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

7th Annual Probabilistic Flood Hazard Assessment Research Workshop

February 15-18, 2022 (Via MS Teams)
Start time: 10:00AM EST

ABSTRACTS

Day 1 (Feb 15th, 2020) Oral Presentations

*** denotes speaker**

1A-1: Opening Remarks

Ray Furstenau*
Director, Office of Nuclear Regulatory Research, U.S. Nuclear Regulatory Commission

No Abstract

1A-2: Update on the NRC PFHA Research Program

Thomas Aird*, *U.S. Nuclear Regulatory Commission*

This presentation will provide an update on the NRC probabilistic flood hazard assessment (PFHA) research program. Topics will include the completion of Phase 1 (technical basis research), the activities and status of Phase 2 (pilot studies) and plans for Phase 3 (guidance development)

1A-3: Moving FEMA towards Probabilistic Flood Risk Analysis and Probabilistic Flood Hazard Analysis

David Rosa*, Christina Lindemer, *Federal Emergency Management Agency*

FEMA is responsible for supporting the largest single-peril flood insurance program in the world. In support of this regulatory program, the agency has legislative authority for mapping the floodplains of the nation. The traditional regulatory products produced by FEMA that govern federal minimum standards for mandatory purchase of flood insurance and flood related building codes have become the defacto flood risk communication products for our nation. However, FEMA acknowledges the limitation of the current regulatory products, which generally present flood risk as a binary in-or-out status. To improve the nation's understanding of flood risk and to more effectively achieve the mission of reducing disaster suffering, FEMA is pursuing efforts to advance the coverage of probabilistic flood hazard and risk products for the nation. This presentation will describe FEMA's Future of Flood Risk Data initiative, an ambitious effort that leverages close coordination with the other technical agencies to improve our nation's tomorrow.

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

John Nakoski*, *U.S. Nuclear Regulatory Commission (WGEV Chair)*

The Committee on the Safety of Nuclear Installations Working Group on External Events (CSNI/WGEV) was established in 2014 by the Organization for Economic Cooperation and Development Nuclear Energy Agency (OECD/NEA). This presentation will briefly describe WGEV's structure and membership, recently completed activities, currently ongoing activities, and potential future activities.

1B-1: Flood & Fire Sensors for Resilient Communities

Jeffrey Booth*
Department of Homeland Security, Science & Technology Directorate

Flooding and Wildland Fires are the nation's leading natural disasters, accounting for the greatest loss of life, property damage and economic impact while threatening the resiliency of communities across the country. Current flood damage is estimated at $5 billion per year and wildland fires annualized losses are estimated to range from $63.5 billion to $285 billion. The human cost is much greater.

The Department of Homeland Security (DHS) has been working with small businesses on the development, evaluation, and commercialization of low-cost Internet of Things (IoT) flood and wildland fire sensors. The goal is to provide earlier alerts, warnings and notifications of rising waters and fire ignitions, allowing communities the ability to better respond, mitigate and possibly prevent catastrophic disasters.

1B-2: USACE Instrumentation and Monitoring Program

Georgette Hlepas*, Christopher Schaal*, *U.S. Army Corps of Engineers*

USACE's instrumentation and monitoring program monitors over 700 dams and 4,000 miles of levees. As part of USACE'S advancement in monitoring, this presentation will focus on the MIDAS (Monitoring Instrumentation Data Acquisition System) project, an enterprise-wide instrumentation database. USACE will also provide an overview of their ongoing evaluation of DHS developed Low-Cost IoT Flood Inundation Sensors, and their potential use to complement USACE's monitoring programs.

1B-3: USGS Water Mission Area Observing Systems Research and Development Program

R. Russell Lotspeich*, *U.S. Geological Survey*

The USGS has a long history of evaluating water technologies for use in monitoring and research applications carried out to characterize the nation's water resources. This is done to verify manufacturer specifications as well as to evaluate technologies

for use in new environments and under a range of environmental conditions. Not all technologies are well-suited for all environments and understanding instrument limitations is critical to selecting the best instrument for a given location and to properly interpreting the data generated.

The USGS Water Mission Area (WMA) began receiving congressional appropriations in 2018 to develop a Next Generation Water Observing System (NGWOS) program in select basins across the U.S. This program includes significant investments into evaluating new technologies and transitioning the most promising ones into national operations. Of interest to the program are new and innovative monitoring methods and instrumentation that result in increased efficiencies, accuracy, new data types, and(or) temporal and spatial resolution of water data across networks. Imagery, remote sensing, and artificial intelligence are just a few examples of technologies that are currently being evaluated through the NGWOS program.

The USGS has historically held all the traditional types of water data it provides to the public to a uniform standard for data quality and uncertainty. With advances in technology providing exciting and useful alternative methods for measuring parameters such as water level, water velocity, and water temperature, some of the most promising technologies, unfortunately, do not meet that single standard. Because these data are still of great value to stakeholders and the USGS in defining the temporal and geographic variability in hydrologic conditions, there is a desire to move forward with operational implementation of many of these new systems. So that the new data types and results of new collection methods can be interpreted by end users with as much confidence as the traditional USGS data, the USGS WMA is evaluating systems of data classification that will clearly identify differing levels of quality and uncertainty associated with each new data type, and the NGWOS program is leading this effort.

1B-4: State and Local Experience in Virginia Implementing IoT Sensors and Data Systems

David Ihrie*, *Virginia Innovation Partnership Corporation*

The Commonwealth of Virginia and local government partners now have increasing experience implementing IoT sensors such as flood and wildfire sensors, and their related data systems and user facing applications This talk provides a description of the journey, lessons learned, and a look towards the future as these increasingly ubiquitous sensors become a primary driver for situational awareness and delivery of services.

