8th Annual Probabilistic Flood Hazard Assessment Research Workshop

March 21-24, 2023 (Hybrid)

- *NRC HQ, One White Flint North, 11555 Rockville Pike, Rockville, MD 20852*
- *MS Teams (see specific MS Teams links)*

Start time: 10:00AM Eastern Time

ABSTRACTS

Day 1 (March 21, 2023)

*** 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) and Phase 2 (pilot studies) and the status of Phase 3 (guidance development).

1A-3: Presentation and Training: Resilience Analysis and Planning Tool (RAPT)

Karen Marsh, Benjamin Rance, Scott Mahlik*
Federal Emergency Management Agency (FEMA)

Many of the utilities that own nuclear generating facilities and the relevant off-site response organizations (ORO) can benefit from the Resilience Analysis and Planning Tool (RAPT), as there is an increased focus on equity in emergency management, including a need for federal, state and local governments, utility companies and disaster support organizations to better understand the community and population demographics in areas surrounding these facilities.

FEMA's National Integration Center would like to present the updated and improved RAPT, a free GIS web map that allows users to examine the interplay of census data, infrastructure locations, and hazards. RAPT helps users visualize and analyze data about their community to inform resilience, response, and recovery actions. Participants will learn how to use RAPT to understand their community and the populations that may have more difficulty receiving an alert and/or following the proscribed protective action, such as those with limited English, individuals without access to a vehicle, or with a disability.

The RAPT includes information from FEMA's Community Resilience Index (CRI), derived from the science-based Community Resilience Indicator Analysis report. The CRI allows users to identify areas of the community with greater potential challenges to resilience while also providing census-tract level information on each of the indicators that contribute to the CRI. In addition to the community and population demographic information, the session will also provide an overview of unique analysis tools that allow users to isolate specific incident areas and identify, summarize, and export information as needed. The information in RAPT can benefit all stakeholders and we hope to facilitate discussion and collaboration amongst attendees.

In addition to a presentation, we would also provide an in-depth, interactive demonstration of the tool to participants. This demonstration will show participants demographic information for their specific communities, demonstrate the powerful analysis tools in RAPT and examine local data layers. We believe this presentation opportunity would help participants use RAPT to understand community dynamics and demographics in areas surrounding nuclear facilities.

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

Minkyu Kim*, *Korea Atomic Energy Research Institute, Division of Structural and Seismic Safety (WGEV Chair)*

The March 2011 accident at the Fukushima Daiichi nuclear power plant triggered discussions about the natural (external) events that are low-frequency but high-consequence. To address these issues and determine which events would benefit from international co-operative work, the Working Group on External Events (WGEV) was established in CSNI. WGEV is composed of a forum of experts for the exchange of information and experience on external events in member countries, thereby promoting co-operation and maintenance of an effective and efficient network of experts.

WGEV already finalized some international collaboration works as below; severe weather and storm surge, examination of approaches for screening external hazards, riverine flooding - hazard assessment and protection of NPPs, concepts, and definitions for flooding protective measures, benchmark exercise to validate hazard frequency and magnitude for external events risk assessment. Also, WGEV now performing several activities for high wind and tornado - hazards assessment and protection of Nis, combined external hazards, uncertainties in the assessment of natural hazards (Excluding Earthquakes), sources of uncertainties and methods to deal with uncertainties, and local intense precipitation.

1B-1: Overview of U.S. Global Change Research Program (USGCRP)

Michael Kuperberg*
U.S. Global Change Research Program

The U.S. Global Change Research Program (USGCRP) is a federal program mandated by Congress to coordinate federal research and investments in understanding the forces shaping the global environment, both human and natural, and their impacts on society. USGCRP facilitates collaboration and cooperation across its 14 federal member agencies to advance understanding of the changing Earth system and maximize efficiencies in federal global change research. Together, USGCRP and its member agencies provide a gateway to authoritative science, tools, and resources to help people and organizations across the country manage risks and respond to changing environmental conditions. This presentation will provide an overview of USGCRP, its structure and major responsibilities.

1B-2: A Coastal Flood Regime Shift is on the Horizon

William Sweet*
NOAA National Ocean Service

The US Interagency Sea Level Rise Task Force recently released their 2022 report that 1) updated the 2017 sea level rise scenarios for the U.S., 2) provided extreme water level probabilities based upon a regional frequency analysis of tide gauge data and 3) assessed how minor, moderate, and major flood probabilities associated with contemporary infrastructure-vulnerability and emergency-response criteria will change in the coming decades unless action is taken. This talk will review the findings of the 2022 report and discuss some next steps to continue to quantify coastal flood risk today and tomorrow.

1B-3: Observation-based Trajectory of Future Sea Level for the Coastal United States Tracks Near High-end Model Projections

Benjamin Hamlington*[1], Don Chambers[2], Thomas Frederikse[1], Soenke Dangendorf[3], Severine Fournier[1], Brett Buzzanga[1,2], R. Steven Nerem[4]
[1]NASA Jet Propulsion Laboratory, [2]University of South Florida College of Marine Science, [3]Tulane University Department of River-Coastal Science and Engineering, [4]University of Colorado Boulder Cooperative Institute for Research in Environmental Sciences, Earth Science and Observation Center

With its increasing record length and subsequent reduction in influence of shorter-term variability on measured trends, satellite altimeter measurements of sea level provide an opportunity to assess near-term sea level rise. Here, we use gridded measurements of sea level created from the network of satellite altimeters in tandem with tide gauge observations to produce observation-based trajectories of sea level rise along the coastlines of the United States from now until 2050. These trajectories are produced by extrapolating the altimeter-measured rate and acceleration from 1993 to 2020, with two separate approaches used to account for the potential impact of internal variability on the future estimates and associated ranges. The trajectories are used to generate estimates of sea level rise in 2050 and subsequent comparisons are made to model-based projections. It is found that observation-based trajectories of sea level from satellite altimetry are near or above the higher-end model projections contained in recent assessment reports, although ranges are still wide.

1B-4: National Weather Service Forecasts for the late December 2022 to mid-January 2023 West Coast Atmospheric Rivers

Mark Fresch[1]*, Alex Lamers[2]
[1]NOAA National Weather Service Office of Water Prediction, [2]NOAA National Weather Service Weather Prediction Center

Accurate precipitation and hydrologic forecasts are crucial for mitigating natural disasters such as floods or droughts and optimizing reservoir operations for diverse and sometimes competing user needs. This presentation will describe the heavy precipitation and flooding impacts from a sequence of 9 atmospheric rivers into the state of California in approximately 3 weeks from late December 2022 to mid-January 2023. In that time frame, the state of California received an average of over 11 inches of precipitation. The presentation will describe how the National Weather Service (NWS) forecasts these atmospheric rivers, the challenges of forecasting and communicating the expected precipitation and associated impacts, and new frontiers in forecasting these events.

The NWS has also developed the Hydrologic Ensemble Forecast Service (HEFS). The HEFS uses “raw” precipitation and temperature forecasts from weather and climate forecast models and provides bias-corrected ensemble forcing and streamflow forecasts at forecast locations across the US. Streamflow forecasts from the HEFS have shown consistently better quality than those from the climatologically based Ensemble Streamflow Prediction (ESP), which is being replaced by the HEFS. This presentation explains HEFS, shows validation results for HEFS, including from January 2023 atmospheric river events, and describes future enhancements for the HEFS.

1B-5: Sharpening of Cold-Season Storms over the Western United States

Xiaodong Chen, L. Ruby Leung*, Yang Gao, Ying Liu, Mark Wigmosta
Pacific Northwest National Laboratory

Winter storms are responsible for billion-dollar economic losses in the western United States. Because storm structures are not well resolved by global climate models, it is not well established how single events and their structures change with warming. Here we use regional storm-resolving simulations to investigate climate change impact on western U.S. winter storms. Under a high-emissions scenario, precipitation volume from the top 20% of winter storms is projected to increase by up to 40% across the region by mid-century. The average increase in precipitation volume (31%) is contributed by 22% from increasing area coverage and 19% from increasing storm intensity, while a robust storm sharpening with larger increase in storm centre precipitation compared with increase in storm area reduces precipitation volume by 10%. Ignoring storm sharpening could result in overestimation of the changes in design storms currently used in infrastructure planning in the region.

