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

Workshop on
Probabilistic Flood Hazard Assessment (PFHA)

January 29 - 31, 2013, 8:30 a.m.–6:30 p.m. (EST)

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

PROGRAM

Program Notes

The U.S. Nuclear Regulatory Commission's (NRC's) Offices of Nuclear Regulatory Research (RES), Nuclear Reactor Regulation (NRR), and New Reactors (NRO), in cooperation with Federal agency partners: U.S. Department of Energy (DOE); Federal Energy Regulatory Commission (FERC); U.S. Army Corps of Engineers (USACE); U.S. Bureau of Reclamation (BoR); and U.S. Geological Survey (USGS) have developed this "Workshop on Probabilistic Flood Hazard Assessment (PFHA)." This is a research workshop devoted to the sharing of information on probabilistic flood hazard assessments for extreme events (i.e., annual exceedance probabilities much less than 2.0 E-3 per year) from the Federal community. The organizing committee has chosen the presenters and panelists who have extensive knowledge and experience in the workshop topics.

Workshop Objectives

The aim of the workshop is to assess, discuss, and inform participants on, the state-of-the-practice for extreme flood assessments within a risk context with the following objectives:

- Facilitate the sharing of information between both Federal agencies and other interested parties to bridge the current state-of-knowledge between extreme flood assessments and risk assessments of critical infrastructures.

- Seek ideas and insights on possible ways to develop a probabilistic flood hazard assessment (PFHA) for use in probabilistic risk assessments (PRA). Flood assessments include combinations of flood-causing mechanisms associated with riverine flooding, dam and levee safety, extreme storm precipitation, hurricane and storm surges, and tsunami.

- Identify potential components of flood-causing mechanisms that lend themselves to probabilistic analysis and warrant further study (i.e., computer-generated storm events).

- Establish realistic plans for coordination of PFHA research studies as the follow-up to the workshop observations and insights.

- Develop plans for a cooperative research strategy on PFHA for the workshop partners.

Focus

The workshop will focus on the following activities:

- Understand the flood assessment needs of the participating Federal agencies with respect to the evaluation of critical industry infrastructure.

- Leverage the flood hazard risk assessment studies performed to date to assess the applicability and practicality of using probabilistic approaches for extreme flood hazard assessments within a risk framework.

- Discuss research or other activities needed to address identified gaps or challenges in the use of PFHA for extreme flood assessments within PRA.

- Determine how these PFHA approaches and methods can be best utilized in conjunction with more traditional deterministic approaches.

Workshop Structure

The workshop is designed to obtain answers to questions posed to the session panelists. Eight technical panel sessions will be convened consisting of presentations and discussions by invited presenters and panelists. The presenters will inform the workshop attendees on subjects related to their expertise regarding the various session themes. Following these presentations, a panel discussion will be held, with the session co-chairs acting as moderators. Each session will have rapporteurs to collect observations and insights from the presentations and discussions which will be summarized for the concluding session.

The workshop is an NRC **Category 2 Public Meeting**. At the end of each day, the public will have the opportunity to ask questions and to make comments.

Panel 1: Federal Agencies' Interests and Needs in PFHA
Co-Chairs: Nilesh Chokshi, NRC and Mark Blackburn, DOE

Panel 1 will be a forum to highlight the participating Federal agencies' interests and needs regarding Probabilistic Flood Hazard Assessments (PFHA). The presentations will include NRC staff's perspectives on the development of a PFHA approach within a risk context. Other presentations will focus on probabilistic approaches presently used or under development by the participating agencies, as well as ongoing efforts to develop consensus standards.

Panel 2: State-of-the-Practice in Identifying and Quantifying Extreme Flood Hazards
Co-Chairs: Timothy Cohn, USGS and Will Thomas, Michael Baker, Jr., Inc.

Panel 2 focuses on the state-of-the-practice in identifying and quantifying extreme flood hazards including their frequency and associated flood conditions within a risk context. Additional discussion on how extreme events (i.e., with an annual exceedance probability of much less than 2E-3 ranging to 1E-6) not historically observed or normally anticipated (i.e., "black swans") could be estimated. The panel will also discuss uncertainties in the estimation of flood levels and conditions.

Panel 3: Extreme Precipitation Events
Co-Chairs: John England, BoR and Chandra Pathak, USACE

Panel 3 focuses on extreme precipitation events and their impacts on flooding due to local or watershed-scale responses. Antecedent conditions such as snowpack releases and combination of extreme storms (e.g., the possibility of sequential hurricanes or extratropical storms) will be included, as well as, various data sources and climate perspectives.

Panel 4: Flood-Induced Dam and Levee Failures
Co-Chairs: Tony Wahl, BoR and Sam Lin, FERC

Panel 4 focuses on defining the current state-of-the-art and –practice, and research needs, related to estimating probabilities of failure and flooding associated with dams and levees. Presenters will address methods for estimating probabilities of failure, making probabilistic *assessments of flood hazards, and determining inflow design floods. The emphasis will be on potential failure modes tied to hydrologic events and the associated erosion of embankments/foundations, not limited to overtopping failures.*

Panel 5: Tsunamis Flooding
Co-Chairs: Eric Geist, USGS and Henry Jones, NRC

Panel 5 focuses on Probabilistic Tsunami Hazard Analysis (PTHA) as derived from its counterpart, Probabilistic Seismic Hazard Analysis (PSHA) to determine seismic ground-motion hazards. The Panel will review current practices of PTHA, and determine the viability of extending the analysis to extreme design probabilities (i.e., 10^{-4} to 10^{-6}). In addition to earthquake sources for tsunamis, PTHA for extreme events necessitates the inclusion of tsunamis generated by submarine landslides, and treatment of the large attendant uncertainty in source characterization and recurrence rates. Submarine landslide tsunamis will be a particular focus of Panel 5.

Panel 6: Riverine Flooding
Co-Chairs: Will Thomas, Michael Baker, Jr., Inc. and
Rajiv Prasad, Pacific Northwest National Laboratory

Panel 6 focuses on riverine flooding including watershed responses via routing of extreme precipitation events and antecedent conditions such as snowpack releases. This session is linked to Panel 3 and 4. {Flood-induced dam and levee failures will be addressed separately in Panel 4.}

Panel 7: Extreme Storm Surge for Coastal Areas
Co-Chairs: Donald Resio, Univ. of North Florida and Ty Wamsley, USACE

Panel 7 focuses on extreme storm surge for coastal areas due to hurricanes, extratropical cyclones and intense winter storms. The panel will also discuss seiche flooding on closed or semi-closed water bodies.

Panel 8: Combined Events Flooding
Co-Chairs: David Margo, USACE and Joost Beckers, Deltares

Panel 8 focuses on identifying and evaluating combined event scenarios within a risk-informed framework. Combined events can include flooding caused by seismically-induced dam or levee failure; flooding caused by combinations of snowmelt, rainfall and ice; flooding caused by combinations of coastal and riverine events; basin or system-wide performance and impacts; human and organizational factors; and other scenarios.

Panel 9: Summary of Significant Observations, Insights and Identified Opportunities for Collaboration on PFHA
Panel Co-Chairs: Tom Nicholson and Christopher Cook, NRC

Panel 9 will be a forum to provide summaries of significant observations and insights from the previous technical panel presentations and discussions.

Workshop Contacts:
Workshop Co-Chair: Thomas Nicholson, NRC/RES Thomas.Nicholson@nrc.gov
Workshop Coordinator: Wendy Reed, NRC/RES Wendy.Reed@nrc.gov

Registration:
No fee. For security purposes, each workshop attendee must complete and submit a registration form prior to the workshop. This form is available on the NRC Public Website under "Public Meeting Schedule." Please e-mail the completed form to registrationPFHAworkshop@nrc.gov. All workshop attendees must have two forms of photo-identification for the security review to obtain access to the NRC auditorium.

General Questions:

- What aspects of flood-causing mechanisms for extreme events can be assessed in a probabilistic manner? What new methods are in development for assessing extreme storm precipitation, dam and levee breaches, hurricane and storm surge, tsunami, and riverine flooding? What are the extreme probabilities for these methods?

- How best to quantify uncertainties associated with extreme flood estimates?

- Are there regions of the United States that would facilitate a more probabilistic approach than other regions (e.g., paleoflood analyses)?

- What is the interrelationship of deterministic and probabilistic approaches, and how can insights from both of these approaches be used in a Probabilistic Flood Hazard Assessment (PFHA)?

- How can PFHA be used in risk assessments for critical infrastructures with appropriate consideration of uncertainties and state-of-the-art hydrometeorological modeling?

- How can uncertainties be determined when estimating flood frequencies and magnitudes (e.g., storm surge analyses) of extreme events? Should uncertainty analyses be included for all flood assessments?

- How can peer review strategies be used in PFHA?

- How should flood analysts interact with PRA specialists for incorporating probabilistic estimates of extreme flood events in risk assessments?

Information Needs:

- Explain the concepts of probabilistic risk assessment as used in evaluating the safety of major engineered structures such as nuclear power plants, dams and levees.

- Relationship between natural and anthropogenic systems, and probabilistic estimates of external hazards (i.e., extreme flooding events) within a performance-based, risk-informed assessment.

- Discuss the estimation of hydrologic flood frequencies for these risk assessments.

- Review existing hydrologic frequency analysis methods and possible way to extend them.

- Explain the nature of uncertainties in the probabilistic risk assessments, and how they are considered in a decision-making context.

- Review strategies presently used in probabilistic hazard assessments to explore possible parallels for establishing a Probabilistic Flood Hazard Assessment (PFHA) strategy that augments current approaches for estimating Design Basis Floods.

- Focus on extreme flood events and hazards for rivers, oceans, lakes, and site flooding due to local intense precipitation as identified in NRC's guidance (i.e., NUREG-0800, Standard Review Plan for the Review of Safety Analysis Reports for Nuclear Power Plants: LWR Edition).

- Discuss relationship between deterministic methods presently used, and evolving probabilistic approaches (e.g., NUREG/CR-7046, "Design-Basis Flood Estimation for Site Characterization at Nuclear Power Plants in the United States of America").

- Explore issues dealing with hydrometeorological event frequency, magnitude, duration and areal distributions for assessing potential consequences within a PFHA.

- Identify hydrologic hazard models and their potential usefulness in risk assessments.

- Outline research needs for developing a probabilistic flood hazard assessment strategy for extreme flood events within a risk context.

- Identify existing PFHA strategies, their applications and verification programs.

Product

A workshop proceedings will be developed and documented as a NRC NUREG/CP (conference proceeding) report. This NUREG/CP will document: the presenters' extended abstracts and/or technical papers with references and URLs; panel discussion summaries, and principal observations and insights for consideration in developing future PFHA strategies.

Workshop Organizing Committee

Tom Nicholson, Richard Raione and Christopher Cook, NRC, Co-Chairs; John England and Tony Wahl, BoR; Mark Blackburn, DOE; Tony Cheesebrough and Joel Piper, DHS; Siamak Esfandiary, FEMA; Sam Lin and David Lord, FERC; Chandra Pathak, David Margo and Ty Wamsley, USACE; Timothy Cohn and Eric Geist, USGS; Donald Resio, University of North Florida; Joost Beckers, Deltares; Fernando Ferrante, Joe Kanney, Sunil Weerakkody, Jeff Mitman, Nathan Siu and Wendy Reed, NRC.

Workshop Oversight Committee

Nilesh Chokshi, Deputy Director, NRC/NRO/DSEA; Doug Coe, Deputy Director, NRC/RES/RES; NRC Office and Division Directors to review the workshop development.

Agenda

Workshop on Probabilistic Flood Hazard Assessment (PFHA)

Time: January 29 – 31, 2013, 8:30 a.m. – 6:30 p.m. (EST)
Location: NRC Headquarters Auditorium, 11555 Rockville Pike, Rockville, MD 20852
WebStreaming: http://video.nrc.gov

Tuesday, January 29, 2013

8:30 a.m. ***Welcome and Introductions***
Brian Sheron, Director, NRC/RES

8:35 ***Importance of Risk-Informed, Performance-Based Regulations***
NRC Commissioner George Apostolakis

9:00 **Panel 1: Federal Agencies' Interests and Needs in PFHA**
Co-Chairs: Nilesh Chokshi, NRC and Mark Blackburn, DOE

9:10 *NRC Staff Needs in PFHA*……………………………. Fernando Ferrante, NRC

9:30 *Probabilistic Hazard Assessment Approaches: Transferable Methods from Seismic Hazard* ……………………………………..…. Annie Kammerer, NRC

9:50 *Reclamation Dam Safety PFHA Perspective*........................John England, BoR

10:10 *FERC Need for PFHA* ……………………………………………..David Lord, FERC

10:30 Break

10:40 *American Nuclear Society Standards Activities to Incorporate Probabilistic Approaches* …………………….………………………………………………….
…………...John D. Stevenson, chair of ANS-2.31; Ray Schneider, Westinghouse

10:55 **Panel 1 Discussion:**
Moderators: Nilesh Chokshi, NRC and Mark Blackburn, DOE
Rapporteurs: Chris Cook, NRC (NRO) and Marie Pohida, NRC (NRO)
Panelists: Fernando Ferrante, Annie Kammerer and Charles Ader, NRC
John England, BoR
David Lord and Patrick Regan, FERC

Panel Questions

1. What are the roles of deterministic and probabilistic hazard analysis in determining a design basis and conducting a risk assessment? How should they complement each other?
2. What is the status of PFHA? For which flood causing mechanisms PFHAs can be conducted? What improvements are needed for their use in a risk assessment?
3. Given the inherent large uncertainties, how should these be dealt with?
4. What are the impediments, if any, for other flood causing mechanisms to develop PFHA approaches? How they can be overcome?
5. What are your perceptions about the utility and usefulness of a PFHA for your agency missions?
6. Is formal expert interaction approach like SSHAC a viable approach for PFHA? What PFHA specific consideration should be applied?
7. What are the roles of deterministic and probabilistic hazard analysis in determining a design basis and conducting a risk assessment? How should they complement each other?
8. What is the status of PFHA? For which flood causing mechanisms PFHAs can be conducted? What improvements are needed for their use in a risk assessment? How can uncertainties be reduced?
9. What are the impediments, if any, for other flood causing mechanisms to develop PFHA approaches? How they can be overcome?
10. What are your perceptions about the utility and usefulness of a PFHA for your agency missions?
11. Is expert elicitation a viable approach for PFHA?
12. Given the use of PFHA in the development of Design Basis Flooding determination, what is, or should be, the role of Beyond Design Basis Flooding in design and, if required how should it be determined?

11:25 Lunch

12:20 p.m. **Panel 2: State-of-the-Practice in Identifying and Quantifying Extreme Flood Hazards**
Co-Chairs: Timothy Cohn, USGS and Will Thomas, Michael Baker, Jr., Inc.

12:25 *Overview and History of Flood Frequency in the United States*..Will Thomas, Michael Baker Corp.

12:50 Keynote: *Extreme Flood Frequency: Concepts, Philosophy, Strategies* ……………………………………………………….....Jery Stedinger, Cornell University

1:15 *Quantitative Paleoflood Hydrology*……………………………Jim O'Connor, USGS

1:40 *USACE Methods* ……………………………………. Douglas Clemetson, USACE

2:05: *Hydrologic Hazard Methods for Dam Safety* ………………......John England, BoR

2:30 **Panel 2 Discussion**:
Moderators: Timothy Cohn, USGS and Will Thomas, Michael Baker, Jr., Inc.
Rapporteurs: Joseph Giacinto and Mark McBride, NRC (NRO); and
Randy Fedors, NRC (NMSS)
Panelists: Jery Stedinger, Cornell University
John England, BoR
Douglas Clemetson, USACE
Jim O'Connor, USGS

Panel Questions

1. How has the federal agency that you have represented approached the problem of estimating the risk of extreme floods?
2. What is the historical basis for statistical estimation procedures employed by your agency?
3. To what extent are the details of physical processes considered in determining risk of extreme floods?
4. What criteria are employed in evaluating risk estimation procedures employed by your agency?
5. How could data collection and availability be improved for your agency?
6. What additional data and research are needed to reduce the uncertainty associated with extreme flood frequency estimates?
7. To what extent do operational requirements limit your agency's ability to employ accurate risk estimates?
8. Do fundamentally different issues arise associated with estimating the 50%, 10%, 1%, 0.01%, and 0.0001% exceedance events?
9. Where are the greatest opportunities for improving the way that your agency estimates the risk of extreme floods?

3:00 Break

3:10 **Panel 3: Extreme Precipitation Events**
Co-Chairs: John England, BoR and Chandra Pathak, USACE

3:10 *Introduction of Panel, Objectives, and Questions* …….........John England, BoR

3:15 *An Observation-Driven Approach to Rainfall and Flood Frequency Analysis Using High-Resolution Radar Rainfall Fields and Stochastic Storm Transposition*………
……………………………………...……......Daniel Wright, Princeton University

3:40 *Regional Precipitation Frequency Analysis and Extremes including PMP – Practical Considerations*…….…......Mel Schaefer, MGS Engineering Consultants

4:05 *High-Resolution Numerical Modeling As A Tool to Assess Extreme Precipitation Events*..Kelly Mahoney, NOAA-ESRL

4:30 *Precipitation Frequency Estimates for the Nation and Extremes – A Perspective*
……………………..……... Geoff Bonnin, NWS-OHD

4:50 *Extreme Precipitation Frequency for Dam Safety and Nuclear Facilities – A Perspective*………………………………………………………….Victoria Sankovich, BoR

5:15 **Panel 3 Discussion**:
Moderators: John England, BoR and Chandra Pathak, USACE
Rapporteurs: Nebiyu Tiruneh, NRC (NRO) and Brad Harvey, NRC (NRO)
Panelists: Daniel Wright, Princeton University
Mel Schaefer, MGS Engineering Consultants
Kelly Mahoney, NOAA-ESRL
Geoff Bonnin, NWS-OHD

Panel Questions

1. Describe the advancements and improvements in extreme storm rainfall and precipitation observations and data bases over the past 30 years. Are there opportunities with radar, point observations, reanalysis data sets, and other data that can readily be utilized for extreme precipitation analyses, understanding, and applications for critical infrastructure?

2. Outline the advances in statistical and data processing methods that can be used for extreme precipitation frequency estimation. These might include regional precipitation frequency, regionalization of parameters, Geographic Information Systems, climatological estimation (such as PRISM), and other areas. How might these tools be applied in practice, and include uncertainty estimates?

3. Describe the advances in physical and numerical modeling of extreme precipitation (such as the Weather Research and Forecasting Model, WRF) that can give insights into the processes and magnitudes of extreme precipitation, including spatial and temporal distributions. How can these tools be applied to provide practical limits to extreme precipitation magnitudes, spatial and temporal storm patterns, transposition, and other extreme storm scaling?

4. The National Research Council (1994) report on extreme precipitation suggested research in several areas, including: radar hydrometeorology and storm catalog, numerical modeling of extreme storms in mountainous regions, and estimating probabilities of extreme storm rainfalls. Are there existing technical barriers to fully probabilistic extreme storm estimation for assessing critical infrastructure, as opposed to Probable Maximum Precipitation?

6:00 Public Attendees' Questions and/or Comments

6:30 Adjourn

Wednesday, January 30, 2013

8:30 a.m. **Panel 4: Flood-Induced Dam and Levee Failures**
Co-Chairs: Tony Wahl, BoR and Sam Lin, FERC

8:35 *Risk-informed Approach to Flood-induced Dam and Levee Failures*……………….
…………………………………………David Bowles, RAC Engineers & Economists

9:00 *Dutch Approach to Levee Reliability and Flood Risk* ……………………………
……………………......... Timo Schweckendiek, Deltares Unit Geo-engineering

9:25 *Risk-Informed Decision-Making (RIDM) Approach for Inflow Design Flood (IDF) Selection and Accommodation for Dams: A Practical Application Case Study*.......
……………………………………................................... Jason Hedien, MWH

9:50 Break

10:05 *Incorporating Breach Parameter Estimation and Physically-Based Dam Breach Modeling into Probabilistic Dam Failure Analysis*…… ……….. Tony Wahl, BoR

10:30 *USACE Risk Informed Decision Framework for Dam and Levee Safety*…………..
………………………………………………………………David Margo, USACE

10:45 **Panel 4 Discussion**:
Moderators: Tony Wahl, BoR and Sam Lin, FERC
Rapporteurs: Jacob Philip, NRC (RES); Hosung Ahn, NRC (NRO); and Juan Uribe, NRC (NRR)
Panelists: Eric Gross, FERC, Chicago (Dam)
Timo Schweckendiek, Deltares Unit Geo-engineering (Levee)
Martin W McCann Jr., Stanford University (Dam/Levee)
David Margo, USACE (Dam/Levee)
Gregory Baecher, University of Maryland (Risk Analysis)
Jery Stedinger, Cornell University (Dam)
David Bowles, RAC Engineers & Economists (Dam/Levee)

<u>Panel Questions</u>

1. What does history tell us about the probability of dam/levee failure from various causes?
    - Hydrologic/Hydraulic
        - Overtopping
        - Failure of spillways (concrete lined or earthen/natural rock) or outlet works during extreme floods
        - Seepage and piping
    - Mechanical/Operational
2. What aspects of an event need to have probabilities assigned?
    - Probability of failure itself
    - Probability of flooding of a given severity
3. There are many different triggers for failure. For example, variability of soils and slope protection of embankment dams can be an extreme source of uncertainty. How are the failure thresholds reasonably assumed such as the overtopping depth on an embankment dam based on its existing conditions?
4. What can modeling do to help us understand probabilistic aspects of dam/levee failure?
5. What roles can dam and levee failures play in PFHA or PRA and how can they be integrated? (i.e. make an inventory of relevant issues)
6. Is system behavior (as will be shown in Timo's presentation) relevant for PFHA?
7. What level of detail is appropriate for levee reliability modeling in PFHA?

8. What are the roles of probabilistic safety assessment and probabilistic safety criteria for hydrologic safety of dams?
9. What is different about dam/levee failure impact on downstream as compared to other causes of flooding? For example, dam failure releases large quantities of sediment as well as water, so debris-flow considerations may be more important than for other flooding causes.
10. Do we endorse use of probabilistic methods and risk analysis for the following reasons?
    - Less conservatism than modifying dams for extreme loads
    - Levels playing field and considers relative ranking of all PFMs at a facility
    - Provides a means of prioritizing future studies and modifications
11. Are the below potential improvements and research needs or more?
    - Spillway debris issues
    - Spillway gate failure issues
    - River system failures (coordination with other owners)
12. What comes after failure? There are, such as: What failure-induced flood parameters or consequences may be important for assessing the safety of assets besides water depth or flow velocities? (e.g. wave impact, scour holes affecting foundations etc.)

11:35 Lunch

12:35 p.m. **Panel 5: Tsunami Flooding**
Co-Chairs: Eric Geist, USGS-Menlo Park, CA and Henry Jones, NRC

12:40 *Probabilistic Tsunami Hazard Analysis* .... Hong Kie Thio, URS Corp.

1:05 *Recent advances in PTHA methodology*…...
....Randy LeVeque, University of Washington

1:30 *Landslide Tsunami Probability* …………………........................Uri ten Brink, USGS

1:55 *Modeling Generation and Propagation of Landslide Tsunamis*..............................
....Pat Lynett, USC

2:20 **Panel 5 Discussion**:
Moderators, Eric Geist, USGS and Henry Jones, NRC
Rapporteurs: Mark McBride, NRC (NRO) and Randy Fedors, NRC (NMSS)
Panelists: Randy LeVeque, University of Washington
Uri ten Brink, USGS
Pat Lynett, USC
Annie Kammerer, NRC
Frank González, University of Washington
Yong Wei, NOAA/PMEL
Tom Parsons, USGS
Chuck Real, California Geological Survey

Panel Questions

1. What input parameters/uncertainties are important to include in PTHA for extreme tsunamis?

2. What are the appropriate probability distributions (as determined by statistical testing and model selection) that define uncertainty of input parameters for PTHA? What databases exists for earthquakes and landslides to test model distributions and assess uncertainty.

3. What is the best framework (e.g., logic-tree) for including landslides tsunamis into PTHA, given the inherent uncertainties associated with the phenomena? (follow-up to the 2011 NRC/USGS Woods Hole workshop)

4. How does a landslide composed of multiple failures generate a tsunami? By constructive interference of many small failures, by only failure of a dominant large cohesive block, or by hydraulic jump of thick coalesced debris flows from a large area?

5. How do PTHA techniques currently used in the U.S. differ from implemented in Japan, especially with regard to extreme tsunami hazards?

6. What are the fundamental needs of improving PTHA (e.g. seafloor mapping/sampling, paleoseismic/paleotsunami deposit analysis, validation of modeled current velocities, etc.), and how should the U.S. move forward to make these improvements (organizationally and funding)?

1. How should the NRC and other organizations work towards verification and consistency of PTHA methods?

2:50 Break

3:00 **Panel 6: Riverine Flooding**
Co-Chairs: Will Thomas, Michael Baker, Jr., Inc. and
Rajiv Prasad, Pacific Northwest National Laboratory

3:05 *Riverine PFHA for NRC Safety Reviews – Why and How?...*Rajiv Prasad, PNNL

3:30 *Flood Frequency of a Regulated River - the Missouri River*……………………..……..
……………………………………………………………..Douglas Clemetson, USACE

3:55 *Extreme Floods and Rainfall-Runoff Modeling with the Stochastic Event Flood Model (SEFM)*...Mel Schaefer, MGS Engineering

4:20 *Use of Stochastic Event Flood Model and Paleoflood Information to Develop Probabilistic Flood Hazard Assessment for Altus Dam,Oklahoma*…………………
……………………………………………………………….. Nicole Novembre, BoR

4:45 *Paleoflood Studies and their Application to Reclamation Dam Safety*…………...…
…………………………………………………………………… Ralph Klinger, BoR

5:10 **Panel 6 Discussion**:
Moderators: Will Thomas, Michael Baker, Jr., Inc. and Rajiv Prasad, PNNL

Rapporteurs: Peter Chaput, NRC (NRO) and Jeff Mitman, NRC (NRR)
Panelists: Douglas Clemetson, USACE
Nicole Novembre, BoR
Ralph Klinger, BoR
Jery Stedinger, Cornell University
Mel Schaefer, MGS Engineering

Panel Questions:

1. Runoff simulation-based approaches for riverine PFHA could use either event-based or continuous model simulations. What are the strengths and weaknesses of the two approaches? What R&D is needed to address weakness/gaps?

