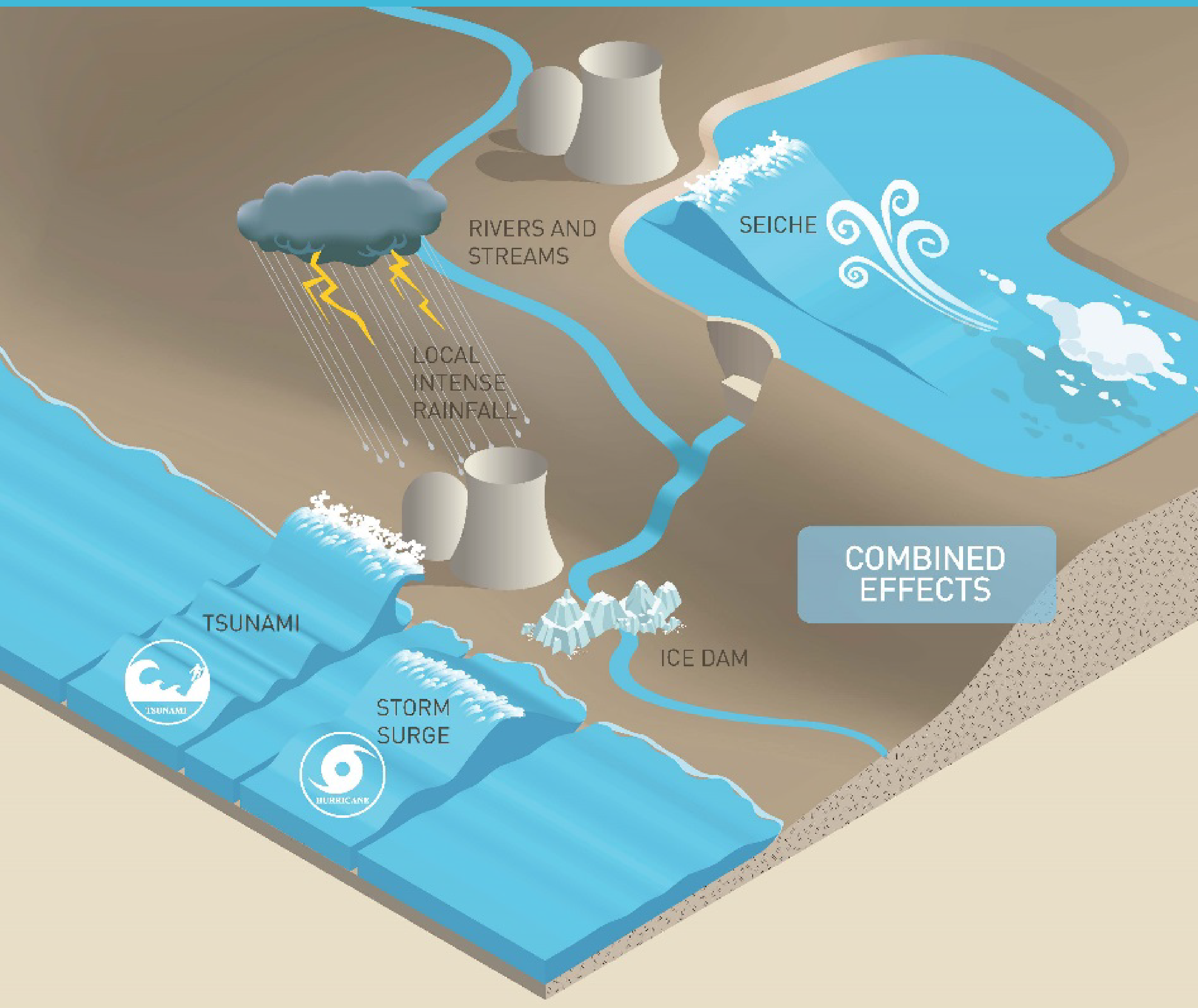
2nd Annual Probabilistic Flood Hazard Assessment Research Workshop

January 23-25, 2017

U.S. NRC Headquarters Auditorium
11555 Rockville Pike, Rockville, MD 20852

PROGRAM



Program Notes

The purpose of this workshop is to inform internal NRC stakeholders, partner federal agencies, industry, and the general public about PFHA research being conducted by the NRC Office of Research and the Electric Power Research Institute under a NRC-EPRI MOU on Collaborative Nuclear Safety Research. NRC licensing staff and industry representatives will present their perspective on PFHA research needs and priorities.

Workshop Structure

Technical presentations will be given by NRC and EPRI contractors and staff. Partner Federal agencies will be invited to take part in a panel discussing and taking questions on their PFHA research and development programs. Technical presentations will include time for clarifying questions. General question and answer periods will be scheduled at the end of each day for feedback and generic questions about research related to PFHA for nuclear facilities.

Workshop Contacts:

Workshop Facilitator is Kenneth Hamburger, Fire Protection Engineer, NRC/RES/DRA/FXHAB at e-mail: Kenneth.Hamburger@nrc.gov and phone 301-415-2022

Workshop Coordinator is Dr. Meredith Carr, Hydrologist, NRC/RES/DRA/FXHAB at e-mail: meredith.carr@nrc.gov and phone: 301-415-6322

Registration:

No fee. For security purposes, each workshop attendee must complete and submit a registration form prior to the workshop. Please e-mail the completed form to Meredith.Carr@nrc.gov. All workshop attendees are required to show a government-issued photo identification, such as a valid driver's license or passport, for the security review to obtain access to the NRC auditorium. International participants should contact the Workshop Coordinator for appropriate documentation.

Remote participation via webinar is available by registering at
https://attendee.gotowebinar.com/register/2336988154289086722
After registering, you will receive a confirmation email containing information about joining the webinar.

Participation by phone is available at (415) 655-0060, Access Code: 432-396-182.

Product

A workshop proceedings will be developed and documented as a NRC NUREG/CP (conference proceeding) report. This NUREG/CP will document: the workshop agenda, presenters' abstracts, presentations and/or references and URLs.

Workshop Organizing Committee

Tom Aird, Meredith Carr, Mark Fuhrmann, Kenneth Hamburger, Joe Kanney, and Tom Nicholson, Mark Salley, and Elena Yegorova, NRC Office of Nuclear Regulatory Research.