1C-1: Big Stories from the Historic Winter of 2020/21

David Novak*, *National Oceanic and Atmospheric Administration, National Weather Service (NOAA/NWS)*

This review will highlight some of the "big stories" of the 2020-21 historic winter season, including one of the snowiest Octobers on record in the CONUS, an historic

early season ice storm in Oklahoma, a December nor'easter with 40" of snow in 15 hours, and most, notably, an historic and devastating February cold wave. Winter dryness over the west foreshadowed a devastating drought for the remainder of 2021. Notable events in the early part of the 21-22 season will also be reviewed. These events will be used to illustrate the impacts of extreme winter conditions on society and the national infrastructure, and the weather enterprise's efforts in building public readiness for such events. Winter 2020-21 will be best known for the February cold wave - the most destructive and costly winter event to affect the United States in recorded history. The event was responsible for 172 deaths and over $20 Billion in direct losses (nearly doubling the inflation-adjusted cost of the 1993 Superstorm). This talk will review the rare meteorological circumstances of the event, which contributed to cascading failures in the power, water, and transportation infrastructure. In reviewing the events of the 2020-21 season, this presentation will also highlight successes and challenges in building industry readiness for winter weather, including new product and messaging innovations.

1C-2: Linking Arctic variability and change with extreme winter weather in the US including the Texas Freeze of February 2021

Judah Cohen*[1], Laurie Agel[2], Mathew Barlow[2], Chaim Garfinkel[3], Ian White[3]
[1]Atmospheric and Environmental Research, [2]University of Massachusetts Lowell, [3]Hebrew University of Jerusalem

The Arctic is warming at a rate twice the global average and severe winter weather is reported to be increasing across many heavily populated mid-latitude regions, but there isn't yet agreement on whether there is a physical link between the two phenomena. Here I will present observational analysis to show that a lesser-known stratospheric polar vortex (SPV) disruption that involves wave reflection and stretching of the SPV is linked with extreme cold across parts of Asia and North America, including the recent February 2021 Texas cold wave, and has been increasing over the satellite era (post 1980). I will also present numerical modeling experiments forced with trends in autumn snow cover and Arctic sea ice to establish a physical link between Arctic change and SPV stretching and surface impacts. This phenomenon is also active in January 2022 and if time permits, I will present on the weather of January 2022.

1C-3: 2021 U.S. Billion Dollar Weather and Climate Disasters in Historical Context including New County-Level Exposure, Vulnerability and Projected Damage Mapping

Adam Smith, *National Oceanic and Atmospheric Administration, National Centers for Environmental Information (NOAA/NCEI)*

NOAA National Centers for Environmental Information (NCEI) released the final update to its 2021 Billion-dollar disaster report (www.ncdc.noaa.gov/billions), confirming what much of the nation experienced throughout 2021: another year of frequent and costly extremes. The year came in second to 2020 in terms of number of disasters (20 versus

22) and third in total costs (behind 2017 and 2005), with a price tag of $145 billion. The events included: 1 winter storm/cold wave event (focused across the deep south and Texas); 1 wildfire event (combined impacts of wildfires across Arizona, California, Colorado, Idaho, Montana, Oregon and Washington); 1 drought and heat wave event (summer/fall across western U.S.); 2 flood events (in California and Louisiana); 3 tornado outbreaks (including the December tornado outbreaks); 4 tropical cyclones (Elsa, Fred, Ida and Nicholas); and 8 severe weather events (across many parts of the country, including the December Midwest derecho). The costliest 2021 events were Hurricane Ida ($75 billion), the mid-February Winter Storm / Cold Wave ($24.0 billion), and the Western wildfires ($10.9 billion). Adding the 2021 events to the record that began in 1980, the U.S. has sustained 310 weather and climate disasters where the overall damage costs reached or exceeded $1 billion. The cumulative cost for these 310 events exceeds $2.15 trillion. In broader context, the total cost of U.S. billion-dollar disasters over the last 5 years (2017-2021) is $742.1 billion, with a 5-year annual cost average of $148.4 billion, both of which are new records and nearly triple the 42-year inflation adjusted annual average cost. The U.S. billion-dollar disaster damage costs over the last 10-years (2012-2021) were also historically large: at least $1.0 trillion from 142 separate billion-dollar events. It is concerning that 2021 was another year in a series of years where we had a high frequency, a high cost, and large diversity of extreme events that affect people's lives and livelihoods—concerning because it hints that the extremely high activity of recent years is becoming the new normal. 2021 marks the seventh consecutive year (2015-21) in which 10 or more separate billion-dollar disaster events have impacted the U.S. The 1980–2021 annual average (black line) is 7.4 events (CPI-adjusted); the annual average for the most recent 5 years (2017–2021) is 17.2 events (CPI-adjusted). To better reflect multi-hazard risk – the Billion-dollar disaster site now provides a new mapping tool that provides county-level information on natural disaster hazards across the United States. This interactive NOAA mapping tool provides detailed information on a location's susceptibility to weather and climate hazards that can lead to billion-dollar disasters—such as wildfires, floods, drought and heat waves, tornado outbreaks, and hurricanes. The tool expands upon FEMA's National Risk Index to provide a view of a location's risk for, and vulnerability to, single or multiple combinations of weather and climate hazards for every county and county-equivalent in all 50 states: https://www.ncdc.noaa.gov/billions/mapping In addition, the 2021 annual U.S. billion-dollar disaster report is available here: https://www.climate.gov/news-features/blogs/beyond-data/2021-us-billion-dollar-weather-and-climate-disasters-historical

Day 2 (Feb 16th, 2020) Oral Presentations

2A-1: Uncertainty in Precipitation Frequency Estimates Under Current and Future Climate