1B-6: 2022 U.S. Billion-dollar Weather and Climate Disasters Analysis and Tools

Adam Smith, *NOAA National Centers for Environmental Information (NCEI)*

The NOAA National Centers for Environmental Information (NCEI) has released the final update to its 2022 Billion-dollar disaster report (**www.ncei.noaa.gov/access/billions**), confirming another intense year of costly disasters and extremes throughout much of the country.

In 2022, the U.S. experienced 18 separate weather and climate disasters costing at least 1 billion dollars. That number puts 2022 into a three-way tie with 2017 and 2011 for the third-highest number of billion-dollar disasters in a calendar year, behind the 22 events in 2020 and the 20 events in 2021. It was another year with a high diversity of destructive disasters:

- 1 winter storm/cold wave event (across the central and eastern U.S.).
- 1 wildfire event (wildfires across the western U.S. including Alaska).
- 1 drought and heat wave event (across the western and central U.S.).
- 1 flooding event (in Missouri and Kentucky).
- 2 tornado outbreaks (across the southern and southeastern U.S.).
- 3 tropical cyclones (Fiona, Ian and Nicole).
- 9 severe weather/hail events (across many parts of the country, including a derecho in the central U.S).

2022 was also third highest in total costs (behind 2017 and 2005), with a price tag of at least $165.0 billion. Over the last seven years (2016-2022), 122 separate billion-dollar disasters have killed at least 5,000 people and cost >$1 trillion in damage. In addition, the $100 billion cost figure has been eclipsed in 5 of the last six years (2017-2022 with 2019 being the exception). One of the drivers of this cost is that the U.S. has been impacted by landfalling Category 4 or 5 hurricanes in five of the last six years, including Hurricanes Harvey, Irma, Maria, Michael, Laura, Ida, and Ian.

The increase in population and material wealth over the last several decades are an important cause for the rising costs. These trends are further complicated by the fact that much of the growth has taken place in vulnerable areas like coasts, the wildland-urban interface, and river floodplains. Vulnerability is especially high where building codes are insufficient for reducing damage from extreme events. Climate change is also supercharging the increasing frequency and intensity of certain types of extreme weather that lead to billion-dollar disasters—most notably the rise in vulnerability to drought, lengthening wildfire seasons in the Western states, and the potential for extremely heavy rainfall becoming more common in the eastern states. Sea level rise is worsening hurricane storm surge flooding. Given all of these compounding hazard risks, there is an increased need to focus on where we build, how we build, and investing in infrastructure updates that are designed for a 21st-century climate.

Day 2 (March 22, 2023)

2A-1: NOAA's Exploration of Future Probable Maximum Precipitation Datasets and Methods

Kelly Mahoney*[1], Janice Bytheway[2], Diana Stovern[2], James Correia[3], Sarah Trojniak[3], Ben Moore[1]
[1]NOAA Physical Sciences Laboratory (PSL), [2]NOAA PSL/University of Colorado Boulder & Cooperative Institute for Earth System Research and Data Science (CIESRDS), [3]University of Colorado Boulder & CIESRDS, NOAA/NWS/Weather Prediction Center

Under recent Congressional support, NOAA has renewed ability to study, develop, and operationalize updated probable maximum precipitation (PMP) estimates. One of the first steps in this process is NOAA's support of a National Academies of Science, Engineering, and Medicine (NASEM) study to examine the pressing questions, needs, and modern scientific capabilities to inform the process. This study is now underway, and we will provide information about its objectives, process, and intended outcomes.

NOAA is also actively performing research to optimize for extreme precipitation estimation analyses of existing, experimental, and possible future operational datasets. These include quantitative precipitation estimation (QPE), quantitative precipitation forecast (QPF), and numerical weather prediction (NWP) based datasets, as well as exploration of approaches to generate new datasets. This talk will highlight early results focusing on the assessment of the strengths and weaknesses of NOAA's operational QPE products, particularly in areas of complex terrain and limited observations. We will also highlight emerging results from characterization of the QPF skill and error characteristics of NOAA's operational high-resolution forecast models, including the High-Resolution Rapid Refresh (HRRR) and High Resolution Ensemble Forecast (HREF) model datasets. We will detail next steps for further exploration and will welcome feedback and discussion from the audience of these research plans, as well as invite potential stakeholder partnerships for testing and evaluation.

2A-2: The "Perfect Storm": Can Atmospheric Models Improve Confidence in Probable Maximum Precipitation (PMP)?

Emilie Tarouilly*
University of California, Los Angeles

The flood that would result from the greatest depth of precipitation "meteorologically possible", or Probable Maximum Precipitation (PMP) is used to ensure the safety of nuclear power plants, among other high-risk structures. Historically, PMP has been estimated by scaling (extrapolating) depth-area-duration relationships obtained from severe historical storms, following guidelines from the so-called Hydrometeorological Reports (HMRs). Over the last decade, frameworks that leverage numerical weather prediction models to predict precipitation resulting from the addition of moisture (called relative humidity maximization, or RHM) have been developed. Incorporating current understanding of precipitation processes in those model-based methods represents an important advance.

Nonetheless, model-based PMP still relies on key assumptions: (1) that severe historical storms achieved maximum efficiency (moisture conversion to precipitation), such that only moisture needs to be maximized and (2) that maximizing moisture (i.e., saturating the atmosphere) near the target basin is realistic and consistently maximizes precipitation. Numerical weather prediction models allow us to re-evaluate those assumptions and perform scenario analyses to develop physically-based guidelines on how to reliably maximize storms. Additionally, as the use of model-based tools introduces new challenges such as model uncertainty, our scenarios include different model setups and parametrizations that aim to characterize the magnitude of this uncertainty.

Focusing on the Feather River basin in California, we downscale the most severe historical storms from ERA5 reanalysis using the WRF model. Using this ensemble of high-resolution simulations, we seek to identify key attributes of these storms (storm orientation, convection and large-scale convergence) that control precipitation efficiency and we characterize the nonlinear precipitation response to the addition of moisture in our simulations. In so doing, we highlight that PMP would be better presented as an ensemble of values, such that uncertainty can be communicated, rather than a single estimate, and develop guidance for the engineering community on how to consistently maximize storms.

2A-3: Improving the Reliability of Stochastic Modeling of Short-Duration Precipitation by Characterizing Spatiotemporal Correlation Structure and Marginal Distribution

Giuseppe Mascaro[1]*, Simon Papalexiou[2], Daniel Wright[3]
[1]Arizona State University, [2]University of Calgary, [3]University of Wisconsin-Madison

Realistic space-time stochastic simulations of short duration (≤24 h) precipitation (P) provide critical support for flood hazard assessment. In this talk, we improve the accuracy of space-time simulations by increasing the ability to characterize and model the spatiotemporal correlation structure (STCS) and the marginal distribution of short-duration P. We design a framework that relies on multisite Monte Carlo simulations with the Complete Stochastic Modeling Solution (CoSMoS) which we test with a dense network of 223 high-resolution (30 min) rain gages in central Arizona. We first show that an analytical model and a three-parameter probability distribution capture the empirical STCS and marginal distribution of P, respectively, across Δt's from 0.5 to 24 h in both the summer and winter seasons. We then carry out Monte Carlo multisite stochastic simulations of P time series with CoSMoS which reveal significant seasonal differences in the statistical properties of short-duration P, especially at low Δt: summer P exhibits weaker STCS and heavy-tailed distributions because of the dominance of localized convective thunderstorms, whereas winter P has stronger STCS and distributions with lighter tails as a result of more widespread and longer frontal systems. Moreover, P is largely characterized by a homogeneous and isotropic STCS across the region, and by marginal distributions with constant shape parameters and scale parameters and P occurrence dependent on elevation. The only exception is winter P at $\Delta t \geq 3$ h, where the motion of frontal storms could introduce anisotropy, and additional factors are required to explain the variability of the scale parameter. The findings of this work are useful to generate more realistic stochastic P models and validate convection-permitting atmospheric models.

