration, 1-89, 1-90, 1-101, 1-123, 1-158, 1-161, 1-177, 2-207, 2-312, 2-317, 3-67, 3-70, 3-144, 3-146, 3-202, 4-25, 4-75, 4-105, 4-217, 4-227, 4-313, 4-332, 4-369
CAPE, 1-60, 1-139, 2-96, 2-381, 4-136, 4-144, 4-161, 4-218
CASC2D. See 2D:model CASC2D
CDB. See current design basis:
CDF, 1-152, 1-164, 4-66
center, body, and range, 1-136, 1-207, 2-354, 2-359, 3-94, 3-314, 3-320, 4-266, 4-313
CFHA. See flood hazard:flood hazard assessment:comprehensive
CFHA. See coastal flood hazard assessment
CFSR. See reanalysis:Climate Forecast System Reanalysis
CHS. See Coastal Hazard System
Clausius-Clapeyron, 1-58, 2-89, 4-353, 4-384
cliff-edge effects, 1-12, 1-31, 2-43, 3-15, 3-373, 3-382, 4-15, 4-474
climate, 1-51, 1-54, 1-98, 1-151, 1-196, 1-209, 1-267, 2-16, 2-77, 2-88, 2-223, 2-372, 2-402, 3-29, 3-81, 3-120, 3-133, 3-136, 3-179, 3-189, 3-208, 4-11, 4-105, 4-113, 4-119, 4-125, 4-132, 4-137, 4-335, 4-354, 4-369, 4-379, 4-380, 4-383
anomalies, 1-61, 3-196
hydroclimatic extremes, 4-335
index, 2-338, 2-345, 3-304, 3-310, 3-313
mean precipitation projections, 4-341
mean precipitation trends, 4-339
models, 1-58, 1-63, 1-95, 2-97, 2-100, 2-112
downscaling, 4-341
patterns, 1-56, 2-88, 3-29, 3-192
predictions, 1-96
projections, 1-22, 1-51, 1-55, 1-96, 2-48, 2-89, 2-112, 2-373, 3-19, 3-30, 3-47, 3-67, 3-162, 4-335, 4-356, 4-369
precipitation, 4-344
regional, 1-74, 1-123
scenarios, 4-341
science, 1-22, 1-52, 2-90, 2-405, 3-193, 4-381
temperature changes, 3-32
trends, 4-335
variability, 2-100, 4-137, 4-225, 4-371, 4-377
climate change, 1-22, 1-51, 1-63, 1-95, 1-162, 1-188, 2-48, 2-77, 2-88, 2-98, 2-102, 2-114, 2-168, 2-199, 2-307, 2-366, 3-19, 3-29, 3-35, 3-38, 3-115, 3-195, 3-398, 4-20, 4-30, 4-33, 4-98, 4-260, 4-355, 4-364, 4-370, 4-378, 4-380, 4-383, 4-454
high temperature event frequency increase, 2-94
hydrologic impacts, 2-99
mean changes, 2-99
precipitation changes, 2-91
scenarios, 2-93
streamflow change, 2-98
coastal, 1-148, 1-267, 4-34, 4-93, 4-317
CSTORM, 2-379
StormSim, 2-379
coastal flood hazard assessment, 1-194
Coastal Hazard System, 2-379, 3-328
incident and correlated flooding, 2-40, 3-10, 3-15, 3-395, 3-403, 4-15, 4-19, 4-318, 4-448
incident events, 1-12, 2-43, 2-332, 3-15, 4-15, 4-86
combined effects, 1-12, 1-30, 2-43, 4-432, 4-440
combined events, 1-25, 1-31, 1-37, 1-133, 2-89, 2-356, 2-419, 3-318, 3-380, 3-386, 4-95, 4-440, 4-451, 4-454, 4-456, 4-477
combined processes, 1-25
compound event framework, 4-320
concurrent hazards, 1-228, 2-276, 3-374, 3-377
correlated hazards, 2-52, 2-410, 3-26
confidence interval, 1-72, 1-157, 3-15, 3-139, 4-14, 4-199, 4-214
confidence limits, 1-178, 1-194, 1-199, 2-36, 2-196, 3-94, 3-108, 4-57, 4-69, 4-232, 4-253
NOAA Atlas 14, 2-373
convective potential energy. See CAPE
correlation spatial and temporal, 2-340, 3-307
cumulative distribution function. See CDF
current design basis, 1-10, 1-23, 1-247, 2-21, 2-42, 2-202, 2-255, 3-12, 3-154, 4-381, 4-480
design basis flood, 4-454
event, 3-245
return period, 3-352
flood walkdown, 2-254
dam, 1-210, 2-201, 2-244, 2-307, 2-329, 2-338, 2-400, 3-15, 3-136, 3-149, 3-194, 3-197, 3-267, 3-314, 3-338, 3-405, 4-14, 4-130, 4-208, 4-224, 4-228, 4-253, 4-257, 4-278, 4-281, 4-312, 4-404, 4-425, 4-451, 4-476
assessments, 4-196
breach. See breach, dam/levee
case study, 1-65, 1-74, 2-348, 2-378, 3-143, 3-333, 3-336, 3-355, 3-358, 4-125, 4-213, 4-218, 4-238, 4-298, 4-329
computational model, 4-405
embankment. See embankment dam
erosion. See erosion: dam
failure, 1-6, 1-11, 1-37, 1-172, 1-227, 2-12, 2-34, 2-52, 2-276, 2-288, 2-322, 2-325, 2-329, 2-340, 2-353, 2-409, 3-22, 3-26, 3-136, 3-197, 3-217, 3-266, 3-353, 3-371, 3-374, 3-378, 3-388, 3-395, 4-14, 4-228, 4-295, 4-318, 4-322, 4-455, 4-476
failure analysis, 4-324
models, 1-159, 3-191
operations, 2-384
Oroville, 3-339, 3-361, 3-389, 4-258
overtopping, 3-277, 3-303, 3-367, 4-330, 4-333, 4-407
physical model, 1-209, 1-216, 3-268, 4-405
potential failure modes, 2-340
regulation, 1-155, 1-188, 4-289
releases, 2-97, 3-37, 4-287, 4-318, 4-363
risk, 1-24, 2-378, 2-416, 3-138, 3-197, 3-369, 3-400, 4-20, 4-287, 4-320, 4-334
risk assessment, 4-321
system of reservoirs, 3-334
data collection, 4-458
regional information, 1-154
transposition, 4-123
prior. See Bayesian: prior distribution
probability, 3-99, 4-89
quantiles, 2-155
tails, 2-207
temporal, 1-160, 2-179, 4-121, 4-290
triangle, 4-205, 4-208, 4-229, 4-328
type, 3-101
uniform, 4-205, 4-208, 4-257, 4-328
Wakeby (WAK), 1-83, 2-159, 2-193, 2-197, 2-373, 3-77
Weibull (WEI), 1-155, 1-196, 1-207, 2-63, 2-69, 2-187, 2-193, 2-197, 2-200, 3-100, 3-103, 4-328
Weibull plotting position, 4-64
Weibull type, 4-68
EC. See Environmental Conditions
EHC. See External Hazard Center of Expertise
EHID. See Hazard Information Digest
EMA. See expected moments algorithm
embankment dam, 1-21, 1-148, 1-209, 2-47, 3-19, 3-267, 3-269, 3-272, 3-276, 3-336, 4-19, 4-424
erosion. See erosion: embankment
rockfill, 1-216, 3-273, 4-330, 4-404
zoned rockfill, 3-274
ensemble, 1-85, 1-124, 1-144, 2-100, 2-152, 2-161, 3-81, 3-86, 4-41, 4-52, 4-56, 4-97, 4-114, 4-117, 4-123, 4-381
approaches, 4-123
Global Ensemble Forecasting System, GEFS, 4-35, 4-56
gridded precipitation, 2-152, 2-160, 3-71, 3-81, 3-86, 3-89
models, 4-55, 4-56
real-time, 4-49
storm surge, 4-34, 4-35, 4-36
ENSO. See Multi-decadal: El Niño-Southern Oscillation
Environmental Factors, 1-19, 1-21, 1-223, 1-238, 2-31, 2-47, 2-271, 2-276, 2-415, 3-19, 3-250, 3-398, 4-20, 4-441
epistemic uncertainty. See uncertainty, epistemic
erosion, 1-11, 1-153, 1-222, 2-245, 3-15, 3-261, 4-14, 4-81, 4-96, 4-230, 4-330, 4-334, 4-404, 4-417
dam, 3-271, 3-284, 3-292, 3-302, 3-303, 4-407, 4-414, 4-424
embankment, 1-19, 1-21, 2-47, 3-19, 3-277, 3-292, 3-301, 4-19, 4-407
rockfill, 1-209, 4-404, 4-424
zoned, 3-267, 4-422, 4-424
zoned rockfill, 3-267, 4-404
equations, 4-420
erodibility parameters, 3-273, 3-303, 4-404, 4-415, 4-422
headcut, 3-267, 4-414, 4-416, 4-418
internal, 1-213, 3-136, 3-267, 3-272, 3-290, 3-292, 3-300, 3-302, 3-303, 4-416
parameters, 1-221, 3-285
processes, 1-21, 1-148, 1-221, 3-270, 4-407, 4-425
rates, 1-221, 3-267, 3-285, 4-404, 4-415
resistance, 3-267, 3-270, 4-407, 4-417
spillway, 3-136, 3-343, 4-211
surface, 2-330, 3-267, 3-284, 4-414, 4-416, 4-418, 4-422, 4-424
tests, 1-209, 1-215, 1-217, 3-267, 3-286, 4-404, 4-405
error, 1-35, 1-125, 1-166, 1-195, 2-56, 2-200, 2-317, 3-67, 3-105, 4-34, 4-41, 4-57, 4-76, 4-87, 4-90, 4-95, 4-102, 4-228, 4-262, 4-468
Bayesian Total Error Analysis, BATEA, 1-161
bounds, 3-116, 3-117
defined space, 4-35
distribution, 2-56, 4-49
episodic uncertainty, 3-94
estimation, 4-108
forecasting, 4-35
instrument characteristic, 4-102
mean absolute, 4-62
mean square, 3-130
measurement, 1-161, 1-164, 4-262
model, 1-162, 2-193, 2-403, 4-57, 4-69, 4-79
operator, 2-284, 3-247, 3-257
quantification, 2-189, 4-59
random, 4-105, 4-107
relative, 3-48
root mean square, RMSE, 4-151, 4-306
sampling, 1-71, 2-192, 3-332, 4-79
seal installation, 2-267
simulation, 1-197, 2-57, 2-102, 3-42, 3-67, 3-97, 3-105
space, 4-35, 4-52
term, 2-53, 2-57, 2-73, 3-94, 3-96, 4-57, 4-60, 4-228
unbiased, 3-97, 4-60
undefined space, 4-35
EVA. See extreme value analysis
evapotranspiration, 3-40
event tree, 1-22, 1-46, 1-260, 2-28, 2-288, 2-297, 2-300, 2-401, 2-405, 2-417, 3-301, 3-303, 3-389, 4-324, 4-440
analysis, 4-313, 4-477
EVT. See extreme value theory
ex-control room actions, 4-474, 4-475
expected moments algorithm, 1-156, 1-186, 1-188, 2-187, 2-194, 2-199, 2-207, 2-212, 2-214, 3-117, 3-122, 3-139, 3-141, 3-149, 4-208, 4-214, 4-252, 4-257
expert elicitation, 1-135, 2-338, 2-343, 2-347, 3-326, 4-220, 4-226, 4-229, 4-313
external flood, 2-247, 2-259, 2-288, 3-22, 3-198, 4-385, 4-429
equipment list, 3-262, 3-264, 4-435
operator actions list, 3-262, 3-264
human action feasibility, 3-264
warning time, 3-264
risks, 3-260
scenarios, 3-132, 3-261
external flood hazard, 2-290, 4-455
frequency, 2-79
model validation, 2-394
external flooding PRA. See XFRA
External Hazard Center of Expertise, 2-15
extratropical cyclone, 1-11, 1-17, 1-18, 1-58, 1-91, 1-196, 2-77, 2-89, 2-97, 4-55, 4-98, 4-346, 4-355
reduced winter frequency, 4-362
extreme event, 4-290
extreme events, xxxvii, 1-56, 2-30, 2-88, 2-101, 2-168, 2-201, 2-307, 2-400, 3-29, 3-42, 3-140, 3-181, 3-193, 3-304, 3-313, 3-371, 4-281, 4-315, 4-349, 4-381, 4-475
external events, 4-29
meteorology, 4-352
extreme precipitation, 1-58, 1-90, 1-100, 2-88, 2-89, 2-104, 2-105, 2-153, 2-167, 3-33, 3-35, 3-40, 3-45, 3-70, 3-398, 4-101, 4-110, 4-347, 4-354
change, 2-91
classification, 1-92, 2-105, 3-44
climatic trends, 4-342
climatic change, 2-91
classification, 1-92, 2-105, 3-44
climatic trends, 4-339
Colorado/New Mexico study, 4-144, 4-159, 4-383
event, 1-91
increases, 2-94
spatial coherence, 4-337
temporal coherence, 4-337
variability, 4-337
extreme storm data, 3-334