Azin Al Kajbaf*, Michelle Bensi, Kaye Brubaker
University of Maryland, Department of Civil and Environmental Engineering

Over the past decades, the intensity of precipitation events in the Northeast of the United States has shown an increasing trend. As climate change continues to affect the characteristics and frequency of rainfall events, it is important to account for these changes in the Intensity/Depth Duration Frequency (IDF/DDF) curves used in engineering design and planning. This study develops model-based precipitation frequency estimates under current and projected future climate in Maryland. Specifically, IDF/DDF curves for selected durations from 15 minutes to 48 hours are developed from statistical analyses of synthetic data from the North American Regional Climate Change Assessment Program (NARCCAP) suite of models. In the NARCCAP suite, 6 regional climate models covering most of North America at a spatial resolution of 50 km are driven by different atmosphere-ocean general circulation models, for a total of 12 climate simulations, both historic and future. NARCCAP synthetic time-series are available at a 3-hour temporal resolution. Machine learning models are used to temporally downscale the NARCCAP time-series to durations as short as 15 minutes. Using the developed time-series, suites of IDF/DDF curves are developed that account for a range of modeling decisions associated with climate model selection and other statistical assumptions. The suites are then used to produce averaged IDF/DDF curves. Graphical tools are developed to comparatively assess the uncertainty associated with climate model selection and the other modeling decisions used to develop IDF/DDF curves. A particular focus is placed on understand differences in drivers of uncertainty under current and future climate conditions.

2A-2: Gridded Surface Weather Data with Uncertainty Quantification - Daymet V4

Peter Thornton*, *Oak Ridge National Laboratory*

Observation-based estimates of surface weather are necessary inputs for many environmental studies and assessments. When uncertainties associated with surface weather estimates can be quantified, researchers and applications specialists can make informed decisions about the utility and appropriateness of data products to meet project requirements. The purpose of the Daymet gridded daily surface weather products is to provide necessary inputs to a broad range of environmental and ecological applications, while also providing the best possible quantification of uncertainty in those products. This presentation will briefly review the history of Daymet development, and will explore the improvements in algorithm and data processing that led to the recently released Daymet v4. The cross-validation metrics for precipitation and temperature will be described, with a focus on statistics for the spatial and

temporal distribution of precipitation frequency and event size distributions. The relationship between surface weather and hydrological processes relevant to flooding hazards will also be discussed.

2A-3: Utility of Weather Types to Improve Nonstationary Frequency Analysis of Extreme Precipitation

Giuseppe Mascaro*, *Arizona State University*

Theoretical arguments suggest that extreme precipitation (EP) will increase in a warmer climate. Climate projections and, in part, observational studies support these arguments, indicating the need to incorporate nonstationarity in EP frequency analysis. Here, a statistical framework is presented that addresses this need through changes in weather type (WT) occurrence. The framework is based on mixed populations of peak-over-threshold (POT) series of EP associated with the dominant WTs in a given region. The Poisson distribution with time-varying parameters is used to model the WT occurrence, while the Generalized Pareto distribution with constant parameters is adopted to model POT series of EP. The value of the proposed method is demonstrated by focusing on the U.S. Midwest, where it has been recently showed that the occurrence of a dominant WT related to heavy precipitation has been increasing since 1949. It is first showed that the statistical uncertainty of the nonstationary framework is comparable to a stationary approach based on the Generalized Extreme Value distribution fitted to annual precipitation maxima, often used in current engineering design. Next, historical and future climate simulations of a set of general circulation models from CMIP6 are used to quantify projected changes in EP frequency in the region, along with the associated uncertainty.

2A-4: Characteristics and Causes of Extreme Snowmelt over the Conterminous United States

Joshua Welty*[1], Xubin Zeng[2]
[1]*U.S. Navy Fleet Numerical Meteorology and Oceanography Center,* [2]*University of Arizona*

Snowmelt is an essential process for the health and sustenance of numerous communities and ecosystems across the globe, though it also presents potential hazards when ablation processes are exceedingly rapid. Using 4-km daily snow water equivalent, temperature, and precipitation data for three decades (1988–2017), here we provide a broad characterization of extreme snowmelt episodes over the conterminous United States in terms of magnitude, timing, and coincident synoptic weather patterns. Larger-magnitude extreme snowmelt events usually coincide with minimal precipitation and elevated temperatures. However, certain regions, particularly mountainous regions and the northeastern United States, exhibit greater likelihood of extreme snowmelt events during pronounced rain-on-snow events. During snowmelt extremes, snowmelt rate often exceeds precipitation in many regions. Meteorological patterns and associated water vapor transport most directly connected to extreme

events over different regions are classified via a machine-learning technique. Over the 30-yr study period, there is a weakly increasing trend in the frequency of extremes, though this does not necessarily signify an increase in snowmelt magnitudes.

2A-5: LIP PFHA Pilot Study

Rajiv Prasad*, Arun Veeramany, Rajesh Singh
Pacific Northwest National Laboratory

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

PNNL has completed Tasks 1 and 2 of this project. The findings from these tasks were presented in previous PFHA Workshops. In Task 3, a PFHA was performed for a NPP site. The LIP flood model developed for the post-Fukushima flood hazard reevaluation was leveraged for this study. The LIP flood model was implemented using the FLO-2D™ flood simulation software package. The model was first subjected to a sensitivity analysis to determine the major sources of uncertainty in model predictions. The flood hazards were found to be sensitive to two sources: (1) input precipitation (aleatory variability) and (2) surface roughness (epistemic uncertainty). The flood hazards did not show significant variation with respect to initial soil moisture content, saturated hydraulic conductivity, and presence of storm drains.