2A-4: Stochastic Design Storm Sequence in the Lower Mississippi River Basin

Yuan Liu*, Daniel Wright
University of Wisconsin-Madison

This study aims to address major limitations of conventional univariate rainfall frequency analysis, which includes the difficulty of incorporating information from relevant atmospheric variables and representing the frequency of areal extremes that is relevant for flooding. Here we proposed a new method of estimating extreme rainfall frequency based on rainstorm tracking and atmospheric water balance. A rainstorm tracking algorithm STARCH was developed to identify two-dimensional precipitation systems over the Mississippi Basin based on ERA5 hourly precipitation data from 1951 to 2020. The 70-year annual maximum rainstorm precipitation was extracted and fitted to a multivariate distribution of atmospheric water balance components using vine copulas. We used this approach to estimate precipitation frequency for rainstorm areas from 5,000 to 100,000 km2 and duration from 2 to 72 hours in the Mississippi Basin and its five major subbasins. The estimated precipitation distribution fits well with the reference data and is close to the conventional GEV distribution. The approach can estimate precipitation frequency at arbitrary rainstorm duration and area and provides an alternative way to characterize the depth-area-duration relationships of major storms in a basin. Our approach explicitly modeled the contribution of atmospheric water balance components to extreme precipitation. Of these, the water vapor flux convergence is the major contributor, while the water vapor storage and a mass residual term can also be important, especially for rainstorms with short durations and small areas. The approach can utilize additional atmospheric variables to inform precipitation frequency analysis and benefits from advancements in reanalysis products and storm tracking techniques. In the end, some recent work on developing stochastic design storms for the Lower Mississippi River Basin will also be covered.

2A-5: NOAA - An Update to the NOAA Atlas 14 National Precipitation Frequency Standard

Michael St Laurent*, Sandra Pavlovic, Carl Trypaluk, Dale Unruh, Fernando Salas
NOAA National Weather Service, Office of Water Prediction

The National Weather Service's Office of Water Prediction (OWP) has produced an authoritative atlas of precipitation frequency estimates as volumes of the NOAA Atlas 14 "Precipitation-Frequency Atlas of the United States", and these estimates are published on a Precipitation Frequency Data Server with an interactive map interface. The Atlas 14 estimates are the de-facto standard for a wide variety of design and planning activities under federal, state, and local regulations, and are used to design stormwater management and transportation infrastructure, develop design considerations for floodplain and watershed management, and perform hydrologic studies for reservoir and flood protection projects.

With support from the 2022 Bipartisan Infrastructure Law, OWP has received funding to update the precipitation frequency standard. These updated precipitation frequency estimates will be referred to as NOAA Atlas 15 and will be presented in two volumes. The first volume would apply a consistent methodology that accounts for temporal trends in historical observations, and the second volume would use future climate projections to generate adjustment factors for the first volume. This new update is anticipated to (1) develop a seamless spatial national analysis, (2) replace current Atlas 14 estimates based on historical data (historical estimates), (3) add new product features to account for future precipitation information (future estimates), and (4) enhance service delivery via new Web visualizations and data services.

This presentation will review the planning, and development efforts on the proposed NOAA Atlas 15 update, and will discuss in detail the proposed methodology as well as additional research that is anticipated to complete product development. The Atlas 15 estimates, once completed, will provide critical information for the design of national infrastructure under a changing climate.

2B-1: Lowering the Barriers to Process-Based Probabilistic Flood Frequency Analysis using the NextGen Water Modeling Framework

Daniel Wright*[1], Ankita Pradhan[1], MohammadSadegh Abbasian[1], Benjamin FitzGerald[1], Gary Aaron Alexander[1], Luciana Cunha[2], Fred Ogden[2]
[1]*University of Wisconsin-Madison,* [2]*U.S. NOAA National Weather Service, Office of Water Prediction*

Explicit modeling of the joint roles of rainfall, soil moisture, snowpack, and other hydrologic processes can improve estimates of flood frequency metrics such as the 100-year flood—as well as provide insights into the combinations of physical hydrologic processes that control such floods. These capabilities are particularly relevant for nonstationary climatic and land use conditions, where conventional flood frequency analysis techniques, which ignore or oversimplify flood physics, tend to suffer. This complexity of process-based approaches to flood frequency analysis, however, place them beyond the expertise and resources of many users. Under this project, we are developing an open-source workflow and Monte Carlo simulation system that combines the NextGen Water Modeling Framework from NOAA's National Water Center with the RainyDay rainfall analysis system from the University of Wisconsin-Madison. It will leverage NextGen's hydrofabric, model selection, calibration, and intercomparison tools, as well as unique high-performance computing resources at University of Wisconsin. Project goals include expanding the usability, reliability, and reproducibility of process-based hydrologic modeling for flood frequency research and practice.

2B-2: Towards the Development of a High-resolution Historical Flood Inundation Reanalysis Dataset for the Conterminous United States

Sudershan Gangrade*[1], Ganesh Ghimire[1], Shih-Chieh Kao[1], Mario Morales-Hernández[2], Michael Kelleher[1], Alfred Kalyanapu[3]
[1]*Oak Ridge National Laboratory,* [2]*AUniversity of Zaragoza, Spain,* [3]*ATennessee Technological University*

To evaluate regional flood risks and develop long-term flood mitigation and resilience measures, a high-resolution historical flood inundation dataset covering the entire conterminous United States (CONUS) can be very valuable. The accurate representation of flood dynamics at a large scale necessitates the solution of full 2D shallow water equations at a locally relevant spatial resolution. We introduce a CONUS-wide implementation of a GPU-accelerated 2D hydrodynamic model – TRITON (https://triton.ornl.gov/) to reconstruct major historic flood events for all HUC04 subregions. TRITON is driven by historic runoff and streamflow simulated by a calibrated VIC-RAPID hydrologic modeling framework forced with National Center for Environmental Prediction Stage IV hourly Quantitative Precipitation Estimates from 2002 to 2018. The baseline terrain information for the TRITON inundation model is provided by a 10m National Elevation Dataset. The default TRITON implementation is driven by long-term climatic mean runoff and streamflow to obtain steady-state channel flow conditions, which serve as initial water depths and velocity information for event-based TRITON simulation. The performance of simulated flood inundation maps is evaluated using various temporally static benchmark information, including high-water marks, remote sensing-derived inundation maps, and local high-fidelity simulation maps. The temporal evolution of flood simulations is evaluated using U.S. Geological Survey stage data. Finally, we discuss the challenges and barriers in national/continental scale high-resolution inundation modeling, calibration and validation, and future developments targeted to improve the representation of flood regimes, and their implications for real-time flood forecasting.

2B-3: Quantifying Uncertainty for Local Intense Precipitation and Riverine Flooding PFHA at Critical Structures on the Idaho National Labs Property

Ryan Johnson*[1], Shaun Carney[1], Paul Micheletty[1], Debbie Martin[1], Bruce Barker[2]
[1]*RTI International,* [2]*MGS Engineering*

Research Triangle Institute (RTI) International is performing Probabilistic Flood Hazards Analyses (PFHA) for critical structures on the Idaho National Lab (INL) property to satisfy requirements outlined in Department of Energy (DOE) STD-1020-2016, “Natural Phenomena Hazards Analysis and Design Criteria for DOE Facilities”. Flooding hazards are separated into two classifications in the DOE STD-1020-2016 standard—riverine flooding hazards and flooding due to local intense precipitation (LIP). Depending on the location of a structure within the INL property, both of these flood mechanisms and their associated aleatory variability and epistemic uncertainty are considered. All structures regardless of location are evaluated for flooding from LIP events. Structures located next to rivers are also evaluated for riverine flooding. Sources of uncertainty evaluated for LIP and riverine flooding include precipitation frequency characteristics, breaches of upstream embankments, hydrologic model parameters, Manning’s surface roughness and culvert blockage. The Stochastic Event Flood Model (SEFM is used in combination with U.S. Corps of Engineers (USACE) Hydrologic Engineering Center (HEC) Hydrologic Modeling System (HEC-HMS) and River Analysis System (HEC-RAS) models to conduct stochastic simulations, generate hydrologic hazard curves, and characterize uncertainty in flood frequency estimates for specific buildings of interest. This presentation will discuss the methods used to characterize uncertainties and propagate these through to uncertainties in key flood metrics for critical infrastructure, as well as discussing methods employed to address computational challenges with employing detailed structure-level hydraulic modeling in a stochastic framework.