extreme storm database, 2-377
increase, 4-359
frequency, 4-364
intensity, 4-364
model, 1-65, 2-153, 3-72
advances, 2-341
risk, 4-337
extreme value analysis, 1-194, 3-328
extreme value theory, 3-304, 3-313, 4-114, 4-151
fault tree, 1-46, 1-260, 4-324
FHRR. See Near Term Task Force: Flooding Hazard Re-Evaluations
FLEX, 2-24, 2-288, 2-304, 3-199, 3-248, 3-258, 3-263, 4-314, 4-381, 4-440
flood, 2-415, 3-31
causing mechanisms, 4-318
complex event, 4-449
depths, 1-34
design criteria, 3-352
duration, 1-31, 1-34, 1-255, 2-30, 2-291
dynamic modeling, 1-255, 2-291, 2-304
elevations, 1-51
event, 1-253, 2-289
extreme events, 1-172, 2-207, 4-466
gates, 4-473
hazard, 1-12, 1-153, 2-44, 3-16, 4-15
diverse, 4-447
increase, 4-364
mechanisms, 1-31, 1-132, 2-309, 2-325, 2-356, 4-432
mitigation, 2-30
operating experience, 4-11
organizational procedure, 3-245
response, 3-245
risk, 1-177
riverine, 1-6, 1-16, 1-133, 1-148, 1-150, 1-168, 1-175, 1-267, 2-46, 2-202, 2-227, 2-288, 2-338, 2-353, 2-355, 3-15, 3-18, 3-22, 3-27, 3-115, 3-198, 3-246, 3-314, 4-11, 4-14, 4-24, 4-31, 4-164, 4-197, 4-228, 4-255, 4-265, 4-295, 4-311, 4-455 routing, 1-11
runoff-induced riverine, 4-318
SDP example, 1-43
simulation, 2-52
situation, 4-202
sources, 4-456
sparse data, 4-30
stage, 4-480
warning time, 1-34, 2-30
flood events
Blayais, 4-465
Cruas, 4-466
Dresden, 4-466
Hinkley Point, 4-466
St. Lucie, 4-466
flood frequency, 2-30, 3-118, 3-398, 4-252, 4-330, 4-473
analysis, 1-13, 1-148, 1-150, 1-153, 1-172, 1-176, 1-180, 2-45, 2-81, 2-187, 2-190, 2-202, 2-227, 2-244, 3-17, 3-116, 3-119, 3-126, 3-129, 3-135, 3-137, 3-142, 3-163, 3-199, 3-234, 3-325, 4-18, 4-246, 4-265, 4-474
gridded, 3-92
methods, 1-13, 2-45, 3-17
benchmark, 4-33
curve, 3-112, 3-355, 4-176, 4-253
extrapolation, 2-218
extrapolation, 3-139
limits, 2-170
methods, 1-191
flood hazard, 1-10, 1-27, 1-30, 2-16, 2-42, 2-43, 2-182, 2-309, 3-12, 3-151, 3-371, 4-14, 4-327, 4-473
curves, 4-266
combining, 4-219
family of, 2-54, 3-108, 3-380, 4-71, 4-267, 4-475
dynamics, 3-385
flood hazard analysis, 3-354
case study, 4-191
riverine pilot, 2-50
flood hazard assessment, 1-29, 3-328, 3-336, 4-318
comprehensive, CFHA, 1-152
influencing parameters, 4-202
probabilistic analysis, 1-30
re-evaluated, 1-248
riverine, 2-307
scenarios, 4-458
static vs. dynamic, 3-368
Flood Hazard Re-Evaluations. See Near
Term Task Force: Flooding Hazard Re-
Evaluations
flood mitigation, 4-20, 4-472
actions, 3-379
approaches, 4-449
fragility, 3-381
proceduralized response, 3-245
procedures, 4-473, 4-475
strategies, 2-254
flood protection, 1-255, 2-51, 2-248, 2-250, 2-291, 3-22, 3-25, 3-242, 4-21, 4-24, 4-33, 4-472
barrier fragility, 2-52, 2-410, 3-26, 3-395
criteria, 2-250
failure modes, 3-374
features, 2-250, 3-245, 3-262, 3-265, 4-27, 4-435
fragility, 3-377, 3-379
inspection, 2-250
maintenance, 2-254
oversight, 3-246
reliability, 1-37
survey, 2-257
testing methods, 2-250
training, 2-254
work control, 3-245
flood protection and mitigation, 1-11, 1-21, 2-21, 2-43, 2-180, 2-271, 2-415, 3-13, 3-16, 3-150, 3-250, 4-11, 4-14
training, 3-245
flood seals, 1-19, 1-44, 1-223, 1-265, 2-19, 2-47, 2-247, 2-251, 2-260, 2-265, 3-19, 3-235, 3-240, 4-20, 4-384, 4-392, 4-393, 4-402, 4-403, 4-426, 4-473
characteristic types and uses, 1-266, 2-262, 3-237, 4-386, 4-394, 4-397
condition, 4-387, 4-435
critical height, 4-435
failure mode, 4-387
fragility, 3-381
historic testing, 2-251
impact assessment, 4-387
performance, 1-19, 2-47, 2-261, 3-19, 3-235, 4-393
ranking process, 4-388
risk significance, 4-386
tests, 1-20, 1-265, 2-262, 3-236, 4-394
criteria development, 2-251
plan, 2-264, 3-238, 4-395
procedure, 1-265, 3-239, 4-396
results, 4-400, 4-401
series, 4-397
Focused Evaluations. See Fukushima Near Term Task Force: Focused Evaluations
FPM. See flood protection and mitigation
fragility, 1-11, 3-13, 4-14
analysis, 1-259
curve, 4-324
flood barrier. See flood protection: barrier fragility
framework
NARSIS, 4-327
simulation based dynamic flood analysis (SBDFA), 1-253, 1-256, 2-292
TVA Probabilistic Flood Hazard Assessment, 2-320, 2-404, 4-277
scenarios, 4-282
Fukushima Near Term Task Force, 1-9, 1-23, 1-27, 1-32, 2-17, 2-20, 3-263, 4-11, 4-386
Flooding Hazard Re-Evaluations, 1-23, 4-440, 4-471, 4-480
Fukushima Flooding Reports, 4-471
re-evaluated flooding hazard, 4-480
Focused Evaluations, 3-263, 4-471
Integrated Assessment, 2-21, 3-263, 4-386
Mitigating Strategies Assessments, 3-263, 4-440, 4-475
post Fukushima process, 4-472
Recommendation 2.1, 4-480
Recommendation 2.3, 4-435, 4-479
Gaussian, 2-67
Gaussian process metamodeling, 3-102, 4-59, 4-61
local correction, 4-61
uncertainty, 4-61
GCM. See Global Climate Model, See Global Climate Model
GEFS. See ensemble:Global Ensemble Forecasting System
GEV. See distribution:generalized extreme value
GLO. See distribution:generalized logistic
Global Climate Model, 1-128, 1-162, 2-53, 2-55, 2-63, 2-67, 2-71, 2-77, 2-96, 2-99, 2-403, 3-41, 3-47, 3-94, 3-100, 3-103, 4-99, 4-114, 4-163, 4-260, 4-360
downscaling, 2-55, 3-102
model forcing, 2-71
Global Precipitation Measurement, GPM, 4-100, 4-117
global regression model, 4-61
global sensitivity analysis, 4-198, 4-327
case studies, 4-202
simple case, 4-205
GNO. See distribution:generalized ‘skew’ normal
goodness-of-fit, 2-102, 2-187, 2-194
tests, 1-71
GPA. See distribution: generalized Pareto
GPD. See distribution:generalized Pareto
GPM. See Gaussian process metamodeling
Great Lakes, 3-31
water levels, 4-366
decreases, 4-368
lowered, 3-40
GSA. See global sensitivity analysis
hazard
analysis, 3-349, 4-450
assessment, 3-22
hydrologic, 3-136, 3-195, 4-115
identification, 2-82
probabilistic approach, 4-471
quantification, 2-315
hazard curves, 1-11, 1-51, 1-164, 2-43, 2-68, 2-84, 2-218, 3-13, 3-100, 3-104, 3-332, 4-14, 4-90, 4-474, 4-477
comparison, 4-281
full, 1-12, 2-43, 3-15, 4-15
full range, 2-30
integration, 4-60, 4-70
MCI, 2-70
MCLC, 2-69
weight and combine methods, 4-210
Hazard Information Digest
External, 3-149, 3-399
Flood, 1-13, 1-223, 1-241, 2-45, 2-180, 2-181, 2-186, 2-413, 3-17, 3-149, 3-161, 4-18
flood beta, 2-183, 3-152
flood workshop, 1-252, 2-183, 3-152
Natural, 3-151
population, 2-183, 3-152
hazardous convective weather, 1-57, 1-60, 3-31, 3-36, 3-40, 4-368
NDSEV, 3-35
NDSEV increase, 4-361
severe weather, 4-30
monitoring, 3-245
HCW. See hazardous convective weather
headcut. See erosion: headcut
HEC, 3-195, 3-201
-FIA, 4-261
-HMS, 2-376, 3-202, 4-166, 4-263
MCMC optimization, 2-376
-LifeSim, 4-261
-MetVue, 2-377
models, 4-312
-RAS, 4-166, 4-207, 4-230, 4-244
-RAS 2D hydraulics, 2-377
-ResSim, 4-166, 4-258
-SSP, 4-262
-SSP, flood frequency curves, 3-334
-WAT, 2-378, 4-161, 4-165, 4-166, 4-256, 4-261, 4-263, 4-313, 4-316
FRA, 4-196
hydrologic sampler, 4-191
MCRAM runs, 2-378
HEC-RAS, 4-191, 4-236
historical
data, 1-96, 3-117, 3-120, 3-122, 3-131, 4-30, 4-215, 4-269
flood information, 1-154
floods, 1-187
intervals, 3-131
observations, 1-55, 3-80
peak, 1-155, 3-123
perception thresholds, 3-131
records, 2-62, 3-21, 3-183
records extrapolation, 2-80
spatial patterns, 4-141
streamflow, 1-183
water levels, 2-50, 3-24, 3-113
homogeneous region, HR, 1-71, 1-77, 2-151, 2-155, 2-159, 2-167, 3-70, 3-75, 3-83
human factors, 3-388, 4-471
HRA, 2-30, 4-475
HRA/HF, 1-24
human actions, 2-19, 3-385, 4-446, 4-473
Human Error Probabilities, 2-280
human errors, 2-293
human performance, 2-273, 3-251
human reliability, 4-474
operator actions, 4-474
organizational behavior, 3-379, 3-382, 3-385, 4-473
organizational response, 4-473, 4-479
humidity, 1-53, 4-358
HURDAT, 1-207
hurricane, 1-57, 1-95, 2-51, 2-53, 2-77, 2-81, 2-89, 2-105, 2-407, 3-26, 3-37, 3-43, 3-111, 3-247, 3-393, 4-25, 4-34, 4-35, 4-73, 4-98, 4-113, 4-259, 4-326, 4-370, 4-380, 4-480
2017 season, 4-371
Andrew, 4-474
Category, 4-41, 4-98
Florence, 4-481
Frances, 1-101
Harvey, 3-180, 3-329, 3-361, 3-367, 3-391, 4-95, 4-114, 4-124, 4-160, 4-259
Ike, 4-56
Isaac, 3-53, 3-69
Katrina, 1-194, 2-53, 4-263
Maria, 4-211
Sandy, 4-259
hydraulic, 2-226, 2-266, 2-288, 2-307, 2-354, 2-400, 3-198, 3-199, 3-234, 3-315, 4-144, 4-170, 4-230, 4-254, 4-257, 4-262, 4-326
detailed channel, 1-11
models, 1-133, 1-158, 1-186, 2-311, 2-420, 3-195, 4-60, 4-70, 4-198, 4-326
dependent inputs, 4-326
hydraulic hazard analysis, 2-324
hydrologic
loading, 4-232
models, 1-63, 1-133, 1-158, 2-311, 2-376, 4-123, 4-282, 4-331, 4-381
risk, 1-15, 2-46, 3-18, 4-329
routing, 2-387
runoff units (HRU’s), 3-143
simplified model, 3-337
simulation, 4-279
hydrologic hazard, 2-378, 3-331, 4-211
analysis, 3-334, 4-115
analysis, HHA, 1-85, 2-207, 3-136, 4-114, 4-125
curve, 1-15, 1-170, 2-45, 2-204, 2-340, 3-17, 4-130, 4-219, 4-329
stage frequency curve, 4-213
Hydrologic Unit Code, HUC, 4-149
watershed searching, 4-150
hydrology, 2-151, 2-202, 2-226, 2-307, 2-338, 2-354, 2-369, 2-400, 2-411, 3-70,
A-10