LIP PFHA simulations are being performed using a stratified sampling approach. The input precipitation is obtained from the National Oceanic and Atmospheric Administration (NOAA) precipitation frequency data server. Point precipitation frequency estimates for annual maximum precipitation at the site were obtained and extrapolated to an annual exceedance probability of 1×10-6. Storm temporal distributions from NOAA Atlas 14 were used to construct storms of 6, 12, 24, and 96-h durations. The relative frequencies of temporal distribution types (peak intensity in various quartiles) were preserved. The NPP site's spatial distribution of surface roughness (represented by Manning's surface roughness coefficient) were preserved. The epistemic uncertainty in surface roughness was represented by a uniform distribution of multipliers applied to the original spatial distribution.

The model runs for the PFHA simulations are being performed on PNNL's high-performance supercomputer. To this end, the FLO-2D™ software was tested and modified to run under a Microsoft Windows™ emulator on the Linux system. A set of Python scripts are used to sample input parameters, populate input files, perform flood

simulations, collect predicted results, and estimate the flood hazard curves. The total probability theorem is applied to estimate the flood hazard curves.

2B-1: Flood Typing and Application to Mixed Population Flood Frequency Analysis: An Interagency Collaborative Effort

Nancy Barth*[1], Michael Bartles[2], John England[2], Jory Hecht[1], Gregory Karlovits[2], William Lehman[2]
[1]*U.S. Geological Survey,* [2]*U.S. Army Corps of Engineers*

An improved understanding of the frequency and magnitude of floods is critical for the design of transportation and water-conveyance structures as well as insurance studies and floodplain management. Methods for estimating annual exceedance probabilities (AEPs) (or return intervals) in the United States were recently updated in Bulletin 17C. These methods assume homogeneous flood distributions but acknowledge that floods at a given location can be generated by multiple causal mechanisms, such as snowmelt, intense convective rainfall events, or tropical cyclones, representing a mixed population. Mixed population flood events may not only impact the fit of the flood frequency curve in the range of the observed floods but may also impact the quality of AEP estimates in the upper tail of the flood frequency distribution. The 'Future Studies' section in Bulletin 17C acknowledges shortcomings in the handling of mixed-population datasets and highlights the need for additional studies before guidance for conducting mixed-population flood frequency analysis can be confidently developed. Classification of individual events by flood generating mechanisms, or flood type classification, might enable a mixed population analysis. The flood type classifications can be defined in terms of both proximal atmospheric causal mechanisms, such as different storm types, as well as antecedent watershed conditions, such as soil moisture storage and snowpack water content. Currently, the largest national database of annual peak flows, the U.S. Geological Survey (USGS) National Water Information System (NWIS) database, contains little information about the flood type classification for each annual peak-flow event. The U.S. Army Corps of Engineers (USACE) and USGS have begun a multi-year collaborative effort to develop methods for efficiently categorizing flood data stored in NWIS by causal mechanisms. In addition, this collaboration includes the design of a database framework for storing peaks-over-threshold (POT) events. This would ensure that all floods taking place in years with multiple large flood events would also be recorded in the database, including information on the mechanisms that generated them. The POT data could be used for mixed population analyses that includes frequency, duration, and volume.

2B-2: Applying Stochastic Weather Generation and Continuous Hydrologic Simulation for Probabilistic Flood Hazard Assessments

Joe Bellini*[1], Bill Kappel[2], Dennis Johnson[2], Doug Hultstrand[2]
[1]*Aterra Solutions,* [2]*Applied Weather Associates*

Applied Weather Associates teamed with Aterra Solutions to complete a stochastic weather modeling study to provide long term meteorological realization for hydrologic modeling, flood frequency analysis, and flood recurrence interval analyses. This utilized a multisite stochastic modeling approach using daily observations of precipitation, temperatures, and snow water equivalent (SWE) from 49 sites in the upper Midwest through the Multi-site Auto-regressive Weather GENerator (RMAWGEN)) framework. Stochastic weather generators are statistical models that simulate realistic or plausible random sequences of atmospheric variables. Resulting sequences provide meteorological realizations that can be used for risk evaluations and reliability assessments for various systems such as dams and nuclear generating facilities. Observed precipitation and temperature records were used to calibrate RMAWGEN for the 1949–2019 period. Validation was performed on the calibration period data. Results demonstrate that the model was able to capture spatiotemporal characteristics of observed precipitation and temperature. The model generated 12 iterations of 1,000-years of daily weather sequences of precipitation, temperatures, and SWE. Climate change projections were applied using RCP 4.5 and 8.5 to generate 12 iterations of 1,000-years of future sequences of precipitation, temperatures, and SWE. Weather outputs were used in a continuous simulation hydrologic model built using HEC-HMS. This was calibrated against 3 different years of daily flow data at locations throughout an 88,000 mi2 basin. Normal, wet, and dry years were used for calibration. The final calibrated model was used to simulate runoff for each 12x1000-year simulations, including the three climate change projections. Uncertainty analyses, using a Monte-Carlo framework within HMS, bracketed potential outflow possibilities based on variability in hydrologic inputs identified in the calibration phase. Annual maximum flows were used to characterize probabilistic flood hazards (to as low as a 10-6 annual exceedance probability), considering a wide range of event parameters such as snow accumulation, spring melt patterns, and rainfall. Results will be used in safety assessments and seasonal flood operation planning.