AGENDA

MONDAY, JANUARY 23RD, 2017

Session 1A: Introduction

13:00 – 13:10	**Welcome**	
13:10 – 13:25	Introduction *Mike Weber, Director, Office of Nuclear Regulatory Research*	1A-1
1325 – 13:45	PFHA Research Needs for New and Operating Reactors *NRC/NRO/DSEA*	1A-2
13:45 - 14:05	Use of Flooding Hazard Information in Risk-Informed Decisionmaking *Mehdi Reisi Fard NRC/NRR/DRA*	1A-3
14:05 - 14:40	Flooding Research Needs: Industry Perspectives on Development of External Flood Frequency Methods *Ray Schneider*, Westinghouse Electric Corporation, & Joe Bellini*, Aterra Solutions*	1A-4
14:40 - 14:55	NRC Flooding Research Program Overview *Joseph Kanney*, Meredith Carr, Tom Aird, Elena Yegorova, Mark Fuhrmann & Jake Philip, NRC/RES*	1A-5
14:55 - 15:10	EPRI Flooding Research Program Overview *John Weglian, Electric Power Research Institute (EPRI)*	1A-6
15:10 - 15:25	**BREAK**	

Session 1B: Storm Surge Research

15:25 - 16:05	Quantification of Uncertainty in Probabilistic Storm Surge Models *Norberto C. Nadal-Caraballo*, Victor Gonzalez and Jeffrey A. Melby, U.S. Army Engineer R&D Center, Coastal and Hydraulics Laboratory*	1B-1
16:05 - 16:45	Probabilistic Flood Hazard Assessment – Storm Surge *John Weglian, EPRI*	1B-2
16:45 - 17:05	**Daily Wrap-up and Public Comments/Questions**	

* indicates speaker, ^ indicates remote speaker

TUESDAY, JANUARY 24TH, 2017

08:00 - 08:05 **Welcome, Day 2**

Session 2A: Climate and Precipitation

08:05 - 08:40	Regional Climate Change Projections: Potential Impacts to Nuclear Facilities *L. Ruby Leung^, Rajiv Prasad* & Lance Vail, Pacific Northwest National Laboratory*	2A-1
08:40 - 09:20	Numerical Modeling of Local Intense Precipitation Processes *M. Lev Kavvas*, Kei Ishida* & Mathieu Mure-Ravaud*, Hydrologic Research Laboratory, Dept. of Civil & Envr. Engineering, University of California, Davis*	2A-2
09:20 - 09:55	Extreme Precipitation Frequency Estimates for Orographic Regions *Andrew Verdin*, K. Holman and D. Keeney, Flood Hydrology and Meteorology Group, Technical Services Center, U.S. Bureau of Reclamation*	2A-3
09:55 - 10:10	**BREAK**	
10:10 - 10:50	Local Intense Precipitation Frequency Studies *John Weglian, EPRI*	2A-4

Session 2B: Leveraging Available Flood Information I

10:50 - 11:20	Development of Flood Hazard Information Digests for Operating NPP sites *Curtis Smith*, Kellie Kvarfordt, Idaho National Laboratory*	2B-1
11:20 - 12:00	At-Streamgage Flood Frequency Analyses for Very Low Annual Exceedance Probabilities from a Perspective of Multiple Distributions and Parameter Estimation Methods *William H. Asquith^, U.S. Geological Survey, Lubbock, Texas and Julie Kiang, U.S. Geological Survey, Reston, Virginia*	2B-2
12:00 - 12:30	Extending Frequency Analysis Beyond Current Consensus Limits *Keil Neff* & Joseph Wright, US Bureau of Reclamation, Technical Service Center, Flood Hydrology & Meteorology*	2B-3
12:30 - 13:45	**LUNCH**	

CONTINUED… TUESDAY, JANUARY 24TH, 2017

Session 2C: Leveraging Available Flood Information II

13:45 - 14:25	Collection of Paleoflood Evidence *John Weglian, EPRI*	2C-1
14:25 - 15:05	Paleofloods On The Tennessee River - Assessing The Feasibility Of Employing Geologic Records Of Past Floods For Improved Flood Frequency Analysis *Tess Harden*, USGS Oregon Water Science Center & Jim O'Connor*, USGS, GMEG, Portland, Oregon*	2C-2
15:05 - 15:20	**BREAK**	

Session 2D: Reliability of Flood Protection and Plant Response to Flooding Events I

15:20 - 16:00	EPRI Flood Protection Project Status *David Ziebell and John Weglian*, EPRI*	2D-1
16:00 - 16:40	Performance of Flood- Rated Penetration Seals *William (Mark) Cummings*, Fire Risk Management, Inc.*	2D-2
16:40 - 17:00	**Comments/Questions from Public**	
17:00 - 17:10	**Daily Wrap-up**	

WEDNESDAY, JANUARY 25TH, 2017

08:00 - 08:05	**Welcome, Day 3**	

Session 3A: Reliability of Flood Protection and Plant Response to Flooding Events II

08:05 - 08:45	Effects of Environmental Factors on Manual Actions for Flood Protection and Mitigation at Nuclear Power Plants *Rajiv Prasad*, Garill Coles^ & Angie Dalton^, Pacific Northwest National Laboratory, Kristi Branch & Alvah Bittner, Bittner and Associates, Scott Taylor, Batelle Columbus*	3A-1
08:45 - 09:25	Modeling Total 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*	3A-2

Session 3B: Frameworks I

09:25 - 10:05	Technical Basis for Probabilistic Flood Hazard Assessment *Rajiv Prasad* and Philip Meyer, Pacific Northwest National Laboratory*	3B-1
10:05 - 10:20	**BREAK**	

Session 3C: Frameworks II

10:20 - 11:00	Evaluation of Deterministic Approaches to Characterizing Flood Hazards *John Weglian, EPRI*	3C-1
11:00 - 11:40	Probabilistic Flood Hazard Assessment Framework Development *Brian Skahill*, U.S. Army Corps of Engineers, Engineer Research and Development Center, Coastal and Hydraulics Laboratory, Hydrologic Systems Branch, Watershed Systems Group*	3C-2
11:40 - 12:20	Riverine Flooding and Structured Hazard Assessment Committee Process for Flooding (SHAC-F) *Rajiv Prasad* and Robert Bryce, Pacific Northwest National Laboratory; Kevin Coppersmith*, Coppersmith Consulting*	3C-3
12:20 - 13:35	**LUNCH**	

CONTINUED… WEDNESDAY, JANUARY 25TH, 2017

Session 3D: Panel Discussion

13:35 - 15:05	Probabilistic Flood Hazard Assessment Research Activities in Partner Agencies, *Panel Chair: Joseph Kanney, U.S. NRC* National Oceanic and Atmospheric Administration/National Weather Service *Sanja Perica* US Army Corps of Engineers *Christopher Dunn, Norberto Nadal-Caraballo, John England* Tennessee Valley Authority *Curt Jawdy* Department of Energy *Curtis Smith, INL* Institut de Radioprotection et de Sûreté Nucléaire (France's Radioprotection and Nuclear Safety Institute IRSN) *Vincent Rabour*	3D
15:05 - 15:20	**BREAK**	

Session 3E: Future Work in PFHA

15:20 - 15:50	Future Work in PFHA at EPRI *John Weglian*, EPRI*	3E-1
15:50 - 16:20	Future Work in PFHA at NRC *Joseph Kanney, Meredith Carr*, Tom Aird, Elena Yegorova, Mark Fuhrmann & Jake Philip, NRC/RES*	3E-2
16:20 - 16:40	**Public Comments/Questions**	
16:40 - 16:55	**Final Wrap-up**	

ABSTRACTS

Session 1B: Storm Surge Research

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

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

Quantification of the storm surge hazard is an integral part of the probabilistic flood hazard assessment (PFHA) of structures and facilities located in coastal zones. The U.S. Army Engineer Research and Development Center's 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. Modern stochastic assessment of coastal storm hazards in hurricane-prone coastal regions of the U.S. requires the development of a joint probability analysis (JPA) model of tropical cyclone (TC) forcing parameters. The joint probability method with optimal sampling (JPM-OS) has become the standard probabilistic model used to assess coastal storm hazard in these areas, having been adopted by the Federal Emergency Management Agency (FEMA) and the U.S. Army Corps of Engineers (USACE) in most post-Katrina coastal hazard studies. Different JPM-OS approaches have been developed but they typically follow a common general methodology. Nevertheless, the details in the application of these approaches can vary significantly by study, depending on the adopted solution strategies. Variations between studies, for example, can be found in the computation of storm recurrence rate (SRR), definition of univariate distributions and joint probability of storm parameters, and development of the synthetic storm suite (e.g., different optimization methods). The treatment of uncertainties in the JPM-OS methodology also varies by study and is typically limited to the quantification and inclusion of uncertainty as an error term in the JPM integral.