3-135, 3-195, 3-304, 3-315, 3-325, 3-366, 3-387, 4-114, 4-122, 4-127, 4-144, 4-161, 4-211, 4-229, 4-244, 4-276, 4-313, 4-381
initial condition, 1-90, 1-95, 2-104, 3-44
Integrated Assessments. See Fukushima Near Term Task Force: Integrated Assessment
internal flooding, 3-25, 4-386
scenarios, 3-25
inundation
mapping, 3-367, 3-368
dynamic, 3-368
modeling, 4-176
period of, 3-261
river flood analysis, 4-327
JPM, joint probability method, 1-35, 1-195, 1-199, 1-209, 2-34, 2-53, 2-56, 2-74, 2-77, 3-94, 3-99, 3-112, 4-25, 4-57, 4-64, 4-73, 4-77, 4-88, 4-228, 4-318
integral, 1-199, 2-56, 3-97, 4-60
parameter choice, 2-62
storm parameters, 1-197, 1-207, 2-57, 3-97, 3-100, 4-68, 4-76
surge response function, 4-78
JPM-OS, joint probability method, with optimal sampling, 1-194, 1-196, 2-53, 2-55, 2-73, 2-77, 3-94, 3-102, 4-81
hybrid methodology, 2-68
KAP. See distribution: Kappa
kernel function, 2-56, 3-99, 4-68
Epanechnikov, EKF, 2-58, 2-65, 3-98
Gaussian, GKF, 1-200, 1-202, 2-58, 2-60, 3-98, 4-99
normal, 2-65
triangular, 2-65
uniform, UKF, 2-60, 2-65, 3-98
land use, 1-24, 2-420
urbanization, 2-98
land-atmosphere interactions, 1-57
levee breach. See breach, dam/levee
likelihood, 3-78
functions, 1-166
LIP. See local intense precipitation
L-moment ratio, 2-194, 3-77
diagram, 2-174
local intense precipitation, 1-6, 1-17, 1-22, 1-34, 1-54, 1-64, 1-76, 1-88, 1-100, 1-130, 1-133, 1-144, 1-223, 1-255, 2-34, 2-47, 2-50, 2-97, 2-101, 2-103, 2-168, 2-175, 2-287, 2-291, 2-297, 2-322, 2-326, 2-337, 2-341, 2-353, 2-370, 2-421, 3-19, 3-22, 3-42, 3-47, 3-198, 3-246, 3-314, 3-315, 4-19, 4-24, 4-264, 4-295, 4-311, 4-455
analysis, 4-480
framework, 1-17, 2-46, 2-104, 3-18
screening, 3-369
severe storm, 1-90, 3-46, 4-361
numerical simulation, 1-90, 1-95
logic tree, 2-56, 2-63, 2-85, 2-369, 3-94, 3-97, 3-107, 3-114, 4-57, 4-81, 4-86, 4-93
branch weights, 4-91
LP-III. See distribution: log Pearson Type III
manual actions, 1-21, 1-31, 2-272, 2-415, 3-245, 3-250, 3-398, 4-449, 4-473
decomposing, 2-275
modeling time, 3-257
reasonable simulation timeline, 3-246
timeline example, 3-256
maximum likelihood, 1-156
Bayesian, 1-186
estimation, 1-70, 2-404
MCMC. See Monte Carlo: Markov Chain
MCS. See mesoscale convective system
MEC. See mesoscale storm with embedded convection
mesoscale convective system, 1-18, 1-57, 1-59, 1-64, 1-91, 1-97, 1-100, 1-111, 1-123, 2-101, 2-104, 2-112, 2-150, 3-29, 3-31, 3-33, 3-42, 3-47, 3-49, 3-52, 3-67, 4-133, 4-355
intense rainfall increase, 4-361
precipitation increase, 3-40, 4-368
rainfall, 4-360
reduced speed, 4-361
simulations, 2-144
mesoscale storm with embedded convection, 2-381, 3-357, 4-128, 4-135, 4-142, 4-159, 4-161, 4-218
Meta-models, 4-61, 4-206
Meta-Gaussian Distribution, 4-59, 4-64, 4-69
example, 4-67
meteorological inputs, 4-132
model, 1-133, 1-158, 2-311
MGD. See Meta-models: Meta-Gaussian Distribution
mid-latitude cyclone, 2-382, 4-120, 4-128, 4-133

