3rd Annual Probabilistic Flood Hazard Assessment Research Workshop

PROGRAM

December 4-5, 2017
U.S. NRC Headquarters, Rockville, Maryland
Room T02-B3 (ACRS Meeting Room)

The purpose of this workshop is to inform internal Nuclear Regulatory Commission (NRC) stakeholders, partner agencies, industry, and the general public about Probabilistic Flood Hazard Assessment (PFHA) research being conducted by the NRC Office of Nuclear Regulatory Research and the Electric Power Research Institute (EPRI) under a NRC-EPRI MOU on Collaborative Nuclear Safety Research. Technical presentations will be given by NRC and EPRI contractors and staff. Partner agencies will take part in a panel discussing and taking questions on their PFHA research and development programs. A second panel comprised of NRC and industry experts will provide perspectives on challenges in implementing external flooding PRAs. The PFHA research group in the NRC Office of Nuclear Regulatory Research look forward to receiving feedback and perspectives from our NRC and EPRI colleagues, industry, partner federal agencies, other organizations, and the public. Conference proceedings including abstracts and presentations will be available following the workshop.

Technical presentations will include time for clarifying questions. General questions and answers periods will be scheduled at the end of each day for feedback and generic questions about research related to PFHA for nuclear facilities.

AGENDA: MONDAY, DECEMBER 4TH, 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 & 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* & 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* & Alain Dib* Hydrologic Research Laboratory, Dept. of Civil & Envr. Engineering, University of California, Davis*	1B-2
10:45 – 11:15	Research to Develop Guidance on Extreme Precipitation Estimates in Orographic Regions *Kathleen Holman^, A. Verdin & D. Keeney, U.S. Bureau of Reclamation, Technical Service Center, Flood Hydrology & 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-Caraballo, & Victor Gonzalez*, U.S. Army Engineer R&D Center, Coastal and Hydraulics Laboratory*	1C-1
11:45 – 12:15	Probabilistic Flood Hazard Assessment – Storm Surge *John Weglian*, EPRI*	1C-2
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 *Karen Ryberg*, Kelsey Kolars & Julie Kiang, U.S. Geological Survey*	1D-1
13:45 – 14:15	Extending Frequency Analysis Beyond Current Consensus Limits *Keil Neff* & Joseph Wright, U.S. Bureau of Reclamation, Technical Service Center, Flood Hydrology & Meteorology*	1D-2
14:15 – 14:45	Development of External Hazard Information Digests for Operating NPP sites *Kellie Kvarfordt* & Curtis Smith, Idaho National Laboratory*	1D-3
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 *Tess Harden*, Jim O'Connor & Mackenzie Keith, U.S. Geological Survey*	1E-1
15:30 – 16:00	Collection of Paleoflood Evidence *Lisa Davis*, University of Alabama & Gary Stinchcomb, Murray State University*	1E-2
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[1,2], Gary E. Stinchcomb[1,2], Steven L. Forman[3], Lisa Davis[4] Rachel Lombardi[4], Emily Blackaby[3], Owen Craven[3], William Hockaday[3]
1. Department of Geosciences, Murray State Univ.; 2. Watershed Studies Institute, Murray State Univ.; 3. Department of Geology, Baylor Univ.; 4. Department of Geography, Univ. of Alabama

A regional chronology of floods and river activity during the last 10,000 years in the Eastern U.S

Lisa Davis[1], Rachel Lombardi[1], Gary Stinchcomb[2], C. Lance Stewart[3], Matthew D. Therrell[1], Matthew Gage[4]
1. Department of Geography, Univ.of Alabama; 2. Watershed Studies Institute, Murray State Univ.; 3. Department of Geosciences, Murray State Univ.; 4. Office of Archeological Research, Univ. 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

Shi-Chieh Kao and Scott DeNeale, Oak Ridge National Laboratory

Quantification of Uncertainty in Probabilistic Storm Surge Models

Norberto Nadal-Caraballo, Victor Gonzalez, 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, 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