An alternative for the treatment and quantification of uncertainty is derived from probabilistic seismic hazard assessment (PSHA) guidance, where the epistemic uncertainty arises from the application of different, technically defensible, data, methods, and models relevant to hazard assessment and proposed by the larger technical community. This allows for the computation of a family of hazard curves, with associated weights, that represents each of the alternate modeling approaches. The present study has the objective of assessing the technically defensible data, models, and methods that have been applied to individual components of the JPM-OS methodology, along with the characterization of their respective uncertainties. The quantification of uncertainty associated with the SRR, for example, focused on the characterization of the SRR variability due to the selection of computational approach, optimal kernel size, TC intensity, period of record, observational data, and data resampling. The development of univariate probability distributions of storm parameters was evaluated by fitting multiple distributions to each relevant TC parameter, focusing on three different datasets, including observational data from the National Hurricane Center (NHC) and synthetic data from a global climate model (GCM). The uncertainty related to optimal sampling techniques was examined by constructing a reference storm set using a Gaussian process metamodel that was trained with data from the North Atlantic Coast Comprehensive Study (NACCS) recently performed by the USACE. Numerical experiments were also designed for the assessment of methods typically used for the discretization of and incorporation of uncertainty.

Probabilistic Flood Hazard Assessment – Storm Surge 1B-2

*John Weglian**
EPRI

It is important to evaluate risks to nuclear power plants and other vital structures from external hazards that could simultaneously impact multiple, diverse equipment relied upon for accident mitigation. External flooding hazards can lead to floodwaters, which overwhelm a site's response, especially when the flood levels exceed the plant's design basis. A probabilistic flood hazard assessment (PFHA) provides a mechanism to determine the risk to a site from an external flooding hazard, including from extremely rare, beyond-design-basis events. One of the external flooding hazards that can impact a site is a storm surge – the elevation in water level at the shore due to the atmospheric effects of a large storm.

Many storm surge methods and analyses are focused on assessing the flooding impacts from a tropical storm making landfall; however, other types of storms can also cause storm surges, and these events can occur on large lakes as well as oceans. EPRI has published a technical report, Probabilistic Flooding Hazard Assessment for Storm Surge with an Example Based on Historical Water Levels, EPRI ID 3002008111. http://www.epri.com/abstracts/Pages/ProductAbstract.aspx?ProductId=000000003002008111

The report describes multiple methods for performing a PSSHA; however, the detailed example is based on the assessment of a storm surge at an inland lake site based on historical water levels and wave heights.

The process of performing a PSSHA begins with identification that a site is potentially subject to a storm surge. The PSSHA then utilizes a qualitative or quantitative screening approach to determine if the hazard can be screened out form further consideration. If the hazard cannot be screened, a probabilistic approach is used to determine the frequency of the storm surge flooding parameters (e.g., water level). At each step in the process, the uncertainty in the analysis is considered and characterized. The PSSHA process includes the use of a peer review to provide an independent assessment of the process and decisions made in the analysis.

The report includes an example that uses historical information to assess the probability that a storm surge on one of the Great Lakes could impact a particular site. The historical data was used to determine the lake level, surge level, and wave heights. Additional evidence from paleo data was used to extend the historical record for lake level. This information was used to determine probabilistic distribution functions (PDFs) for the parameters of interest. These PDFs were used in a Monte Carlo Simulation to estimate the storm surge-frequency hazard curve for the site. This hazard curve provides the likelihood that a particular flood level at the site would be exceeded by a storm surge per year. This information can then be used to develop a probabilistic risk assessment (PRA) model to determine the core damage frequency, large early release frequency, or other metrics.

Session 2A: Climate and Precipitation

Regional Climate Change Projections: Potential Impacts to Nuclear Facilities 2A-1

L. Ruby Leung^, Rajiv Prasad, Lance Vail*
Pacific Northwest National Laboratory

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 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 with regard to 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 safety 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. The current focus is on the southeast region consisting of 11 southeastern states in the conterminous U.S. Except for Kentucky, all states have currently operating nuclear power plants. New nuclear power reactor permit and license applications submitted to the NRC in the recent past were for sites located in several of the southeastern states (Virginia, North Carolina, South Carolina, and Florida).

The literature review includes an overview of the climate of Southeast U.S., focusing on temperature and precipitation extremes, floods and droughts, strong winds (hurricanes and tornadoes), sea level rise and storm surge. The southeast region occasionally experiences extreme heat during summer and extreme cold during winter. Floods can be produced by several mechanisms including locally heavy precipitation, slow-moving extratropical cyclones during the cool season, tropical cyclones during summer and fall, late spring rainfall on snowpack, storm surge near coastal areas from hurricanes, and occasional large releases from upstream dams. Hurricanes cause major economic lost but also contribute significantly to the region's rainfall. Combined with sea level rise, hurricanes pose significant threats to storm surge and inland inundation. The report is followed by discussions of projected changes in the aforementioned climatic aspects. For example, depending on the future emission scenarios, seasonal precipitation shows moderate increases to significant decreases in magnitude. Very heavy precipitation events are projected to increase in frequency, while annual maximum precipitation is expected to increase in magnitude. Although precipitation intensity generally scales with the Clausius-Clapeyron rate of 7% per degree warming, precipitation intensity decreases at higher temperatures because of the transition to a moisture-limited environment. Besides climate change, urbanization and changing land use may result in changes in runoff and flooding. On the contrary, both short-term and longer-term droughts are expected to intensify in the Southeast. Streamflow is expected to decline as evapotranspiration generally increases with warmer temperatures. Urbanization and population growth may increase stress on water supplies. As sea surface temperatures increase in the future, hurricanes are projected to intensify as the thermodynamical environments for major hurricanes become more favorable. With sea level projected to rise and more intense hurricanes, there is increased probability for storm surge along the southeast coastline. Lastly, a current assessment of climate modeling and federal agency activities related to climate change will be presented.