A-10
Midwest, 4-357, 4-368
floods, 4-363
intense snowpack, 4-363
Region, 3-31
MLC. See mid-latitude cyclone
model, 1-90
alternative conceptual, 4-470
averaging, 2-352
dependence, 3-310
improved, 1-12, 2-44, 3-16, 4-15
nested domain, 3-53
nested grids, 4-55
numerical modeling, 1-97, 4-327
nested domain, 1-101
parameter estimation, 2-313
parameters, 4-176
selection, 2-346
warm-up, 2-385
moisture
maximization, 3-45
saturation deficit, 1-61
saturation specific humidity profile, 1-58
sources, 1-76
water vapor, 1-61, 4-347
Monte Carlo, 1-163, 1-185, 2-77, 2-187, 2-286, 2-411, 3-23, 3-79, 3-93, 3-94, 3-199, 4-57, 4-162, 4-175, 4-257, 4-330
analysis, 3-21, 3-111
Integration, 2-70, 3-103
Life-Cycle Simulation, 2-69, 3-103, 4-64
Markov Chain, 1-161, 1-171, 2-402
sampling, 4-201
simulation, 2-55, 2-74, 2-81, 2-85, 3-102, 3-111, 3-113, 3-328, 4-59
MSA. See Fukushima Near Term Task Force: Mitigating Strategies
Assessments
Multi-decadal
Atlantic Meridional Mode (AMM), 4-370, 4-373, 4-376, 4-379
Atlantic Multi-Decadal Oscillation (AMO), 4-373
El Niño-Southern Oscillation (ENSO), 1-206, 4-370, 4-373, 4-376, 4-379
North Atlantic Oscillation (NAO), 4-370, 4-374, 4-376, 4-379
Pacific Decadal Oscillation (PDO), 4-354
persistence, 4-113, 4-354
multivariate Gaussian copula, 3-104, 4-59
MVGC. See multivariate Gaussian copula
NACCS. See North Atlantic Coast Comprehensive Study
NAO. See Multi-decadal: North Atlantic Oscillation
National Climate Assessment, 4th, 3-42, 4-335
NCA4. See National Climate Assessment, 4th
NEB. See non-exceedence bound
NEUTRINO, 4-291, 4-297, 4-314, See also smoothed particle hydrodynamics, SPH
NOAA Atlas 14, 1-72, 1-185, 2-158, 2-168, 2-171, 2-179, 2-181, 2-201, 3-87, 4-127, 4-144
future needs, 2-372
gridded, 1-73
tests, 2-373
non-exceedence bound, 4-229, 4-230, 4-236, 4-238
nonstationarity/nonstationary, 1-37, 1-155, 1-162, 1-177, 1-188, 1-191, 3-117, 3-133, 3-315, 4-264
change points, 3-125, 3-127
model, 2-373
processes, 1-12, 1-55, 2-44, 3-16, 4-15
trends, 3-125, 3-128
North Atlantic Coast Comprehensive Study, 1-196, 2-53, 3-102, 4-94, 4-99
numerical weather models, 1-18, 1-89, 1-95, 2-104, 3-44, 3-103, 4-55
regional, 2-104, 3-45
observations, 1-71
based, 3-81
data, 1-95
record, 3-121
satellite
combination algorithms, 4-105, 4-108, 4-112
combinations, 4-104
multi-satellite issues, 4-108
operating experience, 1-31, 4-447, 4-473
data sources, 4-465
operational event, 4-464
chronology review, 4-466
orographic precipitation. See precipitation, orographic
paleoflood, 1-24, 1-154, 1-181, 2-87, 2-216, 2-217, 2-225, 2-369, 2-400, 2-407, 2-416, 3-21, 3-26, 3-116, 3-117, 3-136, 3-140, 3-163, 3-179, 3-181, 3-195, 3-207,
analytical framework, 4-233
analytical techniques, 4-242
benchmark, 4-252
case study, 4-234, 4-236
data, 1-181, 1-186, 2-51, 2-81, 2-206, 2-219, 3-113, 3-117, 3-120, 3-123, 3-141, 3-179, 3-333, 3-394, 4-30, 4-215, 4-221, 4-246, 4-269
database, 3-208, 3-213
deposits. See deposits
event, 3-139
hydrology, 2-229, 3-164, 4-247
ice jams, 4-235
indicators, 3-181
interpretation, 3-394
reconnaissance, 2-235, 3-168, 4-233, 4-237
record length, 4-247
screening, 4-242
studies, 3-333
  humid environment, 2-228, 3-163
  suitability, 2-235, 3-167, 3-394
terrace, 4-236, 4-242
viability, 4-234
partial-duration series, 1-165, 2-201, 2-373
PCHA. See Probabilistic Coastal Hazard Assessment
PDF. See probability density function
PDO. See Multi-decadal: Pacific Decadal Oscillation
PDS. See partial-duration series
PFA. See precipitation frequency: analysis
PFHA, 1-257, 2-79, 2-218, 3-307, 3-353, 4-10, 4-453, 4-477
case study, 2-380
combining hazards, 4-207
documentation, 4-460
framework, xxxviii, 1-12, 1-16, 1-148, 1-157, 1-163, 1-166, 1-175, 2-44, 2-46, 2-307, 2-311, 2-322, 2-338, 2-345, 2-353, 2-401, 3-16, 3-18, 3-304, 3-359, 3-398, 4-11, 4-15, 4-19, 4-455
aleatory, 1-163
peer review, 2-87
regional analysis, 2-342, 2-348
riverine, 1-16, 2-46, 2-308, 2-312, 2-413, 3-18
site-specific, 2-309
hierarchical approach, 4-458
high level requirements, 4-459
paleoflood based, 4-289
results, 4-459
river, 4-207
statistical
  model, 2-84
team, 4-458
PFSS
  historic water levels, 2-81, 3-111
  pilot studies, 3-70, 3-386, 3-404, 4-11, 4-16, 4-22, 4-312, 4-440
  pilot studies, 2-418
  plant response, 1-255, 2-20, 2-289, 2-291, 3-261, 3-398, 4-20
  model, 1-260, 3-377
  proof of concept, 1-255
  scenarios, 1-260
  simulation, 1-22
  state-based PRA, 1-260
total, 1-253, 2-304, 2-415
PMF, 1-150, 2-25, 2-80, 2-202, 2-205, 2-400, 3-21, 3-141, 3-149, 3-266, 3-355, 3-390, 4-230, 4-454, 4-474
PMP, 1-50, 1-56, 1-66, 1-69, 1-73, 2-25, 2-153, 2-168, 2-169, 2-179, 2-405, 3-69, 3-149, 3-391, 4-114, 4-117, 4-120, 4-158, 4-160, 4-383
State SSPMP Studies, 3-338
  traditional manual approaches, 2-104
PRA, 1-11, 1-42, 1-256, 2-24, 2-28, 2-43, 2-79, 2-168, 2-179, 2-202, 2-216, 2-268, 2-287, 2-289, 2-337, 2-370, 2-401, 2-417, 2-421, 3-1, 3-13, 3-21, 3-25, 3-199, 3-259, 3-266, 3-315, 3-365, 3-368, 3-386, 3-390, 3-396, 3-405, 4-14, 4-264, 4-312, 4-323, 4-385, 4-391, 4-403, 4-429, 4-461, 4-462, 4-463, 4-469, 4-471, 4-474
  bounding analysis, 4-468
dams, 1-24
dynamic, 1-22
external flood. See XFPRA
  initiating event frequency, 1-47, 2-79
  inputs, 1-132
  insights, 4-476
internal flooding, 3-262, 4-440
LOOP, 4-469, 4-474
peer review, 4-461
performance-based approach, 4-451
plant fragility curve, 4-476
quantitative insights, 4-464
recovery times, 4-469
risk
information, 4-464
insights, 4-478
safety challenge indications, 4-465
Standard, 3-377
precipitation, 1-11, 1-53, 1-64, 1-160, 1-267, 2-88, 2-168, 2-179, 2-181, 2-201, 2-226, 2-260, 2-270, 2-288, 2-307, 2-353, 2-369, 2-381, 2-402, 3-15, 3-27, 3-31, 3-38, 3-40, 3-42, 3-52, 3-56, 3-67, 3-115, 3-134, 3-136, 3-150, 3-162, 3-198, 3-248, 4-11, 4-14, 4-56, 4-100, 4-113, 4-127, 4-144, 4-158, 4-210, 4-218, 4-228, 4-315, 4-326, 4-335, 4-353, 4-359, 4-380
classification, 2-105, 3-45
cool season, 3-307
distribution, 3-363, 4-114
duration, 2-155, 2-179, 3-74
field area ratio, 3-48
gridded, 2-161, 3-81
historical analysis, 1-19
increases, 3-40, 4-359, 4-364, 4-368
instrumentation, 4-102
modeling framework, 3-46
near-record spring, 3-37
numerical modeling, 1-17
patterns, 4-120, 4-140
point, 2-382, 2-417, 3-359, 4-18, 4-101, 4-146
processes, 1-90
quantile, 3-74
regional models, 4-117
seasonality, 1-72, 2-171, 2-382, 3-32
simulation, 1-89, 2-103, 3-48
warm season, 2-340, 3-33, 3-38
precipitation data, 3-156, 4-147
fields, 1-125
gage, 1-79, 2-156, 3-83, 4-117
go0IR, 4-102
Liveneh, 3-308, 4-119, 4-143
microwave imagers, 4-102
observed, 1-96, 1-181, 2-154, 3-48, 3-140
regional, 1-181
satellite, 4-101, 4-104, 4-112
precipitation frequency, 1-19, 1-64, 1-185, 2-151, 2-154, 2-168, 2-181, 2-211, 2-270, 2-372, 3-70, 3-72, 3-81, 3-150, 3-198, 3-224, 4-119, 4-127, 4-132, 4-141, 4-144, 4-146, 4-158, 4-161, 4-218, 4-228, 4-282, 4-290, 4-312, 4-315
analysis, 1-66, 1-73, 1-175, 3-74, 4-128, 4-138
curve, 3-75
estimates, 4-144
exceedance, 2-95
large watershed, 3-359
regional analysis, 4-133
relationship, 1-67, 1-85, 1-87, 3-73, 4-129
precipitation, orographic
linear model, 1-86
methodology, 1-66
regions, 1-17, 1-65, 2-153, 2-156, 2-167, 2-414, 3-72, 3-398, 4-18
pressure setup, 4-36, 4-37
Probabilistic Coastal Hazard Assessment, 3-328
Probabilistic Flood Hazard Assessment. See PFHA
Probabilistic Risk Assessment. See PRA
probabilistic safety assessments, 4-472, 4-474
probabilistic seismic hazard assessment, 1-30, 2-58, 3-94, 4-57, 4-59, 4-477
probabilistic storm surge hazard assessment, 2-53, 2-78, 4-81
probability density function, 1-57, 1-133, 1-152, 1-163, 1-164, 1-201, 2-79, 2-85, 3-113, 4-205, 4-207, 4-316
probable maximum flood. See PMF
probable maximum precipitation recirculation. See PMP
PSHA. See probabilistic seismic hazard assessment
PSSHA. See probabilistic storm surge hazard assessment
rainfall. See precipitation rainfall
rainfall-runoff, 4-210
methods, 1-15, 2-46, 3-18
model, 1-11, 1-152, 1-157, 1-183, 2-211, 2-384, 2-386, 2-398, 3-15, 3-143, 4-14, 4-134, 4-217
Austrailian Rainfall and Runoff Model, 1-70, 1-73, 1-150, 1-185, 2-212
SEFM, 1-151, 2-213, 2-216, 3-23, 3-28, 3-149, 4-276, 4-316, 4-329
stochastic, 1-151
stochastic, HEC-WAT, 3-334
VIC, 4-119, 4-369
reanalysis, 2-56, 2-151, 4-114, 4-122, 4-125, 4-143, 4-160, 4-269
Climate Forecast System Reanalysis (CFSR), 1-95, 2-102, 2-113, 2-150, 3-47, 4-118
PRISM, 4-117, 4-163, 4-370
Stage IV, 1-96, 1-100, 2-113
record length
effective, 3-126
equivalent independent, ERIL, 2-175
equivalent, ERL, 4-159, 4-221, 4-230
historical, 2-66
period of record, 2-53, 2-151, 2-373, 3-70, 3-83, 3-136, 4-113
regional growth curve, RGC, 1-77, 1-80, 1-84, 2-151, 2-155, 2-166, 3-75, 3-85, 3-89, 3-91
uncertainty, 1-82
regional L-moments method, 1-71, 1-73, 1-87, 1-185, 2-151, 2-154, 2-159, 2-161, 2-165, 2-167, 2-174, 2-179, 2-187, 2-201, 2-404, 3-70, 3-72, 3-77, 3-85, 3-93, 3-143, 3-387, 4-127, 4-332
regional precipitation frequency analysis, 2-151, 2-154, 2-167, 3-70, 3-71, 3-72, 3-75, 3-93, 3-144, 3-334, 4-218
reservoir, 4-170
operational simulation, 4-279
rule-based model, 4-281
system, 4-287
RFA. See regional precipitation frequency analysis
RIDM. See Risk-Informed Decision-Making
risk, 1-39, 1-50, 2-20, 2-154, 2-340, 2-380, 3-21, 3-138, 4-166
analysis, 1-51, 1-177, 2-203, 2-205, 2-401, 3-136, 3-149, 3-197, 3-217, 3-361, 4-175, 4-462
assessment, 4-92, 4-196, 4-233, 4-473
computational analysis, 3-378
qualitative information, 3-385
risk informed, 1-6, 1-10, 1-29, 1-40, 1-149, 2-42, 2-182, 2-392, 3-12, 3-151, 3-202, 4-10, 4-14, 4-129, 4-322, 4-451
approaches, 2-26
oversight, 2-28
use of paleoflood data, 2-51
Risk-Informed Decision-Making, 1-151, 2-24, 2-246, 2-288, 3-135, 3-196, 3-332, 3-337, 4-127, 4-210, 4-229, 4-279, 4-323, 4-330
calibration, 4-124, 4-233, 4-268, 4-471, 4-473, 4-477
external flood hazard, 4-31
Farmer, 1967, 4-477
flood, 4-456
hazard, 2-82
methods, 4-328
non-conservative, 4-477
Probabilistic Flood Hazard Assessment, 3-369
SDP, 1-10, 1-41, 1-51, 1-248, 2-28, 2-42, 2-180, 3-12, 3-116, 3-149, 3-325
floods, 2-30
Seals, 1-44
sea level rise, 1-53, 2-89, 2-97, 4-86, 4-92, 4-355, 4-381
nuisance tidal floods, 2-93
projections, 2-100
SLR, 1-57
sea surface temperature, SST, 4-370, 4-373
anomalies, 4-374, 4-377, 4-378
SEFM. See rainfall-runoff: model: SEFM
seiche, 1-6, 2-52, 2-409, 3-395, 4-318, 4-455
seismic, 1-6, 4-451
self-organizing maps, SOM, 1-77, 2-151, 2-157, 2-167, 3-70, 3-83, 3-93
Senior Seismic Hazard Assessment Committee. See SSHAC
sensitivity, 4-76
analysis, 4-326
analysis ranking, 4-200
quantification, 4-476
to hazard, 4-476
SHAC-F, 1-16, 1-64, 1-130, 2-46, 2-353, 3-18, 3-314, 3-325, 3-388, 4-264, 4-290, 4-311
Alternative Models, 1-142, 4-266
coastal, 2-419, 3-403, 4-19
framework, 1-132, 1-133
highly site specific, 3-319
key roles, 2-360
Levels, 4-268, 4-269, 4-271
LIDAR data, 4-271
LIP, 1-138, 1-142, 4-19
LIP Project Structure Workflow, 3-318
participatory peer review, 4-266
project structure, 2-360
LIP, 2-363
riverine, 2-367, 3-323
redefined levels, 3-322, 3-324
riverine, 2-366, 4-19
site-specific, 3-324
Work Plan, 1-135
significance determination process. See SDP skew
at-site, 4-214
regional, 4-214
SLOSH, Sea Lake and Overland Surges
from Hurricanes, 4-38
smoothed particle hydrodynamics, SPH, 1-263, 3-25, 3-378, 4-291, 4-296, See also NEUTRINO
validation, 4-306
snowmelt, 1-133, 2-340, 3-307, 4-217
energy balance, 2-376
extreme snowfall, 1-60
flood, 1-183
rain on snow, 2-97
site, 3-308
snow water equivalent, SWE, 3-306, 4-224, 4-332
snowpack increased, 3-37
VIC, snow algrorithm, 3-308
soil moisture, 3-40
reduction, 1-57
space for time, 1-77, 2-207
spillway. See erosion: spillway
SRR, 1-196, 1-202, 2-57, 2-59, 3-96, 4-60, 4-70, 4-86
models, 2-58, 3-98, 3-99
rate models, 2-60
sensitivity, 4-88
variability, 2-59
SSCs, xxxviii, 1-152, 1-260, 1-265, 2-288, 2-307, 2-309, 2-353, 3-198, 3-262, 3-264, 4-264, 4-429, 4-435, 4-440, 4-445
flood significant components, FSC, 4-387
fragility, 3-371, 3-381, 4-32
safety, 4-472
SSHAC, 1-30, 1-64, 1-132, 2-85, 2-354, 3-317, 4-93, 4-229, 4-264, 4-274, 4-313
Project Workflow, 3-321
state-of-practice, 1-176, 4-61, 4-321, 4-444, 4-447
statistical approaches, 1-179, 4-320
copula-based methods, 4-320
extreme value analysis, 4-320
statistical models, 4-268, 4-269
streamflow based, 1-15, 2-46, 3-18
stochastic, 1-185, 1-257, 3-143
flood modeling, 4-129, 4-132
model, 3-100, 4-458
approach, 3-332
inputs, 4-119
storm parameters, 4-74
simulation, 3-103, 3-328, 4-279, 4-281, 4-320
storm generation, 4-140
storm template, 3-145
storm transposition, SST, 4-120
weather generation, 3-334
Stochastic Event-Based Rainfall-Runoff Model. See rainfall-runoff:model:SEFM
storm
local scale, 4-133
maximization, 4-120
parameters, 4-41
patterns, 3-144, 3-364, 4-120, 4-257, 4-276, 4-286, 4-332
precipitation templates, 2-383
seasonality, 4-134, 4-331
synoptic scale, 4-133
storm recurrence rate. See SRR
storm surge, 1-6, 1-17, 1-35, 1-57, 1-192, 1-193, 2-34, 2-47, 2-53, 2-78, 2-87, 2-97, 2-259, 2-288, 2-322, 2-337, 2-369, 2-411, 3-19, 3-22, 3-24, 3-26, 3-29, 3-94, 3-109, 3-110, 3-112, 3-115, 3-198, 3-229, 3-328, 3-361, 3-364, 3-396, 4-25, 4-30, 4-34, 4-35, 4-57, 4-70, 4-73, 4-81, 4-93, 4-228, 4-259, 4-295, 4-311, 4-317, 4-355, 4-382, 4-451, 4-455
case study, 2-84
data partition, 4-70
deterministic, 2-331
wind-generated wave and runup, 2-333
hazard, 2-54, 2-55, 4-84
hurricane driven, 3-394
model, 1-194, 4-75
numerical surge simulation, 3-105
PCHA Studies, 2-379
probabilistic approaches, 2-50
Probabilistic Flood Hazard Assessment, 2-407, 3-393, 4-24
probabilistic model, 3-97, 4-60
P-Surge model, 4-53
tidal height, 3-111
total water level, 2-86
uncertainty, 3-398, 4-19
storm transposition, 2-81, 2-377, 3-21, 3-47, 3-54, 3-357, 4-133, 4-281
storm typing, 2-381, 3-334, 3-356, 4-119, 4-133, 4-138, 4-217, 4-282, 4-286
large winter frontal storms, MLC, 3-357
scaling and placement, 3-359
seperation, 3-359
summer thunderstorm complexes, MEC, 3-357
tropical storm remants
TSR, 3-357, 4-134
stratified sampling, 4-282
stratiform
leading, 1-93, 1-94
parallel, 1-93, 1-94
trailing, 1-93, 1-94
stratigraphy, 3-163, 3-183, 3-199, 3-200, 3-234, 4-18, 4-250
analysis, 2-227
record, 4-251
streamflow
data, 3-157
gage regional data, 1-181
historical, 3-38
Structured Hazard Assessment Committee
Process for Flooding. See SHAC-F
structures, systems, and components. See SSCs
synoptic storms, 1-91, 2-105, 3-45
synthetic
datasets, 2-62, 4-269
storm, 2-67, 2-81, 2-386, 3-21, 3-96, 3-102, 4-60, 4-62, 4-70, 4-78, 4-279, 4-282
storm simulations sets, 2-73
storms, 2-57
systematic data
gage record, 1-177, 2-206, 3-119, 3-123, 3-130, 3-183, 4-252
TC. See tropical cyclone
TELEMAC. See 2D:model:TELEMAC
temperature, 1-53
change, 2-91
high, 1-57
profiles, 4-122
trends, 4-357
Tennessee River
Valley, 2-153, 2-156, 3-83, 3-182
Watershed, 4-246
TRMM, Tropical Rainfall Measuring Mission,
4-100, 4-111
tropical cyclone, 1-11, 1-17, 1-64, 1-67, 1-91, 1-100, 1-123, 1-194, 1-198, 1-204, 2-53, 2-55, 2-59, 2-71, 2-89, 2-95, 2-101, 2-105, 2-112, 3-15, 3-29, 3-42, 3-47, 3-53, 3-67, 3-99, 3-101, 3-193, 4-14, 4-35, 4-51, 4-57, 4-61, 4-68, 4-73, 4-98, 4-125, 4-138, 4-346, 4-355, 4-370, 4-380
parameters, 2-65
P-Surge, 4-49
variable cross track, 4-51
tropical storm remnant, 3-357
TSR, 2-382, 4-127
tsunami, 1-6, 2-52, 2-409, 2-420, 2-395, 4-318, 4-455
model, 1-25
uncertainty, 1-36, 1-72, 1-125, 1-148, 1-167, 1-178, 1-187, 1-197, 2-30, 2-53, 2-74, 2-78, 2-87, 2-152, 2-165, 2-177, 2-179, 2-187, 2-219, 2-270, 2-320, 2-338, 2-340, 2-377, 2-400, 2-403, 3-21, 3-29, 3-40, 3-67, 3-71, 3-90, 3-94, 3-105, 3-119, 3-126, 3-136, 3-138, 3-149, 3-163, 3-194, 3-202, 3-246, 3-304, 3-315, 3-326, 3-334, 3-389, 4-30, 4-34, 4-35, 4-57, 4-81, 4-88, 4-95, 4-114, 4-163, 4-196, 4-197, 4-207, 4-228, 4-244, 4-254, 4-256, 4-264, 4-275, 4-282, 4-291, 4-313, 4-355, 4-381, 4-426, 4-450, 4-462, 4-477
analytical, 4-242
Bayesian, 1-86
bounds, 1-89
discretized, 4-64
distribution choice, 2-187, 2-193, 2-197, 3-70
full, 1-15, 2-45, 3-17
hazard curve evaluation, 2-317
hydrologic, 2-99, 3-338, 4-233
integration results, 2-76
joint probability analysist, 2-47, 3-19
knowledge, 2-356, 3-317, 4-175, 4-233
PRA, 3-373
reduced, 2-219, 3-357
SLR projections, 2-100
sources, 1-42
SRR, 2-60
storm surge, 1-17, 1-193, 2-47, 2-54, 3-19, 3-95, 4-58
temporal, 1-257
tolerance, 4-215
uncertainty analysis, 2-87, 4-326, 4-476
UA, 4-198
uncertainty characterization, 1-15, 2-46, 2-74, 2-81, 2-341, 3-18, 3-105, 4-233
APPENDIX  B:  INDEX OF CONTRIBUTORS