2. How can we best combine flood frequency analysis approaches (including historical paleoflood information) with simulation approaches to estimate magnitudes and frequencies for extreme flooding events? Is there additional R&D needed in this area?

3. A full-blown PFHA that includes both sensitivity analysis and uncertainty analysis may be very demanding in terms of computational resources (i.e. large numbers of simulations may be needed). What approaches are available to provide useful results while minimizing the number of simulations that need to be performed?

4. A full-blown PFHA will also be demanding in terms of workload for the analyst. What software tools are available to assist in streamlining the workflow? Is there a significant need for new/improved tools? If so, what is the most critical need?

5. What approaches are available for handling correlations in events/processes that combine to generate extreme riverine floods?

6. In a full-blown PFHA using runoff simulation approach, probability distributions of hydrometeorologic inputs and model parameters are needed. What methods or approaches are available to estimate these probability distributions?

7. Uncertainty in runoff simulations can arise because of uncertainties in inputs, model parameters, and the model structure. What methods or approaches are available to estimate these uncertainties?

8. How do you validate a runoff model for extreme floods?

9. How do you think non-stationarity (that has already occurred in the past, e.g., land-use changes and may occur in the future, e.g., global climate change) can be accounted for in a runoff simulation approach for PFHA?

6:00 Public Attendees' Questions and/or Comments

6:30 Adjourn

Thursday, January 31, 2013

8:30 a.m. **Panel 7: Extreme Storm Surge for Coastal Areas**
Co-Chairs: Donald Resio, Univ. of N. Florida and Ty Wamsley, USACE

8:35 *Coastal Flood Hazard in the Netherlands*…………………Joost Beckers, Deltares

9:00 *Recent Work and Future Directions in Coastal Surge Modeling within NOAA*…....
……………………………………………………………….. Stephen Gill, NOAA

9:25 *FEMA's Coastal Flood Hazard Analyses in the Atlantic Ocean and Gulf of Mexico*……………………….……………………….…Tucker Mahoney, FEMA

9:50 *Modeling System for Applications to Very-Low Probability Events and Flood Response*……………………………………………………...Ty Wamsley, USACE

10:15 Break

10:30 *Coastal Inundation Risk Assessment* ……………………………………………….
………………………………………..Jen Irish, Virginia Polytechnic Institute (VPI)

10:55 **Panel 7 Discussion**:
Moderators: Donald Resio and Ty Wamsley
Rapporteurs: Mark Fuhrmann, NRC (RES) and Ferrando Ferrante, NRC (NRR)
Panelists: Joost Beckers, Deltares
Stephen Gill, NOAA
Tucker Mahoney, FEMA
Jen Irish, VPI

Panel Questions

1. Relative to probabilistic hazard prediction, what are some significant advances that your group/organization has made in the last few years or expects to complete in the near future?

2. Relative to probabilistic hazard prediction for NRC, what do you feel could be an important contribution by your group/organization?

3. How should we quantify uncertainty for probabilistic forecasting?

4. What do you feel are some significant shortcomings/lacks of knowledge that could hamper our probabilistic hazard forecasting for the NRC?

5. How can we quantify the effects of upper limits on probabilistic hazards?

11:20 Break

11:25 **Panel 8: Combined Events Flooding**
Co-Chairs: David Margo, USACE and Joost Beckers, Deltares

11:30 *Combined Events in External Flooding Evaluation for Nuclear Plant Sites…..……. ……………………………………………………….. Kit Ng, Bechtel Power Corp.*

11:45 *Assessing Levee System Performance Using Existing and Future Risk Analysis Tools* …………………………………………………………Chris Dunn, USACE

12:00 *Seismic Risk of Co-Located Critical Infrastructure Facilities – Effects of Correlation and Uncertainty*………………… Martin McCann, Stanford University

12:15 p.m. Lunch

1:00 **Panel 8: Combined Events Flooding (continued)**

1:00 *Storm Surge - Riverine Combined Flood Events*………….Joost Beckers, Deltares

1:15 *Combining Flood Risks from Snowmelt, Rain, and Ice – The Platte River in Nebraska* ….…………………………………………… Douglas Clemetson, USACE

1:30 *Human, Organizational, and Other Factors Contributing to Dam Failures*………… ……………………..………………………………………. Patrick Regan, FERC

1:45 **Panel 8 Discussion:**
Moderators: David Margo and Joost Beckers, Deltares
Rapporteurs: Michelle Bensi, NRC (NRO) and Jeff Mitman, NRC (NRR)
Panelists: Kit Ng, Bechtel Power Corporation
Chris Dunn, USACE
Martin McCann, Stanford University
Joost Beckers, Deltares
Douglas Clemetson, USACE
Pat Regan, FERC

Panel Questions

1. How can a risk informed framework be utilized to identify plausible event combinations that are relevant to the flood hazard assessment?

2. How can we estimate the probabilities and risks associated with event combinations?

2:30 Break

2:35 **Panel 9: Summary of Significant Observations, Insights, and Identified Opportunities for Collaboration on PFHA**
Panel Co-Chairs: Tom Nicholson and Christopher Cook, NRC
Rapporteurs: Wendy Reed, NRC (RES) and Jacob Philip, NRC (RES)

2:40 Panel 1 Co-Chairs and Rapporteurs

2:55	Panel 2 Co-Chairs and Rapporteurs	
3:10	Panel 3 Co-Chairs and Rapporteurs	
3:25		Break
3:40	Panel 4 Co-Chairs and Rapporteurs	
3:55	Panel 5 Co-Chairs and Rapporteurs	
4:10	Panel 6 Co-Chairs and Rapporteurs	
4:25	Panel 7 Co-Chairs and Rapporteurs	
4:40	Panel 8 Co-Chairs and Rapporteurs	
4:55	Workshop and Public Attendees' Questions and/or Comments	
6:00		Adjourn

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ABSTRACTS

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Panel 1: Federal Agencies' Interests and Needs in PFHA

Co-Chairs: Nilesh Chokshi, NRC and Mark Blackburn, DOE

Rapporteurs: Chris Cook, NRC (NRO) and Marie Pohida, NRC (NRO)

Presenters:
Commissioner George Apostolakis, NRC
Fernando Ferrante, NRC
Annie Kammerer, NRC
John England, BoR
David Lord, FERC
John Stevenson, ANS 2.8 Working Group
Ray Schneider, Westinghouse

Panelists: Fernando Ferrante, Annie Kammerer and Charles Ader, NRC
John England, BoR
David Lord and Patrick Regan, FERC

U. S. Nuclear Regulatory Commission Staff Needs in Probabilistic Flood Hazard Assessment

Fernando Ferrante, Ph. D.

U.S. Nuclear Regulatory Commission, Washington DC, USA

The US Nuclear Regulatory Commission (USNRC) is an independent federal agency whose mission is to license and regulate the Nation's civilian use of byproduct, source, and special nuclear materials to ensure the adequate protection of public health and safety, promote the common defense and security, and protect the environment [1]. In order to support its mission, the USNRC performs licensing, rulemaking, incidence response, and oversight activities to ensure the safe operation of critical infrastructure, such as large operating commercial nuclear reactors, research and test reactors, and nuclear fuel cycle facilities.

Specific parts in Title 10 of the Code of Federal Regulations [2], which prescribe the requirements under the authority of the USNRC, also include consideration of natural phenomena such as floods. For example, for commercial nuclear reactors, principal design criteria establishing design requirements for structures, systems, and components that provide reasonable assurance that the facility can withstand the effects of natural phenomena without undue risk to the health and safety of the public are described [3]:

(1) Appropriate consideration of the most severe of the natural phenomena that have been historically reported for the site and surrounding area, with sufficient margin for the limited accuracy, quantity, and period of time in which the historical data have been accumulated,
(2) appropriate combinations of the effects of normal and accident conditions with the effects of the natural phenomena and
(3) the importance of the safety functions to be performed.

Significant regulatory guidance and research has been developed in order to address the evaluation of various flooding phenomena and mechanisms such as extreme meteorological events (e.g. severe storms, tides, and waves), seiche/tsunami, and dam failures [4 - 9]. Understanding the risks posed to the facilities regulated by the USNRC is also important in terms of resource allocation (e.g. prioritization of inspections, incident response) and emergency planning. It is recognized that, for different natural phenomena, the maturity of available methodologies and data for assessing the likelihood of occurrence of hazards that may challenge plant safety varies significantly from hazard to hazard and can involve wide uncertainty in both the intensity and frequency of the event.

The USNRC has spent significant resources to develop and incorporate the use of risk assessment tools for risk-informed decision-making in a variety of applications related to regulatory licensing and oversight [10]. The drivers prompting the staff to use these tools include a policy statement on the use of probabilistic risk assessment (PRA) in regulatory activities [11] as well as guidance for specific activities (e.g., [12]) where quantitative risk assessments may be used in risk-informed regulatory actions.

In the area of oversight, the USNRC oversees licensees' safety performance through inspections, investigations, enforcement, and performance assessment activities, in which risk tools and risk criteria are routinely applied. In particular, the USNRC has established the Reactor Oversight Process (ROP) which is the Agency's program to inspect, measure, and assess the safety performance of commercial nuclear power plants and to respond to any decline in performance [13]. This includes determining the safety significance of inspection findings through a number of risk-informed activities, including the use of PRA models for individual reactor that are developed and maintained by Idaho National Laboratory (INL) for use by the USNRC [14]. Typically, these models consider a number of potential events that may challenge plant safety such as loss of AC power necessary to operate critical equipment and/or the loss of capability to cool the nuclear reactor core. As the characteristics of events that may challenge plant safety are identified, the capacity of the safety systems designed to protect critical functions is evaluated for the conditional probability of failure, thus resulting in an overall measure of the available protection with respect to the likelihood of the intervening event. One of the commonly used risk measures in PRA models is the core damage frequency (CDF), a measure of the likelihood of severe damage to the nuclear fuel used for heat generation in US commercial nuclear reactors.

In many cases, the models are based on events occurring internal to the plant (e.g., random equipment failure, operator errors) while less focus has historically been placed on detailed modeling of extreme natural phenomena, although some studies evaluating the risk contribution of flooding events exist [15 - 21]. Typical CDF results for overall plant risk obtained in USNRC risk analysis range from an annualized core damage frequency of 1E-4/year to 1E-6/year for all contributing risk scenarios. In the hydrologic community, it has long been recognized that estimating the annualized frequency of severe floods tends to be restrained to a great extent by the historical record available, with significant effort made in the development of methods and approaches to extend frequency estimates beyond typically observed events [22]. The result is that there exists significant uncertainty associated to the ranges of interest of USNRC risk applications such as the ones described above, where severe flood estimates may range from 1E-3/year to 1E-6/year and below [23], depending on the quantity and quality of data available as well as the refinement of the methodology used to derive such estimates.

The USNRC has been engaged in risk assessment of natural hazards, such as floods, well before the 9.0-magnitude earthquake that struck Japan 2011 on March 11, 2011 that eventually lead to extensive damage to the Fukushima Dai-ichi nuclear site. However, the formation of Near-Term Task Force (NTTF) to review insights from this event [24] and the subsequent activities [25 – 27] that include a reevaluation of potential flooding hazards for nuclear facilities regulated by the USNRC have re-focused the review and potential enhancement of the treatment and evaluation of very low probability/high consequence events with respect to critical infrastructure.

Coupled with the already existing risk framework and tools used in licensing and oversight for commercial nuclear reactors as well as other applications regulated by the USNRC, a probabilistic flood hazard assessment (PFHA) effort could provide significant input in the area of flood hazard characterization, and the probabilistic treatment of flood protection and mitigation strategies with respect to PRAs. In particular, there is a strong interest for further development in the following areas in applications related to the risk assessment of nuclear facilities licensed and regulated by the NRC:

- Development of methods to consistently estimate annualized flood frequencies in the ranges of interest of USNRC applications with respect to potential contributors to CDF, including extrapolations beyond the available historical record.

- Characterization of a broader spectrum of flood risk contributors, rather than focusing on deterministically-derived “worst” case scenarios, in order to capture the impact of extreme events as well as less severe but more frequent floods.

- Consideration of the feasibility of screening methodologies that take into account the range of locations of facilities licensed and regulated by the USNRC (i.e., with distinct hydrological, meteorological, and geographical characteristics) to identify sites for which certain flooding mechanisms may be more applicable and therefore may require more detailed risk assessment considerations.

- Risk assessment of dam failures (including downstream dam failures that may affect the availability of water from a large body of water relied on to cool various thermal loads during plant operations) on safe operations of nuclear facilities. This would include probabilistic treatment of various individual failure mechanisms, such as overtopping, internal erosion, spillway and hydro-turbine failures, seismic events, and credible combination of events; within the frequency range of interest to USNRC applications.

- Possible probabilistic treatment of flood protection structures and barriers (including temporary barriers), while considering potential for degradation from debris impact, erosion, and other effects during severe flooding events.

- Development of a probabilistic assessment of the capacity of mechanical, structural, and electrical systems relied on for safe operation of nuclear facilities to withstand flooding impacts, similar to fragility curves typically associated with seismic risk assessments (e.g., conditional probability of failure with respect to a specific loading or flood level).

- Feasibility of operator manual actions during extreme flooding events in a probabilistic framework, which may be associated with actions such as the installation of flooding protection (e.g., floodgates), construction of barriers (e.g., sandbag barriers), and other actions.

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Probabilistic Hazard Assessment Approaches: Transferable Methods from Seismic Hazard

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Quantitative assessment of all natural hazards share common attributes and challenges. These include the need to determine the best estimate and uncertainty of the hazard levels, limited data, high levels of uncertainty, and the need to include expert judgment in the assessment process. Over the last several decades, approaches for assessing seismic hazard have matured and current approaches are transferable to other types of hazard. While the level of uncertainty in seismic hazard remains high, particularly in low to moderate seismicity regions, highly structured methods of expert interaction and model development have been developed and applied with success. In 1997, the Senior Seismic Hazard Analysis Committee (SSHAC) developed a structured, multilevel assessment framework and process (the "SSHAC process"), described in NUREG/CR-6372, "Recommendations for Probabilistic Seismic Hazard Analysis: Guidance on Uncertainty and Use of Experts," that has since been used for numerous natural hazard studies since its publication. In 2012, the NRC published NUREG-2117, "Practical Implementation Guidelines for SSHAC Level 3 and 4 Hazard Studies," after studying the experience and knowledge gained in the application of the original guidance over the last 15 years. NUREG-2117 provides more detailed guidelines consistent with the original framework described in NUREG/CR-6372, which is more general and high level in nature. NUREG-2117 provides an extensive discussion of the Level 3 process, which is well suited to the assessment of other natural hazards.

When seismic hazard assessments are conducted for critical facilities such as nuclear power plants, the judgments of multiple experts are required to capture the complete distribution of technically defensible interpretations (TDIs) of the available earth science data. The SSHAC process provides a transparent method of structured expert interaction entirely focused on capturing the center, body, and range (CBR) of the full suite of TDIs of the available data. The goal is not to determine the single best interpretation; rather, it is to develop and integrate all TDIs into a logic tree framework wherein the weights of the various branches are consistent with the level to which the data and information available supports the interpretation. This approach leads to greater assurance that the "true" hazard at a site is captured within the breadth of the probabilistic seismic hazard assessment (PSHA) results.

To achieve this, a study following in the SSHAC process goes through a series of steps that can be separated into evaluation and integration phases. The fundamental goal of the SSHAC Level 3 process is to properly carry out and completely document the activities of evaluation and integration, defined as follows:

Evaluation: The consideration of the complete set of data, models, and methods proposed by the larger technical community that are relevant to the hazard analysis.

Integration: Representing the CBR of TDIs in light of the evaluation process (i.e., informed by the assessment of existing data, models, and methods).

As discussed in detail in NUREG 2117, the process includes a number of well-defined roles for participants, as well as three required workshops, each with a specific objective. The evaluation process starts by the Technical Integrator (TI) team identifying (with input from resource and proponent experts) the available body of hazard-relevant data, models, and methods—including all those previously produced by the technical community—to the extent possible. This body of existing knowledge is supplemented by new data gathered for the study. The first workshop is focused on with the identification of hazard-relevant data, models, and methods. The TI team then evaluates these data, models, and methods and documents both the process by which this evaluation was undertaken and the technical bases for all decisions made regarding the quality and usefulness of these data, models, and methods. This evaluation process explicitly includes interaction with, and among, members of the technical community. The expert interaction includes subjecting data, models, and methods to technical challenge and defense. Workshop #2 provides a forum for proponents of alternative viewpoints to debate the merits of their models. The successful execution of the evaluation is confirmed by the concurrence of the Participatory Peer Review Panel (PPRP) that the TI team has provided adequate technical bases for its conclusions about the quality and usefulness of the data, models, and methods, and has adhered to the SSHAC assessment process. The PPRP will also provide guidance on meeting the objective of considering all of the views and models existing in the technical community.

Informed by this evaluation process, the TI team then performs an integration process that may include incorporating existing models and methods, developing new methods, and building new models. The objective of this integration process is to capture the CBR of TDIs of the available data, models, and methods. The technical bases for the weights on different models in the final distribution, as well as the exclusion of any models and methods proposed by the technical community, need to be justified in the documentation. Workshop #3 provides an opportunity for the experts to review hazard-related feedback on their preliminary models and to receive comments on their models from the PPRP. To conclude the project satisfactorily, the PPRP will also need to confirm that the SSHAC assessment process was adhered to throughout and that all technical assessments were sufficiently justified and documented.

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Bureau of Reclamation Dam Safety Probabilistic Flood Hazard Analysis Perspective

John F. England, Jr.[1] and Karen M. Weghorst[1]

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The Bureau of Reclamation uses risk analysis to assess the safety of dams, recommend safety improvements, and prioritize expenditures (Reclamation, 2011). Reclamation has been using risk analysis as the primary support for dam safety decision-making for over 15 years, and has developed procedures to analyze risks for a multitude of potential failure modes. By definition, "risk" is the product of the likelihood of an adverse outcome and the consequences of that outcome. The likelihood of an adverse outcome is the product of the likelihood of the loading that could produce that outcome and the likelihood that the adverse outcome would result from that loading. Risk analysis, from a hydrologic perspective, requires an evaluation of a full range of hydrologic loading conditions and possible dam failure mechanisms tied to consequences of a failure.

The Bureau of Reclamation conducts risk analysis at different levels, from screening level analyses performed by an individual (with peer review) during a Comprehensive Facility Review (CFR), to full blown facilitated team risk analyses, which include participation by "field" personnel. One key input to a risk analysis is the loading characteristic; this is generally in the form of hydrologic hazard curves or seismic hazard curves for floods and earthquakes. Manuals, guidelines, and practical reference material detailing risk analysis methodology for dam safety applications based on Reclamation's experience are available (Reclamation, 2011). This presentation provides an overview of the Dam Safety Act, Reclamation's risk process, and risk reduction. Risk analysis at the Bureau of Reclamation has evolved over the years and will continue to evolve.

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Other reports related to Reclamation's Public Protection Guidelines are here:

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FERC Need for Probabilistic Flood Hazard Analysis (PFHA) Journey From Deterministic to Probabilistic

David W. Lord, P.E.[1],

Abstract

The Federal Energy Regulatory Commission's (FERC) has a well developed program[2] to calculate a deterministic value for the Probable Maximum Flood (PMF) based on the Probable Maximum Precipitation (PMP). The PMF determinations are based on the precipitation estimates in the applicable Hydro Meteorological Reports (HMR) or increasingly from site-specific or state wide[3] studies. These site specific or state wide studies use the general concepts contained in the HMRs and update and applies them to smaller areas. The application of these updated PMP studies have taken out much of the conservatism inherent in the HMR estimates of PMP as they have reduced the PMP estimates up to 56 percent[4]. The significant reduction of historical PMP estimates raises concern on the reasonableness of these new estimates.

Another problem is that the PMP and thus Probable Maximum Flood (PMF) numbers are treated as having zero probabilities, i.e., as upper bounds that can't be exceeded, rather than having a relatively low probability. For some interior parts of the country, farther from a warm ocean moisture source, PMP estimates are likely to have very low annual exceedance probabilities, about 1×10^{-7} or lower. However, in coastal regions closer to warm moisture sources, the estimates of the PMP[5] and thus PMF probability may be much higher, possibly several orders of magnitude higher, possibly between 1×10^{-3} and 1×10^{-5}. This results in both uneven treatment between dams, and the possibility of flood risks that have not been adequately evaluated because the PMP and resulting PMF is a relatively frequent event.

Another fundamental issue is that many dam overtopping failure modes are from a combination of circumstances, such as trash build-up on spillway gates or inability to open a spillway gate

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[1] Senior Civil Engineer, Risk-Informed Decision-Making, FERC, Division of Dam Safety and Inspections, Portland Regional Office, 503-552-2728, david.lord@ferc.gov

[2] Chapter 8 of the FERC Engineering Guidelines

[3] State wide PMP studies have been approved for Wisconsin and Michigan (EPRI 1993), and Nebraska 2008. State wide PMP studies are ongoing for Arizona, Ohio and Wyoming. EPAT study for the State of Colorado does not follow HMR methodology and has not been approved for developing PMP estimates at an FERC Project.

[4] Reduced the PMP value of the HMR for a 24-hour, 20,000 sq. mi. storm from 6.8 inches to 3.0 inches in western Nebraska.

[5] Schaefer MG, PMP and Other Extreme Storms, Concepts and Probabilities Safety, 1995 ASDSO Annual Conference Proceedings, Lexington KY, October 1995.

during a relatively frequent flood. The frequency of events between 1 X 10^{-2} and 1 X 10^{-4} might be of greater concern in combination with these events than an extreme flood event.

The FERC's modern dam safety program started with implementing regulations in 1981. The FERC's Division of Dam Safety and Inspections (D2SI) has regulatory responsibility for approximately 3000 dams and approximately 950 dams classified as high and significant hazard potential. The high hazard classification is based on whether generally worst case dam failures would have the potential to cause loss of life. Significant hazard dams are reserved for economic or sensitive environmental issues. As discussed above, our dam safety program has relied on generally conservative deterministic analyses until recently.

In 2000, D2SI established a Potential Failure Modes Analysis (PFMA) program for all high and significant hazard (HSH) dams. In 2009, the Commission adopted a strategic plan to develop a probabilistically oriented program, titled Risk-Informed Decision Making (RIDM). D2SI recently has initiated development of risk informed engineering guidelines included a Hydrologic Hazard Analysis (HHA) chapter. Drafts of these guidelines are to be completed by September 2013.

You will hear more extensive discussions of flood risks to and from dams later in this workshop. Reclamation has a well respected program for developing estimates for Annual Exceedance Probabilities (AEP) of extreme precipitation and flood events and for developing resulting reservoir exceedance curves. Our new HHA chapter will rely heavily on the current Best Practices used by Reclamation. However, we are a regulator and not a dam owner like Reclamation, so our guidelines will require us to be able to communicate with hundreds of dam owners and dozens of consultants that may or may not have comprehensive knowledge of probabilistic hydrologic hazard analyses.

While Reclamation can make an informed decision based on the information they develop, we will have to be able to use information primarily developed by the owners and consultants in consultation with our staff. Some of the questions about extreme flood frequency are as follows:

1. Should the PMP be the upper bound of any frequency estimates of extreme storms?
2. Are there simple procedures for rare to extreme flood and precipitation frequency estimates to judge whether more robust estimates are needed at a dam?
3. What circumstance, i.e., level of risk would require an owner to develop new flood frequency estimates at a dam, i.e., when does a probabilistic estimate augment or replace a deterministic estimate?
4. If the current PMP and PMF estimates are inadequate at a dam, do we complete new deterministic estimates, or should we rely only on new probabilistic calculations?

American Nuclear Society (ANS) Standards Current Activities

ANS-2.8 Status[1]

[1]Raymond E. Schneider, ANS 2.8 development working group and Westinghouse

The Status presentation, **ANSI/ANS-2.8 WG Status "Determine External Flood Hazards for Nuclear Facilities"** will present a brief introduction on the background, the objective, the scope, the standard for external flood hazards determination, the current status of the ANS-2.8 Working Group (WG) Activities and the relationship to the PFHA Workshop.

U.S. Department of Energy and Probabilistic Flood Hazard Assessment

W. Mark Blackburn, P.E.[1]

[1]Director, Office of Nuclear Facility Safety Programs
U.S. Department of Energy (DOE)

The U.S. Department of Energy (DOE) has used Probabilistic Flood Hazard Analysis for many years. The usage of Probabilistic Flood Hazard Analysis is endorsed in a recently approved DOE document called DOE Standard DOE-STD-1020-2012, *Natural Phenomena Hazards Analysis and Design Criteria for Department of Energy Facilities*. This document references a 1988 paper entitled *Preliminary Flood Hazard Estimates for Screening Models for Department of Energy Sites* by McCann and Boissonnade. This current endorsement has its roots in two archived documents: 1) DOE Standard 1022-94, *Natural Phenomena Hazards Characterization Criteria*; and 2) DOE Order 6430.1A, *General Design Criteria*. All of these documents recommended usage of Probabilistic Flood Hazard Analysis for sites which had flood as one of the predominant design basis events. Because this technique is used at our sites, we are interested in learning about its usage in other agencies which may have similar applications as those in DOE.

Panel 2: State-of-the-Practice in Identifying and Quantifying Extreme Flood Hazards

Co-Chairs: Timothy Cohn, USGS and
Will Thomas, Michael Baker, Jr., Inc.