Numerical Modeling of Local Intense Precipitation Processes 2A-2

M.L. Kavvas, K. Ishida* and M. Mure-Ravaud**
Hydrologic Research Laboratory, Dept. of Civil & Envr. Engineering, Univ. of California, Davis

As population and infrastructure continue to increase, our society has become more vulnerable to extreme events. A flood is an example of a hydro-meteorological disaster that has a strong societal impact. Tropical Cyclones and Mesoscale Convective Systems are recognized for their ability to generate intense precipitation that may in turn create disastrous floods. Tropical Cyclones are intense atmospheric vortices that form over the warm tropical oceans, while Mesoscale Convective Systems 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, we assessed the suitability of a regional numerical weather model to simulate local intense precipitation processes within intense Tropical Cyclones and Mesoscale Convective Systems. More specifically, we used the Weather Research and Forecasting (WRF) model at 5-km resolution in order to reconstruct the intense precipitation fields associated with several historical Tropical Cyclones and Mesoscale Convective Systems which affected the United States. The WRF model was run in the simulation mode, which means that 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.

Numerous studies have shown that regional numerical weather models perform relatively well in reconstructing such storms in the forecasting mode where such techniques are used to improve the model's performances. However, in the context of climate change where one may be interested in simulating the storms of the future, it is important to evaluate the performances of regional numerical weather models in the simulation mode, since no observation is available for the future which would allow using nudging or data assimilation. The storm systems that we simulated were selected within the time period from 2002 to present, based on the NCEP Stage-IV precipitation dataset, which is a mosaic of regional multi-sensor analysis generated by 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 initial and boundary conditions for our simulations were obtained from the Climate Forecast System Reanalysis (CFSR) dataset, which is provided by National Centers for Environmental Prediction (NCEP) at 0.5 x 0.5 degree spatial resolution and 6-hour temporal resolution. For the simulations of the Mesoscale Convective Systems, 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. However, several sets of simulation nested domains were prepared for the simulations of the Tropical Cyclones because of the diversity in the paths of these systems. More precisely, while the outer domain was the same for all cases and was chosen so as to cover the paths of all the identified severe Tropical Cyclones, different inner domains were set up so as to include the severe precipitation areas caused by each individual Tropical Cyclone. With these sets of simulation nested domains, the WRF model was configured to obtain the best results for the simulation of each of the selected severe Mesoscale Convective Systems and Tropical Cyclones storm events with respect to the simulated and observed precipitation fields.

We compared the simulations results with observations from the Stage IV precipitation dataset. More precisely, on the one hand, the simulation results were evaluated by means of several goodness-of-fit statistics: the relative error for the simulation inner-domain total precipitation, and the percentage of overlapping between the simulated and observed fields for several precipitation thresholds. On the other hand, the simulated and observed precipitation fields were plotted so as to visually appreciate the similarities and differences in the fields' texture and structure. We showed 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 texture of the intense precipitation fields in the historical Tropical Cyclones and Mesoscale Convective Systems. The model's options that we investigated include the parameterization schemes such as microphysics, cumulus parameterization, planetary boundary layer physics, long wave and short wave radiation physics, etc., the vertical resolution (number of layers), the initial date for the simulation, the time step, and other options related to the physics and dynamics. Although certain combinations of the parameterization schemes provided in each case realistic results in terms of the precipitation fields' textures and structures, placing these fields in the correct spatial locations required additional efforts, so that the best set of the model's options varies from one storm system to the other.

Extreme Precipitation Frequency Estimates for Orographic Regions 2A-3

A. Verdin, K. Holman, and D. Keeney*
Flood Hydrology and Meteorology Group, Technical Services Center,
U.S. Bureau of Reclamation

We present an update to the research project "Phase II: Research to Develop Guidance on Extreme Precipitation Frequency Estimates for the Tennessee Valley." The focus of this presentation is the use of sophisticated statistical techniques for identifying homogeneous regions within greater orographic domains and the subsequent fitting of extreme value distributions for point-scale return level estimates of precipitation within each homogeneous region. Identification of homogeneous regions is essential for regional frequency analysis. Regional analyses are based on the assumption that data from stations within each homogeneous region come from the same theoretical distribution, which is a common method of extending environmental datasets. Parameter estimation is sensitive to a number of influential factors, the period of record being one of the most important. It is essential, then, to strengthen the parameter estimates by substituting "space for time." We discuss the Self Organizing Maps (SOM) algorithm, a widely used method of identifying homogeneous regions, and our application of the SOM algorithm to the Tennessee River Valley. Results from the SOM algorithm are consistent with subjective methods of regionalization. For each homogeneous region, we apply two distinct methods of regional frequency analysis for estimating the extreme value distribution parameters of the regional growth curve: L-Moments and Bayesian. The regional growth curve for each homogeneous region is produced using scaled annual maximum precipitation data. Subsequently, a point-scale return level is estimated by scaling the regional growth curve by the at-site mean of the location of interest. However, it may be of interest to estimate precipitation magnitudes at locations where no historical observations exist. To this end, we illustrate the benefit of using gridded reanalyses as input to regional frequency analysis. Specifically, the Newman et al. (2015) dataset offers an ensemble of gridded daily precipitation for 33 years. The ensemble contains 100 members, each of which are equally plausible precipitation totals for the grid cell of interest. Similar to the identification of homogeneous regions, we assume that all ensemble members come from the same theoretical distribution, which extends the period of record by two orders of magnitude. We illustrate how the ensemble members may be collapsed into a single dataset, and the extreme value distribution parameters are estimated independently at each grid cell. We discuss differences in the inherent assumptions and resulting differences in the two methods. This presentation ends with an illustration of the two methods' abilities in quantifying small exceedance probability precipitation events with associated uncertainty.

Local Intense Precipitation Frequency Studies 2A-4

*John Weglian**
EPRI

To ensure that nuclear power plants are adequately protected against extreme rainfall plant design has traditionally relied on deterministic requirements to define the extent of flooding that might need to be accommodated. For purposes of probabilistic risk assessment (PRA), a more comprehensive understanding of the relationship between the frequency and amount of extreme rainfall is necessary. Such an understanding is also needed to provide further perspective on the challenges posed by precipitation corresponding to the deterministic criteria.

To explore the state of the technology and data available to support a more comprehensive probabilistic evaluation, EPRI undertook an evaluation of the precipitation-frequency relationship for two sites in the United States, one an inland site and the other an Atlantic Ocean coastal site. The study was primarily based on regional precipitation-frequency relationships that embody National Weather Service data from a large number of precipitation measurement stations in the vicinity of the plant sites. The study was published as Local Precipitation-Frequency Studies: Development of 1-Hour/1-Square Mile Precipitation –Frequency Relationships for Two Example Nuclear Power Plant Sites, EPRI ID 3002004400. http://www.epri.com/abstracts/Pages/ProductAbstract.aspx?ProductId=000000003002004400

Plants in the United States are designed to be protected against flooding that could result from local intense precipitation (LIP). For design purposes, LIP is defined based on precipitation associated with a 1-hour/1-square mile probable maximum precipitation (PMP) event. The method described in this report was applied to calculate the probability of the PMP occurring for the two example sites as well.

The approach employed in this report successfully demonstrated the feasibility of a probabilistic technique for establishing precipitation-frequency relationships for local precipitation events. The regional analyses also found that an event corresponding to the 1-hour/1-square mile PMP would result in an extremely large amount of precipitation and would be extremely rare.