This index includes authors, co-authors, panelists, poster authors and self-identified participants from the audience who spoke in question and answer or panel discussions.

Adams, Lea, 4-162
Ahn, Hosung, 5-490
Aird, Thomas, 2-38, 2-407, 3-11, 3-195, 3-380, 4-12, 4-378, 4-419, 5-490
Al Kajbaf, Azin, 4-312
Allen, Blake, 4-323
Anderson, Victoria, 3-354, 3-370, 3-374
Andre, M.A., 4-287
Archfield, Stacey A., 4-206
Asquith, William, 2-184
Bacchi, Vito, 4-195, 4-320
Baecher, Gregory, 3-197, 3-213, 4-315
Bardet, Philippe M., 4-287, 4-306, 4-309
Barker, Bruce, 4-323
Bellini, Joe, 2-30
Bender, Chris, 4-91, 4-92, 4-94, 4-97
Bensi, Michelle, 1-24, 4-312, 4-435, 4-464, 4-465, 4-466, 4-469, 4-471, 4-473, 5-490
Bertrand, Nathalie, 4-195, 4-320
Bittner, Alvah, 1-220, 2-267, 3-240
Blackaby, Emily, 3-5, 3-195, 3-209
Bowles, David, 4-323
Branch, Kristi, 1-220, 2-267, 3-240
Breithaupt, Steve, 3-346, 5-490
Bryce, Robert, 1-129, 2-349
Byrd, Aaron, 1-166
Caldwell, Jason, 4-112, 4-323
Campbell, Andrew, 2-12, 4-357, 4-422, 4-455, 4-470, 4-473, 5-490
Carney, Shaun, 3-346, 4-272, 4-306, 4-307, 4-308, 4-310
Carr, Meredith, 2-38, 2-407, 3-9, 3-11, 3-380, 4-9, 4-12, 4-162, 4-252, 4-311, 4-456, 4-472, 4-474, 5-490
Charkas, Hasan, 5-490
Cheok, Michael, 5-490
Cohn, Timothy, 1-174, 4-250
Coles, Garill, 1-220, 2-267, 3-240
Cook, Christopher, 1-24, 3-351, 3-374, 5-490
Coppersmith, Kevin, 1-129, 2-349, 3-304, 4-261
Correia, Richard, 1-5, 5-490