2B-4: Back to the Future: Paleoflood Hydrologic Analyses Provide Insights into Extreme Flood Risk in the Tennessee River Basin

Lisa Davis*[1], Ray Lombardi[2], Matthew Gage[3]
[1]*University of Alabama Department of Geography,* [2]*University of Memphis,* [3]*University of Alabama Office of Archeological Research*

Extreme floods are likely underrepresented in many flow records. Quantitative paleoflood hydrologic (QPH) techniques can reliably estimate the timing and magnitude of past extreme floods, helping to increase their observations. Including paleoflood hydrologic data greatly reduces the uncertainty associated with flood frequency analyses of low annual exceedance probability floods. Because of their proximity to major population centers and river infrastructure, many alluvial rivers urgently need new flood frequency analyses that incorporate a wider range of hydroclimate regimes than possible with instrumented records alone. Erosion and deposition causes channel dimensions to change over time in alluvial rivers, challenging the application of many QPH methods originally developed in bedrock channels. In this presentation, we will discuss several advances in QPH methods we used to develop paleoflood hydrologic

data in the Tennessee River (USA), which were then applied in probabilistic flood hazard assessments made in collaboration with the Tennessee Valley Authority.

2B-5: Testing New Approaches to Integrating Sediment-Based Flood Records into Flood Frequency Models

Ray Lombardi*[1], Lisa Davis[2], Tessa Harden[3,4], John F. England, Jr.[5]
[1]University of Memphis Department of Earth Sciences, [2]University of Alabama Department of Geography, [3]Thomas College School of Arts and Sciences, [4]U.S. Geological Survey, [5]U.S. Army Corps of Engineers, Risk Management Center

Increasingly probabilistic flood risk assessments for infrastructure (e.g., dams and levees) use paleoflood hydrologic data (geomorphic and botanical evidence of past floods). Statistical procedures, such as the Expected Moments Algorithm, incorporate paleoflood data into flood frequency analyses (FFA) as a number of exceedances over perception thresholds (PTs). Similarly, Non-exceedance bounds (NEBs) can constrain the right-tail of flood distributions by defining a threshold that has not been exceeded over a specified period. Rivers vary in their hydrogeomorphic complexities, and this can complicate the selection and application of PTs and NEBs. We revisited these concepts, using case studies from previous work, to examine challenges and potential alternatives for defining critical thresholds for FFA. We found that when moderate and extreme paleoflood discharges are available selecting the smallest identified paleoflood discharge as the PT discharge overestimates model certainty and reduces the discharge estimates for flood with rare exceedance probabilities (< 0.01). In these cases, one alternative involves using the 90th percentile discharge of the flood distribution to set a higher PT and to determine which paleofloods are opportunistic peaks. Additionally, in locations where evidence for a NEB is spatially inconsistent across a topographic surface, we one of the following approaches can be taken: 1) defining a "hydrogeomorphic bound," which is a surface elevation representing the natural upper limit to fluvial activity identified using geomorphic evidence of where the hillslope process domain ends and the fluvial process domain begins; or 2) using NEBs for years with known paleoflood estimates. By expanding these concepts, we can apply paleoflood hydrologic data more consistently and in understudied regions.

2B-6: Using Paleoflood Analyses to Improve Hydrologic Loading for USACE Dam Safety Risk Assessments: A Nationwide Approach

Keith Kelson*[1], Justin Pearce[2], Amy LeFebvre[2], Ryan Clark[3], Bryan Freymuth[4], Nathan Williams[5], John England, Jr.[2]
[1]U.S. Army Corps of Engineers (USACE), South Pacific Division Dam Safety Production Center, [2]USACE Risk Management Center, [3]USACE Dam Safety Modification Mandatory Center of Expertise, [4]USACE Northwest Division Risk Cadre, [5]USACE Lakes and Rivers Division Risk Cadre

Since 2015, results from paleoflood analyses (PFA) have been used to reduce uncertainties in hydrologic loading components of USACE dam-safety risk assessments. A tiered approach allows reductions of uncertainties through analyses having progressively greater detail, if supported within the risk-based decision framework. Tier 1 efforts are conducted to address watershed PFA viability and to

recommend actions for minimizing uncertainties in initial hydrologic loading estimates. If appropriate, Tier 2 PFA are conducted where results are likely to improve confidence and reduce uncertainties in hydrologic loadings, and therefore benefit the risk assessment. Tier 2 PFA involve an integrated program of geologic and hydraulic analyses to identify and characterize paleostage indicators (PSI) and non-exceedance bounds (NEB) that constrain long-term paleoflood chronologies. Tier 2 often includes geologic and geomorphic characterization of riverine flood-terrace and slackwater deposits to identify and date specific flood events in the historic and pre-historic record, coupled with detailed hydraulic modeling to characterize peak flood magnitudes. These efforts involve state-of-art deposit and soil characterization, multiple age-dating techniques (i.e., relative soil development, radiometric, optically stimulated luminescence, mass spectrometry analyses), and 1D/2D hydraulic modeling using HEC-RAS software to define flood water-surface elevations. The best-estimates and ranges in peak discharge and age for all PSI/NEB are included into flow-frequency statistics through use of perception thresholds and flow intervals, and sensitivity analyses provide guidance on the value of PFA datasets in reservoir-stage frequency analyses. If needed, Tier 3 efforts are then conducted to resolve specific technical issues with a focus on characterizing specific uncertainties in parameters that drive hydrologic loading. Incorporating PFA results into flow-frequency curves has shown that frequencies of rare and extreme peak discharges can be either over- or under-estimated compared to analyses using only historical data. PFA have been successfully applied to USACE dam-safety risk assessments throughout many geographic and meteorologic domains including projects on the Willamette River in Oregon, Missouri River in North Dakota and South Dakota, and Carbon Canyon Wash and Mojave River in California. These projects demonstrate applicability of PFA across the Nation. PFA are currently being applied to ongoing risk assessments for USACE dams on the White River in Missouri and Arkansas, the Naugatuck River in Connecticut, the Guadalupe, North Concho, and Red Rivers in Texas, the Kootenai River in Montana, and the Arkansas River in Colorado. Overall, these PFA add significant value to USACE dam-safety risk assessments by improving confidence and reducing uncertainty in hydrologic loadings.

Day 3 (March 23, 2023)

Poster Presentations

3A-1: Identifying and Cataloging Major Storm Events from Gridded Quantitative Precipitation Estimates for use in Stochastic Storm Transposition

Alyssa Dietrich*, Eric King, Seth Lawler
Dewberry

Stochastic Storm Transposition (SST) is a modern technique used to move observed precipitation associated with a storm event from its original location to multiple, randomly selected alternate locations within a climatologically comparable region. Storm transposition has its root in deterministic probable maximum precipitation studies for the purpose of supplementing storm data in locations with limited observed historical events. Advancements in computational speed and technology allow for the "stochastic" component of storm transposition, where a suite of realistic spatial precipitation patterns can be created that are suitable for probabilistic modeling.

In order to do SST, there is first a need for a storm catalog or database from which the suite of moderate to extreme storms can be selected. Selecting storms for a catalog has traditionally been a subjective process, limited by a storm being observed at a precise location and the quality of gauge-based precipitation observations. Combining computational approaches with the availability of CONUS-wide, remotely-sensed, gridded daily and hourly precipitation datasets provide a unique opportunity to overcome many of these traditional limitations. Utilizing published gridded datasets eliminates the requirement for a storm to be analyzed from gauge data to determine total storm magnitude; and their use ensures that a large event, no matter where it occurred, is not missed due to lack of ground observations. While remotely-sensed gridded datasets remain imperfect, a notable flaw being their relatively short record lengths, year after year datasets continue to grow. For example, the StageIV dataset from the National Center for Environmental Prediction now has over two decades worth of data, and the Analysis of Record for Calibration (AORC) dataset from the National Weather Service contains hourly data back to the 1970s.