Tess Harden, U.S. Geological Survey, Oregon Water Science Center

AGENDA: TUESDAY, DECEMBER 5TH, 2017

08:00 – 08:10	Day 2 Welcome	

Session 2A: Reliability of Flood Protection and Mitigation

Session Chair: Mehdi Reisi Fard, NRC/NRR

08:10 – 08:40	Performance of Flood-Rated Penetration Seals *William (Mark) Cummings*, Fire Risk Management, Inc.*	2A-1
08:40 – 09:10	EPRI Flood Protection Project Status *David Ziebell^ & John Weglian, EPRI*	2A-2
09:10 – 09:40	A Conceptual Framework to Assess Impacts of Environmental Conditions on Manual Actions for Flood Protection and Mitigation at Nuclear Power Plants *Rajiv Prasad*, Garill Coles, Angela Dalton, & Nancy Kohn, Pacific Northwest National Laboratory; Kristi Branch & Alvah Bittner, Bittner and Associates; R. Scott Taylor, Battelle*	2A-3
09:40 – 09:55	BREAK	
09:55 – 10:25	External Flooding PRA Walkdown Guidance *John Weglian*, EPRI*	2A-4
10:25 – 10:55	Erosion Testing of Zoned Rockfill Embankments *Tony Wahl^, U.S. Bureau of Reclamation*	2A-5

Session 2B: PFHA Frameworks

Session Chair: John Weglian, EPRI

10:55 – 11:25	A Framework for Inland Probabilistic Flood Hazard Assessments: Analysis of Extreme Snow Water Equivalent in Central New Hampshire *Brian Skahill* & Carrie Vuyovich, U.S. Army Corps of Engineers, Engineer Research and Development Center*	2B-1
11:25 – 11:55	Structured Hazard Assessment Committee Process for Flooding (SHAC-F) for Riverine Flooding *Rajiv Prasad* & Phillip Meyer, Pacific Northwest National Laboratory; Kevin Coppersmith, Coppersmith Consulting*	2B-2
11:55 – 13:00	LUNCH	

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* *John England, U.S. Army Corps of Eng., Risk Management Center* *Kenneth Fearon, Federal Energy Regulatory Commission, Office of Energy Projects, Division of Dam Safety & Inspections* *Sharon Jasim-Hanif, Department of Energy, Office of Nuclear Safety* *Gabriel Miller, Tennessee River Valley Authority, River Management Department*	2C-1
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*	2C-2
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*	2D-1
16:15 – 16:35	Future Work in PFHA at NRC *Joseph Kanney, Meredith Carr*, Tom Aird, Elena Yegorova, Mark Fuhrmann & Jacob Philip, NRC/RES*	2D-2
16:35 – 17:00	Final Wrap-up and Public Comments/Questions	

ABSTRACTS

MONDAY, DECEMBER 4TH, 2017

** denotes presenter, ^ denotes remote presenter*

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

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

L. Ruby Leung* & Rajiv Prasad, Pacific Northwest National Laboratory

This project is part of the U.S. Nuclear Regulatory Commission's (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.

1B-2 Numerical Modeling of Local Intense Precipitation Processes

M. Levent Kavvas, Mathieu Mure-Ravaud* & Alain Dib*
Hydrologic Research Laboratory, Department of Civil & Environmental Engineering, University of California, Davis

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.

1B-3 Research to Develop Guidance on Extreme Precipitation Estimates in Orographic Regions

Kathleen Holman^, A. Verdin & D. Keeney
U.S. Bureau of Reclamation, Technical Service Center, Flood Hydrology & Meteorology

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.

Session 1C: Storm Surge; Chair: Joseph Kanney, NRC/RES

1C-1 Quantification of Uncertainty in Probabilistic Storm Surge Models

Norberto C. Nadal-Caraballo, & Victor Gonzalez*
U.S. Army Engineer R&D Center, Coastal and Hydraulics Laboratory

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-CHL) is performing a comprehensive assessment of uncertainties in probabilistic storm surge models in support of the U.S. Nuclear Regulatory Commission's (USNRC) efforts to develop a framework for probabilistic storm surge hazard assessment for nuclear power plants. The treatment of uncertainties in the JPM-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 JPM-OS 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 body, center, 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.

1C-2 **Probabilistic Flood Hazard Assessment – Storm Surge**

John Weglian*, EPRI

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.

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

1D-1 **Flood Frequency Analyses for Very Low Annual Exceedance Probabilities using Historic and Paleoflood Data, with Considerations for Nonstationary Systems**

Karen Ryberg*, Kelsey Kolars & Julie Kiang, U.S. Geological Survey

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.

1D-2 Extending Frequency Analysis Beyond Current Consensus Limits

Keil Neff* & Joseph Wright
U.S. Bureau of Reclamation, Technical Service Center, Flood Hydrology & Meteorology

This project is part of the Nuclear Regulatory Commission's (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 1×10-4) from the context of the Bureau of Reclamation (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 in 104 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.

1D-3 Development of External Hazard Information Digests for Operating NPP sites

Kellie Kvarfordt* & Curtis Smith, Idaho National Laboratory

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.