Rapporteurs: Joseph Giacinto and Mark McBride, NRC (NRO);
Randy Fedors, NRC (NMSS)

Presenters: Will Thomas, Michael Baker, Jr., Inc.
Jery Stedinger, Cornell University
Jim O'Connor, USGS
Beth Faber, USACE
John England, BoR

Panelists: Jery Stedinger, Cornell University
John England, BoR
Douglas Clemetson, USACE
Jim O'Connor, USGS

Overview and History of Flood Frequency in the United States

Wilbert O. Thomas, Jr.[1]

[1] Michael Baker, Jr., Inc., Manassas, VA 20110

Characterizing the frequency of flood peak discharges is essential in designing critical infrastructure such as dams, levees, bridges, culverts, and nuclear power plants and in the definition of flood plains for land use planning. Estimates of flood frequency are needed for gaged and ungaged locations but this discussion is focused primarily on frequency analysis on gaged streams with observed flood data. Statistical flood frequency analysis provides the risk of structures being overtopped or flood plain areas being inundated.

Statistical flood frequency analysis in the United States started with a paper by Fuller (1914) who analyzed long records of daily flows and peak flows around the world, but particularly from the United States. Fuller (1914) developed equations for estimating floods of a given return period T as a function of drainage area and is typically credited with having the first published formula or equation involving flood frequency (Dawdy et al. 2012). In his 1914 paper, Fuller also discussed plotting positions for analyzing flood distributions and suggested plotting at the median which later became known as the Hazen plotting position. Fuller (1914) apparently used plotting positions for the at-site frequency analysis and then developed equations for estimating the T-year flood discharges for ungaged locations.

Hazen (1914), in his discussion of Fuller's paper, presented for the first time the concept of probability paper and argued for the use of the lognormal distribution as a model of peak flows (Dawdy et al., 2012). Hazen (1930) describes his plotting position method in detail in his 1930 book on "Flood flows" and provides examples of estimating flood discharges for New England streams. Hazen's approach involved plotting flood data on graph paper with the normal probability scale on the horizontal axis (percent chance exceedance) and the ratio to the mean annual flood on a logarithmic vertical axis (lognormal probability paper) and adjusting for the skew in the data. The Hazen plotting position estimates the exceedance probability as (2m-1)/2N where m is the order number starting with one as the largest and N is the total number of data points. This plotting position assigns a return period of 2N for the largest flood in N years of record.

The use of plotting positions was the prevalent approach for flood frequency analysis in the period 1930 to 1967. Beard (1943) developed the median plotting position (m-0.30/N+0.4 with m and N as defined above) and this plotting position is still being used by the U.S. Army Corps of Engineers (USACE) for graphical display of flood data. In the 1940s, the U.S. Geological Survey (USGS) adopted the Weibull plotting position (m/N+1) as described by Kimball (1946) for estimating T-year flood discharges (Dalrymple, 1960; Benson, 1962). The USGS approach was to plot flood data on Gumbel probability paper with either a logarithmic or arithmetic vertical scale for discharge and draw a smooth curve through the data. The graphical procedures required significant engineering judgment and there was variation among engineers and hydrologists in applying these methods.

Beard's 1952 and 1962 publications on "Statistical Methods in Hydrology" documented flood frequency procedures being used by USACE in this time period (Beard, 1952, 1962). By 1962 the USACE was using the log-Pearson Type III method that involved fitting the logarithms of the annual peak flows to the Pearson Type III distribution. Foster (1924) introduced the Pearson system of frequency distributions to the American engineering profession and applied these methods to the study of annual runoff for gaging stations in the Adirondack Section of New York. Foster (1924) used the untransformed data but Beard (1962) recommended the use of logarithms of the annual peak data.

In April 1966, the Subcommittee on Hydrology under the Inter-Agency Committee on Water Resources (IACWR) published Bulletin No. 13 on “Methods of Flow Frequency Analysis” (IACWR, 1966). Five methods of flow frequency analysis **currently in common use** were described: Hazen, Pearson Type III, Gumbel, gamma and graphical distribution-free methods. This appears to be the first interagency effort to describe methods for flood frequency analysis. Bulletin 13 summarized and described several methods of determining flood frequency but did not recommend any particular methods. No testing or comparison of the various methods was attempted.

In August 1966, the 89th Congress passed House Document No. 465 entitled “A Unified National Program for Managing Flood Losses”. This document recommended the establishment of a panel of the Water Resources Council (WRC) to “present a set of techniques for frequency analyses that are based on the best known hydrological and statistical procedures”. House Document No. 465 also recommended the creation of a national flood insurance program that was eventually created in 1968. In response to House Document No. 465, the Executive Director of WRC in September 1966 assigned the responsibility for developing a uniform technique to the WRC Hydrology Committee. The Hydrology Committee established a Work Group on Flow-Frequency Methods comprised of members of 12 Federal agencies and two statistical consultants. The work group applied the following six methods at 10 long-term stations (records greater than 40 years):

- 2-parameter gamma distribution,
- Gumbel distribution,
- log-Gumbel distribution,
- log-normal distribution,
- log-Pearson Type III distribution, and
- Hazen method.

The work group published Bulletin No. 15 in December 1967 “A Uniform Technique for Determining Flood Flow Frequencies” with the recommendation to fit the logarithms of the annual peak discharges to a Pearson Type III distribution using the method of moments (USWRC, 1967). The reasons for adopting this method were:

1. Some Federal agencies were already using the log-Pearson Type III distribution (e.g., USACE) and computer programs were available.
2. The log-normal is a special case of both the Hazen and log-Pearson Type III method with zero skew.
3. The log-Pearson Type III distribution utilizes skew as third parameter and it was felt this would provide more flexibility and applicability in estimating flood discharges nationwide.
4. The Hazen method was partially graphical and required more subjectivity in its application.

Manuel Benson, USGS, who chaired the Bulletin 15 work group published a journal article that provided additional details on the analyses performed by the work group (Benson, 1968).

It soon became evident that Bulletin 15 was not as uniform method as originally conceived. Some of the reasons were non-uniform treatment of outliers, skew and historical data. In January 1972, the Hydrology Committee of WRC initiated review of Bulletin 15 and the need for more uniform guidelines. The Work Group on Flood Flow Frequency of the Hydrology Committee was comprised of members of 12 Federal agencies. In March 1976, the Hydrology Committee of WRC published Bulletin 17 "Guidelines For Determining Flood Flow Frequency". Bulletin 17 recommended the continued use of the log-Pearson Type III distribution with the method of moments for parameter estimation (USWRC, 1976). This recommendation was based on a study by Beard (1974), who was at the University of Texas, conducted for the work group that applied eight combinations of distributions and estimation techniques to annual peak discharges at 300 long-term gaging stations (records greater than 30 years). To correct problems noted with Bulletin 15, Bulletin 17 recommended the use of a low outlier test for censoring low peaks, use of generalized (or regional) skew based on a study by Hardison (1974) and a mathematical procedure for adjusting for historical data based on a weighted-moments procedure suggested by Fred Bertle, Bureau of Reclamation.

Shortly after Bulletin 17 was published, it was noted that there was a discrepancy about the order of the historical adjustment and the determination of weighted skew. In June 1977, Bulletin 17A, "Guidelines For Determining Flood Flow Frequency", was published that clarified the historical adjustment was to be applied before the weighting of skew (USWRC, 1977). This clarification is the only significant difference between Bulletins 17 and 17A. A few editorial corrections were also made.

With time, problems with the Bulletin 17A methodology began to surface. These problems can be summarized as follows:

1. The low-outlier test did not adequately identify all the low outliers.
2. There was some confusion over the estimation and use of generalized skew.
3. There were inconsistencies in the use of the conditional probability adjustment for low outliers.

In September 1981, the Hydrology Committee of WRC published Bulletin 17B "Guidelines For Determining Flood Flow Frequency" (USWRC, 1981). The Work Group on Revision of Bulletin 17 of the Hydrology Committee was comprised of members of six Federal agencies: Soil Conservation Service, USACE, USGS, National Weather Service, Bureau of Reclamation, and the Tennessee Valley Authority. The following technical changes were in Bulletin 17B to correct problems noted in Bulletin 17A:

1. Revised guidelines for estimating and using generalized skew.
2. A new procedure for weighting generalized and station skew based on research by Tasker (1978) and Wallis et al. (1974).
3. A new test for detection high outliers and a revised test for detection low outliers based on research by Grubbs and Beck (1972).
4. Revised guidelines for the application of the conditional probability adjustment.

In March 1982 several editorial corrections were made in Bulletin 17B and the guidelines were republished by the Hydrology Subcommittee of the Interagency Advisory Committee on Water Data (IACWD). The new sponsorship of Bulletin 17B was necessitated by the dissolution of the Water Resources Council in the fall of 1982. The Hydrology Subcommittee membership of the six Federal agencies remained the same under the two different sponsors. Bulletin 17B, "Guidelines for Determining Flood Flow Frequency" that was published in March 1982 by the

Hydrology Subcommittee of IACWD is still the guidelines used by Federal agencies and most state and local agencies for flood frequency analyses for gaged streams (IACWD, 1982).

In January 2000, a Hydrologic Frequency Analysis Work Group (HFAWG) was formed to consider improvements in the current guidelines for hydrologic frequency analysis computations (e.g. Bulletin 17B) and to evaluate other procedures for frequency analysis of hydrologic phenomena. The HFAWG is a work group under the Hydrology Subcommittee of the Advisory Committee on Water Information (ACWI). The HFAWG, the Hydrology Subcommittee and the ACWI are all comprised of Federal and non-Federal organizations. This is a change from the past where Bulletins 15, 17, 17A and 17B were developed solely by Federal agencies.

The HFAWG has met several times since January 2000 and the minutes of those meetings are on the HFAWG web site http://acwi.gov/hydrology/Frequency/. In November 2005 the HFAWG developed a plan for updating Bulletin 17B (see web site for details). The **major** improvements in Bulletin 17B that are being evaluated include:

- Evaluate and compare the performance of a new statistical procedures the Expected Moments Algorithm (EMA) to the weighted-moments approach of Bulletin 17B for analyzing data sets with historical information,
- Evaluate and compare the performance of EMA to the conditional probability adjustment of Bulletin 17B for analyzing data sets with low outliers and zero flows,
- Described improved procedures for estimating generalized (regional) skew, and
- Describe improved procedures for defining confidence limits.

During 2012 considerable progress has been made in testing and evaluating the EMA procedure and in developing a new test for detecting influential low peaks. A March 2012 report titled "Updating Bulletin 17B for the 21st Century" that is posted on the HFAWG web site describes the results of testing EMA and current Bulletin 17B techniques. It is anticipated that a revised draft version of Bulletin 17B will be developed in 2013.

In summary, at-site flood frequency techniques have been evolving in the United States over the last 100 years. Since the publication of House Document No. 465 in August 1966, the emphasis has been on developing a uniform and consistent technique that can be used by all Federal agencies. Thomas (1985) and Griffis and Stedinger (2007) describe in more detail the evolution of Bulletin 17 to the current Bulletin 17B technique. Ongoing research and testing by the HFAWG should result in an improved version of Bulletin 17B in 2013.

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Quantitative Paleoflood Hydrology

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Paleoflood hydrology (Kochel and Baker, 1982) is the reconstruction of the magnitude and frequency of past floods using geological or botanical evidence. The following synopsis of paleoflood hydrology is derived from Benito and O'Connor (in press). Over the last 30 years, paleoflood hydrology has achieved recognition as a new branch of geomorphology and hydrology (Baker, 2008), employing principles of geology, hydrology, and fluid dynamics to infer quantitative and qualitative aspects of unobserved or unmeasured floods on the basis of physical evidence left behind. Flood evidence includes various geologic indicators (flood deposits and geomorphic features) and flotsam deposits, as well as physical effects on vegetation. Resulting inferences can include timing, magnitude, and frequency of individual floods at specific sites or for specific rivers, as well as conclusions regarding the magnitude and frequency of channel forming floods. The obvious benefit of paleoflood studies is obtaining information on floods from times or locations lacking direct measurements and observations. Findings from paleoflood studies support flood hazard assessments as well as understanding of the linkages between climate, land-use, flood frequency and channel morphology.

Paleoflood studies typically take one of two forms: (1) analyses focused on determining quantitative information for specific events, such as the timing, peak discharge, and maximum stage of an individual flood or floods; and (2) studies investigating more general spatial and temporal patterns of flooding, commonly to assess relations among climate, land-use, flood frequency and magnitude, and geomorphic response (such as channel morphology or floodplain sedimentation and erosion processes). Both types of investigations share approaches and techniques, but, in general, studies of specific paleofloods are most typically conducted in bedrock or otherwise confined river systems for which preservation of stratigraphic and geomorphic records of individual floods are more likely (Kochel and Baker, 1982), although many studies have obtained valuable paleoflood information for alluvial rivers (Knox, 1999; Knox and Daniels, 2002). Studies relating channel form or floodplain morphology to past flood characteristics more typically are conducted for alluvial river corridors, and follow from the classic studies of Schumm (1968) and Dury (1973). In general, quantitative information of specific events is likely to be most appropriate for assessing risk to nuclear facilities; consequently, the emphasis of this section is on studies that can provide specific information on the timing, magnitude, and frequency of individual floods.

Quantitative paleoflood hydrology relies on identification of evidence of flooding in conjunction with application of hydrodynamic principles to determine flow magnitude. These two aspects of investigation typically lead to four phases of analysis: (1) documentation and assessment of flood evidence; (2) determination of paleoflood ages; (3) estimation of flow magnitude, typically peak discharge, associated with flood evidence; and (4) incorporation of paleoflood data into the flood frequency analysis. The first component is geological and archival, requiring historical research, geomorphology, stratigraphy, sedimentology, and the second involves geochronology in order to identify and date physical evidence of flooding. The third component requires hydraulic analysis to assign a flow magnitude to paleoflood evidence. A common final step is to incorporate paleoflood discharge and chronology information into a flood frequency analysis to determine peak flows associated to probability quantiles. These paleoflood studies generally are more successful and have fewer uncertainties in fluvial systems with resistant boundaries, such as bedrock or semi-alluvial channels. These environments, because of stable depositional sites, tend to have longer and clearer stratigraphic records of floods—sometimes exceeding several thousand years—and have stable boundary conditions, leading to greater confidence in using present topography to determine past hydraulic conditions.

Most paleoflood studies have focused on semiarid and arid regions, although studies have successfully extended flood records in humid environments as well (e.g. Fanok and Wohl, 1997; Springer and Kite, 1997; Kidson and others, 2005). In general, paleoflood studies extend flood records 100s or 1000s of years and commonly provide compelling evidence of flood discharges exceeding those of the observation record (Enzel and others, 1993; O'Connor and others, 1994; Hosman and others, 2003; Harden and others, 2011). In certain areas, very large floods cluster on time scales of decades and centuries, interpreted as a response to climate variability (Ely and others, 1993; Knox 2000; Benito and others, 2003a).

Slackwater Flood Records

Paleoflood records are derived from physical evidence of flood stage. The best high water marks include mud, silt, seed lines and flotsam (e.g. fine organic debris, grass, woody debris) that closely mark peak flood stage. This type of evidence typically only persists for weeks, in humid climates, to several years, in semiarid and arid climates. But more lasting evidence can also be preserved, including fine-textured flood sediment (slack-water flood deposits), gravel and boulder bars, silt lines, and erosion features, as well as botanical evidence such as scars on riparian trees. Depending on the environment, such evidence can persist for millennia (Baker, 1987, 2008; Kochel and Baker, 1988; Webb and Jarrett, 2002).

The most complete paleoflood records generally result from analysis of stratigraphic sequences of fine-grained flood deposits found in slack-water and eddy environments. Slackwater flood deposits are fine-grained sedimentary deposits that accumulate from suspension during floods (Baker and others, 2002). Slackwater sedimentation areas include flooded valley margins subject to eddies, back-flooding, flow separation and water stagnation during high stages. Diminished flow velocities in these areas promote rapid deposition of the fine-grained fraction of the suspended load. The resulting slack-water flood deposits commonly contain sedimentary structures and textures reflecting flow energy, direction and velocities.

Slack-water depositional environments can be any location of diminished flow velocity or flow separation, typically (1) areas of channel widening, (2) severe channel bends, (3) obstacle hydraulic shadows where flow separation causes eddies, (4) alcoves and caves in bedrock walls, (5) back-flooded tributary mouths and valleys, or (6) high surfaces flanking the channel. In narrow bedrock reaches, slackwater flood deposits are commonly found in adjacent caves, alcoves or under rock overhangs.

Paleoflood Chronology

Developing a flood chronology is key to assessing flood frequency and commonly requires numerical age dating of sedimentary flood units and intervening deposits. Numerical dating underlies chronologies, typically by radiocarbon and optically simulated luminiscence (OSL). Radiocarbon dating is the most common absolute dating tool employed in paleohydrologic work, although OSL dating is becoming more common. Organic materials such as wood, charcoal, seeds leaf fragments are entrained by floods and commonly deposited in conjunction with clastic sediment in slackwater sequences. Additionally, flood deposits may cover vegetation or organic cultural materials, as well as in turn be covered by vegetation and organic detritus. All of these types of materials can be radiocarbon dated, thereby providing information on the age of enclosing or bounding flood deposits. Organic materials most likely to provide high fidelity constraints on flood ages are those not likely to have persisted for a long period of time before deposition, such as seeds, fine organic detritus, and twigs. Commonly, however, radiocarbon dating is performed on charcoal contained within flood deposits, which can persist for hundreds or thousands of years prior to incorporation within a flood deposit.

For most studies, it is assumed that radiocarbon ages from detrital material within flood deposits closely approximates the flood date, although the most conservative assumption is that the radiometric date provides a maximum limiting age for the enclosing deposit. This is particularly the case for radiocarbon dates from detrital charcoal. Dating of in-situ organic materials, such as charcoal from ground fires between affected surfaces bracketed by flood deposits, or pedogenic carbon between flood deposits, can provide robust constraints on the timing of flood sequences. As for most geologic investigations, dating of multiple organic materials and multiple deposits within a stratigraphical profile increases confidence in flood age determinations. The 5730 year half-life of 14C limits radiocarbon dating to deposits less than 40,000 years. Also, radiocarbon dating suffers from significant imprecision for the period 1650 to 1950 AD because of the significant fossil fuel burning and introduction of variable amounts of 14C into the atmosphere during the industrial revolution.

The OSL method (Aitken, 1998) is a dating technique which indicates the burial time of deposits, principally quartz and feldspar minerals. This approach allows determination of when sediment was last exposed to light ("bleached"). For the purposes of dating sequences of flood deposits, the general presumption is that the sediment was last exposed to light prior to deposition. Sampling and analysis involves several steps of collecting and analysis of sand-sized sediment from a target deposit without inadvertent exposure to light. Developments in OSL instrumentation are reducing the sample size to individual quartz and feldspar grains. Moreover, new analytical protocols have improved the application OSL dating for alluvial deposits, resulting in numerical dating with age uncertainties within 5-10%, even for g deposits less than 300 years old (Arnold and others, 2009). The technique can be hampered in situations in (1) which the proper species of quartz are not present in the deposits, and (2) for floods where the transported sediment was not bleached by exposure to light, either because of high turbidity levels or because the flood occurred at night. But under appropriate conditions, OSL dating can be an important tool, especially for deposits (1) containing little or no organic materials, (2) older than the range of radiocarbon dating (>40,000 years), or (3) younger than 300 years for which radiocarbon dating cannot yield precise results.

Radiocarbon and OSL dating can be supplemented with analysis of modern radionuclides such as Caesium-137 and Lead-210 (Ely and others, 1992). Both of these isotopes were introduced into the atmosphere during nuclear bomb testing in the 1950s and their presence in flood deposits signifies a post-1950 age. Likewise, human artifacts, such as beer cans (House and Baker, 2001), pottery (Benito and others, 2003a), and other archaeological materials can provide numeric age constraints on enclosing deposits.

Dendrochronology has supported several paleoflood studies because of the identifiable responses of tree growth to damage of the bark and wood-forming tissues, buds, and leaves, and to radial growth following partial up-rooting of the trunk (Yanosky and Jarrett, 2002; Jacoby and others, 2008) For situations when flood damage or effects can be related to tree-ring chronologies derived from the affected tree or from established regional chronologies, flood ages can commonly be determined to the specific year, and in some instances a specific season (Sigafoos, 1964; Ruíz-Villanueva and others, 2010).

Paleoflood Discharge Estimation

Hydraulic analysis is the basis for discharge estimates for most quantitative paleohydrologic studies. In most analyses, discharge estimates follow from the assumption that the elevation of paleostage evidence provides a minimum estimate of the maximum stage attained by an identified flood. In some situations, deposit elevations may closely approximate the maximum flood stage, although this assumption is difficult to verify (Jarrett and England, 2002) except for specific investigations of height differences between flood indicators and actual flood water depth for modern floods (Kochel 1980, Springer and Kite, 1997, Jarrett and England, 2002; House and others, 2002). Uncertainties in the fidelity of paleoflood stage evidence to actual maximum stages can be evaluated in conjunction with most discharge estimation procedures. A number of formulae and models are available to estimate flood discharge from known water surface elevations (O'Connor and Webb, 1988; Webb and Jarrett, 2002), ranging from simple hydraulic equations to more involved, multi-dimensional hydraulic modeling. Most paleoflood studies assume one-dimensional flow with calculations based on (1) uniform flow equations (e.g. Manning equation), (2) critical flow conditions, (3) gradually varied flow models, and (4) one dimensional St Venant equations. In complex reaches, multi-dimensional modeling may reduce uncertainties associated with reconstructing flood discharge (Denlinger and others, 2002; Wohl, 2002). As described by Webb and Jarrett (2002), the appropriate approach for a particular site depends on local hydraulic conditions.

Incorporating Paleoflood Information into Flood Frequency Analysis

Paleoflood information provides tangible information on the occurrence and magnitude of large and infrequent floods. Although paleoflood information may not be as precise gaged or observed records and are not continuous in the manner of many measurement programs, understanding of the timing and magnitude of the largest floods can substantially reduce uncertainties in flood quantile estimates when considered in a statistically appropriate manner. Several statistical methods have been applied to estimate distribution function parameters for paleoflood datasets. The most efficient methods to incorporating imprecise and categorical data are: (1) maximum likelihood estimators (Stedinger and Cohn, 1986), (2) the method of expected moments (Cohn and others, 1997; England and others, 2003a) and (3) Bayesian methods (O'Connell and others, 2002; O'Connell, 2005; Reis and Stedinger, 2005). Some examples of employing these techniques for flood frequency analysis using both gaged and paleoflood records include O'Connor and others (1994), Bureau of Reclamation (2002), England and others (2003b), Levish and others (2003), Hosman and others, (2003), Thorndycraft and others, (2005a), England and others (2010), and Harden and others, (2011). In nearly all cases, the addition of paleoflood information greatly improves estimates of low probability floods, most commonly indicated by markedly narrower confidence limits about flood quantile estimates.

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Hydrologic Hazard Methods for Dam Safety

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Historically, dam design and analysis methods have focused on selecting a level of protection based on spillway evaluation flood loadings. Traditionally, the protection level is based on the Probable Maximum Flood (PMF). Reclamation uses risk analysis to assess the safety of dams, recommend safety improvements, and prioritize expenditures (Reclamation, 2011). Risk analysis, from a hydrologic perspective, requires an evaluation of a full range of hydrologic loading conditions and possible dam failure mechanisms tied to consequences of a failure. This risk approach is in contrast to the traditional approach of using single upper bound, maximum events such as the PMF from a risk perspective have no probability of occurrence and resulting potential consequences are not clearly defined.

The flood loading input to a dam safety risk analysis within Reclamation is a hydrologic hazard curve that is developed from a Hydrologic Hazard Analysis (HHA). Hydrologic hazard curves (HHC) are peak flow and volume probability relationships. These hazard curves are presented as graphs and tables of peak flow and volume (for specified durations) versus Annual Exceedance Probability (AEP). The range of AEPs that is displayed on these graphs is intended to be sufficient to support the decision making needs of the organization.

The hydrologic load inputs to a risk analysis may consist of peak flows, hydrographs and reservoir levels and their annual exceedance probabilities. From a prioritization of resources perspective, it is difficult to accomplish dam safety goals from a true or false assessment of whether a structure is capable of withstanding a Probable Maximum Flood. Therefore, a single, deterministic flood estimate such as the PMF is no longer adequate to evaluate the hydrologic safety of a dam. As an alternative, Reclamation has approached prioritization and modification needs through estimates of flood magnitudes and volumes and their associated exceedance probabilities up to the PMF. This is a risk analysis approach.

Hydrologic hazard curves provide magnitudes and probabilities for the entire ranges of peak flow, flood volume (hydrograph), and reservoir elevations, and do not focus on a single event. The peak flow, flood volume, and maximum reservoir level frequency distributions for dams with potentially high loss of life might extend to very low probabilities. For dam safety risk assessments, flood estimates are needed for AEPs less than 1 in 10,000 (1×10^{-4}) to satisfy Reclamation's public protection guidelines (Reclamation, 2011).

Reclamation has developed and applied numerous methods to estimate hydrologic hazard curves - extreme flood magnitudes and probabilities for dam safety. These methods can be broadly classified into streamflow-based statistical approaches, and rainfall-based with runoff statistical approaches. Current hydrologic hazard curve methods used by Reclamation are summarized in Table 1, and are generally ranked according to the level of effort involved. Methods are described in Swain et al. (2006); improvements to these current methods and other tools and approaches are ongoing and may be added as project needs and experience dictates.

Recent comparisons in California and Colorado have shown relatively close agreement between stochastic rainfall-runoff models and paleoflood-based frequency curves in some detailed study cases. The methods used and some principles involved in estimating hydrologic hazards are presented.