Session 2B: Leveraging Available Flood Information

Development of Flood Hazard Information Digests for Operating NPP sites 2B-1

Dr. Curtis Smith, Kellie Kvarfordt*
Idaho National Laboratory

The objective of the Development of Flood Hazard Information Digests for Operating NPP sites project is for Idaho National Laboratory (INL) to develop and demonstrate a database architecture for a Flood Hazard Information Digest to facilitate gathering, organizing, and presenting a variety of flood hazard data sources. Additionally, INL is assisting in the population of the digests.

The objective of the Development of Flood Hazard Information Digests for Operating NPP sites project is for Idaho National Laboratory (INL) to develop and demonstrate a database architecture for a Flood Hazard Information Digest to facilitate gathering, organizing, and presenting a variety of flood hazard data sources. Additionally, INL is assisting in the population of the digest.

The goal of the project is to provide information and tools to support external flooding-related activities, particularly the risk-informed aspects of the Significance Determination Process (SDP). Under the SDP the use of probabilistic flood 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 flooding hazard estimates on an ad hoc basis, in a limited manner, with acknowledged limitations with respect to the technical defensibility of the resulting estimates.

A particular challenge in developing probabilistic flooding hazard estimates within the SDP is that the required flood 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 flooding information at operating reactor sites and improve its accessibility for NRC staff performing SDP analyses. The Flood Hazard Information Digest application has been developed to address these needs.

The following major data sources have been identified and targeted for inclusion in the Flood Hazard Information Digest:

- flood hazard information, including flood protection and mitigation strategies, available from sources that include NUREGs, FSARs, IPEEE submittals, and SDP analyses
- Fukushima NTTF Recommendations
  - 2.1 Flood Hazard Reevaluation submittals,
  - 2.3 walk down submittals
- available precipitation frequency information from NOAA Atlas 14 database
- available flood frequency information from USGS databases
- available information for hurricane landfall/intensity along US coastal areas

In addition to providing access to these and other data sources, the flood digest must provide, where needed, guidance for using the available information.

The Flood Hazard Information Digest 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 emphasis of the Safety Portal is to serve as a resource to promote collaboration between producers and users of information. The flood digest shares available services such as user account management, file sharing, and a publications/ permissions/ subscriptions model.

The Flood Hazard Information Digest application is available to eligible users at https://safety.inl.gov/flooddigest. New users will be prompted to register for access. Sample data for selected plants is currently available, and data population efforts for remaining operating NPP sites are underway. The bulk of data population is targeted for completion by end of this fiscal year. The flood digest application has been implemented in such a way as to facilitate inclusion of additional external event hazards if needed.

At-Streamgage Flood Frequency Analyses for Very Low Annual Exceedance Probabilities from a Perspective of Multiple Distributions and Parameter Estimation Methods — 2B-2

*William H. Asquith^*
U.S. Geological Survey, Lubbock, Texas

Julie E. Kiang
U.S. Geological Survey, Reston, Virginia

The U.S. Geological Survey (USGS), in cooperation with the U.S. Nuclear Regulatory Commission, is investigating statistical methods for flood hazard analyses. One task is to provide guidance on very low annual exceedance probability (AEP) estimation and the quantification of corresponding uncertainties using streamgage-specific data. The term "very low AEP" implies exceptionally rare events defined as those having AEPs less than about 0.001 or 10^{-3} in scientific notation. Such low AEPs are of great interest of flood frequency analyses for critical infrastructure, such as nuclear power plants. Flood frequency analyses at streamgages are most commonly based on annual instantaneous peak streamflow data and a probability distribution fit to these data. The fitted distribution provides a means to extrapolate to small AEPs. Within the United States, the Pearson type III probability distribution, when fit to the base-10 logarithms of streamflow is widely used, but other distribution choices exist. The USGS-PeakFQ software implementing well-known guidelines of Bulletin 17B (method of moments) and pending updates ("Bulletin 17C," the expected moments algorithm (EMA) using the Pearson type III) was specially adapted for an "Extended Output" user option to provide estimates at selected AEPs from 10^{-3} to 10^{-6}. Parameter estimation methods in addition to product moments and EMA include L-moments, maximum likelihood, and maximum product of spacings (maximum spacing estimation). This project comprehensively studies multiple distributions and parameter estimation methods for two USGS streamgages (01400500 Raritan River at Manville, New Jersey and 01638500 Potomac River at Point of Rocks, Maryland). The results of this task involving the four techniques of parameter estimation and up to nine probability distributions including the generalized extreme value, generalized log-normal, generalized Pareto, and Weibull. Uncertainties in streamflow estimates related to AEP are depicted and quantified as two primary forms: quantile (*aleatoric* [random sampling] uncertainty) and distribution-choice (*epistemic* [model] uncertainty). Sampling uncertainties of a given distribution are relatively straightforward to compute from analytical or Monte Carlo-based approaches. Distribution-choice uncertainty stems from choices of potentially applicable probability distributions for which divergence amongst the choices increases as AEP decreases. Conventional goodness-of-fit statistics, such as Cramér–von Mises, and L-moment ratio diagrams are demonstrated to hone distribution choice. The results in a generalized sense show that distribution choice uncertainty is larger than sampling uncertainty for very low AEP values. Future work includes consideration of non-standard flood data at streamgage locations, regional information, and non-stationarity in flood frequency analyses.

Extending Frequency Analysis Beyond Current Consensus Limits 2B-3

*Joe Wright and Keil Neff**
US Bureau of Reclamation, Technical Service Center, Flood Hydrology & Meteorology

Traditionally, deterministic methods have been used to determine Inflow Design Floods (IDF) based on a particular loading event to meet regulatory criteria. For infrastructure with high hazard potential, including nuclear facilities and many large dams, the Probable Maximum Flood (PMF) has often been used as the IDF. Risk-informed decision-making (RIDM) is currently used by the Bureau of Reclamation, the Army Corps of Engineers, and other agencies to assess the safety of dams, recommend safety improvements, and prioritize expenditures. This involves developing estimates of hydrologic hazards to perform probabilistic risk assessments (PRA). Hydrologic hazard curves provide magnitudes and probabilities for the entire ranges of peak flow, flood volume, and water surface elevations. There are multiple methods available to estimate magnitudes and probabilities of extreme flood events; these methods can be generally classified as streamflow-based statistical analyses or rainfall-based with statistical analyses of the modeled runoff. Method selection is based on the level of detail necessary and site-specific consideration including data availability, hydrologic complexity, and required level of confidence. This presentation will focus on describing recommended methods and approaches for extending frequency analysis methods beyond current consensus limits (Annual Exceedance Probabilities (AEP) greater than 1:105) for both rainfall and riverine flooding applications.

Session 2C: Leveraging Available Flood Information II

Collection of Paleoflood Evidence 2C-1

*John Weglian**
EPRI

In a probabilistic risk assessment (PRA), it is important to estimate the frequency of initiating events (events that can cause or demand an immediate trip of the reactor). The estimation of this frequency is challenging for rare events and particularly so for external hazards like external flooding, where the historical record is limited to about one to two hundred years. An external flooding PRA would use a flood hazard frequency curve that plots

Various techniques are available to extend the data at a particular site including the use of storm transposition and numerical generation of synthetic storms, but these are still based on data collected in the recent past. The investigation of paleoflood evidence (evidence of flooding that occurred outside of the observed record) has the ability to inform the record of actual past flooding events in the region of interest.