Craven, Owen, 3-5, 3-195, 3-209
Cummings, William (Mark), 2-256, 3-227, 4-386, 4-419, 4-420, 4-421, 4-422
Dalton, Angela, 1-220, 2-267, 3-240
Daoued, A. Ben, 4-315
Davis, Lisa, 3-5, 3-195, 3-209
DeNeale, Scott, 3-197, 3-198, 3-213, 3-219, 4-111, 4-142, 4-312, 4-315, 4-320
Denis, Suzanne, 4-464, 4-467, 4-468, 4-469, 4-472, 4-473
Dib, Alain, 3-42
Dinh, N., 4-287
Dong, John, 4-323
DuLuc, Claire-Marie, 2-391, 4-195, 4-252, 4-253
Dunn, Christopher, 2-370, 2-398, 4-162
England, John, 2-370, 2-396, 2-400, 2-401, 3-68, 3-319, 3-347, 3-348, 3-349, 3-372, 3-373, 4-112, 4-156, 4-157, 4-159, 4-160, 4-161, 4-206, 4-252, 4-253, 4-254, 4-255, 4-256, 4-258, 4-259, 4-260, 4-307, 4-311, 4-363
Fearon, Kenneth, 3-322, 3-347, 3-372
Ferrante, Fernando, 3-315, 3-351, 3-370, 3-372
Fuhrmann, Mark, 2-38, 2-407, 3-11, 3-163, 3-375, 3-380, 4-12, 4-162, 4-252, 5-490
Furstenau, Raymond, 4-1, 4-9, 5-490
Gage, Matthew, 3-209
Gaudron, Jeremy, 4-464, 4-465, 4-467, 4-472
Gifford, Ian, 4-456, 4-464, 4-467
Godaire, Jeanne, 3-195, 3-205
Gonzalez, Victor M., 1-190, 2-50, 3-94, 3-198, 3-223, 3-316, 3-347, 3-348, 3-349, 3-350, 4-56, 4-91, 4-95, 4-97
Gupta, A., 4-287
Hall, Brian, 4-227
Hamburger, Kenneth, 5-490
Hamdi. Y, 4-315
Han, Kun-Yeun, 4-328
Harden, Tessa, 2-224, 3-163, 3-194, 3-199, 3-226, 4-242, 4-243, 4-252, 4-253, 4-255, 4-256, 4-258
Hartford, Des, 4-470
Hockaday, William, 3-5, 3-195, 3-209
Holman, Katie, 1-63, 2-148, 3-70
Huffman, George J., 4-98, 4-156, 4-158, 4-160, 4-161
Ishida, Kei, 1-86, 2-98
Jasim-Hanif, Sharon, 3-335, 3-348
Jawdy, Curt, 2-375, 2-396, 2-400, 4-272
Kanney, Joseph, 1-7, 2-38, 2-266, 2-367, 2-407, 3-11, 3-94, 3-193, 3-316, 3-348, 3-349, 3-369, 3-380, 4-12, 4-33, 4-91, 4-242, 4-256, 4-306, 4-307, 4-309, 4-310, 4-329, 4-363, 4-374, 4-421, 4-423, 4-455, 4-456, 4-464, 4-465, 4-473, 5-490
Kao, Shih-Chieh, 3-197, 3-198, 3-213, 3-219, 4-111, 4-142, 4-156, 4-157, 4-160, 4-312, 4-320
Kappel, Bill, 3-41, 3-69
Kavvas, M. Levent, 1-86, 2-98, 3-42, 3-69
Keeney, David, 1-63, 2-148, 3-70
Keith, Mackenzie, 3-163, 4-243
Kelson, Keith, 3-192, 4-208, 4-227, 4-252, 4-253, 4-255, 4-256, 4-257, 4-259
Kiang, Julie, 2-184, 3-116
Kim, Beomjin, 4-328
Kim, Minkyu, 4-328
Klinger, Ralph, 3-195, 3-205
Kohn, Nancy, 1-220
Kolars, Kelsey, 3-116
Kovach, Robin, 4-364
Kunkel, Kenneth, 4-329, 4-376, 4-378
Kvarfordt, Kellie, 1-238, 2-177, 3-149
Lehman, Will, 4-162, 4-252, 4-253, 4-254, 4-255, 4-257, 4-258, 4-260, 4-306, 4-307, 4-308, 4-309, 4-311
Leone, David, 4-80
Leung, Ruby, 1-50, 2-85, 3-29, 3-115, 4-349, 4-363, 4-374, 4-375
Lim, Young-Kwon, 4-364, 4-374
Lin, L., 4-287
Littlejohn, Jennene, 5-490
Lombardi, Rachel, 3-209
Ma, Zhegang, 1-250, 2-284, 3-199, 3-223, 3-360
Mahoney, Kelly, 3-68, 3-69
McCann, Marty, 3-40, 3-388
Melby, Jeffrey, 1-190, 2-50
Meyer, Philip, 1-129, 2-303, 4-261
Miller, Andrew, 4-423, 4-464, 4-467, 4-468, 4-469, 4-471, 4-472, 4-474
Miller, Gabriel, 3-339, 3-345, 3-346
Mitman, Jeffrey, 1-36
Mohammadi, Somayeh, 4-312
Molod, Andrea, 4-364
Montanari, N., 4-287
Mouhous-Voyneau, N., 4-315
Muro-Ravaud, Mathieu, 1-86, 2-98, 3-42
Muto, Matthew, 4-323
Nadal-Caraballo, Norberto, 1-190, 2-50, 2-370, 2-399, 3-94, 3-198, 3-223, 3-316, 4-56, 4-91, 4-94, 4-95, 4-96, 4-97
Nakoski, John, 4-1, 4-28
Neff, Keil, 2-199, 3-135
Nicholson, Thomas, 3-347, 3-349, 3-369, 4-261, 4-306, 5-490
Novembre, Nicole, 4-323
O’Connor, Jim, 2-224, 3-163, 4-242, 4-243
Ott, William, 1-5, 5-490
Pawson, Steven, 4-364
Pearce, Justin, 4-227
Perica, Sanja, 2-367, 2-399, 2-400
Pheulpin, Lucie, 4-195, 4-320
Philip, Jacob, 1-261, 2-38, 2-407, 3-11, 3-380, 4-12, 4-419, 4-421, 4-422, 5-490
Pimentel, Frances, 3-354
Prasad, Rajiv, 1-50, 1-129, 1-147, 1-220, 2-85, 2-303, 2-349, 2-365, 3-29, 3-19, 3-193, 3-240, 3-304, 3-315, 4-261, 4-306, 4-307, 4-349, 4-363
Prasad, Rajiv, 2-267
Prescott, Steven, 2-284, 3-194, 3-199, 3-223, 4-287
Quinlan, Kevin, 4-156, 4-162, 4-374, 4-377, 5-490
Ramos-Santiago, Efrain, 3-198, 3-223
Randelovic, Marko, 4-23, 4-72, 4-384, 4-386, 4-423, 5-490
Randelovic, Marko, 4-378
Rebour, Vincent, 2-391, 2-399, 4-195
Reisi-Fard, Mehdi, 2-22, 3-227, 5-490
Ryan, E., 4-287
Ryberg, Karen, 3-116, 3-192, 3-194
Salisbury, Michael, 4-72, 4-91, 4-96
Salley, Mark Henry, 5-490
Sampath, Ramprasad, 2-284, 3-199, 3-223, 4-287
Schaefer, Mel, 4-114, 4-117, 4-125, 4-156, 4-158, 4-159, 4-160, 4-161, 4-286
Schneider, Ray, 2-30, 3-350, 3-362, 3-371, 4-374, 4-375, 4-377, 4-378, 4-384, 4-385, 4-386, 4-419, 4-446, 4-464, 4-466, 4-469, 4-471, 4-472
Schubert, Sigfried, 4-364
Sergent, P., 4-315
Shaun Carney, 4-310
Siu, Nathan, 3-257, 3-367, 3-369, 3-370, 3-372, 4-456
Skahill, Brian, 1-166, 2-334, 2-396, 2-397, 2-399, 2-400, 3-195, 3-200, 3-295, 4-206
Smith, Brennan, 3-197, 3-213
Smith, Curtis, 1-238, 1-250, 2-177, 2-284, 2-387, 2-397, 2-398, 3-149, 3-199, 3-223
Stapleton, Daniel, 4-80
Stewart, Kevin, 4-315
Stewart, Lance, 3-5, 3-195, 3-209
Stinchcomb, Gary, 3-5, 3-179, 3-195, 3-209
Taflanidis, Alexandros, 4-56
Taylor, Arthur, 4-33, 4-91, 4-93, 4-95, 4-96, 4-97
Taylor, Scott, 2-267, 3-240
Thaggard, Mark, 5-490
SUMMARY AND CONCLUSIONS