Table 1. Current methods used by Reclamation to develop hydrologic hazard curves

Class	Method of Analysis and Modeling (*reference*)	Hydrologic Hazard Curve Product	Risk Analysis/Design Level[1]	Level of Effort[2]
Streamflow-based statistics	Peak-flow frequency analysis with historical/paleoflood data - Graphical method (*Swain et al., 2006*)	peak flow frequency, volume frequency; hydrographs	CFR, IE	Low
Streamflow-based statistics	Peak-flow frequency analysis with historical/paleoflood data - EMA (*Cohn et al., 1997*)	peak flow frequency	IE, CAS, FD	Low
Streamflow-based statistics	Peak-flow frequency analysis with historical/paleoflood data - FLDFRQ3 (*O'Connell et al., 2002*)	peak flow frequency	IE, CAS, FD	Low
Streamflow-based statistics	Hydrograph Scaling and Volumes (*England, 2003*)	hydrographs and volumes; based on peak flow frequency	CFR, IE, CAS, FD	Low
Rainfall-based statistics and Runoff Transfer	GRADEX Method (*Naghettini et al., 1996*)	volume frequency; hydrographs	IE, CAS, FD	Moderate
Rainfall-based statistics and Rainfall-Runoff	Australian Rainfall-Runoff Method (*Nathan and Weinmann, 2001*)	peak flow and hydrographs; based on rainfall frequency and PMP	IE, CAS, FD	Moderate
Rainfall-based statistics and Rainfall-Runoff	Stochastic Event-Based Precipitation Runoff Modeling with SEFM (*Schaefer and Barker, 2002*)	peak flow frequency; hydrographs; volume frequency; reservoir elevation frequency	CAS, FD	High
Rainfall-based statistics and Rainfall-Runoff	Stochastic Rainfall-Runoff Modeling with TREX (*England et al., 2006, 2007*)	peak flow frequency; hydrographs; reservoir elevation frequency	CAS, FD	High

[1]CFR: Comprehensive Facility Review; IE: Issue Evaluation; CAS: Corrective Action Study; FD: Final Design

[2]Low: less than 20 staff days; Moderate: 21-100 staff days; High: more than 100 staff days

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Panel 3: Extreme Precipitation Events

Co-Chairs: John England, BoR and Chandra Pathak, USACE

Presenters: John England, BoR
Daniel Wright, Princeton University
Mel Schaefer, MGS Engineering Consultants
Kelly Mahoney, NOAA-ESRL
Geoff Bonnin, NWS-OHD
Victoria Sankovich, BoR

Rapporteurs: Nebiyu Tiruneh and Brad Harvey, NRC (NRO)

Panelists: Daniel Wright, Princeton University
Mel Schaefer, MGS Engineering Consultants
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An Observation-Driven Approach to Rainfall and Flood Frequency Analysis Using High-Resolution Radar Rainfall Fields and Stochastic Storm Transposition

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Spatial and temporal variability in extreme rainfall, and its interactions with land cover and the drainage network, is an important driver of flood response. `Design storms,' which are commonly used for flood risk assessment, however, are assumed to be uniform in space and either uniform or highly idealized in time. The impacts of these and other commonly-made assumptions are rarely considered, and their impacts on flood risk estimates are poorly understood. We develop an alternate framework for rainfall frequency analysis that couples stochastic storm transposition (SST) with "storm catalogs" developed from a ten-year high-resolution (15-minute, 1-km^2) radar rainfall dataset for the region surrounding Charlotte, North Carolina, USA. The SST procedure involves spatial and temporal resampling from these storm catalogs to reconstruct the regional climatology of extreme rainfall. SST-based intensity-duration-frequency (IDF) estimates are driven by the spatial and temporal rainfall variability from weather radar observations, are tailored specifically to the chosen watershed, and do not require simplifying assumptions of storm structure. We are able to use the SST procedure to reproduce IDF estimates from conventional methods for small urban watersheds in Charlotte. We demonstrate that extreme rainfall can vary substantially in time and in space, with important flood risk implications that cannot be assessed using conventional techniques. SST coupled with high-resolution radar rainfall fields represents a useful alternative to conventional design storms for flood risk assessment, the full advantages of which can be realized when the concept is extended to flood frequency analysis using a distributed hydrologic model. A variety of challenges remain which complicate the application of SST to larger watersheds and more complex settings, but the technique nonetheless represents a robust, observation-based alternative for assessing flood risk.

Regional Precipitation-Frequency Analysis and Extremes Including PMP – Practical Considerations

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Precipitation-Frequency relationships are now being developed for watersheds for use in rainfall-runoff modeling of extreme floods extending to Annual Exceedance Probabilities (AEPs) of 10^{-5} and beyond. This capability is made possible by advancements in several technical areas including regional-frequency analysis, L-moment statistics, spatial analysis of storms such as Isopercental analysis and GIS-based spatial mapping using radar data and ground-based precipitation measurements. Methodologies have been developed to derive the precipitation-frequency relationship in a manner that accounts for uncertainties in the various contributing components and provides uncertainty bounds for the mean frequency curve. In the frequency context, Probable Maximum Precipitation (PMP) becomes just another value on the frequency curve, which can be exceeded given the large uncertainties in PMP estimation.
Experience has been gained in application of regional frequency analysis and development of precipitation-frequency relationships at over 20 watersheds in semi-arid to humid climates throughout the western US and British Columbia. This presentation will describe experience gained about the behavior of precipitation-frequency characteristics which will provide guidance and assist judgments in future applications for a range of climatic environments.

High-Resolution Numerical Modeling As A Tool To Assess Extreme Precipitation Events

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Weather and climate data is often downscaled to supply estimates, predictions, or projections to stakeholders and decision-makers at higher, more useful resolution than that provided by contemporary observations and reanalysis datasets. The details of downscaling (e.g., model resolution, domain selection, model physics) become of critical importance when addressing extreme weather phenomena at a local scale, as such events are often determined by and/or sensitive to small-scale processes. Particularly for flood events in complex terrain, it is necessary to resolve the details of both the terrain itself as well as driving fine-scale atmospheric processes to form a realistic picture of future flood risk. This discussion will briefly summarize work that uses high-resolution (1-km) simulations of warm-season intense precipitation events in key geographic regions in both the western US and the southeastern US. The overall objective of the work is to improve understanding of the factors and physical processes responsible for both historical (observed) extreme events, as well as future possible extreme events. In the western U.S., historical events such as the Fort Collins, CO flood of July 1997, are examined as well as select historical events deemed critical to a particular dam's planning purposes. In the Southeast U.S., work is underway to explore the use of high-resolution modeling of key cases (e.g., the Tennessee floods of May 2010 and the Atlanta-area floods of September 2009) for future use in both forecast improvement and better hydrologic-response predictions. High-resolution numerical modeling can be a useful tool to address questions related to storm maximization methods, probable maximum precipitation (PMP) limits, and elevation adjustment strategies -- concepts commonly used for water resources management nationwide. For example, is a storm of PMP magnitude physically able to develop in a specific region? In regions where paleoflood data do not suggest that floods of such magnitude have actually occurred historically, can a model be "forced" to produce such a storm following reasonable maximization of key fields? Do such changes reflect realistic possibilities of future climate change? Additional potential applications for decision-making in the realm of water resources management will be discussed.

Extreme Precipitation Frequency for Dam Safety and Nuclear Facilities – A Perspective

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Federally regulated dams and nuclear power plants are designed to withstand extreme storm rainfall events. Some Federal agencies design their structures to the Probable Maximum Precipitation (PMP; e.g., Prasad et al. 2011, USACE 1984). Probable maximum precipitation is defined, theoretically, as the greatest depth of precipitation for a given duration that is physically possible over a given storm area at a particular geographical location at a certain time of year (HMR; WMO 2009, Hansen et al. 1982). Each of the hydrometeorological reports [joint efforts by the Bureau of Reclamation, National Weather Service, and Army Corps of Engineers, among others] have served as the basis for design precipitation estimates in flood design studies of critical infrastructure for several decades. These estimates are based on storm data that are outdated by up to 40 years. In addition, designing every dam to meet PMP may be a cost-prohibitive and unnecessary approach depending on the associated hazards downstream.

In recent years, the Bureau of Reclamation has been utilizing an approach, which incorporates regional precipitation frequency analysis (L-moments; Hosking and Wallis 1997) and, at times, applies the PMP as an upper limit to the frequency curve (Nathan and Weinmann 2001). Nonetheless, there are many valuable concepts from PMP (i.e., storm analysis, storm maximization, depth-area-duration analysis, storm transposition), which lend information to the decision-making process. For example, observed isohyetal patterns from storms are overlaid on the drainage basin of Federal dams to examine rainfall-runoff relationships. Temporal patterns of observed rainfall are input into hydrologic models to accurately represent the time distribution of precipitation. Recent research by the Bureau of Reclamation into extreme precipitation events using storm maximization concepts suggests that events from the past two decades have the potential to meet or exceed current PMP estimates (Caldwell et al. 2011; e.g., Hurricane Floyd in 1999; Hurricane Fran in 1996).

Here, we outline the methodology applied at various scales of project requirements through the presentation of case studies and recent research efforts at Reclamation. Examples will include: application and extrapolation of existing precipitation frequency curves (e.g., England et al. 2012, Wright et al. 2012a,b); calculation of regional precipitation frequency relationships and uncertainty using L-moments (e.g., England et al. 2012, Novembre et al. 2012); development of spatial and temporal patterns as input to hydrologic models (Novembre et al. 2012); and, the utility of gridded meteorological datasets in hydrologic hazard assessments (Caldwell et al. 2011).

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Panel 4: Flood-Induced Dam and Levee Failures

Co-Chairs: Tony Wahl, USBR and Sam Lin, FERC

Presenters: David Bowles, RAC Engineers & Economists
Timo Schweckendiek, Deltares Unit Geo-engineering
Jason Hedien, MWH
Tony Wahl, BoR
David Margo, USACE

Rapporteurs: Jacob Philip, NRC (RES); Hosung Ahn, NRC (NRO); and Juan Uribe, NRC (NRR)

Panelists: Eric Gross, FERC, Chicago (Dam)
Timo Schweckendiek, Deltares Unit Geo-engineering (Levee)
Martin W McCann Jr., Stanford University (Dam/Levee)
David Margo, USACE (Dam/Levee)
Gregory Baecher, University of Maryland (Risk Analysis)
Jery Stedinger, Cornell University (Dam)
David Bowles, RAC Engineers & Economists (Dam/Levee)

Risk-Informed Approach to Flood-Induced Dam and Levee Failures

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There is a growing use of probabilistic risk assessment as a supplement to traditional engineering approaches in dam safety decision making in the US and overseas. This is referred to as a risk-informed approach in which decision making utilizes information obtained from a risk assessment along with other factors, including good engineering practice and societal concerns. Thus a risk assessment is not the sole basis for a decision, but rather it provides a systematic way of understanding dam failure risk, including the potential consequences and associated uncertainties. Dam safety risk assessments are used for informing decisions about the extent and type of risk reduction, and the urgency, priority and phasing of risk-reduction measures.

This presentation will commence with a brief overview the ownership and regulation of dams in the US. It will then provide an overview of the major steps involved in performing a risk assessment for an individual dam. Emphasis will be given to flood-related failure modes but reference will also be made to failure modes related to other external and internal hazards and human reliability. The requirements for probabilistic flood hazard information will be summarized including the effects of spillway gate reliability. Approaches to evaluating the adequacy of dam safety, the tolerability of estimates risks and using risk analysis outcomes to support dam safety decision making will be provided. An example will be provided for an existing dam and for selecting between risk-reduction alternatives. The paper will close with a summary of some types of information from probabilistic dam and levee flood analysis that might be of value for assessing external hazards for nuclear plants, and some limitations and research needs related to probabilistic risk analysis for flood-induced dam and levee failure.

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Dutch Approach to Levee Reliability and Flood Risk

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Risk-based approaches in flood defense reliability and flood risk management have a long history in the Netherlands, essentially starting right after a coastal flood disaster in 1953, which inundated large parts of the Dutch south-western delta and caused more than 1800 fatalities and 100.000 inhabitants lost their homes. In the same year, Van Dantzig (1953) came up with an economic optimization of dike crest levels comparing the investment cost in flood protection with the benefits in terms of risk reduction. The same basic concept is still the basis of flood protection standards nowadays.

More recently, roughly in the last two decades, safety assessment and design of flood defenses are moving steadily from semi-probabilistic approaches towards fully probabilistic reliability and risk analysis. Probably the best example for the state-of-practice in the Netherlands is the VNK2-project (also known as FLORIS, see Jongejan et al., 2013). In the VNK-2 project all Dutch polders (dike ring systems of so called “primary flood defenses”) are analyzed in terms of probability of failure of the defenses (i.e., levees and hydraulic structures), both on element and on system level, as well as in terms of flood risk. For the latter sets of inundation scenarios are simulated, the outcomes of which in terms of inundation depth and flow velocities serve as input for modeling the expected damage.

The goal of this presentation is to provide an overview of basic concepts and approaches used for analyzing levee reliability and flood risk in the Netherlands. Special attention will be paid to aspects that may be relevant to probabilistic risk assessment (PRA) of single facilities such as power plants. A major issue here can be the definition of critical flood and failure scenarios addressing the conditions which can pose serious hazards to such assets.

Please find below some references you may find useful and do not hesitate to contact me for further information.

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Risk-Informed Decision-Making (RIDM) Approach for Inflow Design Flood (IDF) Selection and Accomodation for Dams: A Practical Application Case Study

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Previous dam safety investigations at two hydroelectric facilities located on the same river in the Midwestern United States have identified insufficient spillway capacity to pass the computed probable maximum flood (PMF) without overtopping and failing the earth embankments at each project. This presentation provides a case study of how risk assessment (RA) and risk-informed decision making (RIDM) for hydrologic hazard analysis can be applied to select the inflow design flood (IDF) for a particular dam.

The two hydroelectric facilities considered each consist of a multiple-unit surface powerhouse integrated with the dam structures, earth embankment dams utilizing concrete core walls as the primary water barrier, concrete gravity and buttress structures, and spillways. The two facilities are separated by a distance of approximately 12 river miles and are run-of-river projects. Although located in a rural farmland region of the Midwest, both facilities are classified as high-hazard dams. Each dam impounds a lake that is heavily utilized for recreation during the summer months. The dams are regulated by the Federal Energy Regulatory Commission (FERC).

Per the FERC Engineering Guidelines for the Evaluation of Hydropower Projects, in the event a dam cannot safely pass the PMF, the dam should be capable of passing the IDF for the dam. In evaluating the options for resolution of the spillway capacity deficiency at the two dams, the owner and FERC agreed to investigate the use of RA and RIDM to assist in defining the IDF for the dams as an alternative to more traditional incremental hazard justification approaches for computing spillway design floods. A risk-based approach allowed for consideration of several factors specific to these two dams when determining the IDF. These factors include: both dams are run-of-river dams and do not have flood storage capacity in their reservoirs, which does not allow for attenuation of the flood hydrograph by storage; the population around the lakes impounded by the dams is significantly greater than the population living along the river below the dams, which means that there could be more significant consequences to rises in water levels upstream of the dams prior to dam failure than to rises in water levels downstream of the dams due to dam failure; the population of the area is significantly greater during the summer months than the winter months, which means that there is an impact of seasonal population differences on the potential for life-loss due to dam failure; and, the winter flood hydrographs are significantly greater in magnitude and rise more quickly than the summer flood hydrographs due to rain-on-snow causing snow melting along with the lack of vegetative ground cover but frozen, wet ground for relatively smaller surface roughness and less infiltration loss to both hydraulically and hydrologically attenuate runoff towards the river. The RA also allowed for the examination of the effect that failure or non-failure of individual project elements would have on consequences.

The first step in development of the RA for determining the IDF consisted of conducting Potential Failure Modes Analyses (PFMAs) in accordance with FERC guidelines. PFMAs consist of two workshops to identify and evaluate potential failure modes (PFMs) for a given dam, with participants from FERC, the owner, consultants, and specialists. For the dams under investigation, the PFMA workshop was followed by a RA workshop involving the same participants. The PFMA identified a number of credible PFMs that the RA workshop participants agreed should be carried forward into the RA process. These PFMs included: overtopping of the earth embankment at various short and high sections of both dams resulting in failure of the dam; overtopping of a low abutment area at one dam resulting in failure of the right abutment of the dam; and, overtopping of a concrete buttress section at one of the dams resulting in sliding failure of that structure. Each of the PFMs identified would be represented in the RA event tree established for each of the dams.

Event trees representing the sequence of events considered to have the potential to lead to breaching of each dam and uncontrolled release of the reservoir were developed for each dam. Development of the event trees for the dams therefore involved incorporating all PFMs and their interrelationships into appropriate positions, or levels, in the event trees. For all PFMs identified in the PFMA, the initiating event is a given flood inflow into each of the reservoirs impounded by the dams. Thus, the first level in the event tree consisted of the range of possible flood inflows to each reservoir up to and including the inflow associated with the PMF. Due to the significant difference in their magnitude and characteristics, warm and cold season floods were considered separately using the same event tree with the resulting failure probabilities being added to estimate the total failure probability.

Subsequent levels in the event trees included the sequence of events leading to potential breaching of the dam and uncontrolled release of the reservoir. These events, or levels, were divided into those that result in a potential rise in the reservoir impounded by each dam and those associated with the dam failure or breaching process. Events resulting in a potential rise in the reservoir impounded by each dam include the flood inflow itself, failure of spillway gates to open to pass the flood inflow downstream, and potential blockage of spillway gates by debris that hinders passage of flood flow downstream. Events associated in dam failure or breaching included overtopping and initiation of erosion of the embankments of each dam, toppling or failure of core wall segments due to erosion of the embankments, the initial width of the breach when a core wall segment fails, and sliding of the buttress section at one of the dams.

In the RA each level of the event tree developed for each dam was assigned a conditional probability of occurrence, or system response probability (SRP). The SRP for each event to include in the event trees was estimated during the RA workshop using information and reports available for each dam, historical performance of comparable dams, experience, and engineering judgment. The probability of failure, or the potential for overtopping and breaching of the dam leading to uncontrolled release of the reservoir, was computed by following all of the possible combinations of events and probabilities in the event tree for each dam incorporating all PFMs. The event trees were applied using the complete range of warm and cold season floods to obtain an estimate of the total annual failure probability (AFP) for each dam considering both types of floods as initiating events.

Consequences evaluated for dam breaches and uncontrolled release of the reservoir impounded by each dam included estimated life loss and representative property damage as a count of affected structures. Economic consequences associated with monetary estimates of property damage and other types of economic losses were not estimated. Estimates of life loss and property damage were computed based on the results of breach-inundation model runs using a set of dam breach and reservoir release events that cover the full range of warm and cold season flood magnitudes for each dam. The number of structures affected by the range of flood events resulting from breaching of the dams was estimated using a database of structures along the river developed from evaluating aerial surveys and photos. Life loss was estimated using the LIFESim methodology (Aboelata and Bowles 2005), a modular life loss modeling approach that considers the effectiveness of warning, evacuation and rescue, the submergence effects of the flooding and the degree of shelter offered by structures, and the potential for survival or life loss in various flood lethality – shelter environments.

For this RA the probability of dam failure and associated consequences were compared with tolerable risk guidelines used by the U.S. Bureau of Reclamation (Reclamation, 2003) and the Australian National Committee on Large Dams (ANCOLD, 2003) to assess the significance of risks for the baseline risk for the existing dams and various risk reduction alternatives considered. The ANCOLD and Reclamation guidelines provided a sampling of widely-used risk guidelines currently in use at the time and applied to dams and reservoirs.

The baseline risk for the dams in their existing conditions was evaluated first. This provided a baseline for evaluating the risks associated with the dams in their current state and the potential benefits/risks and strength of justification provided by structural or non-structural risk reduction measures considered for the dams. Event tree risk models were developed for the dams in their existing conditions and used to estimate the probabilities and consequences of each of the identified PFMs. The baseline RA results indicated that the dams in their existing condition did not meet either the Reclamation tolerable risk guideline for the AFP or the ANCOLD guideline for the annual life loss (ALL). Based on these results, the owner and FERC determined that risk reduction alternatives should be investigated.

Investigating the effectiveness of various structural and non-structural risk reduction measures to accommodate the selected IDFs was carried out as part of the risk reduction assessment (RRA) for the dams. The RRA focused on evaluating the effects of various risk reduction measures on the probability of dam failure and associated consequences, including both downstream and upstream consequences. The RRA process included the following steps: identifying potential risk reduction alternatives for consideration in the RRA at each dam; modification of the event trees in the RA model to incorporate risk reduction alternatives considered for the RRA; developing new peak reservoir pool elevation – annual exceedance probability (AEP) relationships for each risk reduction alternative; evaluating the effect of each risk reduction alternative on AFP, number of affected structures, and life-loss estimates relative to those resulting from the baseline risk and tolerable risk guidelines developed by the Reclamation and ANCOLD; and selecting the preferred risk reduction alternative for further design development with the goal of achieving the most reasonable combination of risk reduction cost effectiveness with respect to capital cost and on-going operation and maintenance costs.

The evaluation of a number of risk reduction alternatives identified for the two dams concluded that adding spillway capacity to each dam by modifying existing structures at each dam to pass additional flows downstream before overtopping failure would meet all tolerable risk guidelines used for the RA and would lower risk to “as low as reasonably possible” (ALARP). In subsequent reviews of the RA results and meetings between FERC and the owner, the additional spillway capacity to be added to each dam was increased somewhat so that the computed warm season PMF could be safely passed during the summer months, when the population that could be impacted by a failure of one of the dams is the greatest.

Implementation of these spillway capacity additions was accepted by FERC while satisfying above referenced tolerable risk guidelines evaluated in the RA. Design and construction of the spillway capacity additions at both dams are currently underway.

The process described in the preceding paragraphs and presented at this workshop provides a case study of how RA and RIDM can be applied to select and accommodate the IDF for a particular dam. In this case, application of RA and RIDM led to the identification of an IDF and spillway capacity improvements that not only are accepted by FERC for selection and accommodation of IDFs, but also reduce computed risks to meet tolerable risk guidelines in use today.

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Incorporating Breach Parameter Estimation and Physically-Based Dam Breach Modeling into Probabilistic Dam Failure Analysis

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Probabilities of dam failure can be modeled through the use of fragility curves that relate the chance of failure to the severity of the loading condition. Fragility curves have often been developed primarily on the basis of experience and judgment. Physically-based dam breach modeling tools now offer the potential to develop failure probability estimates in a more analytical way. Models presently available and under continuing development make it feasible to incorporate probabilistic flood load estimates, variability of embankment materials, and other factors to obtain probabilistic estimates of the likelihood of dam failure as well as breach parameters, erosion rates, and outflow hydrographs.

When a simplified approach is called for, regression equations are still widely used to predict breach parameters. Although most breach parameter estimation methods were developed for use in a deterministic framework, several recent studies have examined uncertainties in breach parameter prediction, and these can provide the basis for developing probabilistic estimates of breach parameters.

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USACE Risk Informed Decision Framework for Dam and Levee Safety

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USACE is moving from a solely standards based approach for its dam and levee safety programs to a portfolio risk management approach. The standards based or essential guidelines approach is included in the risk informed approach and decisions will now be risk informed. One of the bases for risk informed decisions, including the priority and urgency of risk management actions, is a consideration of risk tolerability. Risks may be considered tolerable when society is willing to live with the risk to secure certain benefits and the risks are being properly managed, reviewed, and reduced further when practicable.

Risk informed decisions are based on qualitative and quantitative evidence about inundation risks, which inundation scenario is generating the risk, and the efficiency and effectiveness of options to reduce and manage the inundation risk. The inundation risk arises from one or more of the following four scenarios: 1) breach prior to overtopping, 2) overtopping with a breach, 3) malfunction of system components due to a variety of causes including human error, or 4) overtopping without breach or non-breach risk. Each of these inundation scenarios represents a source of inundation risk to people, economic activity, vulnerable ecosystems, cultural resources, and other valuable resources and activities.

Explicit recognition of uncertainties is an essential part of any risk informed decision. A risk informed decision to reduce and manage inundation risk is one that considers all available information and the confidence in our knowledge and understanding of the risks and the risk drivers. Risk informed decisions are made in the USACE dam and levee portfolio process at a national level. Both quantitative and non-quantitative factors influence practical decision making for the USACE safety programs.

The following guiding principles, which represent a paradigm shift for USACE, have been established for the dam and levee safety programs.

- Life safety will be held paramount in the risk management decisions made within the USACE dam and levee safety programs.
- The principle of ‘do no harm’ will underpin all actions intended to reduce inundation risk. Applying this principle will ensure that proposed actions do not compromise the overall safety of the facility during or as a result of implementing a risk management measure.
- Decisions will be risk informed (not risk based). Risk informed decisions synthesize traditional engineering analyses with risk estimation through the application of experience based engineering judgment.
- The urgency and priority of actions will be commensurate with the level of inundation risk based on available knowledge.
- USACE will use a portfolio risk management process to assess and manage the inundation risks associated with the USACE portfolio of dams and levees. This process supports a national level prioritization to achieve effective and efficient use of available resources.

- The level of effort and scope of risk assessments will be scaled to provide an appropriate level of confidence considering the purpose of the risk management decision.
- Execution of inspections, instrumentation, monitoring, operations and maintenance, emergency action planning, and other routine activities are an essential part of an effective risk management strategy.