To populate the storm catalog an unsupervised python-based algorithm was developed to iterate over an entire period of record (POR) and identify storms contained in gridded precipitation data. For a given SST transposition domain, a storm is identified as a contiguous group of grid cells that accumulate statistically significant precipitation over some defined duration. The unsupervised learning concepts of thresholding and clustering are applied to a sliding window (based on event duration) over each date in the POR. For each of these windows, the time-series grids are aggregated, an accumulated precipitation threshold is calculated, and all grid cells with precipitation greater than the threshold are grouped in clusters. Statistics such as size, mean, total volume, and maximum are gathered for each cluster and stored in a searchable and filterable database. Storm criteria can then be applied as filters to retrieve storms for use in SST.

This poster will present a reproducible methodology to download, analyze, and objectively catalog historical precipitation data suitable for SST studies, including regional precipitation and flood frequency analyses.

3A-2: A Bayesian Network and Monte Carlo Simulation PRA Approach for External Flood Probabilistic Risk Assessments at Nuclear Power Plants

Joy Shen*, Michelle Bensi, Mohammad Modarres
University of Maryland, College Park

This poster presents a hybrid probabilistic risk assessment (PRA) methodology, augmented by a Bayesian network and Monte Carlo simulation to assess external flood risks at nuclear power plants (NPPs). The nuclear industry has employed event trees (ETs) and fault trees (FTs) in the PRA framework to assess potential accidents and the resulting consequences. This methodology has provided a wealth of knowledge and experience over the decades, particularly for static level 1 internal event PRAs. However, conventional PRA tools are limited by the binary component state assumption, system, structure, and component (SSC) independence assumption, and the static treatment of time. These limitations may mask significant vulnerabilities and reduce model accuracy. These limitations are particularly relevant to external flood PRAs, external floods are a spatially and temporally dependent hazard with varying impact on the NPP. Research is needed to investigate hybrid PRA methodologies to develop a framework that utilizes both conventional and novel PRA tools to overcome limitations. This research provides an opportunity to address limitations, as well as contribute to external flood PRA knowledge. This poster proposes to augment the conventional PRA framework with a Bayesian network and Monte Carlo simulation to model the significant external flood considerations. These novel tools address the conventional limitations by modeling partial damage states by incorporating multiple component states, SSC dependencies, and temporal dependencies. Two hybrid approaches are considered in linking the conventional and novel PRA tools. The first approach adapts a hybrid causal logic model to link the Bayesian network to the FT, and the other is a function-focused model to link the Bayesian network to the ET.

3A-3: Probabilistic Compound Flood Hazard Assessment using Two-Sided Conditional Sampling

Somayeh Mohammadi*[1], Ahmed Nasr[2], Muthukumar Narayanaswamy[1], Celso Ferreira[1], Arslaan Khalid[1]
[1]Michael Baker International, [2]University of Central Florida

Compound floods are flood events caused by more than one coincident or nearly coincident flood mechanisms and usually have severe impacts on people, and the natural and built environment. Coastal areas are usually exposed to compound floods due to storm surge, precipitation, and tides. A holistic assessment of flood hazard in coastal areas requires consideration of compounding impacts of these drivers.

This study is focused on probabilistic assessment of compound flood hazard, in a coastal area located in LA, due to surge and precipitation. This study is conducted using NOAA gage data and Analysis of Record for Calibration (AORC) precipitation data. Two-sided conditional sampling is used to generate paired data samples related to both variables. In this method two types of data samples are generated. Each sample is generated by considering the extremal value related to one variable and the maximum value of the second variable within a time window. In the next step after fitting the marginal distributions to the data, a best-fit copula function is used to capture the dependence between variables and generate compound flood return periods. Furthermore, this study has compared the impact of only analyzing the tropical events as opposed to analyzing the entire dataset. Based on the results of this study a stronger correlation is observed between data for hurricane events.

3A-4: Estimation of Probabilistic Flood Hazard Curve at the NPP Site Considering Storm Surge

Beom-Jin Kim*, Minkyu Kim
Korea Atomic Energy Research Institute (KAERI), Structural and Seismic Safety Research Division

The intensity of typhoons hitting Korea is recently increasing due to climate change. Eight typhoons occurred from August to September 2020. Among the eight typhoons, Typhoons Bavi, Maysak, and Haishen, category two or higher, hit Korea, and flood damage occurred due to heavy rain. In particular, nuclear power plants in Korea are installed and operated nearby the coast. Therefore, it is necessary to identify the risk of external hazards that may occur due to typhoons in nuclear power plants. Also, it is necessary to assess the safety of nuclear power plants through risk analysis of external hazards.

To this end, in previous studies, a probabilistic wave height hazard curve by storm surge was estimated at the coast near a nuclear power plant. After that, the overtopping discharge was calculated using the EurOtop model. And based on the results, a two-dimensional flood analysis was conducted at the nuclear power plant site. This study applied a probabilistic method to the flood depth estimated through a two-dimensional flood analysis according to the return period. First, flood probability distribution was estimated through AIC verification. Second, the estimated probability distribution was applied to the flood depth according to the return period. Finally, Monte Carlo simulations were applied to estimate 5%, mean, median, and 95% flood depths by return period. Based on the analyzed flood depth, a probabilistic flood hazard curve due to storm surge was estimated and presented.

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 combined hazards such as local intensive precipitation (LIP) and storm surges.

Acknowledgment: This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government (RS-2022-00144493)

3A-5: Compound Flood Risk Assessment of the Coastal Watersheds of Long Island and Long Island Sound in Connecticut and New York

Liv Herdman*, Robert Welk, Robin Glas, Salme Cook, Kristina Masterson
U.S. Geological Survey, New York Water Science Center

Long Island Sound (LIS) has 600 miles of coastline in New York and Connecticut with over 23 million people living within 50 miles of its shores. Flooding associated with either combined or individual incidents of shallow water tables, heavy rainfall events, and elevated coastal water levels has been reported in multiple locations around LIS and for many communities is a frequently occurring hazard. In recent years, the occurrence of extreme events has amplified the need for an integrated assessment of the vulnerability of coastal communities and infrastructure to compound flood events. For this assessment we have designed a compound flooding vulnerability framework to show the susceptibility to shallow water tables, rainfall events, and elevated coastal water levels at an 800-meter scale. Each process is evaluated individually and jointly to understand the likelihood of compound or simultaneous flood events and conditions. Historical data is used to determine the temporal relationship between each of the drivers (rainfall, water table level, coastal water levels). Groups consisting of one precipitation station, groundwater level station, and coastal level station (triads) are identified to analyze the geographic variability in the occurrence of compound events. Within each time series a peak over threshold approach is used to identify flood events, and the correlation between the timeseries is explored with a lag of plus or minus three days to identify locations where flood types are likely to co-occur. Over the domain, coastal water levels and rainfall tend to have a statistically significant correlation. The slower response time and frequency of measurement (approximately monthly) at many groundwater observation wells makes identifying a correlation difficult. Here we present the results of the analysis of these triads over the study area, as well as a semi-quantitative framework that combines geospatial attributes of compound flood susceptibility.

3A-6: Steps Toward Extensions of Existing Probabilistic Coastal Hazard Analysis for Coastal Compound Flood Analysis Leveraging Bayesian Networks

Ziyue Liu*[1], Michelle Bensi[1], Meredith Carr2, Norberto Nadal-Caraballo[2], Madison Yawn[2], Luke Aucoin[2]
[1]University of Maryland, College Park, [2]U.S. Army Corps of Engineers, Engineer R&D Center, Coastal & Hydraulics Laboratory

In the past decades, coastal floods have caused significant losses to coastal communities. To develop an accurate and complete probabilistic framework for assessing coastal floods, the U.S. Army Corps of Engineers established the

Probabilistic Coastal Hazard Analysis (PCHA) framework. To date, implementations of the PCHA framework have focused primarily on a subset of coastal hazards, particularly storm surges. This poster summarizes recent research activities seeking to build upon the PCHA framework by developing a multi-tier PCHA framework extension to consider compound hazards using Bayesian networks (BNs). In pursuit of that goal, we begin by assessing some of the assumptions and modeling approaches in the PCHA to better understand their use in the compound PCHA framework. We perform a comparative assessment of a series of different Joint Probability Method (JPM) assumptions for modeling dependence among tropical cyclone (TC) atmospheric parameters, which include parameter independence, partial dependence (i.e., only considering dependence between central pressure deficient and radius to maximum winds), and full dependence. Candidate full-dependence models include meta-Gaussian copula and vine copulas combining linear-circular copulas with Gaussian or Frank copulas. Emphasis is placed on modeling the circular behavior of storm heading and its dependencies with other linear parameters since the heading parameter is hypothesized to be comparatively more important when modeling compound hazards. Next, a BN of storm-induced coastal hazards is constructed, where the conditional probability tables of TC atmospheric parameters are computed using copulas. A deaggregation method is implemented to identify the dominant TC parameter combinations for coastal hazard events of interest. The dependence between storm surge and storm rainfall is explored based on the BN. Finally, based on the outcomes of the analysis described, the PCHA is extended and leveraged to develop multiple tiers of BN for modeling compound coastal hazards. The tiers are intended to be useful under different levels of data availability and computational resources for compound flood analysis. Machine learning-based predictive models are used to develop several conditional probability tables required by the BN model.