2B-3: IWRSS Flood Inundation Mapping for Flood Response

Robert Mason*[1], Julia Prokopec*[1], Adam Barker*[2], Cory Winders*[3], Darone Jones*[4]
[1]*U.S. Geological Survey,* [2]*Federal Emergency Management Agency,* [3]*U.S. Army Corps of Engineers,* [4]*National Weather Service*

Traditionally, flood predictions and forecasts have focused on communicating near-term outlooks for flood-peak stages (water-elevations) and flow rates. But modern geospatial and hydrodynamic modeling techniques permit the rapid conversion of such information into flood inundation maps (FIMs) that communicate fair more effectively the expected area extent and timing of a flood and the physical resources and

community populations that will be impacted. Many agencies at the Federal, State, and local levels have evolved these techniques such they are now deployed routinely, and the resulting maps distributed to emergency management agencies.

Sometimes a diversity of approaches, assumptions, or inputs made by the modelers can result in divergent maps that can confuse users. In 2018, the Integrated Water Resources Science and Services (IWRSS; a consortium of the Federal Emergency Management Agency (FEMA), National Ocean and Atmospheric Administration (NOAA), U.S. Army Corps of Engineers (USACE), and the U.S. Geological Survey (USGS)) was tasked with developing a process for coordinating Federal, event-based FIMs and establishing an authoritative source for communication of the coordinated FIM to FEMA. The process was codified in a draft "playbook" that has been exercised and further developed through several recent floods. This presentation will describe the iFIM vision, the evolving playbook, agency roles and products, and efforts to develop a truly integrated and authoritative FIM for the Federal emergency management community.

2B-4: Using HEC-WAT for NRC's PFHA Process

William Lehman*, Gregory Karlovits, David Ho, Leila Ostadrahimi, Brennan Beam, Sara O'Connell, Julia Slaughter
U.S. Army Corps of Engineers Hydrologic Engineering Center

This presentation describes the application of the Nuclear Regulatory Commission's (NRC) Probabilistic Flood Hazard Analysis (PFHA) process through the Hydrologic Engineering Center Watershed Analysis Tool (HEC-WAT). PFHA provides a quantitative relation between of the probability of occurrence (or frequency) and magnitude for various flood hazards. The modeling framework includes hydrologic processes such as infiltration, runoff, discharge routing, reservoir operations, and near-field hydraulic processes. A comprehensive flood hazard assessment comprised probabilistic modeling of individual processes as well as composite modeling of coincident and/or correlated processes. The result is computed flood hazard frequency curves described with uncertainty bounds at various sites across the watershed for many informative variables. HEC-WAT was applied to a pilot watershed to provide a concrete demonstration of methodology to produce the outputs required for PFHA. This pilot project is focused on inland flood riverine flooding mechanisms including upstream dam breaching that may impact Nuclear Power Plants (NPPs).

Day 3 (Feb 17th, 2020) Poster Presentations

3A-1: Flood Fragility Function Methodology for a Conceptual Nuclear Power Plant

Joy Shen*, Michelle Bensi, Mohammad Modarres; *University of Maryland*

Fragility functions quantify the probability that a structure or component will be damaged or fail at a certain intensity measure (IM) of hazard severity (e.g., flood height). Due to limited experience in external flooding probabilistic risk assessment (PRA) in the nuclear energy sector, flooding fragility function development has not been a practical priority for nuclear power plants (NPPs). As a result, there is a gap in the literature related to flooding fragility assessments to support NPP PRAs. However, recent flooding events at Fukushima Daiichi NPP, Fort Calhoun NPP, and other facilities have highlighted the importance of advancing this field. The poster will present a conceptual, illustrative example of an emergency diesel generator (EDG) building with flood barrier components that act as protective measures during an external flood. In addition, this poster will include a brief description of the fragility function development for flood barriers such as penetration seals, doors, floodgates, and louver covers. The data gathered from a literature review and the conservative deterministic failure margin (CDFM) method is used to derive fragility parameters. This information is then used to determine damage states and their associated leakage rate as the external flood enters the building as a result of varying degrees of flood protection damage. Leakage rates and internal flood heights are generated from illustrative geometry and representative hazard characteristics.

3A-2: Quantifying Uncertainty in Hurricane Warning Times to Inform Coastal Hazard PRA

Somayeh Mohammadi*, Michelle Bensi; *University of Maryland*

Nuclear power facilities and other critical infrastructure are often located in coastal regions exposed to the effects of tropical cyclones (e.g., hurricanes and tropical storms). These facilities may employ response strategies that involve actions to install temporary protection or mitigation features. The effectiveness of response strategies may be adversely affected by hardware failures. In addition, there is also a possibility that actions will be unsuccessful due to delayed organizational decision-making, human errors, and differences between the predicted and experienced coastal hazard characteristics. Accurate coastal hazard probabilistic risk assessments for critical infrastructure such as nuclear power facilities must include human reliability assessments that quantify the probabilities that protection and mitigation actions will be unsuccessful. These probabilities depend on the information available to support decisions and the environmental conditions under which actions are performed. A critical input to the human reliability assessment is the time available to perform actions. However, this estimated time is subject to uncertainty due to uncertainty in hurricane and tropical storm forecasts. This study seeks to quantify the uncertainty in the time available to execute actions that are triggered based on storm advisories. Uncertainty assessments are developed using NOAA GIS datasets related to

advisory/forecast and observed storm track data from 2012 to 2020. Specifically, the differences between advisory forecasted track data (e.g., predicted landfall locations and times) at various time points are compared against the final observed track. This provides insights into the likelihood that the time available to perform proceduralized actions triggered by advisory information will be longer or shorter than assumed.