In major flooding events, debris and sediment can be suspended and transported long distances in the fast-moving water. When the water enters a low-flow region, some of the suspended material will sink and become deposits on the surrounding floor. If these deposits are preserved in the environment, they can be used to estimate the time of the event and the flood discharge. Paleoflood evidence can be found terrace or overbank deposits when the water exceeds the riverbank and leaves the deposits on the surrounding land. These deposits may be good for estimating the frequency of flooding events that exceed that particular height, but they may not be good at estimating the flood stage for any particular event. Paleoflood evidence may also be deposited in caves or canyon walls, which could provide a good estimate for the flood stage, but the topography may be more prone to have one flooding event wash away the evidence of previous flooding events.

Paleoflood evidence has been used in arid climates with great success, but it was not clear if the same evidence would be preserved in humid climates. Initial research indicates that paleoflood evidence is preserved in humid environments, but extracting the data may be more challenging than in arid environments.

Paleofloods On The Tennessee River - Assessing The Feasibility Of Employing Geologic Records Of Past Floods For Improved Flood Frequency Analysis 2C-2

Tess Harden – USGS Oregon Water Science Center, Portland, Oregon*
Jim O’Connor – USGS, GMEG, Portland, Oregon*

Our 2015 field survey and stratigraphic analysis, coupled with geochronologic techniques, indicate a rich history of large Tennessee River floods is preserved in the Tennessee River Gorge area. Deposits of flood sediment from the 1867 peak discharge of record (460,000 ft3/s at Chattanooga, Tennessee) appear to be preserved at many locations throughout the study area. Small exposures at two boulder overhangs reveal evidence of three to four earlier floods similar in size or larger than the 1867 flood in the last 3,000 years, one possibly more than 50 percent larger. Flood deposits are also preserved in stratigraphic sections at the mouth of the gorge at Williams Island and near Eaves Ferry about 70 miles upstream from the gorge. These stratigraphic records may extend as far back as ~9,000 years, preserving a long history of Tennessee River floods. Although more evidence is needed to confirm these findings, it is clear that a more in-depth comprehensive paleoflood study is feasible for the Tennessee River. This study also lends confidence to the feasibility of successful comprehensive paleoflood studies in other basins in the eastern U.S.

Session 2D: Reliability of Flood Protection and Plant Response to Flooding Events I

EPRI Flood Protection Project Status 2D-1

*David Ziebell and John Weglian**
EPRI

EPRI is actively helping nuclear electric generating companies manage the risk of external flooding by providing good technical practices where needed. The Flood Protection Systems Guide was published in November 2015 (EPRI ID 3002005423) that describes flood-protection components at nuclear power plants (NPPs) and the design, testing, inspection, and maintenance of these components. This presentation highlights some of the information provided in that EPRI guide, and describes a follow-on R&D effort to identify and communicate good practices in maintaining an external flooding design / licensing basis. These guides are based on information collected from a consensus of industry peers. EPRI's members have asked for information to assist in the development and management of their flood-protection basis requirements in regard to external flooding-related events.

The published guideline gives specific attention to flood barrier penetration seals (FBPSs) because of the relative complexity, varying designs, and lack of existing codes and standards for these components. Although the focus of the guide is on external flooding-related events, this guide provides descriptions of components, design considerations, maintenance activities, and other topics that can apply to both external and internal flood-protection requirements are included. Additional sections within the guide address recent industry events and major considerations for establishing and managing flood-basis requirements at the site level.

The design / licensing basis guide now being developed is based on a detailed survey of design and management practices regarding maintaining adequate basis for operability of external flood-protection components at NPPs. This presentation describes the survey approach and summarize current status of the results being analyzed. In addition, this presentation describes the planned report outline, which constitutes current views as to the kinds of management elements needed for a NPP owner to effectively manage the risk of external flooding.

Examples of key elements to be described in the guide include:

- Design
- Qualification
- Maintenance
- Design Change Process
- Inspection
- Periodic Surveillance of Flood Protection Features
- Mitigating Strategies for off-normal conditions

- Training
- Reevaluations of the adequacy of management methods
- Integrated Assessment
- Documentation and Reporting

Performance of Flood-Rated Penetration Seals 2D-2

*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 method used to mitigate the effects of a flooding event is the implementation of flood rated barriers that isolate areas of the plant from 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. The NRC has 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 provides a status of that research project, along with outlining plans to perform flood testing on candidate seal assemblies. This testing will evaluate the ability of the procedures to adequately address and record the various performance parameters of individual seal assemblies/materials. The results of this research program may be used in the evaluation of a seal assembly/material and whether it is acceptable for protecting penetrations in flood-rated barriers.

Session 3A: Reliability of Flood Protection and Plant Response to Flooding Events II

Effects of Environmental Factors on Manual Actions for Flood Protection and Mitigation at Nuclear Power Plants 3A-1

Rajiv Prasad, Garill Coles^, Angela Dalton^, and Nancy Kohn*
Pacific Northwest National Laboratory

Kristi Branch and Alvah Bittner
Bittner and Associates

Scott Taylor
Batelle Columbus

Following the Fukushima nuclear accident, the U.S. Nuclear Regulatory Commission (NRC) identified the need to ensure the manual actions for flood protection and mitigation (FPM) at nuclear power plants (NPPs) are both feasible and reliable. Environmental factors and conditions associated with floods that trigger manual actions for FPM can adversely affect the operators' ability to perform these actions. In 1994, a study (Echeverria et al., 1994 or NUREG/CR-5680) reviewed available research on the impacts of environmental conditions (ECs) on human performance. The current research is part of the NRC's Probabilistic Flood Hazard Assessment (PFHA) research plan in support of developing a risk-informed licensing framework. It aims to apply the lessons learned from NUREG/CR-5680 and more recent research on how ECs affect human performance for actions similar to NPP FPM manual actions. The first year of the project focused on characterizing manual actions from available NPP FPMs, developing a conceptual framework for assessment of impacts of ECs on human performance, characterizing ECs that are expected to be associated with floods that may trigger NPP FPM procedures, and reviewing the research literature related to effects of ECs on human performance. In the second year of the current research, we have continued to refine the conceptual framework, complete the review of more recently available literature, and propose a proof-of-concept method for application of the available information within the conceptual framework.

The conceptual framework represents FPM procedure as a set of manual actions, tasks and subtasks, generic actions (GAs), and performance demands (PDs). A manual action is a distinct group of inter-related tasks that are performed outside the main control room to achieve an operational goal. A task is one step of a manual action that has a distinct outcome or pre-determined objective contributing to accomplishment of the manual action. A task generally requires both motor and cognitive abilities. Several subtasks may comprise a task. A GA is an individual component of a task or subtask that is sufficiently simple to evaluate impact of ECs on human performance. Successful completion of a GA may require several PDs, which are human abilities including cognitive, motor, and communication. We developed the PDs from three sources: NUREG/CR-5680 performance abilities, O'Brien et al. (1992) task taxonomy, and NUREG-2114 cognitive functions. Our proposed PDs include (1) detection and noticing, (2) understanding, (3) decision-making, (4) action, and (5) teamwork. The PD "action" is further subdivided into fine motor and coarse motor skills and the PD "teamwork" is further subdivided into (a) reading and writing, (b) oral communication, and (c) crew interaction.