Panel 5: Tsunami Flooding

Co-Chairs: Eric Geist, USGS-Menlo Park, CA and Henry Jones, NRC

Presenters: Hong Kie Thio, URS Corp.
Randy LeVeque, University of Washington (UW)
Uri ten Brink, USGS
Pat Lynett, USC

Rapporteurs: Mark McBride, NRC (NRO) and
Randy Fedors, NRC (NMSS)

Panelists: Randy LeVeque, UW
Uri ten Brink, USGS
Pat Lynett, USC
Annie Kammerer, NRC
Frank González, UW
Yong Wei, NOAA/PMEL
Tom Parsons, USGS
Chuck Real, California Geological Survey

Probabilistic Tsunami Hazard Analysis

Hong Kie Thio

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The 2004 Sumatra tsunami disaster has accelerated the development of performance-based solutions to the analysis of tsunami hazard and thus the establishment of a probabilistic framework for tsunami hazard analysis. We have developed a method for Probabilistic Tsunami Hazard Analysis (PTHA) that closely follows, where possible, the methodology of Probabilistic Seismic Hazard Analysis (PSHA) using a hybrid approach. Because of the very strong variability of the seafloor depth, which causes very strong distortions of the wavefield and thus the wave amplitudes, it is not practical to develop analogs to the ground motion prediction equations (GMPE) used in PSHA. Instead, we can use numerical models to directly simulate tsunami wave propagation since the structure of the oceans, i.e. the bathymetry, is generally well-known. In contrast to the deep ocean propagation where the long tsunami waves behave in a linear fashion, the nearshore propagation, inundation and runup are highly non-linear and require a far greater computational effort. We have therefore split the PTHA analysis into two steps, which is somewhat similar to the seismic practice where we often compute probabilistic spectra for rock conditions using simple (quasi-) linear relations, and use these as input for non-linear analysis of the soil response.

In the first step, we use the linear behavior of offshore wave propagation to compute fully probabilistic offshore waveheights using a library of pre-computed tsunami Green's functions for elementary fault elements (usually 50x50 km) from all potential sources. This allows us to efficiently perform a integration over a wide range of locations and magnitudes, similar to PSHA, and incorporate both epistemic uncertainties, through the use of logic trees, and aleatory uncertainties using distribution functions. We have developed maps of probabilistic offshore waveheights for the western United States for a range of return period between 72 an 2500 years. These maps are very useful to compare the hazard between different regions, and also, through disaggregation, identify the dominant sources for that particular region and return period.
The disaggregation results are then used in the next step where we compute inundation scenarios using a small subset of events that are representative of the hazard expressed by the probabilistic waveheights. This process has enabled us to develop probabilistic tsunami inundation maps for the state of California.

Epistemic Uncertainties

An important aspect of the probabilistic approach, especially for longer return periods, is the proper characterization of the uncertainties. Because tsunamis can still be damaging at very large distances, as was demonstrated by the 2004 Sumatra and 2011 Tohoku earthquakes, it is important to include sources from the entire Pacific Basin for a hazard study of the US west coast. Our state of knowledge of these different source zones is however highly variable, and in most cases, the record of observations is rather short and incomplete. We therefore developed a “generic” source characterization based on global scaling relations, plate convergence rates and some assumptions regarding stress-drop and seismogenic thickness. This model can be used in its entirety for subduction zones for which we have little other information, but is also included, as a separate logic tree branch, in cases where we do have more specific information on the fault. Depending on the quality of the constraints we have for the specific source, such as Cascadia, the relative importance (weight) of the generic model is adjusted. As is the case in PSHA, our aim is to strike a balance between empirical models, which tend to be incomplete in terms of the length of record and may include ambiguous observations, and an imperfect understanding of the behavior and recurrence of large tsunamigenic earthquakes.

Aleatory Uncertainties

We include aleatory variability for the different elements of the hazard analysis, including the source characterization, bearing in mind that the large slip (~50 m) observed for the Tohoku earthquake corresponds approximately to the 2 sigma level for maximum slip in the global scaling relations. It is therefore important to be cautious with the truncation of the aleatory distributions. Whereas GMPE’s in seismic hazard analysis automatically include a standard deviation, the numerical approach does not, an we therefore have computed a modeling sigma by comparing modeled tsunami waveheights with observed ones. Finally, we also include tidal uncertainty by convolving the tsunami Green’s functions with the local tidal record and developing a distribution function of the maximum waveheights at every step.

Future work

We have established a framework for performing probabilistic tsunami hazard analysis, which is currently focused on earthquake sources but may also include other types of sources such as sub-marine landslides, for which the range of uncertainties is much larger. Even for the earthquake problem, there are many important issues outstanding, for instance with regard to the very large (M > 9) earthquakes. Accurate characterization of the upper end of the magnitude range of a source is often, perhaps somewhat counter-intuitively, not very important in seismic hazard since the ground motions tend to saturate for very large magnitudes. This is however a critical issue for tsunami hazard analysis, and it is very important to understand the limits for these large earthquakes. In many cases we may be able to assign a maximum rupture length, simply by considering the geometry of the subduction zone, but it is important to understand how the slip scales at these very large magnitudes, for which we have very little data. If we assume some maximum stress-drop arguments, it is possible to constrain the slip using the fault width, but its scaling for large magnitude is also poorly constrained. Likewise, it is important to determine how often these events occur, or whether segmented ruptures are the main mode of rupture. It is therefore essential to collect more empirical data, in particular from paleo-tsunami fieldwork, to extend the tsunami record and provide better constraints on or recurrence models.

Recent Advances in PTHA Methodology

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Probabilistic tsunami hazard assessment (PTHA) techniques have been developed by many researchers over the past decade, largely based on the older field of probabilistic seismic hazard assessment (PSHA). For surveys see Geist and Parsons (2006) and Geist et al. (2009).

Recently the PTHA methodology employed in a study of Seaside, OR (Gonzalez et al. 2009) has been updated in connection with a recent investigation of tsunami hazards in Crescent City, CA.

The original Seaside methodology uses the following steps:

(a) Determine a finite set of potential tsunamigenic earthquakes together with annual probabilities of occurrence.
(b) Simulate the tsunami resulting from each, and the resulting inundation in the target region of interest.
(c) Incorporate tidal uncertainty to adjust the probabilities of flooding a given point from each event.
(d) At each point on a fine-scale spatial grid covering the region, construct a "hazard curve" giving the annual probability of exceedance as a function of some range of exceedance values.
(e) Determine, for example, the 100-year flood depth by interpolating on this curve to find the depth that is exceeded with annual probability 0.01.
(f) Combine these values obtained from the hazard curves for all spatial points to produce a map of the 100-year flood, and contours of the depth that is exceeded with probability 0.01.

The updated methodology makes use of the open source GeoClaw software, which uses adaptive mesh refinement (AMR) to efficiently solve the tsunami propagation and inundation problem, allowing the use of large numbers of potential tsunamis and the possibility of sampling from probability density functions of potential earthquakes rather than using a small set of characteristic events. Past work in this direction has often used a small number of stochastic parameters to characterize the earthquake, such as depth and magnitude (see e.g. Geist and Parsons, 2006), which can be very effective for distant sources for which the runup and inundation are relatively insensitive to the details of the slip distribution. Recent work has focused on exploring the use of a Karhunen-Loeve expansion to represent possible slip distributions on an earthquake fault for the nearfield case. This is an expansion in terms of eigenfunctions of a presumed covariance matrix for the slip distribution over the fault geometry. Guidance on the choice of covariance matrix based on the dimensions of the fault plane and earthquake magnitude can be found in work such as that of Mai and Beroza (2002). The coefficients in this expansion specify a particular realization of this potential earthquake. If a probability density function in the high-dimensional space of coefficients can be determined that accurately describes potential earthquakes, then importance sampling and dimension reduction techniques can be used to derive hazard curves from this stochastic description of potential events. Unfortunately, there is a high degree of epistemic uncertainty that makes it difficult to adequately constrain these density functions for regions such as the Cascadia Subduction Zone, and more work is needed in this direction.

The GeoClaw code also allows the direct computation of inundation for different tide stages. This allows tidal uncertainty to be handled more accurately than in the Seaside study, where the approach of Mojfeld et al. (2007) was used. For each tsunami event studied, inundation is typically computed at three tide stages (MLW, MSL, and MHHW). At each spatial point on the regional grid, and for each exceedance level, these three simulations can be used to estimate the tidal stage that would be necessary for inundation that exceeds the given level. The tide record can then be used to compute probabilities that this tide stage or higher will occur when the tsunami arrives. For tsunamis that consist of multiple large waves, the wave pattern unique to the tsunami can be used to improve on these probabilities.

Interpretation of the resulting hazard curves and maps can be improved by considering methods of plotting the data. Traditional flood maps such as those showing contours of a 100-year flood can be supplemented by contour maps of probability for a given exceedance value. These can be important in understanding the sensitivity of results to probability level chosen, and will better reveal the possibility of much more extreme flooding events that may occur with slightly smaller probability.

Another extension is to study flow velocities, momentum, and momentum flux in addition to flow depth. Forces on structures and the destructive capacity of the flow increase with velocity, particularly when there is debris carried in the fluid. Hazard maps that only consider depth of flow may be inadequate for judging the probability of disaster.

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Geological Perspective on Submarine Landslide Tsunami Probability

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The temporal distribution of earthquakes, other than aftershocks and triggered events, is assumed to follow an exponential distribution that is associated with a stationary Poisson's process (e.g., Parsons, 2002; Coral, 2004; Kagan, 2010). The spatial distribution of earthquakes is heterogeneous, being concentrated in tectonic plate boundaries and other tectonically-active zones, notwithstanding the infrequent intra-plate earthquakes (e.g., Swafford and Stein, 2007).

Are submarine landslide distributions uniform in time and space? Our knowledge of submarine landslide distribution in space is limited by the difficulty of mapping the seafloor at high resolution. Nevertheless, our knowledge improves as more bathymetry and high-resolution seismic data are being collected. For example, the U.S. Atlantic continental margin from North Carolina north is almost completely covered bathymetric data allowing us to map all but the very smallest (< 1 km^2) landslide scars. Inferring the temporal distribution of submarine landslide distribution is more challenging because of our inability to detect slope failures in real time, the considerable work involved in robustly dating landslide features (e.g., Haflidason et al., 2005) and sometimes because of the lack of, or technical limitations of recovering, datable material. Moreover, landslides, being a destructive process often erase the record of previous slides.

It is therefore necessary to use indirect arguments to constrain landslide distributions. One such argument is the ergodic hypothesis in which the age distribution of landslides around the globe can yield the rate of landslide occurrence at a particular location. Caution should be taken in using this argument because of the potential differences between seismically-active and "passive" (i.e., non-active) margins, and between margins that were influenced by glaciers and major river systems and those that were not. Empirical arguments can be made to explain why submarine landslides around the world appear to be more common at the end of the last glacial maximum (LGM) and the beginning of the Holocene (~20,000-7,000 years) than at present. These include the amount of sediment reaching the slope, expected to be higher during low sea level when rivers and glaciers discharged at the shelf edge, the amount of sediment delivered to the coast by catastrophic draining of glacial lakes and by increase erosion due to wetter conditions at the LGM, and the hypothesized increase of seismicity due to unloading of the crust by the melting ice caps (Lee, 2009) and due to sediment and water loading of the margin (Brothers et al., submitted). Pore pressure increase in slope sediments may have accompanied the rapid accumulation of sediments on the continental slope and rise (Flemings et al., 2008 ESPL, Dugan and Flemings, 2000, Kvalstad et al., 2005).

Relative dating of landslides can be determined by the cross-cutting relationships between landslides scars and submarine canyons (Chaytor et al., 2012). In the Atlantic margin we observed scars that have been dissected by canyons while others have blocked canyon flows. Our recent work indicates that most submarine canyons along the Atlantic margin are relict and last active at the end of the last sea level lowstand but some may still be active to some degree today. A better understanding of the oceanographic and sedimentological conditions required to incise submarine canyons (e.g., Brothers et al., in revision) will help to date both canyon activity and the landslides they intersect.

Because the vast majority of landslides tsunamis are associated with earthquakes, and because tsunami height is scaled with landslide volume, earthquake probability may be used to estimate maximum landslide tsunami probability. Volume and area distributions of submarine landslides along the Atlantic margin follow lognormal-like or double-Pareto distribution (Chaytor et al., 2009, ten Brink et al., 2012). These lognormal-like distributions can be simulated (both under water and on land) using slope stability analysis and the expected peak spectral acceleration as a function of distance from the earthquake source (ten Brink et al., 2009). Therefore, the maximum area and volume of a landslide appears to be related to the magnitude of the triggering earthquake. This approach predicts that earthquake magnitudes < 4.5 and earthquakes located more than 100-150 km from the continental slope are generally incapable of generating landslides. This approach can be applied to passive margins with clastic (sand, clay) sediments. Some U.S. margins, such as around Puerto Rico and Florida north to South Carolina, are composed predominantly of carbonate material. These margins are characterized by steep slopes (≤45°), reflecting the strong cohesion of carbonate rocks. Landslide distribution along the carbonate rock margin of Puerto Rico was found to be exponential, not lognormal-like (ten Brink et al., 2006). This distribution can be explained, if carbonate rocks are weakened by fissures that have formed by dissolution. Fissure distribution is random. Therefore landslide size will be determined by the available block size during earthquakes shaking which is random, not by the earthquake magnitude. While many seismically-active margins are also covered by clastic sediments, landslides in these margins may often be much smaller than predicted by earthquake magnitude because the frequency of shaking outpaces the rate of sediment accumulation along the margin. However, to-date we are not aware of a regional landslide distribution study for a seismically active margin.

Earthquakes are the result of slow stress accumulation, of faults that are preferentially oriented within the stress field, and sometime of rheological and compositional condition within the fault zone. Analogous conditions exist for landslides. First, for a landslide to occur, uconsolidated sediment should be available to fail. It is therefore likely that landslide distribution is not uniform in space but is concentrated in regions with thick unconsolidated sediments. Along the Atlantic margin it appears that most landslides have occurred offshore New York and New England, where glacial processes supplied sediment to the margin, and offshore the Mid-Atlantic region where LGM delta fronts are located (Twichell et al., 2009). Because the location and size of landslides depends on sediment availability, one can argue that areas that have already failed will not fail again as long as additional sediments are not introduced to the margin. Such an argument could help identify high hazard vs. low hazard sections of the margin. Landslide history in Norway indicates that large landslides such as the Storegga landslide ~7500 years ago have also occurred at the end of the previous glacial maximum, but not in the intervening period or since ~7500 years ago (Halfidason et al., 2005). However, to date there is no systematic study that could confirm this potentially important prediction. A comparison of size distribution of landslides in passive and active margins, where seismic activity outpaces sediment supply, may provide some constraints.

Slope stability decreases with increasing slope gradient. Some margins are steeper than others owing to pre-existing physiography over which the sediments were deposited. For example, the New England-Georges Banks continental slope is steeper than slopes farther south along the margin because Mesozoic reefs forming “a wall” at shallow depths beneath the slope (Brothers et al., 2013). This must have contributed to the prevalence of landslides in that sector of the margin (Twichell et al., 2009). Stability also decreases with increasing pore pressure. Therefore, landslides can occur at slopes as low as 0.1°-0.5° (off the mouth of the Mississippi Delta, Prior and Coleman, 1978). Large landslide scars are also observed on the open slope of the U.S. Atlantic continental rise where the sea floor has gradients of 1°-2° (Twichell et al., 2009). However, to date there has not been a systematic mapping of pore pressure with sediments in the margin to determine the spatial dimensions of high pore pressure regions. It is unclear whether these dimensions are larger than a kilometer (Sultan et al., 2010). It is possible that canyon incision of the continental slope may lower the regional pore pressure there. Gas venting has been recently detected along canyon walls (http://www.noaanews.noaa.gov/stories2012/20121219_gas_seeps.html), but it is presently unclear how widespread this venting is.

Phrampus and Hornbach (2012) have proposed that changes in the Gulf Stream in the past 5,000 years had caused wide spread gas hydrate destabilization, which perhaps caused the Cape Fear slide. Based on clustering of many head scarps along the Atlantic margin at the expected upper water depth of gas hydrate stability zone, Booth et al. (1993) proposed that gas hydrate dissociation promotes slope failure. However, the age of the Cape Fear slide had been estimated to be between 27,000-10,000 ago (Rodriguez and Paull, 2000) and our newer high-resolution bathymetry maps show no clustering of the head walls at 800 m depth (Twichell et al., 2009; ten Brink et al., 2012). The depth range of the majority of the mapped head scarps is 1000-1900 m. Thus, gas hydrate dissociation cannot be linked directly to the generation of landslides, although it may contribute to increased pore pressure in some locations.

The rise of salt diapirs is expected to increase the slope gradient in certain locations and may even cause slope instability. Rising salt diapirs in the area of Cape Fear and Cape Lookout could have destabilized the slope there, but causal connection has so far not been established. Some landslides in the Gulf of Mexico, such as the large East Break and DeSoto slides are located in areas of salt diapirs. Earthquakes might not have been the cause of these landslides because the seismicity rate is very low and historical earthquakes magnitudes are small (< M6).

An additional challenge to estimating landslide tsunami probability results from the uncertainty in the coupling of energy between the sliding mass and the water column. Tsunamis from two landslides with identical volumes could have different amplitudes depending on the slide speed and bottom friction. Moreover, the suggestion that, in passive margins with clastic sediments, landslide area is related to earthquake magnitude implies that a landslide is in fact an aggregate of many small slope failures within an area that was subject to a super-critical horizontal acceleration. The failure area of the 1929 Grand Banks landslide, which caused a devastating tsunami, exhibits patches of failures interspersed with seafloor patches where no failure was detected (Mosher and Piper, Submarine Mass Movements, 2007). Both the observation of the 1929 slide scar and the suggested linkage between landslide size and earthquake magnitude calls into question the mechanism by which a tsunami is excited from an aggregate failure: Is the tsunami the result of constructive interference of many small failures? Or is it generated when convergence of debris flows converge in existing canyon and valley corridors and become several hundreds of meters thick? Or is it generated when a debris flow ignites into turbidity flow as it undergoes a hydraulic jump? More research is needed into this fundamental question

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Statistical Testing of Hypotheses and Assumptions Inherent to Probabilistic Tsunami Hazard Analysis (PTHA)

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Probabilistic Tsunami Hazard Analysis (PTHA) methods have recently been derived from the well-established Probabilistic Seismic Hazard Analysis (PSHA) method that calculates the probability of ground shaking from earthquakes, as originally developed by Cornell (1968). Both PSHA and PTHA involve three basic steps: (1) source characterization, including definition of source parameter distributions and recurrence rates; (2) calculation of wave propagation and attenuation effects from source to site; and (3) aggregation of hazard probabilities at the site from all sources considered in the analysis (e.g., Geist and Parsons, 2006; Geist et al., 2009). The primary differences between PTHA and PSHA are that distant sources must be considered in PTHA, owing to the slow attenuation of tsunami waves in the ocean and that numerical propagation models can be used in PTHA, in place of empirical attenuation relationships used in PSHA. The standard forms of PTHA involve assumptions, such as sources occurring as a Poisson process, that are often untested in practice. Although different hypotheses representing epistemic uncertainty can be incorporated into PTHA via a logic-tree framework, there are a number of statistical tools available with which we can possibly exclude or confirm certain hypotheses, thus reducing epistemic uncertainty. We focus here on statistical tests of recurrence distributions, size distributions, dependence among parameters, and the ergodic hypothesis. Where standard assumptions may be found to be invalid, new approaches to PTHA need to be developed.

It is often assumed that the recurrence distribution of sources follows an exponential distribution associated with a stationary Poisson process. For earthquakes, the inclusion of aftershocks and triggered events results in temporal clustering at a greater degree than represented by an exponential distribution (e.g., Parsons, 2002; Corral, 2004; Kagan, 2010). For very large earthquakes ($M \geq 8.3$), non-Poissonian behavior has not been observed, given the amount and uncertainty in available earthquake data (Parsons and Geist, 2012). Temporal clustering of tsunamis themselves has been demonstrated and tested against a Poisson null hypothesis (Geist and Parsons, 2011), though aftershocks *sensu stricto* account for only a part of the over abundance of short inter-event times. Non-Poissonian recurrence distributions can approximately be incorporated into standard PTHA methodology, using an apparent Poisson rate parameter (Petersen et al., 2007). For landslide sources, there is very little data to test the Poisson hypothesis, although if the number of landslide events can be determined from marine geophysical data and a basal horizon can be dated, Bayesian techniques can be used to determine the most likely rate parameter and its uncertainty (Geist and Parsons, 2010; Geist and ten Brink, 2012). Optimally, geologic age-dates of landslides from drill hole samples or cores can be used to more accurately obtain recurrence rates and assess various probability models using, for example, Akaike's information criterion (Geist et al., in review). Unfortunately, there are very few locations where such data are available. Another issue with landslide tsunamis is the long-term dependence of submarine landslide activity with glacial cycle and sea-level rise (Lee, 2009). Nonstationary source rates have yet to be incorporated into PTHA.

There has been considerable discussion regarding distribution of tsunami source sizes, particularly for earthquakes. Competing hypotheses include the characteristic earthquake model, in which the largest earthquakes are defined by fault segmentation and the historical record, and the Gutenberg-Richter earthquake model, in which earthquake sizes follow a Pareto distribution (cf. Parsons and Geist, 2009). Although the characteristic earthquake model is commonly used in both PSHA and PTHA, there are a number of studies refuting this model (e.g., Kagan and Jackson, 1995; Rong et al., 2003; Parsons et al., 2012), particularly for subduction zone earthquakes that generate the majority of the world's tsunamis. Submarine landslides also tend to follow a Pareto distribution like their on-land counterparts (ten Brink et al., 2006), although in certain environments, it has been shown that a log-normal distribution is a more appropriate model (ten Brink et al., 2009). The Pareto distribution for source sizes can, in general, be considered the null hypothesis; other distributions can be tested against the Pareto distribution using techniques, for example, reviewed by Clauset et al. (2009).

Independence is often assumed in PTHA and PSHA among source parameters and their uncertainty. It is often difficult to develop methods to accommodate dependent parameters in probabilistic analysis. An example in PTHA is combining nearshore tsunami waveforms with tidal variations: a source of aleatory uncertainty, since tsunami sources cannot be predicted in time. The method of Mofjeld et al. (2007) used in the FEMA Seaside PTHA Pilot Study (Tsunami Pilot Study Working Group, 2006) uses the linear combination of the tsunami amplitude envelope with site-specific distribution of tidal heights. However, landslide tsunami waves can be significantly non-linear, such that differences in antecedent sea level cannot simply be added or subtracted to tsunami wave heights computed at a given vertical datum. Copula methods, common in many hydrology applications, can be applied to examine this and other dependent structures in PTHA. Page and Carson (2006) present an application of copula methods in determining earthquake probabilities given uncertainties in the data and models.

Finally, it can be very useful to assume that spatial variations in source characteristics are equivalent to temporal variations at a point under the ergodic hypothesis (Geist et al., 2009). For example, in the absence of drill-hole data that samples submarine landslides throughout geologic time, one can date submarine landslides expressed at the sea floor over a specified region, yielding an occurrence rate for the entire region. However, this assumes a similar geologic framework (e.g., clastic vs. carbontate) and morphology (e.g., canyon vs. slope) throughout the region. Statistical methods to test whether or not the ergodic hypothesis holds under specific conditions (cf. Anderson and Brune, 1999) need to be developed in the context of PTHA.

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Tsunami Flooding Assessment Using Forecast Tools

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NOAA's Pacific Marine Environmental Laboratory is developing tsunami modeling tools as part of the real-time tsunami forecast system for NOAA's Tsunami Warning Centers. The models are used in combination with the real-time deep-ocean measurements to produce estimates of tsunami parameters for coastal locations before the wave reaches the coast (Titov, 2005 and 2009; Tang et al., 2009 and 2012; Wei et al., 2008 and 2012). This real-time tsunami hazard assessment will help to provide an informative and site-specific warning for coastal communities. Combined with education and mitigation measures, the tsunami forecast and warning will provide an effective means for coastal communities to prevent loss of lives from tsunamis. It will also reduce the chances for unnecessary evacuations due to over-warning.

The modeling tools that have been developed for the real-time forecast could also be used for the long-term tsunami hazard assessment, in terms of deterministic (Tang et al., 2009; Uslu et al., 2010) or probabilistic (González et al. 2009) approach. The forecast models for ocean-wide tsunami propagation and coastal inundation are thoroughly developed and tested to provide the best possible accuracy. These models provide an opportunity for unprecedented quality scope of tsunami hazard assessment for a particular community along U.S. Pacific and Atlantic coastline. Together with PMEL's model database of tsunami propagation, these models are able to relate the PTHA offshore wave height to onshore flooding zones for tsunami hazards associated with certain design return period. PMEL is collaborating with URS and ASCE to explore methodologies to develop 2,500-year tsunami flooding zones based on max tsunami amplitude at 30-m depth obtained through PTHA and their disaggregated tsunami sources.

Several examples of tsunami hazard assessments using the forecast tools will be presented.

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Probabilistic Tsunami Hazard Mapping in California Feasibility and Applications

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As part of California's Tsunami Hazard Mitigation and Preparedness Program, the California Geological Survey (CGS) is investigating the feasibility of designating official tsunami hazard zones under authority of the Seismic Hazards Mapping Act (California Public Resources Code Sec 2731 et seq.) and the generation of other products that would facilitate tsunami hazard mitigation and risk reduction throughout coastal communities. Several pilot projects are underway which are briefly described.

Probabilistic Seismic Hazard Analysis (PSHA) is the foundation for estimating earthquake-resistant design loads for engineered structures in California and has been considered in land-use decisions at state and local levels for more than a decade. Probabilistic Flood Hazard Analysis (PFHA) forms the basis for the National Flood Insurance Program's 100- and 500-year flood maps and California's 200-year flood hazard maps (California Government Code Sec 65300.2 et seq.). A probabilistic approach provides a more quantitative analysis for risk-based decision-making when considering likelihood of loss and actions that can be taken to reduce it. With a sound theoretical basis (Geist and Parsons, 2006) and recent advances in probabilistic tsunami inundation modeling (Thio, 2010; González et al., 2009), it is timely to consider application of Probabilistic Tsunami Hazard Analysis (PTHA) to risk-reduction. For example, the American Society of Civil Engineer's Subcommittee on Tsunami Loads and Effects is currently considering 100-year and 2500-year events in the development of recommended tsunami resilient design provisions for the 2018 International Building Code (ASCE, 2012). However, recent worldwide events have brought to question the reliability of PSHA, particularly considering the long, variable, and uncertain recurrence times of large earthquakes relative to exposure times. High accelerations are often occurring in areas shown as low on hazard maps, even for locations having a long seismic history (Peresan, A. and Panza, G.F., 2012; Stein et al., 2011). Considering difficulties in estimating tsunami frequency brings to question the viability of PTHA, and highlights the need to thoroughly assess the modeling framework and reliability of input data before derivative products can have application to public policy.