3A-3: HEC-WAT Interface and Set Up for the Trinity River PFHA Pilot Project

David Ho*, William Lehman, Brennan Beam, Sara O'Connell, Leila Ostadrahimi
U.S. Army Corps of Engineers, Hydrologic Engineering Center

The Nuclear Regulatory Commission's (NRC) Probabilistic Flood Hazard Analysis (PFHA) utilized Hydrologic Engineering Center Watershed Analysis Tool (HEC-WAT) to provide a quantitative relationship between of the probability of occurrence (or frequency) and magnitude for various flood hazards. HEC-WAT was applied to the Trinity River watershed to demonstrate a method of producing stochastic outputs required for the PFHA. The modeling effort required a number of different applications or "plugins" to perform the PFHA analysis. This poster will show the Trinity River HEC-WAT interface, how the project was set-up for the modeling, which plugins were added, and how the model order was selected.

3A-4: Riverine Flooding HEC-WAT Pilot Project Dam Break Modeling

Brennan Beam*, William Lehman, Sara O'Connell, David Ho, Leila Ostadrahimi
U.S. Army Corps of Engineers, Hydrologic Engineering Center

This poster describes how the Hydrologic Engineering Center's Watershed Analysis Tool (HEC-WAT) is being used to include dam failure in their probabilistic flood hazard assessment (PFHA) process. The technical details associated with viewing a system wide dam failure for a single event using HEC-RAS and HEC-ResSim is the primary focus of the poster.

3A-5: Flooding from Below – The Groundwater Emergence Hazard

Kevin M. Befus*[1], Patrick L. Barnard[2], Peter W. Swarzenski[2], Clifford Voss[2]
[1]University of Arkansas, [2]U.S. Geological Survey

Shallow groundwater levels create hidden flood hazards via 'groundwater emergence'. In such areas, thin vadose zones could accentuate compound flooding events, and rising water tables could reach the ground surface and flood low lying areas. Even without groundwater emergence, a shoaling groundwater table can reduce the effectiveness and lifespans of coastal urban and rural infrastructure, such as storm drains, shoreline armoring, and other buried assets, as well as potentially remobilize soil contaminants. Wetter regional climate, more frequent and intense storms, focused urbanization and projected sea-level rise are just a few processes that will likely expand future zones of groundwater emergence in some regions. Downstream coastal

communities and associated infrastructure are most at risk to the compounded effects of prolonged or chronic groundwater emergence. Numerical simulations of the California coastal region illustrate the expansive extent and nuances of shoaling and groundwater emergence hazards today and predict a substantial increase in groundwater-flooded areas with future sea-level rise. Low-lying areas are most vulnerable to flooding hazards from below due to groundwater emergence, as well as to episodic marine overland flooding and quasi-permanent inundation. Overall, societal exposure to shallow and emergent groundwater with rising sea levels was projected to be 6-9 times higher than overland flooding by the end of the century for coastal California. Thus, responsive flood protection policy and infrastructure should account for not only marine overland flooding but also for groundwater flooding from below. Ongoing work will extend these simulations to coastal aquifers across the southeastern United States.

3A-6: External Flooding PRA Guidance

Marko Randelovic*[1], Raymond Schneider*[2]
[1]Electric Power Research Institute (EPRI), [2]Westinghouse Company

EPRI is currently developing a guidance for performing an external flood PRA for use in the nuclear industry. The guidance establishes a structured framework for treating the spectrum of external flood hazards and provides background materials and examples for the PRA analyst to use. Specifically, the project aids the PRA analyst in:

1) Defining and characterizing the external flood hazard, considering event and plant-specific issues.
2) Estimating external flood hazard frequencies.
3) Developing external flood fragility curves for flood significant Systems, Structures, and Components (SSCs).
4) Preparing an external flood event tree, including consideration of actions preparing the plant for the flood, mitigating the flood hazard, and responding to random and flood-induced failures of initial flood mitigation strategies.

Guidance is being developed to be consistent with expected requirements of the ASME/ANS PRA Standard. To facilitate understanding simple hypothetical example applications illustrate the interface with the probabilistic flood hazard assessment (PFHA), parsing the flood analysis to characteristic event frequencies and the development of various PRA flood event trees and overall quantification overall process. This guidance also includes a potential screening approach for the flood related combined/correlated hazards.

Day 3 (Feb 17th, 2020) Oral Presentations

3B-1: An Overview of CSTORM Model Development and Results for the South Atlantic Coastal Study (SACS)

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The U.S. Army Corps of Engineers (USACE) South Atlantic Division and the Engineer Research and Development Center (ERDC) have been engaged in a large, multi-year project called the South Atlantic Coastal Study (SACS). Following the precedent of other large coastal studies within the USACE, such as the North Atlantic Coastal Comprehensive Study (NACCS), the SACS study was designed to identify and assess coastal hazards risks in the domain of concern on a regional scale and to support future resilience and sustainability efforts in coastal communities. Probabilistic coastal hazards analysis using a state-of-the-art innovative statistical and probabilistic framework for the comprehensive characterization of storm climatology was applied as part of one component of this study. Modeling was performed using the high-resolution Coastal Storm Modeling System (CSTORM-MS), and advanced joint probability analysis of atmospheric forcing and primary storm responses, including associated aleatory and epistemic uncertainties, was conducted. The study was broken into three domains: 1) the southern U.S. East Coast ranging from the border of North Carolina and Virginia to the southern tip of Florida, 2) the Gulf Coast from the southern tip of Florida to the Mississippi and Louisiana state boundary, and 3) Puerto Rico and the U.S. Virgin Islands. The focus of this presentation is on the South Atlantic (SA) and Gulf of Mexico (GoM) domains, for which 1700 unique synthetic tropical storm events, 15 historical tropical storms, and 70 historical extratropical events were simulated for present-day sea level as well as two sea level rise scenarios. An overview of the CSTORM model development and validation process for the two domains will be given, along with details about the storm suite and water levels. A summary of the modeled results and their inclusion in the Coastal Hazards System (CHS) will also be presented.