We structured our literature review to integrate the most recent research information with that assembled in NUREG/CR-5680, address ECs that had not been covered in that review, and to present the findings in a format that is most useful for those reviewing and assessing performance impacts from the range and combinations of tasks, GAs, and PDs pertinent to outdoor work in varying weather conditions. Because we were reviewing literature that represented a wide range of methods, objectives, variables, and rigor, we also provide an overview of the state of the literature on performance effects on a range of ECs that include those associated with extreme weather conditions.

Using an example, we describe a proof-of-concept method to demonstrate how impacts can be assessed on a task that is part of a FPM procedure taken from a real NPP. Research on ECs' impacts in literature is available in four categories: (1) quantitative information that is directly applicable, (2) quantitative information that is less directly applicable, (3) qualitative information that may be used to inform expert judgments or sensitivity analyses, and (4) no information, i.e., a research gap. We note that the proof-of-concept method as illustrated by the example has limitations that need to be addressed. Finally, we present potential future research topics that will further improve upon our conceptual framework and facilitate application of the framework to evaluation of FPM manual actions at operating NPPs.

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Modeling Total Plant Response **3A-2**

Zhegang Ma, Curtis L. Smith, Steven R. Prescott*
Idaho National laboratory, Risk Assessment and Management Services

Ramprasad Sampath
Centroid PIC, Research and Development

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 developed a work plan and framework to perform a simulation based dynamic flooding analysis (SBDFA). The SBDFA framework was 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 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 state-based PRA model was developed to represent two accident sequences in a simplified traditional general transient event tree, along with incorporating 3-D simulation elements into the logic so that the PRA model could communicate with the 3-D simulation models. This integrated EMRALD model was run with 34 3-D dynamic 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).

Session 3B: Frameworks I

Technical Basis for Probabilistic Flood Hazard Assessment 3B-1

Rajiv Prasad and Philip Meyer*
Pacific Northwest National Laboratory

The purpose of this project was to develop technical bases for incorporating probabilistic assessment of riverine flood hazards into U.S. Nuclear Regulatory Commission (NRC) guidance related to permitting, licensing, and oversight activities. Characterization and estimation of floods of return periods significantly greater than those for which statistical approaches are currently established are needed for NRC's purposes.

Probabilistic Flood Hazard Assessment (PFHA) is defined as a site-specific, systematic evaluation of the probabilities and frequencies of exceedance of hazards generated by applicable flood mechanisms to which structures, systems, and components (SSCs) could be exposed during specified exposure times at a nuclear power plant (NPP) site. Flood mechanisms are those hydrometeorological, geoseismic, or structural failure phenomena that may produce a flood at or near an NPP site. Flood flows are characterized by several parameters, such as flood discharge, flood velocity, flood water-surface elevation, flood depth, flood duration, and hydrostatic and hydrodynamic forces, Flood hazards are those flood parameters that directly or indirectly affect the safety of NPP SSCs. All flood hazards may vary spatially and temporally during a flood event. To adequately estimate the potential for failure of and access to the SSCs during a flood, both the spatial and temporal variation in flood hazards should be estimated.

Traditionally, probabilistic flood analysis has focused on estimation of the return period (the inverse of the annual exceedance probability [AEP]) of the annual maximum discharge using observations—these analyses are also called flood-frequency analyses. A nonmechanistic model, typically a parametric probability distribution, is used to represent the frequency of occurrence of observed peak flows. To estimate the complete flood hydrograph and other hydrodynamic flood parameters, a more mechanistic approach is required. A simulation-based framework using precipitation-runoff and hydraulic models with appropriate hydrometeorologic, topographic, bathymetric, and geomorphologic data can be used to provide a more comprehensive estimate of flood hazards. In addition, a simulation-based approach allows for the explicit representation of nonstationary behavior in riverine floods, such as changes in the river basin (e.g., localized changes including installation or removal of a dam or distributed changes including gradual clearing of forests) and climate change effects (e.g., changes in magnitude and frequency of extreme events).

We propose a PFHA framework that is simulation-based and includes a comprehensive evaluation of uncertainties. The framework uses three components: (1) a meteorologic component that provides hydrometeorologic input data; (2) a hydrologic component that estimates runoff discharges from precipitation events given hydrometeorologic input data, watershed initial conditions, and physical watershed data; and (3) a hydraulic component that estimates hydraulic flood parameters, including floodwater-surface elevations and flood velocities given runoff discharges and physical river network properties. In addition, there may be another component to transform the watershed model outputs into the required flood parameters for which hazard curves are required. Aleatory uncertainties are associated with the hydrometeorologic inputs, and with the watershed initial and boundary conditions. These quantities describe the primary irreducible uncertainties affecting the occurrence of future flooding at a site: the depth and intensity of rainfall events in the future, and the watershed conditions at the time of those events. Epistemic uncertainties are associated with the parameters of the watershed model, and describe our lack of knowledge in modeling the precipitation-runoff processes, in characterizing the watershed, and in determining appropriate parameter values for the models. These are the primary uncertainties that could be reduced by collecting additional data. By incorporating available data, a Bayesian approach is used to reduce the epistemic uncertainties. Watershed model outputs either directly represent the flood hazards of interest, or may be transformed to them (e.g., hydrostatic and hydrodynamic loads, scour potential). The aleatory uncertainties result in a distribution of each flood hazard, which constitute a hazard curve. Epistemic uncertainties contribute to the uncertainty in the quantiles of the distribution representing the hazard curve (e.g., the uncertainty in the exceedance probability of a given flood hazard value). We expect to address issues related to implementing the proposed framework in the near future.

Session 3C: Frameworks II

Evaluation of Deterministic Approaches to Characterizing Flood Hazards 3C-1

*John Weglian**
EPRI

Following the earthquake and tsunami that struck Japan in 2011 and led to core damage at three units at the Fukushima Daiichi Nuclear Power Plant, the nuclear power plants in the United States were required to reexamine their risk to flooding from external sources using the current regulatory guidance for new reactor sites. In many cases, these reexamined flood hazards exceeded the plant's original design basis. Many nuclear power plants outside of the United States have also reevaluated their sites for external flooding hazards.

Deterministic, bounding analyses are used to ensure that nuclear power plants are protected from what is expected to be the worst-case flooding events that could impact a site. Utilities will typically use the most conservative and bounding assumptions when initially assessing the flood hazard to a site. If the site is not able to withstand the flood using those bounding assumptions, the analysis is refined using more realistic, but still bounding, assumptions. This process is known as the hierarchical hazard assessment. EPRI published the technical report, Evaluation of Deterministic Approaches to Characterizing Flood Hazards, EPRI ID 3002008113.
http://www.epri.com/abstracts/Pages/ProductAbstract.aspx?ProductId=000000003002008113

The report examines the assumptions, inputs, and methods used for assessing the external flooding hazards for the following flooding mechanisms: local intense precipitation, flooding of streams and rivers, dam breaches and failures, storm surge, wind-generated wave and runup, and hydrodynamic and debris loads.