With support from the National Tsunami Hazard Mitigation Program (NTHMP), CGS and the California Emergency Management Agency are partnered with URS Corporation, the Pacific Earthquake Engineering Research Center, and the California Department of Transportation (Caltrans) to develop probabilistic tsunami hazard maps for the entire California coastline. Initial PTHA results are currently used by Caltrans (a project sponsor for URS work) to evaluate the vulnerability of coastal transportation facilities, while also serving as a means to explore proto-type products for local land-use planning applications. Work completed thus far has focused on the development of a practical PTHA procedure that can be applied to a large region and refinement of nonlinear wave propagation methods for estimating on-shore wave heights, current velocities, and inundation levels from distant sources (Thio and Sommerville, 2010). This work is currently expanding to include the Cascadia Subduction zone and smaller local sources offshore southern and central California. The NTHMP Mapping and Modeling Subcommittee has recommended California's program be considered a "national pilot" for PTHA mapping, and is actively pursuing including this work in the FY2013-2017 NTHMP Strategic Plan. To better understand limitations and uncertainties in PTHA, results from the State project for Crescent City, California are being compared with those of an independent, FEMA sponsored analysis of Crescent City by Baker/AECOM and the University of Washington. That project is evaluating the feasibility of incorporating tsunami into coastal flood hazard mapping for the National Flood Insurance Program based on improvements to the methodology used in a comprehensive PTHA of Seaside, Oregon (González et al., 2009). A committee of experts has been assembled that will evaluate results from the two teams considering the differences in source, propagation, and inundation components and probabilistic framework of each model.

A parallel pilot project is exploring issues related to implementation of PTHA and derivative hazard mitigation products. Application of conceptual and prototype products and associated policies are being discussed with planning and public works departments in Crescent City, a small community with a weak economy, and Huntington Beach, a large affluent community. Results are expected to help identify viable mitigation products and policy adjustments that may be necessary for tsunami hazard mitigation to work given the socio-economic diversity among California's coastal communities.

A third project supported under the FEMA's RISKMAP program is developing high-resolution proto-type products for the maritime sector based on high-resolution hydrodynamic modeling of tsunami induced surge in five California harbors: San Diego Port and Harbor, Ports of Los Angeles and Long Beach, Ventura Harbor, Santa Cruz Harbor, and Crescent City Harbor. The goal is to model wave heights and current flow in order to identify zones of high current velocity that can be used to develop navigation guides for evacuation and for strengthening port infrastructure to reduce tsunami impact. It is anticipated that products will be derived from both deterministic and probabilistic hazard analyses.

In addition to the expert PTHA evaluation panel, California has established a Tsunami Policy Working Group, operating under the California Natural Resources Agency, Department of Conservation, which is composed of experts in earthquakes, tsunamis, flooding, structural and coastal engineering and natural hazard policy from government, industry, and non-profit natural hazard risk-reduction organizations. The working group serves a dual purpose, being an advisor to the State tsunami program and a consumer of insights from the SAFRR Tsunami Scenario project. The latter is a USGS study to evaluate the impact of a magnitude 9.1 mega-thrust earthquake occurring along the Aleutian Islands Subduction Zone that presents the greatest distant tsunami threat to southern and central California. The working groups' role is to identify, evaluate and make recommendations to resolve issues that are preventing full and effective tsunami hazard mitigation and risk reduction throughout California's coastal communities. Committee membership is selected to represent entities responsible for coastal development, insurance, local and regional planning, public works, foreign and domestic disaster preparedness, recovery and seismic policy. Among those selected are representatives of the two cities chosen for the State's tsunami pilot project. Their participation in working group deliberations provides opportunity to bring forth local implementation issues in a forum conducive to multidisciplinary resolution, and an opportunity to incorporate a local perspective while formulating recommendations.

Finally, CGS is participating as an Associate member in the ASCE Subcommittee on Tsunami Loads and Effects where insights from the aforementioned projects are being brought to bear on the development of proto-type products supporting the ASCE 7–2015 recommended provisions for the International Building Code. The State participated in a similar role years ago when

PSHA was introduced into seismic provisions of the building code. Products under consideration are a 2,500-year tsunami inundation zone that would trigger the code process for high-risk category buildings, and production of a database of offshore wave heights and principal tsunami sources along the coast from de-aggregated PTHA that can provide the necessary input for site-specific deterministic inundation analyses used to estimate design loads for proposed construction projects. The work currently underway to evaluate and verify PTHA models is complementary to product and application development, and will facilitate California's adoption of tsunami code provisions when they become available.

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Panel 6: Riverine Flooding

Co-chairs: Will Thomas, Michael Baker, Jr., Inc. and
Rajiv Prasad, Pacific Northwest National Laboratory

Presenters: Rajiv Prasad, PNNL
Douglas Clemetson, USACE
Mel Schaefer, MGS Engineering
Nicole Novembre, BoR
Ralph Klinger, BoR

Rapporteurs: Peter Chaput, NRC (NRO) and Jeff Mitman, NRC (NRR)

Panelists: Douglas Clemetson, USACE
Nicole Novembre, BoR
Ralph Klinger, BoR
Jery Stedinger, Cornell University
Mel Schaefer, MGS Engineering

Flood Frequency of a Regulated River – The Missouri River

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Following the devastating floods that occurred in 1993 along the lower Missouri River and Upper Mississippi River, the Upper Mississippi River Flow Frequency Study (UMRFFS) was initiated. As part of this study, the discharge frequency relationships were updated for the Missouri River downstream from Gavins Point Dam. Establishing the discharge frequency relationships first involved extensive effort in developing unregulated flows and regulated flows for a long term period of record at each of the main stem gaging stations. Once the unregulated and regulated hydrographs were developed, the annual peak discharges were selected for use in the discharge frequency analysis.

In order to provide a homogenous data set from which frequency analysis could be performed, effects of reservoir regulation and stream depletions had to be removed from the historic flow record. This produced a data set referred to as the "unregulated flow" data set for the period 1898-1997. A homogeneous "regulated flow" data set was also developed by extrapolating reservoir holdouts and stream depletions to present levels over the period of record 1898-1997. Flow frequency analyses were performed on the unregulated flow annual peaks using procedures found in Bulletin 17B in order to develop the unregulated flow frequency curves for the spring and summer seasons at each gage location. The spring and summer unregulated flow frequency curves were combined using the "probability of a union" equation by adding the probabilities of the spring flow frequency curve and summer flow frequency curve and subtracting the joint probability of flooding occurring from seasons to obtain the annual unregulated frequency relationships. Next, the period of record regulated flows were developed using existing reservoir regulation criteria and present level basin depletions.

The annual peaks from the regulated and unregulated data sets were then paired against each other in descending order to establish a relationship between regulated and unregulated flow at each gage location. The regulated versus unregulated relationships were extrapolated based on developing design floods by routing historic flows that were increased by as much as 100 percent. This relationship was then applied to the unregulated flow frequency curve to establish the regulated flow frequency curve. Following the record flooding in 2011, the unregulated flow and regulated flow data sets were updated to include the additional period of record 1998-2011 and comparisons were made to the past studies. It was found that the methodology utilized in the 2003 study was robust and no changes to the flow frequency relationships were required after the record flooding in 2011.

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Extreme Floods and Rainfall-Runoff Modeling with the Stochastic Event Flood Model (SEFM)

M.G. Schaefer

MGS Engineering Consultants, Inc.

Stochastic rainfall-runoff modeling provides a methodology for development of magnitude - frequency relationships for flood peak discharge, flood runoff volume, maximum reservoir level, spillway discharge, and overtopping depths for the dam crest and spillways. The basic concept is to use Monte Carlo methods to conduct multi-thousand flood simulations utilizing hydrometeorological inputs and watershed model parameters obtained from the historical record within the climatic region. Storm magnitude is driven by a precipitation-frequency relationship for the watershed and spatial and temporal storm characteristics are simulated using storm templates developed from historical storms on the watershed or transposed from sites within the climatic region. Hydrometeorological inputs such as: storm seasonality; antecedent soil moisture; snowpack depth and density; time-series of 1000-mb air temperature and freezing level; and initial reservoir level are treated as variables rather than fixed values in the flood simulations.

The Stochastic Event Flood Model (SEFM) utilizes these concepts to develop flood-frequency relationships for flood characteristics such as flood peak discharge and maximum reservoir level for use in risk analyses for dams and other facilities. Uncertainties can also be incorporated into the flood simulations to allow development of uncertainty bounds. Development of SEFM began in 1998 and has continued over the past 15-years. During that time, SEFM has been used at over 20 dam and reservoir projects in the western US and British Columbia primarily to assess the likelihood of hydrologic loadings from extreme floods. This presentation will provide a basic description of the operation of SEFM and results from selected case studies.

Use of Stochastic Event Flood Model and Paleoflood Information to Develop Probabilistic Flood Hazard Assessment for Altus Dam, Oklahoma

Nicole J. Novembre, Victoria L. Sankovich, Jason Caldwell, and Jeffrey P. Niehaus

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A Hydrologic Hazard Analysis (HHA) was completed at the request of the Bureau of Reclamation Dam Safety Office (Novembre et al., 2012), as one part of a Corrective Action Study for Altus Dam near Altus, OK. This study is designed to provide flood loading and reservoir elevation information that is needed in support of a risk assessment to reduce the probability of failure under static and hydrologic loading at the dikes.

The main objectives of this study were:

1. Collect at-site, detailed paleoflood data with stratigraphy, radiocarbon ages, and hydraulic modeling within the basin, to supersede the preliminary estimates used in a 2001 study.
2. Develop a precipitation frequency relationship for the drainage area. Develop storm temporal and spatial patterns for use in a hydrologic model.
3. Develop a peak flood frequency curve using Expected Moments Algorithm (EMA).
4. Develop flood frequency relationships and inflow hydrographs with a stochastic event flood model (SEFM) (Schaefer and Barker, 2002; MGS Engineering, 2009).
5. Route the thousands of hydrographs generated with SEFM through Altus Dam with appropriate initial reservoir water surface elevations and provide reservoir water surface elevation frequency curves and quantiles for use in risk analysis.

Paleoflood data were collected on the North Fork Red River near Altus Dam (Godaire and Bauer, 2012). Two study reaches, one located upstream of Lake Altus and one located downstream of Altus Dam, were used to develop paleoflood data. A non-exceedance bound was estimated with a discharge range of 120,000 ft^3/s to 141,000 ft^3/s, that has not been exceeded in the last 610 to 980 years. Three or more paleoflood events with a discharge of 26,000 ft^3/s to 36,000 ft^3/s, that occurred between 790 and 1240 years ago, were estimated.

A peak flood frequency curve was developed from streamflow gage data and the paleoflood data using the Expected Moments Algorithm (EMA). EMA (Cohn et al., 1997; England et al., 2003) is a moments-based parameter estimation procedure that assumes the LP-III distribution is the true distribution for floods, and properly utilizes historical and paleoflood data. The EMA results are presented in Table 3.1 and Figure 3.3.

A Stochastic Event Flood Model (SEFM) was developed for the Altus Dam watershed. Magnitude- frequency rainfall estimates, as well as rainfall storm temporal and spatial patterns, were developed as input to the model. The model was calibrated to observed events and used to develop estimates of hydrographs for the 2% to 0.001% annual exceedance probability events. These hydrographs were routed through Altus Dam to develop reservoir water surface elevation frequency curves to be used as part of the risk analysis for Altus Dam.

The recommended hydrologic hazard curves for risk analysis are the SEFM curves using the lower and median precipitation frequency curves (Table 1 and Figure 1). The risk analysis should assume that each of these flood frequency relationships and their associated hydrographs could occur with equal probability of occurrence. The corresponding reservoir elevations (Table 2) were developed using reservoir operating rules provided by Reclamation's Waterways and Concrete Dams Group, therefore, the routing results can be utilized without modification to evaluate the potential overtopping failure mode of Altus Dam and dikes. These two curves represent equal estimates of the hydrologic hazard for baseline and risk reduction alternatives. Extrapolation of these results should be limited to an AEP of 0.001%. The full uncertainty of the hydrologic hazard is broader than that depicted in these two curves. Uncertainty analysis should consider variations in model parameters, data reliability, and climate variability. Further consultation with a flood hydrologist is needed in the selection of inflow flood loads for corrective action.

Table 1: Recommended peak discharge and 15-day volume values.

Annual Exceedance Probability	Return Period (years)	Lower Precipitation Frequency		Median Precipitation Frequency	
		Peak Discharge (ft^3/s)	15-Day Runoff Volume (ac-ft)	Peak Discharge (ft^3/s)	15-Day Runoff Volume (ac-ft)
1.0%	100	40,000	150,000	48,000	181,000
0.1%	1000	85,000	329,000	108,000	419,000
0.01%	10,000	169,000	665,000	223,000	882,000
0.001%	100,000	292,000	1,098,000	390,000	1,487,000

Table 2: Recommended reservoir water surface elevation.

Annual Exceedance Probability	Return Period (years)	Lower Precipitation Frequency		Median Precipitation Frequency	
		Routing Case 1	Routing Case 2	Routing Case 1	Routing Case 2
1.0%	100	1560.7	1558.8	1561.3	1559.4
0.1%	1000	1565.2	1564.5	1567.9	1567.5
0.01%	10,000	1571.2	1571.1	1572.1	1572.1
0.001%	100,000	1572.7	1572.7	1573.4	1573.4

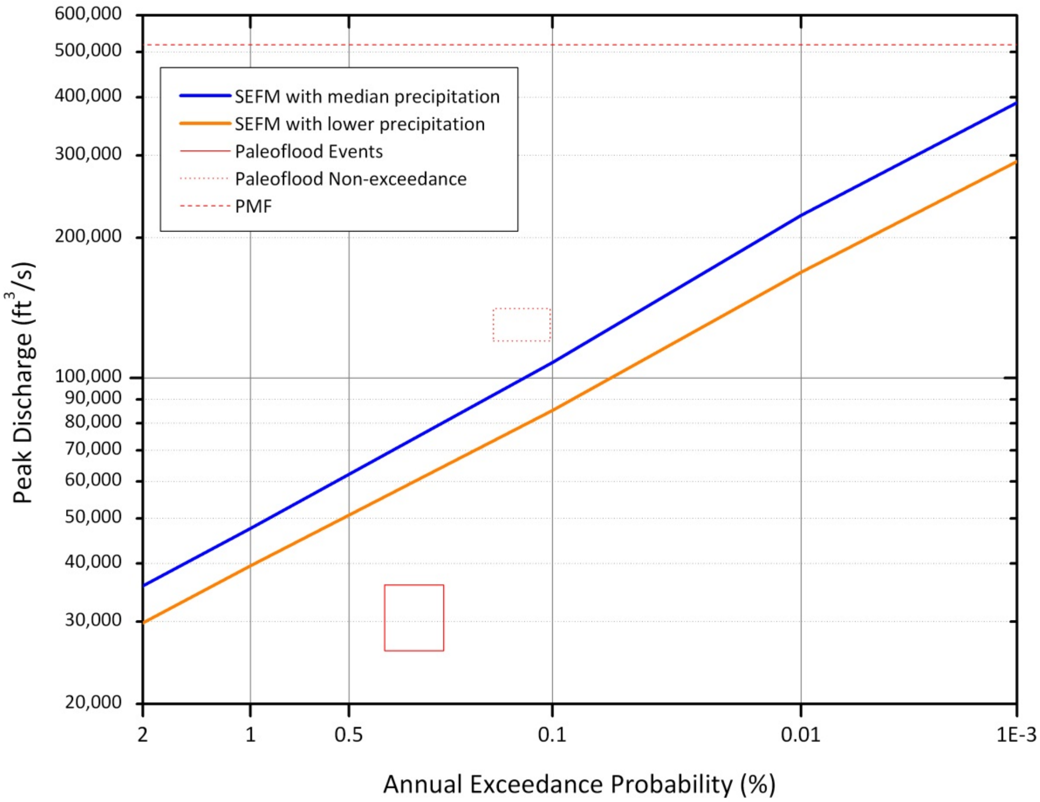

Figure 1: Recommended peak discharge frequency curves.

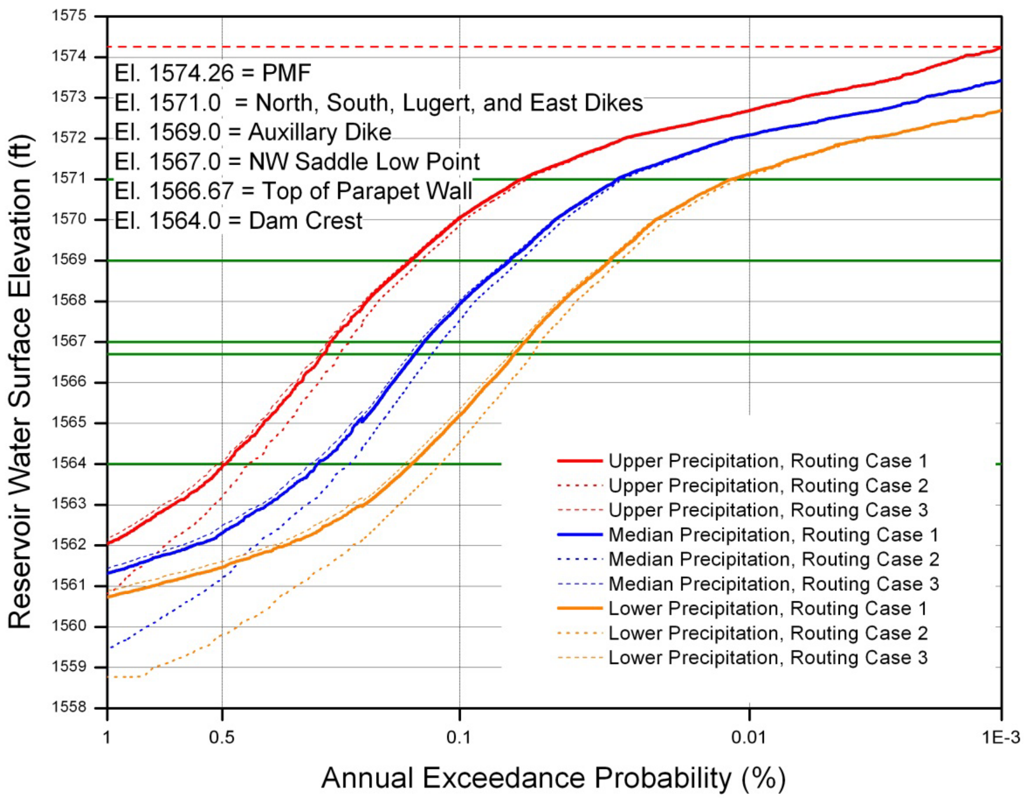

Figure 2: SEFM reservoir water surface elevation frequency curves.

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Paleoflood Studies and their Application to Reclamation Dam Safety

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The Bureau of Reclamation manages more than 350 water storage dams in the western U.S. that primarily provide water for irrigation. Periodically, each structure is subjected to a Comprehensive Review (CR) and the safety of each dam is evaluated on the basis of its current condition, past performance, and its projected response to loads that are reasonably expected to test the structural integrity of the structure and its various components. The findings of the CR are used to assess the potential failure risks and potential for loss of life and property. This risk profile allows the Reclamation Dam Safety Office to better manage its available resources to reduce risk and meet established public safety guidelines.

Hydrologic hazards are one of the hazards used in the CR and in the past Reclamation used traditional deterministic criteria (i.e., the Probable Maximum Flood) for evaluating dam safety. Unfortunately, more than half of the dams in the Reclamation inventory failed to meet these criteria and the costs associated with modifying the dams to meet this standard were considered prohibitive. By utilizing probabilistic flood hazard analyses (PFHA), the Dam Safety Office could better categorize its inventory on the basis risk and prioritize corrective actions. However, using the historical record of flooding alone in a PFHA proved inadequate for accurately estimating the magnitude of less frequent floods. Because paleoflood data can add information on large magnitude floods outside the historical period of record, as well as place outliers in the record into temporal context, paleoflood studies have long been recognized as an avenue for advancement in evaluating flood hazard.

Beginning in 1993, the Bureau of Reclamation began incorporating paleoflood data into hydrologic hazard estimates. Paleoflood studies were structured to collect the information to meet immediate needs for screening-level risk assessments. Larger, more detailed studies were developed to reduce uncertainty and provide the Dam Safety Office with the information needed to make critical decisions regarding public safety. As the result of almost 20 years of developing paleoflood information at more than 150 Reclamation projects - in addition to advances made by others in the fields of geochronology, hydraulic modeling, and statistical hydrology - the incorporation of paleoflood information has vastly improved Reclamation’s ability to accurately estimate flood hazard for its inventory of dams.

Panel 7: Extreme Storm Surge for Coastal Areas

Co-Chairs: Donald Resio, Univ. of North Florida and
Ty Wamsley, USACE

Presenters: Joost Beckers, Deltares
Stephen Gill, NOAA
Tucker Mahoney, FEMA
Ty Wamsley, USACE
Jen Irish, Virginia Polytechnic Institute (VPI)
Donald Resio, University of North Florida

Rapporteurs: Mark Fuhrmann, NRC (RES) and
Ferrando Ferrante, NRC (NRR)

Panelists: Joost Beckers, Deltares
Stephen Gill, NOAA
Tucker Mahoney, FEMA
Jennifer Irish, VPI

Coastal Flood Hazard in the Netherlands

Joost Beckers[1], Kathryn Roscoe[1], and Ferdinand Diermanse[1]

[1]Deltares, Delft, The Netherlands

The Netherlands has a long history of fighting floods. About 60% of the country is flood prone and must be protected by levees or dikes. Up to the first half of the 20th century, design dike heights were roughly 1 m above the highest measured water level. In 1953, a catastrophic storm surge flooded the southern part of the Netherlands. More than 1800 people drowned. In response to this tragedy, a national committee was installed who proposed to shorten the coastline by building storm surge barriers (the Delta Works) and to further decrease the flood hazard by implementing stringent standards for flood protection (Delta Committee 1958).

Nowadays, the Dutch flood defences along the major water systems (rivers, lakes, sea) comprise of a system of dikes (about 3300 km), dunes (about 300 km), storm surge barriers (5) and hundreds of hydraulic structures like sluices. These flood defences surround about 100 areas called dike rings. Each dike ring has been assigned a safety standard, expressed in terms of a maximum failure probability or return period. This can be translated into a maximum hydraulic load that a structure must be able to withstand.

The hydraulic load on a structure can be a combination of a water level, wave conditions or other conditions, depending on the failure mechanism under consideration. The maximum hydraulic load for a given return period is determined by a probabilistic computation that takes into account many possible combinations of external forcings that all lead to hydraulic loads on the flood defence. The probabilistic methods are based on statistical analyses of hydrologic and meteorological measurements and on numerical hydrodynamic and wave growth models.

The safety assessment procedure will be illustrated by considering the wave overtopping hazard for a coastal levee. The probabilistic model that is used evaluates the overtopping discharge and probability of occurrence for hundreds of combinations of storm surge and wind induced waves. The model uses water level and wind speed statistics that are based on observations and that have been extrapolated to exceedance probabilities of 10^{-5} per year. A non-parametric method is used to account for the dependency between wind and water level (De Haan and Resnick, 1977). The SWAN wave growth model (Booij *et al.*, 1999) is used to translate the offshore wind and water level to nearshore wave conditions.

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Recent Work and Future Directions in Coastal Surge Modeling within NOAA

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NOAA's mission with respect to coastal storm surges focuses on the protection of life and property and on improving the resiliency of coastal communities. The former effort focuses on forecasting and warning coastal populations and emergency managers of imminent hazardous conditions, while the later addresses the long term risks coastal communities face. In order to perform these missions, NOAA relies upon models and observations to assess the hazard, and uses a variety of products to communicate the data to the public.

In order to forecast coastal inundation, NOAA uses multiple models, both operational and experimental. The operational model SLOSH (Sea, Lakes, and Overland Surges from Hurricanes) is storm surge model that is designed for fast, efficient prediction of surges in order to meet critical operational timelines. SLOSH uses several techniques in order to provide extremely fast computations, including simplification of nonlinear terms in the governing equations, a basic hurricane forcing model, omission of tide and wave effects, small model domains, and low resolutions. These efficiencies enable SLOSH to run very quickly and its possible to run numerous hurricane tracks in a short time. This capability is used in the generation of the Maximum Envelopes of Water (MEOW) used for hurricane evacuation studies, which requires more than 10,000 simulations. It is also used to generate storm surge probabilities in the P-Surge tool, which runs hundreds of hurricane tracks in real time. P-Surge varies the hurricane prediction by taking historical forecast error into consideration, and is able to determine the probability of surge reaching a specific height for each forecast cycle.

NOAA has also recently transitioned the ADCIRC coastal hydrodynamic model to operations for predicting storm surges from extratropical storms. High resolution ADCIRC predictions have also been evaluated experimentally for their use in real-time tropical cyclone storm surge predictions. ADCIRC tends to be higher resolution and has higher physical fidelity than SLOSH (e.g., includes tides, rivers, waves). These ADCIRC simulations are more precise than their SLOSH counterparts, but because of the cost to run them only a few iterations are possible in real-time. This small ensemble of approximately five members can give a sense of the uncertainty surrounding a prediction, but isn't sufficient to determine storm surge probabilities.

However, when considering issues of coastal resiliency it is important to validate and compare model predictions to observed data records, particularly in light of a changing climate. NOS has a long history of observing and analyzing water level conditions. This data has been used to perform extreme water level analyses that provide an assessment of the probability of extreme conditions occurring. The water level data has also been subject to an analysis of the long-term trend due to factors including global sea level rise and vertical land motion. NOS has recently upgraded online services to provide updated sea level trends for NOAA long-term tide stations and has produced an extreme water levels tool from which exceedance probability levels can be obtained. Recently, NOAA produced an assessment of the expected effects of climate change and sea level conditions.