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

1E-1 Improving Flood Frequency Analysis with a Multi-Millennial Record of Extreme Floods on the Tennessee River near Chattanooga, TN

Tess Harden*, Jim O'Connor & Mackenzie Keith, U.S. Geological Survey

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.

1E-2 Collection of Paleoflood Evidence

Lisa Davis*, University of Alabama & Gary Stinchcomb, Murray State University

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 (USA), as part of a broader effort to develop paleoflood data for flood frequency analyses for the Tennessee River.

Session 1F: Posters: Selected Abstracts; Chair: Tom Aird, NRC/RES

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.

Late Holocene Paleofloods Along the Middle Tennessee River Valley

C. Lance Stewart[1,2], Gary E. Stinchcomb[1,2], Steven L. Forman[3], Lisa Davis[4], Rachel Lombardi[4], Emily Blackaby[3], Owen Craven[3], William Hockaday[3]
[1.] Department of Geosciences, Murray State Univ., [2.] Watershed Studies Institute, Murray State Univ., [3.] Department of Geology, Baylor Univ., [4.] Department of Geography, Univ. of Alabama

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, 13C NMR analysis 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 13C 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.

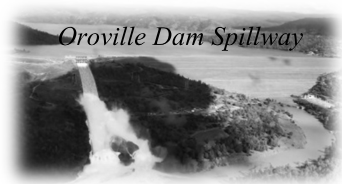
A regional chronology of floods and river activity during the last 10,000 years in the Eastern U.S

Lisa Davis[1], Rachel Lombardi[1], Gary Stinchcomb[2], C. Lance Stewart[3], Matthew D. Therrell[1], Matthew Gage[4]; [1.] Department of Geography, Univ. of Alabama, [2.]Watershed Studies Institute, Murray State Univ., [3.] Department of Geosciences, Murray State Univ., [4.]Office of Archeological Research, Univ. 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.

Critical Review of State of Practice in Dam Risk Assessment

David Watson, Scott DeNeale, Brennan Smith, Shih-Chieh Kao; Oak Ridge National Laboratory, 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.

Modeling Plant Response to Flooding Events

Zhegang Ma[1], Curtis L. Smith[1], Steven R. Prescott[1] and Ramprasad Sampath[2]

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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, Idaho National Laboratory (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 (SBDFA). The SBDFA framework was then applied to a LIP event as a case study. A 3-D plant model for a typical PWR and 3-D 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 3-D 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. 3-D simulation elements were incorporated into the EMRALD model and could communicate with the PRA logic. The integrated EMRALD model was run with 3-D 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).

TUESDAY, DECEMBER 5TH, 2017

Session 2A: Reliability of Flood Protection and Mitigation;

Chair: Mehdi Reisi Fard, NRC/NRR

2A-1 **Performance of Flood-Rated Penetration Seals**

William (Mark) Cummings*, Fire Risk Management, Inc.

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.

2A-2 **EPRI Flood Protection Project Status**

David Ziebell^ & John Weglian, EPRI

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.

2A-3 A Conceptual Framework to Assess Impacts of Environmental Conditions on Manual Actions for Flood Protection and Mitigation at Nuclear Power Plants

Rajiv Prasad*, Garill Coles, Angela Dalton, & Nancy Kohn, Pacific Northwest National Laboratory; Kristi Branch & Alvah Bittner, Bittner and Associates; R. Scott Taylor, Battelle

The U.S. Nuclear Regulatory Commission (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.

2A-4 External Flooding PRA Walkdown Guidance

John Weglian*, EPRI

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.

2A-5 **Erosion Testing of Zoned Rockfill Embankments**

Tony Wahl^, U.S. Bureau of Reclamation

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.

Session 2B: PFHA Frameworks; Chair: John Weglian, EPRI

2B-1 **A Framework for Inland Probabilistic Flood Hazard Assessments: Analysis of Extreme Snow Water Equivalent in Central New Hampshire**

Brian Skahill* & Carrie Vuyovich, U.S. Army Corps of Engineers, Engineer R&D Center

The Nuclear Regulatory Commission's (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 adaptions, 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.

2B-2 **Structured Hazard Assessment Committee Process for Flooding (SHAC-F) for Riverine Flooding;** Rajiv Prasad* & Phillip Meyer, Pacific Northwest National Laboratory; Kevin Coppersmith, Coppersmith Consulting

This research project is part of the U.S. Nuclear Regulatory Commission'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-F 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.