3A-7: Assessing Uncertainty Associated with Hurricane Predictions and Duration to Inform Probabilistic Risk Assessments for Nuclear Power Plants

Kave Faraji Najarkolaie*, Michelle Bensi
University of Maryland, College Park

Hurricanes can cause damage to infrastructure facilities located along the storm track. Critical infrastructure facilities, such as nuclear power plants, will typically take actions to protect against the impacts of hurricane events (e.g., wind, rain, or storm surge). As a result, probabilistic risk assessments for critical infrastructure facilities require information about the warning time available to take action and the duration during which storm conditions will prevail. However, to date, existing literature has not addressed this information need. This presentation describes the recent progress of an ongoing research activity focusing on temporal uncertainties related to probabilistic risk assessment for nuclear power plants exposed to hurricane events.

The National Hurricane Center (NHC) tracks hurricane features and generates forecasts for storm locations and characteristics up to 120 hours in the future. However, these predictions are associated with uncertainty. In this study, we aim to identify and characterize the uncertainty associated with hurricane prediction in a way that could be useful for probabilistic hazard assessment of critical infrastructure like nuclear power plants.

We used the NHC database to gather information on observed and forecasted hurricane tracks. We processed and prepared the storm track data for geospatial and statistical analysis, focusing on storms that originated in the Atlantic Ocean between 2008 and 2022. We analyzed the prediction errors of the track landfall location, wind radii landfall location, and their timing using analyses that extend beyond previously published error assessments. We calculated an hourly interpolation of hurricane features and wind radii for 34, 50, and 64-knot wind speeds. We extracted track and wind landfall location and timing information using the intersection of hurricane track centerlines and wind radii polygons with the land boundary. The wind radii landfall location and timing provide important information regarding when the hurricane winds start to impact a region. We then estimated the duration that a hurricane would affect locations within a region affected by the storm. This helps to develop an understanding of the duration that infrastructure would be affected by the winds generated by a hurricane. Finally, we present the results of this study using visualizations that are intended to help inform external hazard probabilistic risk assessment.

3A-8: Assessment of Uncertainty Associated with the Development of Intensity Duration Frequency Curves under Changing Climate for the State of Maryland

Azin Al Kajbaf*[1], Michelle Bensi[2], Kaye Brubaker[2]
[1]Johns Hopkins University, [2]University of Maryland

The contiguous United States has experienced an increase in mean average precipitation in each decade beginning in the 1950s. These trends, which are expected to continue, will affect water infrastructure and require updates to the associated planning and design policies. Intensity Duration Frequency (IDF) curves are often used as the basis for engineering design decisions involving water infrastructure. However, IDF curves developed using conventional approaches based on historical/observational data may not reflect hazards under a changing climate. Synthetic climate model projections provide information to account for the potential effects of climate change in developing IDF curves. This poster is intended to share with the probabilistic flood hazard assessment (PFHA) community a summary of a recently completed project focused on exploring the uncertainty associated with the development of IDF curves under current and future climate conditions for the State of Maryland. We first apply machine learning to temporally downscale synthetic time-series outputs of climate model projections from the North American Regional Climate Change Assessment Program (NARCCAP) (available at a 3-hour temporal resolution) to durations as short as 15 minutes. We then assess the epistemic uncertainty associated with development of IDF curves on two levels: across model and within model. Across model uncertainty refers to the uncertainty arising from the differences in synthetic precipitation and other meteorological variable time-series resulting from different NARCCAP climate model projections. Within model uncertainty refers to the uncertainty arising from the modeling choices, including temporal downscaling methods, time-series types, distributions, and parameter estimation methods used to develop IDF curves using the synthetic time-series from a single climate model projection. We provide a graphical framework to explore and compare the contribution of sources of uncertainty.

Oral Presentations

3B-1: Flood Inundation Modelling on Nuclear Power Plant Site due to Complex Disasters

Byunghyun Kim*[1], Jaewan Yoo, Beomjin Kim[2], Minkyu Kim[2]
[1]Kyungpook National University, [2]Korea Atomic Energy Research Institute

Recently, the intensity and frequency of typhoons and local intense precipitation are increasing worldwide due to climate change, and Korea is no exception. On July 23, 2020, heavy rain of 83 mm per hour occurred in Busan, South Korea, where the nuclear power plant is located. In addition, the maximum tide level rose to D.L.176cm, which was a record value far exceeding the D.L.46cm of the existing approximately highest high tide level.

The purpose of this study is to provide basic data for reducing flood damage to nuclear facilities and establishing systematic disaster prevention plans through two-dimensional (2D) flood analysis under complex disaster conditions including storm surge and localized heavy rain on the nuclear power plant sites located on the coast. The amount of external inflow into the nuclear power plant site according to the simultaneous occurrence of storm surge and local intense precipitation, which are increasing in frequency and intensity due to climate change, was estimated, and the flood depth and velocity were calculated through 2D flood modeling applying these as boundary conditions. The run-up and overtopping amounts affected by the storm surge on the nuclear power plant site were calculated based on EurOtop (2018). The estimated amount of overtopping was applied as an inflow boundary condition of a 2D flood inundation model that generated a grid with a resolution of 3m. In the case of a complex disaster considering the return period of 10,000 years and the duration of 5 hours, the maximum flood depth was 0.928m in area 1 and 0.522m in area 2.

This study was intended to help decision-making for flood prevention, flood reduction, and preparation of alternatives related to external flooding in nuclear power plant sites due to complex disasters.

3B-2: Probabilistic Flood Hazard Assessment for a Coastal Nuclear Power Plant using Climate Change Projections

Görkem Güngör, Zeynep Arslan
Ministry of Energy and Natural Resources, Turkey

Risk analysts consider the seismic hazard the most critical external threat to the safety and reliability of NPPs. However, inundations caused by extreme rainfall triggered by climate change also has a significant threat to NPPs. Therefore, assessing and modeling flood hazards and their effects on NPPs is critical for preventing initiating events and evaluating NPP safety. The probability of occurrence of such initiating events and their effects on the facility are determined using various statistical data, mathematical models and probabilistic simulations. For example, researchers applied a model combining stormwater management and overland flooding to simulate the flooding process at a coastal NPP in China, using parameters such as extreme rainfall, wave overtopping, and tidal flow. Another study assessed the risk of a spent nuclear fuel storage facility exposed to flood hazards by applying the Bayesian network, in three different time scenarios at the Sizewell-B NPP in the UK. There are also studies testing the validity of flood hazard risk assessment on a synthetic sample by processing the event and fault trees constructed for system-level performance into the Bayesian network. Researchers have conducted risk assessment studies in Turkey to analyze the financial risks for the safety of life and property against seismic, earthquake, volcano, and flood hazards. However, to the author's knowledge, no researcher has conducted a probabilistic flood hazard assessment for nuclear facilities in Turkey considering the impacts of climate change. In the first part of the study, the authors aim to assess the flood hazard assessment using Bayesian inference on a potential site used for benchmark study. In the second part of the study, the authors aim to conduct an extreme value analysis to extrapolate the hazard curves by focusing on the uncertainties related to climate change.