FEMA's Coastal Flood Hazard Analyses in the Atlantic Ocean and Gulf of Mexico

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One of the missions of the Federal Emergency Management Agency (FEMA) is to identify and map the nation's 1%-annual-chance flood hazard risk, in support of the National Flood Insurance Program (NFIP). Presently, FEMA is undertaking a substantial effort to update the Flood Insurance Studies (FIS) and Flood Insurance Rate Maps for the populated coastal areas in the United States. These areas are among the most densely populated and economically important areas in the nation.

Coastal flooding on the Atlantic Ocean and Gulf of Mexico coasts is a product of combined offshore, nearshore, and shoreline processes. The interrelationships of these processes are complex and their relative effects can vary significantly by location. These complexities present challenges in mapping a local or regional hazard from coastal flooding sources. Congress' mandate to FEMA to assess and map the 1%-annual-chance flood hazard based on present conditions simplifies some of these complexities. As part of the study process, FEMA also identifies the 0.2%-annual-chance flood hazard for coastal areas. In some cases, higher frequency risks, such as the 2%, 10%, 25% and 50%, will be examined and made available to communities for informational purposes.

The most severe storms, which dominate the coastal 1%-annual-chance flood risk, on the Atlantic Ocean and Gulf of Mexico coast can generally be classified as either tropical systems or northeasters. Because long term records of water level are spare compared to the risk, FEMA's Guidelines and Specifications require that a probabilistic assessment of storm surge and coastal flooding be undertaken where applicable (FEMA, 2007). Ongoing coastal flood risk studies utilize the Joint Probability Method-Optimal Sampling (JPM-OS) to statistically model the spatial and temporal occurrence and characteristics of tropical systems, typically hurricanes (Resio, 2007; Toro et al. 2010). For the mid- to north-Atlantic coastline, northeasters also contribute to the 1%-annual chance coastal flood risk. The contribution of these storms to the flood hazard risk is evaluated using the Empirical Simulation Technique (Scheffner, et al. 1999).

For each individual storm to be evaluated (be it historical or synthetic), the still water elevation, including wave setup, is determined using a two-dimensional hydrodynamic model and a two-dimensional wave model. Recent FEMA coastal flood hazard studies utilize the coupled SWAN+ADCIRC model to couple together the still water level and wave modeling (Dietrich et al. 2012). The model mesh typically extends well inland from the coast in order to capture the full extent of the storm surge which propagates overland during an extreme event. The smallest cell spacing is typically between 50-100 feet and depending on location, the mesh may extend to the 30 or 50 feet NAVD88 contour. Results of these simulations are used to statistically determine the still water elevation, including wave setup, for a given recurrence interval (i.e. 1%-annual-chance).

After determination of the statistical still-water-elevation, the next step is to simulate the propagation of waves overland using the one-dimensional model Wave Hazard Analysis for

Flood Insurance Studies (WHAFIS), which was developed by the National Academy of Sciences for this purpose (NAS, 1977). Input for WHAFIS is drawn from the nearshore wave model. From the WHAFIS results, FEMA then maps then delineates and maps flood hazard zones on a the Flood Insurance Rate Map.

Although a coastal FIS uses state-of-the-art techniques, improvements are still possible and will likely occur in coming years. For example, more research is needed into two-dimensional overland wave modeling to truly characterize wave conditions and interactions at a specific location. It would be beneficial if variable future conditions, from factors such as shoreline change, sea level rise, or changes in climate, and their impact on the flood hazard could be accounted for. Lastly, a full uncertainty and error analysis is needed.

Other federal agencies and scientific bodies may benefit from some of the tools produced by FEMA for an updated coastal FIS. For each study, a detailed seamless topographic and bathymetric digital elevation model will be created for most locations in the coastal United States using the best and most recently available data. A highly detailed, fully attributed numerical model mesh will be created for most locations on the Atlantic Ocean and Gulf of Mexico coasts and may also be utilized for other flood hazard studies. A mesh can be easily modified to add detail to an area of interest or expanded further upland to simulate larger storm surges than those encountered during a FEMA coastal flood hazard study. Lastly, the JPM framework and variety of input storm conditions may provide useful information to future assessments of coastal flood risk with lower probabilities of occurrence.

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Modeling System for Applications to Very-Low Probability Events and Flood Response

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Modeling coastal surge in complex regions requires an accurate definition of the physical system and inclusion of all significant flow processes. Processes that affect storm surge inundation include atmospheric pressure, winds, air-sea momentum transfer, waves, river flows, tides, friction, and morphologic change. Numerical models now exist that can properly define the physical system and include an appropriate non-linear coupling of the relevant processes. A coupled system of wind, wave, circulation, and morphology models has been developed and implemented for regions in the Gulf of Mexico, Atlantic, and Great Lakes. The US Army Corps of Engineers (USACE) Engineer and Research Development Center's (ERDC) Coastal Storm Modeling System (CSTORM-MS) (Massey et al. 2011) includes a tropical planetary boundary layer model, TC96 MORPHOS-PBL (Thompson and Cardone, 1996), to generate the cyclone wind and pressure fields. It is also possible to use a variety of other wind products including both measured and hindcast winds. The storm surge and current fields are modeled with the ocean hydrodynamic model ADCIRC (Luettich et al. 1992) which computes the pressure- and wind-driven surge component. The regional and nearshore ocean wave models, WAM (Komen et al 1994) and STWAVE (Smith et al 2001) generate the wave fields. The AdH model (Berger and Howington 2002) is applied to simulate the nearshore zone where morphology change is computed and utilizes the CHL 2-Dimensional nearSHORE (C2SHORE) sediment transport and morphology change code through a call to its SEDiment transport LIBrary (SEDLIB).

A physics-based modeling capability must necessarily link the simulation of winds, water levels, waves, currents, sediment transport, and coastal response (erosion, accretion, breaching) during extreme events in an integrated system. A flexible and expandable computational coupler (CSTORM coupler) utilizes design principles from the Earth System Modeling Framework (ESMF) and links the atmosphere, circulation, waves, and morphology models for application on desktop computers or high-performance computing resources. The computational coupler employs a two-way coupling scheme that not only enhances the represented physics, but also results in significant improvements in computational time when compared to file-based approaches. A series of integrated graphical user interfaces within the Surface-water Modeling System (SMS) allows for convenient setup and execution of these coupled models.

The ESMF is a set of open source software tools for both building and linking complex weather, climate and related models. It has support from many agencies within the Department of Defense, the National Oceanic and Atmospheric Administration (NOAA), and the National Aeronautics and Space Administration (NASA). In order for models to use ESMF, they need to be ESMF compliant which means their computer code is organized into three distinct phases: initialization, run and finalization. Models that meet this standard allow for an almost "plug-n-play" capability when being used within an ESMF enabled coupler such as the CSTORM coupler. Therefore, the system is well suited for expansion to include effects from urban flooding or flood propagation at the facility scale.

Flood response operations and hazard mitigation during an event requires knowledge not only of the ultimate high water elevation, but also the timing of the flood wave. A reasonable estimation of the flood hydrograph requires the application of a high resolution model. The modeling system described allows for flexible spatial discretizations which enables the computational grid to be created with larger elements in open-ocean regions where less resolution is needed, and smaller elements can be applied in the nearshore and estuary areas where finer resolution is required to resolve hydrodynamic details and more accurately simulate the timing of storm surge propagation. However, application of high fidelity modeling such as that described above can be time prohibitive in operational mode. The USACE has developed a proof-of-concept operational flood prediction system that utilizes pre-computed high fidelity simulations stored in a database applying surrogate modeling strategies. This approach provides multi-process predictions in seconds for flood hazard assessment and mitigation.

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Coastal Inundation Risk Assessment

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In the last decade, the US has experienced some of its largest surges and hurricane-related damages on record. Understanding the risk posed by extreme storm surge events is important both for effective evacuation and for future coastal engineering planning, management, and design. For the first, effective evacuation in advance of a hurricane strike requires accurate estimation of the hurricane surge hazard that effectively conveys risk not only to government decision makers but also to the general public. Two primary challenges exist with the current structure for surge warning. First, existing computational methods for developing accurate, quantitative surge forecasts, namely surge height and inundation stimation, are limited by time and computational resources. Second, due primarily to the popularity and wide use of the Saffir-Simpson wind scale to convey the complete hurricane hazard, the public's perception of surge hazard is inaccurate. For the second, reliable extreme-value hurricane flooding estimates are essential for effective risk assessment, management, and engineering in the coastal environment. However, both a limited historical record and the range of, and uncertainty in, future climate and sea-level conditions present challenges for assessing future hurricane flooding probability. Historical water level observations indicate that sea level is rising in most hurricane prone regions, while historical observations of hurricane meteorology indicate decadal variation hurricane patterns, to include landfall location and rate of occurrence. Recent studies, including those by the Intergovernmental Panel on Climate Change (IPCC), also suggest that in the future sea-level rise may accelerate and major tropical cyclones may intensify. Methods will be presented for robustly and efficiently quantifying both forecast and extreme-value surge statistics, where the later will incorporate sea-level rise and time-varying hurricane conditions. A joint probability approach will be used with surge response functions to define continuous probability density functions for hurricane flood elevation. Joint probability is assigned based on the probability of the hurricane meteorological parameters, such as rate of hurricane landfall, central pressure, and storm radius. From a theoretical standpoint, surge response functions are scaling laws derived from high-resolution numerical simulations, here with the hydrodynamic model ADCIRC. Surge response functions allow rapid algebraic surge calculation based on these meteorological parameters while guaranteeing accuracy and detail by incorporating high-resolution computational results into their formulation. Thus the use of surge response functions yields continuous joint probability density functions. The form of the surge response functions allows direct assessment, within the joint probability framework, of alternate probability distributions for any hurricane parameter. Uncertainty in the probabilistic estimates will be discussed in the context of extreme-value statistics by considering the variability in future climate and sea level projections. Here, we use dimensionless scaling and hydrodynamics arguments to quantify the influence of hurricane variables and regional geographic characteristics on the surge response. In summary, physical attributes of hurricane surge can be quantified using forecasted, historical, and hypothetical hurricane track information, and this information may be used to more rapidly and accurately convey surge hazard to planners, decision makers, and the public. Note: Abstract is modified from those presented at the American Geophysical Union Fall Meetings in2011 and 2012.

Uncertainty and Very-Low Probability Estimates

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As a wrap-up to the rest of the presentations of the panel, this brief presentation will discuss three potential impacts related to the quantification of hazard probabilities: 1) the role of hybrid storms (such as Sandy) in storm populations; 2) the impact of mixed populations in probabilistic methods; 3) the influence of uncertainty on expected exceedances; 4) the potential role of upper limits on the estimation of very-low probabilities.

Panel 8: Combined Events Flooding

Co-Chairs: David Margo, USACE and Joost Beckers, Deltares

Presenters:
Kit Ng, Bechtel Power Corporation
Chris Dunn, USACE
Martin McCann, Stanford University
Joost Beckers, Deltares
Doug Clemetson, USACE
Pat Regan, FERC

Rapporteurs: Michelle Bensi, NRC (NRO) and Jeff Mitman, NRC (NRR)

Panelists:
Kit Ng, Bechtel Power Corporation
Chris Dunn, USACE
Martin McCann, Stanford University
Joost Beckers, Deltares
Doug Clemetson, USACE
Pat Regan, FERC

Combined Events in External Flooding Evaluation for Nuclear Plant Sites

***Kit Y. Ng*[1]**

[1]Bechtel Power Corporation, Geotechnical & Hydraulic Engineering Services, Frederick, MD 21703

The presentation will review the historical and current practices of assessing combined events for flooding due to external events at nuclear plant sites. The current industry and regulatory guides on the evaluation of combined events flooding including RG 1.59, NUREG/CR-7046, NUREG 0800, and ANSI/ANS 2.8-1992 are primarily deterministic based. As stated in ANS 2.8, no single flood-causing event is an adequate design base for a power reactor. Combined events can be sequential or coincidental occurrences of attendant or causative flood causes. The criteria for selecting the set of combined events depend on the location of the plant and the characteristics of the flood causing phenomena specific to the site. ANS 2.8 also indicates that an average annual exceedance probability less than 1X10-6 is an acceptable goal for selection of flood design bases for power reactor plants. This paper examines the fundamentals of combined events in the deterministic framework. In addition, it explores the challenges of evaluating external flooding in the probabilistic space.

Assessing Levee System Performance Using Existing and Future Risk Analysis Tools

Christopher N. Dunn, P.E., D.WRE[1]

[1]USACE Hydrologic Engineering Center, Davis, CA

A process was defined to apply risk analysis methodologies to identify potential system-wide hydraulic impacts resulting from modifications to the Sacramento River Flood Control Project (SRFCP). This effort demonstrated that existing risk analysis tools can be applied in a systems context to reveal responses of one region of a system from perturbations to another region. The example application illustrates the complexities and effort required to conduct a system-wide risk analysis. US Army Corps of Engineers (USACE) policy, as stated in ER 1105-2-101, "Risk Analysis for Flood Damage Reduction Studies" (USACE, 2006a), requires the use of risk analysis and its results in planning flood risk management studies and are to be documented in principal decision documents. The goal of the policy is a comprehensive approach in which the key variables, parameters, and components of flood risk management studies are subject to probabilistic analysis. The benefit of the process for the evaluation of proposed modifications to the SRFCP is an increased understanding of the potential risk inherent in modification alternatives. A second, but no less important goal of this exercise, was to understand more fully what is required to advance the current methods and tools for risk management assessments. Thus, a major purpose of this effort was to identify and assist the development of methods, tools, and guidance for performing and using risk and reliability assessments that match the complexity and frequency of the assessments. An introduction to the next generation of flood risk analysis tool, HEC-WAT/FRA (Watershed Analysis Tool with the Flood Risk Analysis option), is also presented.

Seismic Risk of Co-Located Critical Infrastructure Facilities – Effects of Correlation and Uncertainty

Martin W. McCann, Jr.[1]

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This paper looks at issues associated with estimating risk of seismically initiated failure of dams and other critical infrastructure facilities that are co-located with respect to each other and the location of future earthquakes. In the case of dams, a seismically initiated failure produces a second hazard, the uncontrolled release of the reservoir, which may impact other dams downstream or other critical facilities located on the waterway. Dams may be on the same river or regionally co-located on different rivers. Failure of one or more dams could lead to serial dam failures on a single river; or produce regional consequences on multiple rivers. In the case of downstream critical infrastructure that may be located in the floodway and also impacted by the same seismic event, the ability to prepare for and respond to potential flood conditions may be compromised by the earthquake. This paper looks at the effect of different sources of correlation or dependence on the risk to a portfolio of co-located dams and other critical infrastructure projects. A parametric study is performed to examine the effect that different sources of uncertainty and correlation have on seismic risk analysis results. Sources of uncertainty and correlation that are discussed include the epistemic uncertainty in the seismic hazard analysis, the inter-event earthquake variability and the intra-event spatial correlation of ground motions in the region impacted by the earthquake. The parametric study that evaluates a number of these factors are described. The consequences of a seismic event are not limited to dam failure and downstream inundation. Since it is far more likely that dams may be damaged (as opposed to failing immediately as a result of the earthquake) as a result of the seismic event, the post-event period may be critical in terms of during a seismic event, these 'other' consequences include loss of function (i.e., hydropower production, control of gate systems or other outlets, etc.) as reservoirs may need to be lowered following the earthquake in order to prevent a subsequent failure (e.g., 1971 Lower San Fernando Dam).

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Storm Surge - Riverine Combined Flood Events

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River deltas are flat areas between riverine and coastal influences. These deltas are at risk of flooding caused by intense rainfall runoff or by a severe storm surge at sea, or by a combination the two phenomena. This implies that there is no single design storm, but rather a collection of likely and less likely combinations of extreme and less extreme rainstorms and storm surges. Together, these combinations constitute the design flood levels. To calculate these flood levels requires a probabilistic assessment of all possible hydraulic conditions and associated probabilities of occurrence. This is a complex and computationally demanding task, especially if the number of combinations is further increased e.g. by the possibility of failure/non-failure of a storm surge barrier. In the probabilistic flood hazard assessment, typically hundreds up to thousands of combinations of external forcings are considered. The design water level at a location of interest is computed for each combination by a hydraulic model. A numerical integration over all possible combinations and their probabilities produces the design flood level for a given return period. The probability of occurrence of a particular combination should take into account the correlation – if any – between the external forcings. Various correlation models can be employed to determine the likelihood of each combination of forcing conditions. An example will be presented in which a copula function was used.

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Combining Flood Risks from Snowmelt, Rain and Ice – The Platte River in Nebraska

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In the past it has been common practice to combine open water and ice-affected flood risks to obtain an all-season flood risk. The all-season stage frequency curve is normally computed using the "probability of a union" equation by adding the probabilities of the open water stage frequency curve and the ice-affected stage frequency curve and subtracting the joint probability of flooding occurring from both types of event. This approach works fine for streams in which both types of events occur every year. However, for the Platte River in Nebraska, ice-affected stages do not occur every year so using this approach would tend to overestimate the frequency of flooding. Therefore, an alternative approach was developed and was subsequently adopted by FEMA for use in Flood Insurance Studies.

The alternate approach involves developing a stage-frequency curve using all annual-maximum stages that are ice-affected events and a separate stage-frequency curve using all the annual-maximum stages that are open water events during the snowmelt/ice season. Each frequency curve is called a "conditional-frequency curve." The ice-affected conditional-frequency curve is "conditioned" in the sense that only annual-maximum peak stages that are ice-affected-related are used in the frequency analysis. To obtain the probability of an ice-affected event exceeding a given stage in any year, the exceedance probabilities from the conditional- frequency curve are multiplied by the fraction of time that ice-affected events produce annual-maximum peak stages during the snowmelt/ice season. The open water conditional-frequency curve is "conditioned" in the sense that only annual- maximum peak stages that are open water events are used in the frequency analysis. To obtain the probability of a open water event exceeding a given stage in any year, the exceedance probabilities from the conditional-frequency are multiplied by the fraction of time that open water events produce annual-maximum peak stages during the snowmelt/ice season. The conditional frequency curves for the snowmelt/ice season frequency curve are then combined to obtain the probability of the annual-maximum stage exceeding a given stage in any year due to either open water or an ice-affected event during the snowmelt/ice season. For the annual-maximum series, the stage-frequency curves for snowmelt/ice season and the rainfall season are then combined to obtain the all-season frequency curve.

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Human, Organizational and Other Factors Contributing to Dam Failures

***Patrick J Regan*[1]**

[1]Principal Engineer – Risk Informed Decision Making, Federal Energy Regulatory Commission

"We pretend that technology, our technology, is something of a life force, a will, and a thrust of its own, on which we can blame all, with which we can explain all, and in the end by means of which we can excuse ourselves."
(T. Cuyler Young, Man in Nature)

A review of investigation reports for several recent failures of dams, pipelines and offshore oil platforms suggests that there are many human and organizational factors that contribute to these failures in addition to the, often more simplistic, "root cause" that generally focuses on a single path of component failures and human errors. Among the contributing factors in infrastructure failures are :

1) Organizations being driven by financial performance resulting in decisions being made to operate systems near the boundaries of safety;
2) Organization safety programs focused on personal safety rather than system safety;
3) A tendency to fixing symptoms of problems rather than determining the underlying causes and fixing the fundamental problems;
4) Organizations that are often complacent about safety due to the low frequency of adverse events, arrogant about the probability of an adverse event happening to them and ignorant of the real risks inherent in their operations;
5) Poor communication within, and outside, of organizations;
6) Organizations focused on meeting the letter of regulatory requirements but ignoring the underlying spirit and purpose of the regulations; and
7) A lack of corporate safety culture in many organizations.

The criticality of including factors such as those listed above derives from the fact that the way our infrastructure systems are built and operated today is significantly different from the way similar structures were constructed and operated in the not so distant past. Nancy Leveson, in Engineering a Safer World , outlines nine reasons why we need new ways to assess the safety of our systems:

1) Fast pace of technology change
2) Reduced ability to learn from experience
3) Changing nature of accidents
4) New types of hazards
5) Increasing complexity and coupling
6) Decreasing tolerance for single accidents
7) Difficulty in selecting priorities and making tradeoffs
8) More complex relationships between humans and automation
9) Changing regulatory and public views of safety

Leveson also provides considerations for a new accident model to help us understand the complex systems that comprise our infrastruture:

1) Expand accident analysis by forcing consideration of factors other than component failures and human errors
2) Provide a more scientific way to model accidents that produces a better and less subjective understanding of why the accident occurred and how to prevent future ones
3) Include system design errors and dysfunctional system interactions
4) Allow for and encourage new types of hazard analyses and risk assessments that go beyond component failures and can deal with the complex role software and humans area assuming in high-tech systems
5) Shift the emphasis in the role of humans in accidents from errors (deviations from normative behavior to focus on the mechanisms and factors that shape human behavior (i.e. the performance-shaping mechanisms and context in which human actions take place and decisions are made.
6) Encourage a shift in the emphasis in accident analysis from “cause” – which has a limiting, blame orientation – to understanding accidents in terms of reasons, i.e. why the events and errors occurred
7) Examine the processes involved in accidents and not simple events and conditions
8) Allow for and encourage multiple viewpoints and multiple interpretations when appropriate
9) Assist in defining operational metrics and analyzing performance data

In summary, we must understand the broader system in which our infrastructure operates. That system necessarily must include the organizations and people who own operate and maintain these facilities. The purpose of this workshop is to explore these concepts. In many cases the ability of a nuclear station to withstand a flood involves a complex interaction between two very complex systems each of which is also affected by other systems such as the electric grid, the road network, communication lines, etc.

Biographies

George Apostolakis: The Honorable George Apostolakis was sworn in as a Commissioner of the U.S. Nuclear Regulatory Commission (NRC) on April 23, 2010, for a term ending on June 30, 2014.

Dr. Apostolakis has had a distinguished career as a professor, an engineer, and risk analyst. He is internationally recognized for his contributions to the science of risk assessment for complex systems. Before joining the NRC, he was a professor of Nuclear Science and Engineering and a professor of Engineering Systems at the Massachusetts Institute of Technology.
Dr. Apostolakis served as a member of the NRC statutory Advisory Committee on Reactor Safeguards (ACRS) from 1995 to 2010. He also served as Chairman of the ACRS in 2001 and 2002.

In 2007, Dr. Apostolakis was elected to the National Academy of Engineering for "innovations in the theory and practice of probabilistic risk assessment and risk management." He founded the International Conference on Probabilistic Safety Assessment and Management. He served as the Editor-in-Chief of the International Journal Reliability Engineering and System Safety. Dr. Apostolakis received the American Nuclear Society (ANS) Tommy Thompson Award for his contributions to improvement of reactor safety in 1999 and the ANS Arthur Holly Compton Award in Education in 2005. He is a Fellow of the ANS and the Society for Risk Analysis.

Dr. Apostolakis holds a Ph.D. in Engineering Science and Applied Mathematics (awarded in 1973) and an M.S. in Engineering Science (1970) both from the California Institute of Technology. He earned his undergraduate degree in Electrical Engineering from the National Technical University in Athens, Greece in 1969.

Gregory Baecher: Dr. Gregory B. Baecher is Glenn L. Martin Professor of Engineering in the Department of Civil and Environmental Engineering, University of Maryland. Dr. Baecher was a member of the Interagency Performance Evaluation Task Force (IPET) that performed the risk analysis for post-Katrina New Orleans, and is a consultant to the water resources sector on risk and safety. He is a member of the National Academy of Engineering and the author of four books on risk related to civil infrastructure.

Joost Beckers: Joost Beckers is a senior researcher at Deltares, an independent research institute for water management issues. Joost holds a PhD in computational physics (1999) and specialized in hydrology and statistics in his professional career. Before joining Deltares in 2005, he was employed at the Dutch Institute for Coastal and Marine Management. At Deltares, he is mainly active in the field of flood risk assessment, with special expertise in extreme value statistics, stochastic modeling and uncertainty. His recent projects involved loss of life risk modeling, establishing design water levels for flood protection and developing probabilistic models for correlated events.

W. Mark Blackburn: Mark is a twenty-six year Federal Service employee. Mark is currently Director, Office of Nuclear Facility Safety Programs (HS-32) within the DOE Office of Health Safety and Security (HSS) with responsibility for developing and maintaining DOE nuclear facility safety programs in general facility safety, nuclear materials packaging,, readiness reviews, oversight of training in nuclear facilities, the DOE facility representative and safety system oversight programs, and nuclear and nonnuclear facility safety for natural phenomena hazards, fire protection, maintenance. Prior to this position, he was Acting Director in the Office of Nuclear Safety Basis and Facility Design with nuclear safety policy responsibility for general nuclear facility safety analysis and design, Specific Administrative Controls, Unreviewed Safety Questions, Justifications for Continued Operations, Criticality Safety and Nuclear Material Packaging.

Before joining HSS in July 2009, Mark served in several capacities with the National Nuclear Security Administration (NNSA) from September 1990 through July 2009. As part of the September 2008 – May 2009 NNSA Acquisition Strategy Team (AST), he was responsible for identifying and evaluating contracting options for all NNSA sites. As the Pantex Site Office Assistant Manager for Oversight and Assessment and the Chief for Safety, Health, and Quality Assurance, he administered programs in occupational safety and health, construction safety, assessments, operations quality assurance, and weapons and operations quality related to nuclear weapons activities. He also worked as the DOE Albuquerque Operations Office Nuclear Materials Transportation Manager and as a nuclear weapons manager and engineer at Pantex while gaining a broad management and technical background in operations, safety, quality, and business. Prior to Pantex, he held engineering positions with the Department of Defense (DOD) in Texas, Kentucky, and Missouri.