Therrell, Matthew, 3-209
Tiruneh, Nebiyu, 3-116, 5-490
Vail, Lance, 1-50, 1-129, 2-85
Verdin, Andrew, 2-148, 3-70
Vuyovich, Carrie, 3-295
Wahl, Tony, 1-206, 3-258, 4-398, 4-419
Wang, Bin, 4-80, 4-91, 4-94, 4-96, 4-97
Wang, Zeechung (Gary), 4-456
Ward, Katie, 4-323
Watson, David, 3-197, 3-213, 4-111, 4-320
Weber, Mike, 2-1, 2-7, 3-1, 3-9, 5-490
Weglian, John, 2-46, 2-75, 2-165, 2-213, 2-243, 2-318, 2-402, 3-20, 3-109, 3-191, 3-192, 3-193, 3-234, 3-250, 3-295, 3-357, 3-369, 3-370, 3-373, 3-374, 3-375, 5-490
Wille, Kurt, 3-195, 3-205
Wright, Joseph, 1-174, 2-199, 3-135, 3-345, 3-346, 3-347, 3-372, 3-373
Yegorova, Elena, 2-38, 2-407, 3-11, 3-29, 3-380, 4-12, 4-98, 4-156, 5-490
Ziebell, David, 2-243, 3-234
<table>
<thead>
<tr>
<th>Agency/Institution</th>
<th>Page Numbers</th>
</tr>
</thead>
<tbody>
<tr>
<td>AECOM</td>
<td>4-485, 4-486</td>
</tr>
<tr>
<td>Agricultural Research Service - USDA</td>
<td>xxxiv</td>
</tr>
<tr>
<td>Alden Research Laboratory</td>
<td>3-393, 4-480</td>
</tr>
<tr>
<td>Amec Foster Wheeler</td>
<td>2-419, 3-392</td>
</tr>
<tr>
<td>American Polywater Corporation</td>
<td>4-479, 4-484</td>
</tr>
<tr>
<td>Appendix R Solutions, Inc.</td>
<td>3-391</td>
</tr>
<tr>
<td>Applied Weather Associates</td>
<td>3-345, 3-394, 4-481, 4-482</td>
</tr>
<tr>
<td>Aterra Solutions</td>
<td>2-3, 2-30, 2-419, 2-422, 3-391, 4-478, 4-483</td>
</tr>
<tr>
<td>Atkins</td>
<td>2-420, 3-392, 4-2, 4-3, 4-72, 4-91, 4-479, 4-485</td>
</tr>
<tr>
<td>Battelle, Columbus, Ohio</td>
<td>1-220, 2-5, 2-267, 3-6, 3-240, 3-395, 4-482</td>
</tr>
<tr>
<td>BCO</td>
<td>1-4, 1-220</td>
</tr>
<tr>
<td>Baylor University</td>
<td>3-5, 3-195, 3-209</td>
</tr>
<tr>
<td>BC Hydro</td>
<td>4-481</td>
</tr>
<tr>
<td>Bechtel Corporation</td>
<td>3-396, 3-397, 4-478, 4-482, 4-483, 4-485, 4-486</td>
</tr>
<tr>
<td>Bittner and Associates</td>
<td>2-5, 2-267, 2-419, 3-6, 3-240</td>
</tr>
<tr>
<td>B&amp;A</td>
<td>xii, 1-4, 1-220</td>
</tr>
<tr>
<td>Booz Allen Hamilton</td>
<td>4-481</td>
</tr>
<tr>
<td>Brava Engineering, Inc.</td>
<td>4-6, 4-323</td>
</tr>
<tr>
<td>Canadian Nuclear Safety Commission</td>
<td>xiii, 3-394, 4-482</td>
</tr>
<tr>
<td>Center for Nuclear Waste Regulatory Analyses</td>
<td></td>
</tr>
<tr>
<td>SwrI</td>
<td>3-392, 3-398</td>
</tr>
<tr>
<td>Centroid PIC</td>
<td>2-5, 2-284, 3-5, 3-199, 3-223, 4-5, 4-287</td>
</tr>
<tr>
<td>Cerema</td>
<td>4-6</td>
</tr>
<tr>
<td>Coastal and Hydraulics Laboratory</td>
<td>xiii, 2-3, 2-6, 2-50, 2-334, 2-421, 2-423, 2-424, 3-4, 3-5, 3-94, 3-195, 3-198, 3-223, 3-393, 3-395, 3-397, 4-2, 4-3, 4-4, 4-56, 4-91, 4-206</td>
</tr>
<tr>
<td>Coppersmith Consulting, Inc.</td>
<td>xii, 2-6, 2-349, 2-420, 3-6, 3-304, 3-392, 4-5, 4-261</td>
</tr>
<tr>
<td>CCI</td>
<td>xii, 1-3, 1-63, 1-129</td>
</tr>
<tr>
<td>Curtiss-Wright</td>
<td>4-479</td>
</tr>
<tr>
<td>Defense Nuclear Facilities Safety Board</td>
<td>2-420</td>
</tr>
<tr>
<td>DNFSB</td>
<td>4-485</td>
</tr>
<tr>
<td>DEHC Ingenieros Consultores</td>
<td>4-483</td>
</tr>
<tr>
<td>Department of Defense</td>
<td>2-302</td>
</tr>
<tr>
<td>Department of Energy</td>
<td>xv, 2-6, 2-387, 3-7, 3-335, 3-394, 3-395, 4-483</td>
</tr>
<tr>
<td>DOE, x, xv, xxii, xxvi, 2-397, 2-398, 3-348, 4-306, 4-309, 4-454, 4-481</td>
<td></td>
</tr>
<tr>
<td>Department of Health and Human Services</td>
<td>3-392</td>
</tr>
<tr>
<td>Department of Homeland Security</td>
<td>3-394, 3-396</td>
</tr>
<tr>
<td>Dewberry</td>
<td>2-424, 3-397, 4-480, 4-485, 4-486</td>
</tr>
<tr>
<td>Dominion Energy</td>
<td>4-486</td>
</tr>
<tr>
<td>Duke Energy</td>
<td>2-422, 2-424, 3-395, 3-398, 4-487</td>
</tr>
<tr>
<td>Electric Power Research Institute</td>
<td>iii, xvi, 2-1, 2-425, 3-393, 4-1, 4-479</td>
</tr>
<tr>
<td>EPRI, iii, xvi, xxii, xxxii, 2-1, 2-3, 2-4, 2-5, 2-6, 2-37, 2-46, 2-75, 2-165, 2-213, 2-223, 2-243, 2-318, 2-333, 2-402, 2-407, 2-421, 3-1, 3-3, 3-4, 3-6, 3-7, 3-20, 3-27, 3-28, 3-109, 3-115, 3-191, 3-193, 3-234, 3-238, 3-250, 3-257, 3-295, 3-315, 3-351, 3-357, 3-369, 3-370, 3-372, 3-374, 3-375, 3-392, 3-398, 4-2, 4-7, 4-8, 4-23, 4-72, 4-378, 4-379, 4-384, 4-423, 4-462, 4-484, 5-490</td>
<td></td>
</tr>
<tr>
<td>Électricité de France</td>
<td>xvi, xxxiii, 2-262, 3-232</td>
</tr>
<tr>
<td>EDF, xvi, 3-232, 3-233, 4-8, 4-226, 4-384, 4-385, 4-434, 4-464, 4-465, 4-477, 4-481</td>
<td></td>
</tr>
<tr>
<td>Enercon Services, Inc.</td>
<td>2-422, 4-480</td>
</tr>
<tr>
<td>Engineer Research and Development</td>
<td></td>
</tr>
<tr>
<td>Center</td>
<td>xvi, 2-3, 2-6, 2-50, 2-334, 2-421, 2-423, 2-424, 3-5, 3-6, 3-7, 3-94, 3-195, 3-198, 3-200, 3-223, 3-295, 3-316, 3-393, 4-56</td>
</tr>
<tr>
<td>ERDC, xvi, 3-94, 4-56, 4-478, 4-480, 4-483, 4-484</td>
<td></td>
</tr>
<tr>
<td>Environment Canada and Climate Change</td>
<td>4-483</td>
</tr>
<tr>
<td>Environmental Protection Agency</td>
<td>xvi, xxxii</td>
</tr>
<tr>
<td>EPA, xvi, 4-260</td>
<td></td>
</tr>
<tr>
<td>Environmentalists Incorporated</td>
<td>2-422, 2-424</td>
</tr>
<tr>
<td>Exelon</td>
<td>4-477</td>
</tr>
<tr>
<td>Federal Emergency Management Agency</td>
<td>xvii, 2-50</td>
</tr>
<tr>
<td>FEMA, xvii, xxii, 2-50, 2-399, 3-349, 3-396, 4-91, 4-259, 4-260</td>
<td></td>
</tr>
<tr>
<td>Federal Energy Regulatory Commission</td>
<td>xvii, 2-420, 2-421, 2-422, 3-7, 3-322, 3-393</td>
</tr>
</tbody>
</table>
NWS, xiii, xx, xxiv, xxv, xxvi, xxvii, xxxi, 2-99, 2-165, 2-256, 2-399, 2-400, 2-421, 2-423, 3-396, 4-2, 4-33, 4-34, 4-480, 4-481, 4-486
Natural Resources Conservation Service
NRCS, xxvi, xxvii, xxxv, 3-393, 3-394
Naval Postgraduate School, 4-480
NIST, 3-395
North Carolina State University, 4-5, 4-7, 4-287, 4-329, 4-482
Nuclear Energy Agency, xxv, 4-1, 4-2, 4-28
NEA, xxv
Nuclear Energy Institute, xxvi, 3-7
NEI, xxvi, 2-333, 3-354, 3-369, 3-370, 3-374, 3-391, 3-396, 4-464, 4-473, 4-484
NuScale Power, 4-487
Nuvia USA, 3-391
Oak Ridge National Laboratory, xxvii, 2-424, 3-5, 3-198, 3-219, 3-392, 3-394, 3-397, 3-398, 4-6, 4-312, 4-315, 4-320, 4-479, 4-482
ORNL, xxvii, 3-5, 3-197, 3-213, 4-3, 4-111, 4-142, 4-156, 4-160
Oklo Inc., 4-484
Oregon Water Science Center - USGS, 2-224, 2-421, 3-5, 3-199, 3-226
Pacific Northwest National Laboratory, xxviii, 2-4, 2-5, 2-6, 2-85, 2-267, 2-303, 2-349, 2-419, 2-420, 2-422, 2-423, 3-3, 3-6, 3-29, 3-240, 3-304, 3-395, 3-396, 4-5, 4-7, 4-261, 4-306, 4-349, 4-374, 4-478, 4-482, 4-484
PNNL, xxviii, 1-3, 1-4, 1-50, 1-63, 1-129, 1-147, 1-220, 3-192, 3-193, 3-240, 4-307
Parsons, 4-480, 4-485
Penn State University, 4-483
PG&E, 4-484
PRISM Climate Group at Oregon State University, xxviii
RAC Engineers and Economists, LLC, 3-391
River Engineering & Urban Drainage Research Centre, 4-482
RTI International, 3-346, 3-391, 3-392, 4-5, 4-272, 4-306, 4-478
Sargent & Lundy, 2-423, 4-485
Schnabel Engineering, 4-480
Science Systems and Applications, Inc., 4-7, 4-364
Secretariat of Nuclear Regulation Authority, 4-481
SEPI, Inc., 4-487
Sorbonne University—Université de Technologie de Compiègne, 4-6, 4-315
Southern California Edison, 4-6, 4-323
Southern Nuclear, 3-397, 4-485
Southwest Research Institute, 2-420, 2-425, 3-398, 4-479
Taylor Engineering, 2-419, 3-391, 4-3, 4-91, 4-478
Technical Services Center - USBR, 2-4, 2-148, 2-199, 2-423, 2-424, 2-425, 3-3, 3-4, 3-5, 3-70, 3-135, 3-195, 3-395
Tennessee Valley Authority, xxiii, 2-6, 2-375, 2-419, 2-421, 2-422, 3-399, 3-391, 3-395, 3-397, 4-5, 4-272, 4-478
TVA, xxiii, 2-223, 2-316, 2-396, 2-400, 2-401, 3-191, 3-345, 3-346, 3-397, 4-5, 4-121, 4-125, 4-142, 4-156, 4-157, 4-159, 4-251, 4-252, 4-272, 4-286, 4-307, 4-308, 4-310
U.S. Army Corps of Engineers, xiii, xvi, xxxiv, 1-147, 2-3, 2-6, 2-420, 2-421, 2-422, 2-423, 2-424, 3-5, 3-6, 3-7, 3-195, 3-198, 3-200, 3-223, 3-295, 3-316, 3-319, 3-393, 4-2, 4-56, 4-113, 4-307, 4-482, 4-483, 4-484
COE, xiii, xxxiv
Corps, xiii, xxxiv, 2-50, 2-334, 2-370, 3-347, 3-348, 3-349, 3-372, 3-373, 4-91, 4-156, 4-159, 4-160, 4-259, 4-260, 4-307, 4-309, 4-311, 4-470, 4-482, 4-483, 4-484
Dam Safety Production Center, 4-208
Galveston District, 4-3, 4-112, 4-478
RMC, Risk Management Center, xxx, 2-420, 3-7, 3-319, 3-347, 3-348, 3-349, 3-393, 4-3, 4-4, 4-112, 4-156, 4-206, 4-208, 4-227, 4-252, 4-308, 4-479
Sacramento Dam Safety Protection Center, xv, 3-394, 4-4, 4-227, 4-252
USACE, xiii, xvi, xvii, xx, xxii, xxx, xxxiii, xxxiv, 1-4, 1-147, 1-166, 1-190, 2-50, 2-199, 2-396, 2-397, 2-398, 2-399, 2-400, 2-401, 3-68, 3-347, 3-348, 3-349, 3-350, 3-372, 3-373, 3-397, 4-3, 4-4, 4-5, 4-91, 4-97, 4-112, 4-125, 4-156, 4-162, 4-206, 4-208, 4-227, 4-228, 4-252, 4-306, 4-478, 4-479, 4-480, 4-482, 4-483, 4-484
U.S. Bureau of Reclamation, xii, xvii, xxxiii, xxxiv, 1-3, 1-63, 2-4, 2-148, 2-199, 2-
421, 2-423, 2-424, 2-425, 3-3, 3-4, 3-5, 3-6, 3-70, 3-135, 3-136, 3-149, 3-192, 3-195, 3-205, 3-258, 3-345, 3-346, 3-347, 3-348, 3-350, 3-372, 3-373, 3-393, 3-394, 3-395, 3-397, 3-398, 4-7, 4-114, 4-117, 4-242, 4-254, 4-259, 4-363, 4-398, 4-419, 4-470, 4-483, 4-486