3B-3: Probabilistic Coastal Compound Flood Hazard Analysis Pilot Study

Victor M. Gonzalez[1], Meredith L. Carr*[1], Luke Aucoin[1], T. Chris Massey[1], Ning Lin[2], Dazhi Xi[2], Norberto C. Nadal Caraballo[1], Karlie Wells[1]
[1]U.S. Army Corps of Engineers, Engineer Research and Development Center, Coastal and Hydraulics Laboratory (USACE/ERDC/CHL), [2]Princeton University

Coastal flooding due to storm surge and waves is often exacerbated by coincident weather events such as rainfall from extreme storms, including associated runoff and riverine flooding. This presentation will report on the Coastal Flooding Probabilistic Flood Hazard Assessment (PFHA) Pilot Study performed for the U.S. Nuclear Regulatory Commission by the U.S. Army Corps of Engineers' (USACE) Engineer Research and Development Center Coastal and Hydraulics Laboratory (USACE/ERDC/CHL). The pilot study demonstrates the application of PFHA to external flooding at a hypothetical nuclear power plant (NPP) location on the Lower Neches River watershed in Texas.

Characterization of the compound flooding hazard, including storm surge, astronomical tide, waves, rainfall, and coincident riverine flooding, along with associated uncertainties, is necessary to fully address storm risk in coastal settings. A joint probability method (JPM)-type Probabilistic Coastal Hazard Analysis (PCHA) framework for quantifying coastal storm hazards was followed herein. It 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. Incorporation of compound effects due to precipitation have previously relied on multivariate statistics and copula approaches of historical observations to quantify joint probability. However, TC rainfall-driven approaches have recently become more feasible, as precipitation models can be forced by the synthetic storm parameters that also drive the surge.

The compound probabilistic modeling approach being implemented here incorporates rainfall using a physics-based parameterized tropical cyclone rainfall (TCR) model driven by the same JPM atmospheric forcing developed for a regional Coastal Texas Coastal Hazard Study (CTX) available through the USACE Coastal Hazards System, allowing concurrent characterization of the compound flooding hazard and associated uncertainties. An optimally selected subset of 144 TCs were used to drive an HEC-HMS watershed model, coupled to a 2D HEC-RAS model of the Lower Neches River, and loosely coupled to the CTX surge at the boundary. A second coupling approach modified the CTX ADCIRC-STWAVE model to incorporate the time varying HMS outflow hydrograph as upstream boundary condition. The impacts of several model options were explored, including seasonally sampled relative humidity for the precipitation model, precipitation-based infiltration parameters, and antecedent riverine flow conditions.

Coastal compound hazards were quantified through the integration of the combined water level responses at sites of interest. A Gaussian process metamodel was trained with the TC parameters and the TC responses to better represent the joint probability between atmospheric forcing parameters, hazard curves and their uncertainties through the development of an increased number of TCs. These results demonstrate the application of a Compound PFHA expansion of the ERDC/CHL PCHA with TC rainfall in the Lower Neches River. Modification of existing models and use of metamodeling in compound space were demonstrated as tools applicable to Compound Coastal Flood Hazard Analyses.

3B-4: HEC-RAS Modeling Framework and Lessons Learned from Coastal Flooding PFHA Pilot Study: Coupling and Automation of HEC-HMS and ADCIRC Outputs to 2D HEC-RAS Model Using Python

Kathleen Harris*, Chase Hamilton, Waleska Echevarria-Doyle, Meredith L. Carr, Victor M. Gonzalez
U.S. Army Corps of Engineers, Engineer Research and Development Center, Coastal and Hydraulics Laboratory (USACE/ERDC/CHL)

The compound flooding impact of combined inland and coastal forcings is a large and growing research area of interest and has implications on damages to vital infrastructure in coastal environments. Complications can easily arise in attempting to couple existing models to simulate the combine effect. A coastal probabilistic flood hazard assessment (PFHA) pilot study was conducted to demonstrate the application of PFHA to external flooding at a hypothetical nuclear power plant location on the Lower Neches River watershed in Texas. This presentation will focus on the modeling framework that was built for the task at hand. Using a python framework, a 2D HEC-RAS model of the Lower Neches River Basin was automated to update boundary conditions, run simulations, and extract and plot results for thousands of hypothetical tropical cyclones (TC). The HEC-RAS model used the HEC-HMS outputs of the TC as the upstream flow boundary condition, the ADCIRC outputs of the corresponding TC as the downstream stage boundary condition, and the rainfall from the same TC within the HEC-RAS 2D domain. Python scripts were created to assign the proper boundary conditions for the TC of interest by altering the HEC-RAS unsteady flow file (.u*) to incorporate the DSS file paths for the TC for the upstream boundary flow and rainfall and writing in the downstream boundary stage from ADCIRC outputs. The model is then run by calling the HEC-RAS executable within the script. Once run, addition python code is used to export the result hdf file to an external location, export results of interest that were saved the HEC-RAS reference points, and plot and save data for accessible viewing. The code then moves on to the next TC, proceeding through the TC numbers provided based on boundary conditions available. The framework was used to run thousands of simulations using various probabilistic inputs and allowed for many lessons learned regarding working with these models and how to automate. Probabilistic results are discussed in other accompanying presentations.

3B-5: An Overview of a Multi-Agency Modeling Effort to Quantify Future Conditions in the Great Lakes

Margaret Owensby*[1], T. Chris Massey[1], Robert Jensen[1], Norberto Nadal-Caraballo[1], Madison Yawn[1], David Bucaro[2], Johnna Potthoff[2], Kaitlyn McClain[2]
[1] U.S. Army Corps of Engineers, Engineer Research and Development Center, Coastal and Hydraulics Laboratory, [2] U.S. Army Corps of Engineers, Chicago District

A large, multi-year modeling effort focused on characterizing current and future hydrodynamic conditions in the Great Lakes is being conducted by a multi-agency team comprised of the U.S. Army Corps of Engineers (USACE), the National Oceanic and Atmospheric Administration's Great Lakes Environmental Research Laboratory (NOAA-GLERL), the U.S. Geological Survey (USGS), the Environmental Protection Agency (EPA), the Federal Emergency Management Agency (FEMA), and various state stakeholders. Carried out as part of the Great Lakes Restoration Initiative and prompted by the need to improve planning, design, and implementation of resilient and sustainable projects in this region, this study is designed to identify the expected range of future water levels and wave heights for each of the five Great Lakes along with Lake St. Clair. A distribution of future static lake level conditions is first computed by employing computationally efficient models to account for potential future changes in temperature and precipitation and calculate expected runoff, evapotranspiration, and ice coverage conditions. When a representative set of static lake levels and ice coverage conditions for each lake is determined, coupled ADCIRC and SWAN models are used to generate the resulting surge and wave responses for a suite of historical extreme storm conditions. Probabilistic hazards analysis will then be conducted on model results to calculate the distribution of total water levels and wave heights for each lake for each climate scenario. The resulting statistics will be made publicly available through USACE's Coastal Hazards System and be used to assess flood risk, provide guidance for future projects, and promote coastal resiliency in the region. This presentation provides a general overview of the entire project, including a summary of the methodologies used for storm selection and statistical hazards analysis.

Day 4 (March 24, 2023)

4A-1: PRA Modeling the FLEX Strategies for External Hazards

John Hanna*, U.S. Nuclear Regulatory Commission, Office of Nuclear Reactor Regulation, Division of Risk Analysis*

The U.S. Nuclear Regulatory Commission (NRC) maintains a set of Level-1 probabilistic risk assessment (PRA) models, called standardized plant analysis risk (SPAR) models, which are the analytical tools used by the agency to perform risk assessments. Following the events in Japan on March 11, 2011, the NRC issued orders to all operating commercial reactors and required implementation of Mitigating Strategies, commonly known as FLEX. The SPAR models now include the FLEX equipment, strategies, procedures, etc. During this presentation, a brief overview of the Mitigating Strategies will be given, current challenges in modeling FLEX in the PRA will be described, and qualitative and quantitative impacts of the Mitigating Strategies provided.

4A-2: Failure to Verify Flood Restoration Times at Millstone Unit 2

Dave Werkheiser*, U.S. Nuclear Regulatory Commission, Region 1, Division of Operating Reactor Safety (RI/DORS)*

During an inspection follow-up to a design basis team inspection, the NRC identified that the apparent time needed to restore from their design basis flooding event (a maximum probable hurricane) was not consistent with their procedure nor the expected inundation and recession time for the flooding event. In addition to a short background, the speaker will discuss the importance of checking/re-checking the licensee's strategies for extreme weather; questioning the feasibility and/or reliability of a licensee's flood mitigation strategies; and importance of inspectors and analysts working together to assess the practical and theoretical elements when analyzing a challenging scenario.