3B-2: Compound Flood Hazard Assessment using a Bayesian Framework

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Compound flooding is a topic that has received high attention recently. These types of flood events are caused by the occurrence of more than one flood mechanism, such as storm surge, precipitation, and tides. Compound flood events can cause more severe

impacts on societies and the built environment than flood events caused by just a single flood mechanism. In this way, a probabilistic assessment of compound flood hazards is necessary for a realistic assessment of flood hazards. This study focuses on the probabilistic assessment of compound flood hazards caused by the simultaneous occurrence of hurricane-induced surge, precipitation, tide, and antecedent river flow. A Bayesian framework is developed to include these flood drivers in the probabilistic flood hazard assessment for a case study on the Delaware River in Trenton. The inputs to this model include storm parameters (i.e., central pressure deficit, forward velocity, heading direction, radius to maximum wind and landfall location), antecedent river flow, and predicted tidal levels. A series of predictive surrogate models are developed to estimate total river discharge accounting for hurricane-driven surge, antecedent flow, and tides. The proposed model can be used to generate a probability distribution for total river discharge at the time of the storm occurrence in the study area. Furthermore, the model can be used to generate a hazard curve representing the annual exceedance frequency of total river discharge caused by the hurricane-induced flood mechanisms mentioned earlier.

3B-3: Coastal Flooding PFHA Pilot Study

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Inundation due to the compound effects of storm surge and rainfall associated with coastal storms can produce widespread damage to coastal infrastructure. A coastal probabilistic flood hazard assessment (PFHA) pilot study is being conducted to demonstrate the application of PFHA to external flooding at a hypothetical nuclear power plant (NPP) location on the Lower Neches River watershed in Texas. Compound flooding hazards being assessed in this study include storm surge, astronomical tide, waves, rainfall, and coincident riverine flooding along with associated uncertainties. The assessment requires the characterization of storm climatology for tropical cyclones (TCs) using the U.S. Army Corps of Engineers' (USACE) Coastal Hazards System (CHS) data based on its Probabilistic Coastal Hazard Analysis (PCHA) framework. The PCHA is a probabilistic framework for quantifying coastal storm hazards that includes storm climatology characterization, high-resolution, high-fidelity numeric atmospheric, hydrodynamic, and wave modeling, and advanced joint probability analysis of atmospheric forcing to develop storm hazard curves and uncertainty. The compound probabilistic modeling approach being implemented here incorporates rainfall within the PCHA framework though the use of a physics-based parameterized tropical cyclone rainfall (TCR) model driven by the same atmospheric forcing, allowing concurrent characterization of the compound flooding hazard and associated uncertainties. Simulation of both coastal and riverine processes driven by TCs will be completed using hydrologic, hydraulic, and hydrodynamic models: synthetic TC rainfall will be applied to a HEC-HMS model of the Neches Watershed and the flow output routed through the inland-coastal boundary through the use of a 2D HEC-RAS model. The compound hazards will be assessed through the application of a loosely coupled HEC-RAS and ADCIRC modeling framework and quantified through the integration of the

combined responses, including uncertainty. As the coupled inland and coastal models are being implemented, the impacts of several modeling options are being explored including: precipitation-based infiltration parameters, antecedent flow conditions, precipitation in the hydraulic model, boundary condition geometry and additional runs of hydrodynamic models for multiple riverine flow conditions.

3B-4: Probabilistic Wave Height Hazard Assessment Method at the NPP Site Considering Storm Surge

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Due to the influence of recent climate change, typhoon invasions of the Korean Peninsula with extreme rainfall frequently occur. Between August and September 2020, three typhoons, Bavi, Maysak, and Haishen, attack to the Korean Peninsula, and the resulting heavy rains that fell caused flood damage. As typhoons Maysak and Haishen passed east of Korea, the local nuclear power plants were automatically shut down. In order to analyze the wave height, wave period, and wave direction characteristics in the front of the nuclear power plant site, the SWAN model was built in the near sea area through nesting technique. First, based on the data presented in the Deepwater design waves report, wave height, period, and sea wind were estimated according to the return period. Second, the SWAN model was established through SMS and GIS programs based on the sea-depth data around the nuclear power plant site. Finally, a probability distribution was applied based on the wave height data, the result of the SWAN model for each return period. Based on the result, the probabilistic wave height hazard assessment (PWHA) of the sea around the nuclear power plant site was estimated. The results of this study are expected to be the basis for the waterproofing design of nuclear power plant sites and the planning of various flood prevention measures caused by the combination of external hazard such as local intense precipitation (LIP) and storm surges.

3B-5: Comparative Assessment of Joint Distribution Models for Tropical Cyclone Atmospheric Parameters in Probabilistic Coastal Hazard Analysis

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The United States Army Corps of Engineers (USACE) has developed the Probabilistic Coastal Hazard Analysis (PCHA) framework to extend and advance the joint probability method, which has been used to establish probabilistic coastal hazard curves over the past decade. The PCHA framework requires characterization of the joint distribution of tropical cyclone (TC) atmospheric parameters (i.e., central pressure deficient, forward velocity, radius of maximum wind, and heading direction). While the assumptions made in developing this joint distribution have changed over the years, the current PCHA framework uses a meta-Gaussian copula (MGC) to characterize the dependence

among TC atmospheric parameters. However, the MGC has limitations associated with modeling of circular variables such as storm heading direction as well as the degree to which it can capture tail dependence. This research investigates the performance of a series of joint distribution models, including the MGC and alternative models. A particular emphasis is placed on characterizing the dependence between linear and circular variables. Specifically, a von Mises kernel function (VKF) is proposed as an alternative to the Gaussian kernel function (GKF) typically in the calculation of the directional storm recurrence rate (DSRR) representing the probability model of heading direction. This study then builds a series of joint distribution models based on assumptions ranging from independence to full dependence models that consider a range of copula models (e.g., MGC and vine copulas combining linear-circular copulas with Gaussian or Frank copulas). The sensitivity of coastal hazard curves to different joint distribution models is assessed for selected locations around New Orleans, LA (USA). The stability of hazard curves generated using an MGC assumption related to the selection of the zero-degree convention is assessed, along with a comparison of tail dependence between copula models.