USBR, xvii, xxv, xxxii, xxxiv, 1-3, 1-4, 1-63, 1-147, 1-174, 1-206, 2-213, 2-241, 2-396, 2-400, 3-192, 3-398, 4-125

U.S. Department of Agriculture, xxxiv

USDA, xxxi, xxxiv, xxxv, 3-393

U.S. Fish and Wildlife Service, xxxiv

USFWS, xxxiv

U.S. Geological Survey, xxxiv, 2-4, 2-178, 2-184, 2-419, 2-421, 2-423, 3-4, 3-5, 3-116, 3-117, 3-163, 3-199, 3-226, 3-391, 3-393, 3-394, 3-395, 3-396, 4-4, 4-206, 4-243, 4-252, 4-259, 4-477, 4-481, 4-482, 4-483

USGS, xxi, xxvii, xxviii, xxxiv, xxxv, 1-4, 1-147, 1-174, 2-5, 2-178, 2-184, 2-198, 2-224, 3-150, 3-162, 3-192, 3-194, 3-196, 3-348, 3-394, 4-242, 4-256, 4-258, 4-259

UNC Chapel Hill, 4-477

University of Alabama, 3-4, 3-5, 3-179, 3-190, 3-195, 3-196, 3-209, 3-392, 3-395

University of California

U.C. Davis, xxi, 1-3, 1-63, 1-86, 2-4, 2-98, 2-422, 2-423, 3-3, 3-42, 3-392, 3-395

University of Costa Rica, 4-483

University of Maryland, xxxiv, 3-5, 3-197, 3-226, 3-391, 4-6, 4-8, 4-312, 4-315, 4-435, 4-464, 4-477, 4-478, 4-483

US Global Change Research Program, 4-477

Utah State University, 2-396, 3-391

Virginia Tech, 2-422

Weather & Water, Inc., 4-6, 4-323

WEST Consultants, 4-479

Western University, 4-486

Westinghouse, 2-3, 2-30, 2-424, 3-7, 3-350, 3-362, 3-371, 3-397, 4-7, 4-8, 4-378, 4-419, 4-446, 4-464, 4-485

Wood, 2-149, 3-391, 5-490

World Meteorological Organization

WMO, xxxv, 4-376

Zachry Nuclear Engineering, 4-484