4A-3: Impact of the 2022 Lake Erie Seiche the Davis-Besse Nuclear Power Station

Daniel Mills*[1], Russ Cassara[1], John Hanna[2]
[1]U.S. Nuclear Regulatory Commission, Davis-Besse Resident Inspector, [2]U.S. Nuclear Regulatory Commission, Office of Nuclear Reactor Regulation, Division of Risk Analysis

The Davis-Besse Nuclear Power Station relies on Lake Erie for water to supply its ultimate heat sink. From December 23-25, 2022, Lake Erie experienced a seiche caused by high winds that resulted in historically low water levels at the southwest basin. Because of the low lake level, the Davis-Besse ultimate heat sink dropped below the level required by the plant's technical specifications. After discussion with the licensee and consideration of risk, the NRC granted the plant enforcement discretion to

allow continued operation. This presentation discusses the event, its impact on the plant, and the considerations NRC used to grant a Notice of Enforcement Discretion (NOED).

4B-1: On Fuzzy-Systems Modeling of Ponded Infiltration, as Analogue to Flooding, in Fractured-Porous Subsurface Media

Boris Faybishenko*
Lawrence Berkeley National Laboratory

The goals of the presentation are to illustrate (1) the application of ponded infiltration tests as a physical analogue for understanding water and contaminant transport phenomena under flooding conditions, and (2) the use of fuzzy soft computing as a suitable technique for numerical modeling of unsaturated-saturated subsurface media, using uncertain field-based information. Fuzzy logic is generally a form of artificial intelligence (AI) software and is considered a subset of AI.

The presentation will include an overview of the design and the results of observations obtained during a series of ponded infiltration tests conducted in fractured basalt in Idaho at the Radioactive Waste Management Complex (Large Scale Infiltration Test), Box Canyon (Meso-Scale infiltration test), and Half-Hells Acre (Small-Scale field test) sites. These results will first be used to demonstrate the complexity of the geometry and physics of flow and transport through fracture-porous media, followed by the analysis of three types of uncertainty representation for modeling of subsurface heterogeneous media: (a) randomness (random fluctuations are described using traditional probabilistic models), (b) fuzziness (using imprecise, subjective, linguistic, or expert-specified information), and (c) fuzzy randomness (incomplete, fragmentary objective, data-based, randomly fluctuating information, which can also be dubious or imprecise). Hydrogeological flooding predictions are subject to two main types of uncertainties: aleatoric uncertainty—mainly caused by subsurface heterogeneities and variability; assessing such variability is subject to ambiguity, vagueness, imprecision, ignorance, etc., and (b) epistemic uncertainty—caused by selection of different conceptual and simulation models and their parameters, involved in hydrogeological modeling.

The application of the fuzzy system approach will be demonstrated using calculations of the fuzzy regression and a fuzzy C-means clustering for the water travel time, based on the results of ponded infiltration tests, fuzzy number presentation of the water flux and hydraulic conductivity of fractured rock, and the fuzzy evaluation of the groundwater recharge as criteria for the assessment of groundwater vulnerability.

4B-2: Probabilistic Flood Hazard Assessment for Local Intense Precipitation at Nuclear Power Plant Sites – A Pilot Study

Rajiv Prasad*, Arun Veeramany[1], Rajesh K. Singh[1], Joseph Kanney[2]
[1]Pacific Northwest National Laboratory, [2]U.S. Nuclear Regulatory Commission

While nuclear power plants (NPP) in the United States provide approximately 19 percent of the nation's energy production, they are also critical infrastructure that are threatened by extreme hydrological events. We describe a methodology to perform probabilistic flood hazard assessments (PFHAs) from local intense precipitation (LIP) for NPP sites. A pilot study was performed at an existing NPP to develop the methodology and obtain insights that can help improve safety. The methodology leverages statistical properties of hydrological inputs and parameters with a deterministic, dynamic hydraulic model to probabilistically estimate flood hazards.

The LIP PFHA was performed using the selected NPP's existing LIP flood model developed to support post-Fukushima flood re-evaluation. A set of sensitivity analyses was performed to understand the sensitivity of the flood model predictions to inputs, model parameters, and site configuration. The LIP PFHA methodology used a stratified sampling approach for the aleatory variables (i.e., precipitation depth and associated storm characteristics). The scope of this study did not include performing a site-specific, precipitation-frequency analysis. Instead, probabilistic precipitation characteristics were obtained from the National Oceanic and Atmospheric Administration Precipitation Frequency Data Server. The epistemic variable (i.e., Manning's roughness coefficient multiplier) was sampled from a uniform, discrete distribution covering a reasonable range of values.

The LIP flood model simulations were performed in FLO-2D™, a two-dimensional flood routing model using the Pacific Northwest National Laboratory high-performance computing cluster. The predicted flood parameters were post-processed to create flood hazard curves at selected locations important to safety of the NPP. The pilot study shows that existing NPP site flood models can be leveraged to perform LIP PFHAs using a statistical-dynamical approach. However, it is recommended that site-specific, precipitation-frequency analyses be used to support these PFHAs.

4B-3: Research Activities on Extreme External Hazard Risk Assessment of Korean NPPs

Minkyu Kim*, Daegi Hahm
Korea Atomic Energy Research Institute, Division of Structural and Seismic Safety

Global climate change is currently underway, and it has already reached an irreversible level, and Korea is already affected by it. Nuclear power is being suggested as a very good alternative to reducing the rate of climate change, but reducing carbon emissions by dramatically increasing the amount of nuclear power plants is not possible in the short term. In reality, it is more urgent to secure the safety of nuclear power plants from the effects of external disasters, which are increasing in intensity and frequency due to climate change. For this reason, the Korean government launched a five year research program to improve the safety of operating nuclear power plants in 2022. The project is led by the Korea Atomic Energy Research Institute, with seven universities and three companies participating.

This research program is constructed into three parts. The first topic is an extreme/combined external hazard assessment, the second topic is a risk assessment of NPP and safety-related infrastructure systems and the last topic is the safety enhancement for operating NPPs in Korea regarding the extreme/external hazard considering climate change. For performing the external hazard assessment, we will develop the simulation and hazard assessment methods for extreme/combined external events. For performing a risk assessment of NPP against extreme/external hazards, we will develop a fragility assessment method and probabilistic safety assessment method for external hazards. For the development of safety enhancement against the external hazard, we will develop an optimal risk mitigation and management strategy based on hazard progress scenarios and SSCs safety enhancement methods and demonstration technology.

4B-4: External Flooding PRA Guidance

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

EPRI is currently developing 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.

4B-5: A Proposal for Paradigm Shift in Hydrological Ensemble Predictions: From Parameter Inference to Probabilistic Error Estimation

Vinh Ngoc Tran[1], Valeriy Y. Ivanov*[1], Donghui Xu[1], Jongho Kim[2]
[1]University of Michigan Department of Civil and Environmental Engineering,
[2]University of Ulsan South Korea, School of Civil and Environmental Engineering

Although the application of sophisticated hydrologic-hydrodynamic models (HHM) to flood forecasting has grown significantly over the last decade, it has remained limited due to the inherent computational burden and data-model uncertainties. We present a novel modeling framework that has the potential to address these issues by combining the advantages of three modeling techniques: HHM, surrogate, and machine learning (ML). Specifically, a comprehensive HHM can integrate a large amount of watershed information and knowledge-based parameter assumptions to provide physics-informed predictions. Surrogate modeling can resolve the computational burden of a high-fidelity HHM, opening the opportunities for uncertainty quantification, sensitivity analysis, and applications in real-time. By combining HHM-surrogate model simulation outputs with observations, the potential of ML approach can be explored to create a novel probabilistic framework capable of forecasting an ensemble of HHM-surrogate errors that include both aleatory and epistemic uncertainties. Overall, the proposed framework advocates practical utility of first-principles, high-fidelity models for flood-forecasting, with surrogate and ML modeling aiding real-time applications and uncertainty quantification.