For each of these flood mechanisms, the report provides several areas where the analysis can be improved to provide a more realistic characterization of the flood hazard. Some examples are provided to describe some of these improvement opportunities. Utilities can use the report to identify opportunities to improve their bounding flood hazard analyses for existing or new plants.

Probabilistic Flood Hazard Assessment Framework Development 3C-2

*Brian Skahill**
U.S. Army Corps of Engineers, Engineer Research and Development Center,
Coastal and Hydraulics Laboratory, Hydrologic Systems Branch, Watershed Systems Group

This research project is part of the Nuclear Regulatory Commission's (NRC) Probabilistic Flood Hazard Assessment (PFHA) Research plan. Its objective is to develop and demonstrate a framework for PFHA for inland nuclear facility sites that will facilitate construction of site-specific flood hazard curves, and support full characterization of uncertainties in site-specific storm flood hazard estimates for the full range of return periods of interest for nuclear power plants. A PFHA must be able to incorporate probabilistic models for a variety of flood related processes, allow for characterization and quantification of aleatory and epistemic sources of uncertainty, and facilitate not only propagation of uncertainties, but also sensitivity analyses. The research project tasks are defined by focus areas and in each case the objective is to develop and demonstrate a conceptual, mathematical, and logical framework for the probabilistic modeling of the given task specific flooding process. The focus areas include:

- Literature review
- Warm Season Rainfall and Local Intense Precipitation
- Cool Season Rainfall, Snow and Snowpack
- Site-scale Flooding from Local Intense Precipitation
- Riverine Flooding – Rainfall or Rainfall and Snowmelt
- Riverine Flooding – Hydrologic Dam/Levee Failure
- Knowledge transfer

This presentation will summarize features of a current draft proposed PFHA framework for warm season rainfall which outlines the use of a spatio-temporal Bayesian Hierarchical Model (BHM) embedded within a multi-model averaging technique to leverage the capacities of Bayesian inference while generalizing the problem of extreme rainfall model selection. The Bayesian inference methodology was selected not only because it supports a probabilistic analysis of extreme rainfall, but also because it is a flexible means by which to combine all available and relevant complementary data. These characteristics of Bayesian inference are either required or highly desirable for extreme rainfall analysis, particularly given the application focus wherein quantile estimates are necessary for low exceedance probabilities. For example, additional data that could be combined with a given station's systematic record for a local or regional analysis of extreme rainfall are data from surrounding stations, information derived from expert elicitation, or including a non-stationary climate index. An additional attractive feature of the Bayesian inference methodology is that it supports the capacity to compute the predictive posterior distribution for a future observation. Several demonstrations of the proposed PFHA framework for warm season rainfall not only reinforce various aspects of the key framework elements, but also underscore the flexibility of the framework to accommodate different data scenarios. The first four demonstrations in aggregate will clearly emphasize the importance of data analysis, model selection, and inference methodology for the evaluation of extreme rainfall risk at a given location. The fifth demonstration emphasizes the flexibility of the Bayesian inference methodology to accommodate treatment of non-stationarity in an analysis of extreme rainfall. The sixth demonstration profiles application of a BHM for the analysis of extreme daily rainfall using annual maxima data from sixty-eight stations located within and surrounding the 11,478 square mile Willamette River Basin in northwestern Oregon. The final demonstration briefly profiles two multi-model averaging techniques to generalize the problem of extreme rainfall model selection. The presentation will conclude with a brief summary of ongoing framework development for the probabilistic modeling of cool season rainfall processes.

Riverine Flooding and Structured Hazard Assessment Committee Process for Flooding (SHAC-F) 3C-3

Rajiv Prasad and Robert Bryce*
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 estimation of flood hazards at new and existing facilities and enhance NRC’s capacity to support reviews of license applications, license amendment requests, and reactor oversight activities. Flood hazards at nuclear power plants (NPPs) result from various flooding mechanisms including local intense precipitation (LIP), precipitation and snowmelt in a river basin, dam failures, and storm surges and tsunamis. These flood events have the potential to challenge off-site power, threaten many on-site NPP structures, systems, and components, challenge the integrity of plant structures, and limit plant access. However, there a no widely-accepted framework for performing a PFHA and there are large uncertainties involved with estimating floods of magnitudes and frequencies of occurrence of interest for safety evaluations at NPPs. In 2013 and 2014, NRC-sponsored workshops discussed the available methods for conducting PFHAs and the development of a structured hazard assessment committee process for flooding (SHAC-F). The need to develop implementation details of SHAC-F methodology was also recognized.

The objective of this project is to develop and apply the SHAC-F process 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 We have started with the overarching guidance from the Senior Seismic Hazard Analysis Committee (SSHAC) process (NUREG/CR-6372, NUREG-2117) used in probabilistic seismic hazard assessments and adapting them to the needs of flood hazard assessments. The SSHAC process is particularly well-suited for structuring hazard assessments for purposes of risk analyses. For SHAC-F, we adapted four levels, similar to SSHAC Levels 1-4. The virtual studies in the current project are carried out to simulate the full scope and activities that would accompany a full SHAC-F Level 3 PFHA. The project is investigating these aspects using virtual studies for LIP floods and riverine floods excluding dam failures.

We will conduct the riverine PFHA SHAC-F virtual study using the same virtual site as for the LIP PFHA SHAC-F virtual study. We anticipate that several of the issues identified and solutions proposed during the LIP PFHA SHAC-F virtual study will inform our riverine PFHA SHAC-F virtual study. These issues include 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. For the riverine flood PFHA, we initially expected to perform two separate Level 3 PFHA virtual studies: (1) riverine flood from precipitation in the river basin and (2) riverine flood from precipitation and snowmelt in the river basin. Because the only difference between the two is the snowmelt component and the expected seasonality, we decided to combine the two virtual studies. The riverine Level 3 PFHA virtual study will have three technical integration (TI) teams: (1) the meteorological model characterization (MMC) team, (2) the hydrologic model characterization (HOMC) team, and (3) the hydraulic model characterization (HAMC) team. For a riverine flood, hydrologic and hydraulic modeling are best handled by separate teams because of the spatially and temporally varied nature of runoff generation and flood routing in streams and rivers. A site visit may not be critical for a riverine SHAC-F study but the TI teams should be familiar with the specific hydrologic and hydraulic characteristics of the river basin. We expect that this objective can be accomplished by selecting the members of the TI team that have extensive experience conducting flood studies in the river basin and by encouraging others familiar with technical and policy matters for the river basin to join the study on the Participatory Peer Review Panel.

Compared to the LIP PFHA SHAC-F virtual study, we expect that significantly larger amount of observed flood data will be available. At the same time, we expect to face new issues related to characterizing the variability of inputs, parameters, and initial and boundary conditions over space, time, and seasons. One additional issue we will need to address is the need for characterizing flood hazards at the local NPP scale—riverine flood models typically use a lumped or semi-distributed hydrologic model and a one-dimensional hydraulic stream reach model. A two-dimensional hydrodynamic model may be necessary to evaluate the effects of the riverine flood overtopping the banks and spreading on the NPP site. Characterization of flood hazards may be needed at a finer spatial scale sufficient to adequately resolve the locations of safety-related SSCs and doors.