Day 4 (Feb 18th, 2020) Oral Presentations

4A-1: Duane Arnold Energy Center (DAEC) Loss of Offsite Power (LOOP) Due to Derecho

Terry Brandt*, *Nextera Energy*

This presentation will give you the initial conditions, timeline of events, and operator actions associated with the Duane Arnold Derecho Event.

4A-2: The NRC's Regional Response to the Duane Arnold Derecho

John Hanna*, *U.S. Nuclear Regulatory Commission*

This presentation, as part of the greater panel on the Duane Arnold derecho, will address Region 3's response to the event including the aspects of immediate event response by the inspection staff, the Management Directive 8.3 event assessment and other regional actions taken. Additionally, risk insights from this event will be shared.

4A-3: Why the Risk of the Extended Loss of Offsite Power Was Almost a Significant Precursor?

Christopher Hunter*, *U.S. Nuclear Regulatory Commission*

On August 10, 2020, a severe storm with heavy rains and very strong straight-line winds (called a derecho) resulted in an extended loss of offsite power (LOOP) at Duane Arnold Energy Center (DAEC). The National Weather Service later estimated wind speed peaks were likely near 130 mph, which resulted in extensive damage to offsite power lines and a number of plant structures including the reactor, turbine, and

FLEX buildings, and nonsafety-related cooling towers. In addition, the high winds led to an ingress of debris into the essential service water that challenged the system strainers and required operator intervention to maintain adequate cooling to one of the two emergency diesel generators. This presentation will cover the important assumptions, results, and key risk insights from the accident sequencer precursor (ASP) analysis. In addition, a comparison with other recent LOOP precursors due to severe weather will show why the event at DAEC had substantially higher risk that these other events.

4A-4: The NRC's Response to the Duane Arnold Derecho Event using the LIC-504 Process

Matthew Leech*, *U.S. Nuclear Regulatory Commission*

When the NRC saw that the risk of the Duane Arnold derecho event was high, the decision was made to perform a LIC-504 analysis to determine if a safety issue risk existed to other power plants in the fleet. The LIC-504 is a risk informed process that the NRC uses to disposition emergent safety issues. This presentation will discuss how the NRC evaluated the risk to a number of other power plants if they experienced a similar event, it will discuss the key insights, and recommendations from the LIC-504.

4B-1: Introduction to Tornado Loads in the New ASCE 7-22 Standard - Including Long Return Period Tornado Hazards Maps with Applications to Nuclear Facilities

Marc Levitan*, *National Institute of Standards and Technology*

The American Society of Civil Engineers ASCE 7 Standard on Minimum Design Loads and Associated Criteria for Buildings and Other Structures is the national standard referenced in model building codes for determination of dead loads, live loads, and loads caused by environmental hazards such as earthquakes, floods and windstorms. This standard has not included loads caused by tornadoes – until now. The 2022 edition of ASCE 7 has a new chapter with requirements for consideration of tornado loads in the design of certain buildings and other structures. The tornado hazard maps and load methodology in ASCE 7 are the result of a decade of research and development led by the National Institute of Standards and Technology (NIST). Key to the tornado load provisions is a new generation of tornado hazard maps. These maps incorporate advances in the understanding of tornado climatology and regional properties of tornadoes, tornado wind fields, tornado wind speeds, and the very significant effects of target size (and shape) on wind speed risk. The Standard includes a series of 48 maps with design tornado speeds for six return periods (from 1,700 to 10 million years) at eight target sizes each (from point targets to 4 million square feet). The map development process included consideration of epistemic (modeling) uncertainties, with support from the Nuclear Regulatory Commission. This presentation provides an overview of the tornado load requirements in ASCE 7-22 and their development. Tornado maps are a main focus of the talk, including introduction of Appendix G (Long Return Period Tornado Hazard Maps) and the ASCE 7 Hazard Tool,

which provides site-specific values for all environmental hazards (including tornadoes) through a webGIS application.

4C-1: National Inventory of Dams

Becky Ragon*, *U.S. Army Corps of Engineers*

The National Inventory of Dams (NID), a congressionally authorized database, has served as a central repository of information on dams in the U.S. and its territories since the 1980s. The site has been updated to make it easier to find and share dam-related data. The U.S. Army Corps of Engineers (USACE) maintains the NID and works in close collaboration with federal and state dam safety agencies to obtain accurate and complete information about dams in the database. The new NID allows agencies to update data in-real time – users can expect fresher data that can be downloaded and shared at any time. The NID also features new information for some dams. USACE is sharing flood inundation maps for its dams in the NID as well as narrative summaries about what their dams do, benefits they provide and risks they pose, and planned and ongoing actions to manage dam risks.

4C-2: National Levee Database

Brian Vanbockern*, *U.S. Army Corps of Engineers*

The National Levee Database (NLD), developed by the U.S. Army Corps of Engineers (USACE), is the focal point for comprehensive information about our nation's levees. The database contains information to facilitate and link activities, such as flood risk communication, levee system evaluation for the National Flood Insurance Program (NFIP), levee system inspections, flood plain management, and risk assessments. The NLD continues to be a dynamic database with ongoing efforts to add levee data from federal agencies, states, and tribes.