Mark holds a Bachelor's degree in Industrial Engineering from Mississippi State University and completed the DOD Maintainability Engineering Intern program and NNSA Mid-level Leadership Development Program (MLDP). As part of the MLDP, he briefed the NNSA Administrator on the Pantex Site contractor's year-end performance evaluation and did a rotation at NNSA Headquarters. He is a licensed Professional Engineer in the State of Texas and a Professional Member of the American Society of Safety Engineers.

Geoff Bonnin: Geoff Bonnin is a civil engineer with the National Weather Service (NWS) Office of Hydrologic Development. He manages science and technique development for flood and stream flow forecasting, and for water resources services provided by NWS. He initiated and oversees the development of NOAA Atlas 14, Precipitation Frequency Atlas of the Unites States and was lead author of the first three volumes. He was a technical advisor for Engineers Australia's update of their precipitation frequency estimates.

His primary areas of expertise are in the science and practice of real time flood forecasting, estimation of extreme precipitation climatologies including the potential impact of climate change, data management as the integrating component of end-to-end systems, and the management of hydrologic enterprises. In 2011 he spent several months with the Australian Bureau of Meteorology to identify specific techniques and technologies for sharing between the Bureau and NWS.

David Bowles: David S. Bowles, Ph.D., P.E., P.H., D.WRE, F.ASCE and his colleagues since 1978 have pioneered the development and practical application of risk-informed approaches to dam safety management. They have completed individual and portfolio risk assessments for more than 800 dams in many countries, ranging from screening assessments to detailed assessments with uncertainty analysis. David has assisted with the development of tailored frameworks for dam and levee safety risk management for government and private owners, regulators and professional bodies in many countries. Clients have included Reclamation, USACE, TVA, FERC, BIA, World Bank, WMO, IAEA, EU, ANCOLD, NSW DSC and numerous private dam owners. He has conducted risk assessments for the failure of dams affecting a nuclear station and currently he advises EPRI on external flooding probabilistic evaluation and dam failures. David has served as an expert witness for law suits related to dam and canal failures, reservoir operation and hydropower generation, toxic tort, and urban flooding. David has provided training programs on six continents and has authored or reviewed numerous guidance documents for dam safety risk analysis, assessment and management. He has led software development for dam risk analysis (DAMRAE) and life-loss estimation (LIFESim with a simplified version in HEC-RAS) for USACE, portfolio risk assessment for a large UK dam owner (ResRisk), and real-time reservoir flood operation for Reclamation, USACE and SAFCA. David is the Managing Principal of RAC Engineers and Economists and an Emeritus Professor of Civil and Environmental Engineering at Utah State University (USU). Previous positions include Director of the Institute for Dam Safety Risk Management and Director of Utah Center for Water Resources Research at USU, Engineering Department Manager and Branch Manager for Law Engineering's Denver office, and a construction and design engineer for a large international contractor based in the UK.

R. Jason Caldwell: Jason Caldwell is a Meteorologist in the Flood Hydrology and Consequences Group in the Technical Service Center (TSC) of the Bureau of Reclamation in Denver, Colorado. He has served in the TSC for 2 years, and has worked in the fields of meteorology, climatology, and hydrology for over 15 years. His earlier positions were as a Hydrometeorological Analysis and Support Forecaster at the Lower Mississippi River Forecast Center and climatologist at the South Carolina State Climate Office. He will complete a Ph.D. in Civil (Water Resources) Engineering from the University of Colorado in 2013. His principal responsibility is providing expert technical advice on gridded meteorological data processing, hydrometeorological statistics, and extreme storm analysis to TSC management and staff concerning hydrologic issues for Reclamation and other Department of Interior facilities.

Nilesh Chokshi: Currently, Dr. Nilesh Chokshi is Deputy Director, Division of Site and Environmental Reviews in the Office of New Reactors. During his 33 years at the NRC, Dr. Chokshi has managed several research and regulatory areas including seismic and structural engineering, materials engineering, operating experience risk analysis, and radiation protection. He has also been extensively involved in the area of probabilistic risk assessment, particularly in the development of external event methodology and the standard. Dr. Chokshi has been Vice-Chairman of Board of Directors of ASME Codes and Standards Technology Institute; past Chairman of CSNI Working Group on Integrity and Aging of Components and Structures; he is a member of Advisory Board of International Association of Structural Mechanics in Reactor Technology (IASMiRT); and was Chairman of International Scientific Committee of 16th SMiRT Conference. Prior to joining the NRC, Dr. Chokshi worked at an architectural/engineering firm involved in designs of nuclear power plants. Dr. Chokshi obtained his Ph. D. in the field of civil engineering (with specialization in structural engineering) from Rice University and Master=s degree from University of Michigan.

Douglas J. Clemetson: Doug Clemetson serves as the Chief, Hydrology Section, Hydrologic Engineering Branch in the Engineering Division of the U.S. Army Corps of Engineers' Omaha District. As Chief of the Hydrology Section, Doug supervises a staff that includes seven hydraulic engineers, a meteorologist, a geographer and a student, who prepare the hydrologic studies required for the planning, design and operation of all the water resource projects in the Omaha District.

In addition, his staff advises and supports Emergency Management prior to and during flood emergencies within the Missouri River Basin. He has extensive experience in flood hydrology, water supply hydrology, statistics, watershed modeling, reservoir simulation, extreme storm analysis, and flood forecasting.

During his career, Doug has worked in the Missouri River Division Technical Engineering Branch and Reservoir Control Center and has served as an H&H Specialist in the HQUSACE Emergency Operations Center following Hurricanes Katrina and Rita in 2005. He has also been the leader of the Inflow Flood Methodology Team for the USACE Dam Safety Program; is the USACE representative on the federal interagency Extreme Storm Events Work Group; is the leader of the USACE Extreme Storm team; and has been a member of the USACE Hydrology Committee since 1996 where he currently serves as vice-chairman of the committee.

Doug earned his bachelor's degree in Civil Engineering from South Dakota State University in 1980. He is a registered Professional Engineer in the State of Nebraska, a member of the American Society of Civil Engineers, and a member of the Association of State Dam Safety Officials. He has been with the Corps of Engineers in Omaha for over 32 years.

Tim Cohn: Tim Cohn works in the USGS Office of Surface Water where he has co-authored more than 25 papers on methods for estimating flood risk and related topics. He previously served as USGS Science Advisor for Hazards and as AGU's 1995-96 AAAS Congressional Science Fellow in the office of Senator Bill Bradley. Tim holds M.S. and Ph.D. degrees from Cornell University and a B.A. from Swarthmore College.

Christopher Cook: Starting in December 2012, Dr. Cook became chief of the Hydrology and Meteorology Branch, Office of New Reactors (NRO), at the Nuclear Regulatory Commission. Prior to joining the branch, he also served as chief of the Geoscience and Geotechnical Engineering Branch and a senior hydrologist in the Office of New Reactors for a number of years. As a hydrologist, Dr. Cook performed numerous technical reviews to support NRC's safety evaluation reports (SER) and environmental impact statements (EIS) associated with Early Site Permit (ESP) and Combined License (COL) applications for new nuclear reactors. Prior to joining the NRC, Dr. Cook supported the U.S. Nuclear Regulatory Commission as a technical reviewer in the area of hydrology while employed at the Pacific Northwest National Laboratory (PNNL). He contributed to technical reviews associated with NRC's safety evaluation reports (SER) and environmental impact statements (EIS) on the North Anna, Clinton, Grand Gulf, and Vogtle Early Site Permit (ESP) applications. Past research at PNNL and the University of California, Davis, focused on multi-dimensional hydrodynamic and water quality modeling of surface water systems, including the use of three-dimensional computational fluid dynamics (CFD) models.

Dr. Cook holds a B.S. in Civil Engineering from Colorado State University, a M.S. in Civil Engineering from the University of California, Davis, specializing in groundwater hydrology, and a Ph.D. from the University of California, Davis, specializing in multi-dimensional hydrodynamic and water quality modeling of surface water systems.

Christopher N. Dunn: Christopher Dunn is the director of the Hydrologic Engineering Center (HEC) in Davis, CA with more than 25 years experience. His expertise includes flood damage and impact analysis, planning analysis, risk analysis, levee certification, river hydraulics, surface water hydrology, storm water management, watershed systems analysis, and ecosystem restoration. He was the project manager for HEC's role in the Sacramento/San Joaquin Comprehensive Study and also lead the development of flood damage reduction, ecosystem restoration, and system analysis software tools. He has also worked on several international projects including water management modeling in Iraq and Afghanistan, training in Japan, and collaboration with the USGS on a Learning Center in Turkey.

John England: John England is a flood hydrology technical specialist with the Bureau of Reclamation in Denver, Colorado, USA. Dr. England's research and project interests include extreme flood understanding and prediction, rainfall-runoff modeling, flood frequency, hydrometeorology, paleoflood hydrology, and risk analysis. For the past 15 years he has developed and applied probabilistic flood hazard techniques to evaluate the risk and safety of Bureau of Reclamation dams, and has overseen implementation of risk-based techniques for the dam safety program. John has numerous publications including journal articles, book chapters, conference proceedings, guidelines, technical manuals, and reports. Dr. England received his M.S. and Ph.D. in hydrology and water resources from Colorado State University. He is a registered Professional Hydrologist with the American Institute of Hydrology, a registered Professional Engineer in Colorado, and holds a Diplomate, Water Resource Engineer (D.WRE) from the American Academy of Water Resources Engineers (AAWRE). Dr. England was awarded the Bureau of Reclamation Engineer of the Year and nominated as one of the top 10 Federal Engineers in 2008.

Fernando Ferrante: Fernando Ferrante is currently working as a Reliability and Risk Analyst with the U.S. Nuclear Regulatory Commission (US NRC) in the application of probabilistic risk assessment (PRA) tools and models to the oversight of operating nuclear reactors in the US. His primary focus is on quantitative risk assessments using the SAPHIRE software, as well as the development of PRA tools for use in analyzing so-called “external” events (e.g., internal fire, seismic and external flooding events).

Prior to joining the US NRC, Dr. Ferrante worked as a Research Engineer at Southwest Research Institute (SwRI) in the Center for Nuclear Waste Regulatory Analysis (CNWRA). His responsibilities included prelicensing activities in support of the US NRC High-Level Waste program, development of risk-informed, performance-based regulatory guidance and performance assessment of a potential nuclear high-level waste repository.

Dr. Ferrante has a Ph.D. from Johns Hopkins University (2005) in Civil Engineering (thesis topic on probabilistic mechanics), MS in Civil Engineering from University of Virginia (2000) and BS in Mechanical Engineering from University College London, England (1997).

Eric Geist: Eric Geist is a Research Geophysicist with the Pacific Coastal & Marine Science Center of the U.S. Geological Survey (USGS), where he has worked for 28 years. Throughout his career, he has focused on computer modeling of geophysical phenomena, including large-scale deformation of the earth in response to tectonic forces and the physics of tsunami generation. For the last ten years, he has led research and developed methods for the probabilistic analysis of tsunami hazards. Eric has authored over 120 journal articles and abstracts, including an article in Scientific American on the devastating 2004 Indian Ocean tsunami and a series of review papers on tsunamis for Advances in Geophysics. Eric received his BS degree in Geophysics from the Colorado School of Mines and his MS degree in Geophysics from Stanford University.

Eric Gross: Eric Gross has a Bachelor's degree from Rensselaer Polytechnic Institute and a Master's in Civil/Water Resources Engineering from the University of Maryland. He is registered as a Professional Engineer (Civil) in the State of Maryland. He has been with the Federal Energy Regulatory Commission for 10 years and is a member of the FERC's Risk Informed

Decision Making (RIDM) team. The RIDM Team is tasked with incorporating risk concepts into FERC's dam safety program. Currently, he is chairing FERC's Risk Technical Resource Group, heading the team writing FERC's guidelines for dam failure consequences determination, and a member of the St. Louis River Project canal embankment failure investigation team. He was a member of the Taum Sauk Dam failure investigation team, and the lead engineer for FERC's first risk informed inflow design flood determination.

Jason Hedien: Jason Hedien is Vice President and a Principal Geotechnical Engineer and Project Manager with MWH. At MWH Jason has over 18 years of experience in the management, inspection, analysis and design of dams and hydropower projects, infrastructure and waterway/port projects, and wastewater and water supply projects. Jason's professional experience includes conducting deterministic and probabilistic seismic hazard analyses, risk assessments, earthquake engineering for dams and civil infrastructure projects, and dam safety engineering for the evaluation of dam safety and implementation of dam safety improvements for dams and ancillary structures.

Jennifer L. Irish: Dr. Irish is an associate professor of civil engineering at Virginia Tech with expertise in storm surge dynamics, storm morphodynamics, vegetative effects, coastal hazard risk assessment, and general coastal engineering. She is a Diplomate of Coastal Engineering and licensed Professional Engineer with 18 years of experience. Dr. Irish has published more than 30 journal papers. Irish recently received the Department of the Army Superior Civilian Service Award (2008) and Texas A&M University's Civil Engineering Excellence in Research Award (2010). Dr. Irish teaches coastal engineering and fluid mechanics and leads research on extreme event and climate change impacts at the coast.

Henry Jones: Henry Jones is a hydrologist in the Division of Site Safety and Environmental Analysis of the Office of New Reactors within the U.S. Nuclear Regulatory Commission (U.S. NRC). He has worked at the U.S. NRC for 6 years in the Branch of Hydrology and Meteorology. Prior to working at the U.S. NRC, Henry Jones served 28 years in the United States Navy as a physical oceanographer and meteorologist. His principal responsibility is providing expert technical advice to NRC management and staff concerning tsunami and storm surge hydrologic issues for NRC-licensed facilities.

Annie Kammerer: Dr. Annie Kammerer is a senior seismologist and earthquake engineer in the Office of Nuclear Regulatory Research at the United States NRC, where she coordinates the NRC's Seismic Research Program. In this role, she is responsible for overseeing research on a broad range of seismic topics ranging from seismic and tsunami hazard assessment to seismic risk assessments for nuclear facilities. She was project manager and contributing author on the NRC's current guidance on conducting seismic hazard assessments (Regulatory Guide 1.208 and NUREG 2117). She is also currently the NRC project manger and representative on the Joint Management Committee for "Next Generation Attenuation-East" project, which is developing ground motion prediction equations for central and eastern North America for use with the recently published CEUS SSC for Nuclear Facilities model. She was a member of the Participatory Peer Review Panel for the CEUS SSC project. Dr. Kammerer is currently the NRC's technical lead for the seismic walkdowns being conducted at all 104 operating reactors in the US as part the NRC's Post-Fukushima activities. Dr. Kammerer has authored over 3 dozen publications, including regulatory guidance, technical reports, journal articles, a book chapter, conference proceedings and papers, and an ASCE special publication. She was a contributing author on the tsunami guidance contained in IAEA Safety Standard Guide 18.

Dr. Kammerer holds three degrees from the University of California, Berkeley, including a BS degree in Civil Engineering, a MS degree in Geotechnical Engineering, and a PhD in Geotechnical Earthquake Engineering, with minors in Seismology and Structural Engineering.

Ralph Klinger: Ralph Klinger is a Quaternary Geologist and Geomorphologist at the Bureau of Reclamation's Technical Service Center in Denver, Colorado. He received his B.S. and M.S. in Geological Sciences from San Diego State University and his Ph.D. in Geology from the University of Colorado, Boulder. He has been involved in studying the geologic record of natural hazards throughout the western U.S. for almost 30 years. His principal responsibility at Reclamation is to provide technical expertise to the Dam Safety Office and advise the engineering staff on seismic and flood hazards and their use in the evaluation of risk.

Randall LeVeque: Randy LeVeque is a Professor of Applied Mathematics at the University of Washington, where he has been on the faculty since 1985. He is a Fellow of the Society for Industrial and Applied Mathematics (SIAM) and of the American Mathematical Society (AMS). His research is focused on the development of numerical algorithms and software for the solution of wave propagation problems. For the the past 10 years he has been working on development and application of the GeoClaw software for tsunami modeling and other hazardous geophysical flows.

S. Samuel Lin: S. Samuel Lin, PhD, P.E., D.WRE is a civil engineer specialized in hydrologic and hydraulic (H&H) safety and associated risk analyses of hydropower generation dams under Federal Energy Regulatory Commission's jurisdiction. He has been a Federal and State dam safety regulator for 24 years. He also worked in a consulting practice as water resources engineer specializing in planning and H&H analyses for design of dams. He is presently serving on the steering committee for FEMA's update national guidelines on Selecting and Accommodating Inflow Design Flood (IDF) for Dams for hydrologic safety of dams. He also serves on ICODS' Frequency of Extreme Hydrologic Events Guidance Development Task Group. He was Chair of the federal interagency Subcommittee on Hydrology (SOH) for 2005-2007. He is the recipient of the Leadership Recognition and Certificate of Appreciation for chairing of the SOH from USGS and ACWI, respectively.

Tucker B. Mahoney: Tucker Mahoney is a coastal engineer for FEMA, Region IV. Ms. Mahoney is the FEMA project manager for coastal Flood Insurance Studies in the southeastern United States. She also participates on coastal policy and coastal outreach forums within FEMA. Prior to joining FEMA, Ms. Mahoney was a coastal engineer for Moffatt & Nichol, where she completed a variety of hydrodynamic and sediment transport modeling studies and related construction projects.

David Margo: David Margo earned a bachelor of science degree in engineering in 1993 and a master of science degree in civil engineering in 1995, both from the University of Pittsburgh. He has worked for the U.S Army Corps of Engineers for 17 years on various civil works projects. His areas of expertise and professional experience include risk analysis for dams and levees, flood frequency analysis, surface water hydrology, river hydraulics, and levee certification. David has been involved in probabilistic risk studies for a number of dams and levees in the USACE portfolio, including the Dallas Floodway and Bluestone Dam. He is also involved in methodology and policy development for the USACE dam and levee safety programs and is one of the lead developers for the USACE risk informed levee screening tool.

Martin McCann, Jr.: Dr. McCann received his B.S. in civil engineering from Villanova University in 1975, an M.S. in civil engineering in 1976 from Stanford University and his Ph.D. in 1980, also from Stanford University.

His areas of expertise and professional experience includes probabilistic risk analysis for civil infrastructure facilities and, probabilistic hazards analysis, including seismic and hydrologic events, reliability assessment, risk-based decision analysis, systems analysis, and seismic engineering. He currently teaches a class on critical infrastructure risk management in the Civil and Environmental Engineering Department at Stanford.

He has been involved in probabilistic risk studies for critical infrastructure (dams, levees, nuclear power plants, ports, chemical facilities) since the early 1980's. He has performed probabilistic flood hazard assessments for a number of Department of Energy sites and commercial nuclear power plants. Recently, Dr. McCann led the Delta Risk Management Strategy project that conducted a risk analysis for over 1,100 miles of levee in the Sacramento and San Joaquin Delta. He was also a member of the U.S. Army Corps of Engineers' IPET Risk and Reliability team evaluating the risk associated with the New Orleans levee protection system following Hurricane Katrina.

Dr. McCann developed the SHIP risk analysis software that is used to perform risk and uncertainty calculations for facilities exposed to external hazards.

He is currently serving on the ANS 2.8 committee that is updating the requirements for the assessment of external flood hazards at nuclear facilities.

Kit Y. Ng: Kit Ng is a senior principal hydraulic and hydrology specialist and also serves as the assistant chief of Bechtel Power Corporation's Geotechnical & Hydraulic Engineering Services Group. She has 22 years of industry experience and is the technical lead in Bechtel Power on hydrologic and hydraulic design and modeling, specifically on flooding hazard evaluation for nuclear power facilities, design of cooling water systems, intake and outfall hydraulic design, water resource management, storm water management, site drainage, erosion & sediment controls, coastal hydrodynamics and contaminant mixing and transport modeling in both surface water and groundwater. Kit has a Ph.D in environmental hydraulics from the California Institute of Technology. She has served as the chair for the Computational Hydraulic Committee of ASCE/EWRI and is currently a member of the ANSI/ANS 2.8 and 2.31 standard committees on design basis flood determination for nuclear facilities and estimating extreme precipitation at nuclear facility sites. She is also participating in the new ANS 2.18 standard committee on evaluating radionuclide transport in surface water for nuclear power sites.

Thomas Nicholson: Thomas Nicholson is a Senior Technical Advisor in the Division of Risk Analysis of the Office of Nuclear Regulatory Research within the U.S. Nuclear Regulatory Commission (U.S. NRC). He has served in the research office for 32 years, and has worked at the U.S. NRC for 35 years receiving numerous awards including the U.S. NRC Meritorious Service Award for Scientific Excellence. His earlier positions were as a senior hydrogeologist and hydrologist in the Offices of Nuclear Regulatory Research, Standards Development and Nuclear Reactor Regulation.

His principal responsibility is providing expert technical advice to NRC management and staff concerning radionuclide transport in the subsurface at NRC-licensed facilities. He has formulated and directed numerous research studies, as a senior project manager, involving estimation of extreme flood probabilities in watersheds; radionuclide transport in fractured rock; and integration of subsurface monitoring and modeling. He presently serves as chair of the Extreme Storm Event Work Group under the Federal Subcommittee on Hydrology of the Advisory Committee on Water Information. He is the NRC liaison to the Water Science and Technology Board of the National Academies of Sciences.

He holds a B.S. in geological sciences from Pennsylvania State University, and a M.S. in geology from Stanford University. At Stanford, he was a student of Professors Ray Linsley and Joseph Franzini in the hydrology program completing the core courses in hydrology. He is an active member of the American Geophysical Union, American Institute of Hydrology, Geological Society of America, International Association of Hydrological Sciences, the International Hydrogeologic Society, the National Ground-Water Association and registered Professional Geologist.

Nicole Novembre: Nicole Novembre, P.E., is a hydrologic engineer with the Bureau of Reclamation Technical Service Center Flood Hydrology and Consequences Group in Denver, Colorado. She has been with Reclamation for 3 years. Previously she spent 2 years in private consulting after earning her Hydrology, Water Resources, and Environmental Fluid Mechanics M.S. degree from the University of Colorado at Boulder in 2007. Her principal responsibility is to develop hydrologic hazard loadings for use in Bureau of Reclamation Dam Safety risk assessments.

Jim O'Connor: Jim O'Connor is a Research Hydrologist at the U.S. Geological Survey Oregon Water Science Center in Portland, Oregon, USA. He is a U.S. Pacific Northwest native long interested in the processes and events that shape the remarkable and diverse landscapes of the region. Following this interest with a Geological Science major at University of Washington and M.S. and Ph.D. degrees at University of Arizona (1990), he has spent the last 23 years focused on floods, fluvial geomorphology and Quaternary geology, primarily in the western United States.

Chandra Pathak: Dr. Chandra S. Pathak, Ph.D., P.E., D.WRE, F.ASCE, has a distinguished career with over 33 years of experience in wide ranging areas of water resources engineering that included surface and ground water hydrology and hydraulics, stormwater management, wetland, water quality, drought management, GIS, and hydrology, hydraulic and water quality computer models. Currently, he is a principal engineer at the US Army Corps of Engineers, headquarters at Washington, DC. Before that he was a principle engineer at the South Florida Water Management District for twelve years. He is an adjunct professor at Florida Atlantic University and Florida International University. Previously, he was a practicing consulting engineer in the United States for over twenty years. He obtained a bachelor of technology in 1976 and a master of engineering in water resources in 1978 and a doctorate in hydrologic engineering in 1983 from Oklahoma State University. Since 2006, he has been serving as an associate editor of Journal of Hydrologic Engineering. He has numerous presentations, speeches, and technical papers to his credit in the areas of water resources engineering. In 2007, he was awarded Diplomate of Water Resources Engineering and Fellow Member of the American Society of Civil Engineers (ASCE).

Rajiv Prasad: Dr. Prasad has over 20 years of experience as a Civil Engineer. His PhD dissertation at Utah State University focused on spatial variability, snowmelt processes, and scale issues. He has been employed at the Pacific Northwest National Lab for the last 13 years. His research has included application of spatially distributed models for water management, watershed process characterization, and impacts from global climate change. Dr. Prasad started working on the NRC permitting and licensing reviews since the wave of new power reactor applications started around 2003-04. Dr. Prasad has led PNNL's effort in updating NRC's Standard Review Plan in 2007, developing staff guidance related to tsunamis in 2009, and revising the technical bases for design-basis flood estimation at nuclear power plant site in 2010-11. Currently, Dr. Prasad is leading the PNNL team tasked to provide technical bases for a comprehensive probabilistic flood hazard assessment at nuclear power plant sites.

Charles R. Real: Charles Real is a Registered Geophysicist in California, and has worked in the field of earthquake hazards for over 35 years. He is currently a Supervising Engineering Geologist with the California Geological Survey, where he helped establish and currently manages California's Seismic Hazard Zonation Program. During his career he has been principal investigator for numerous federal grants, and has recently been elected to the Board of Directors for the Northern Chapter of the Earthquake Engineering Research Institute. He currently Co-chairs a California Tsunami Policy Working Group, focusing on ways to reduce coastal communities' tsunami risk.

Wendy Reed: Dr. Reed is a radiochemist in the Environmental Transport Branch, Division of Risk Analysis of the Office of Nuclear Regulatory Research in the U.S. Nuclear Regulatory Commission (U.S. NRC). She has worked at the U.S. NRC for over 3 years. She holds a B.Sc. (Honors) and a Ph.D., both in chemistry, from the University of Manchester in the United Kingdom.

Patrick J. Regan: Pat Regan is the Principal Engineer, Risk-Informed Decision-Making in the Division of Safety of Dams and Inspections, Office of Energy Projects, Federal Energy Regulatory Commission (FERC-D2SI). He has worked in the hydroelectric generation field for 36 years for a dam owner, as a consultant and since 2000 for FERC-D2SI. He has authored or co-authored several papers on use of risk assessment in dam safety and has received both the United States Society on Dams Best Paper award and the Association of State Dam Safety Officials' West Region Award of Merit. His principal responsibility is leading the development of the FERC's Risk-Informed Decision-Making program.

Donald T. Resio: Dr. Resio is the Director of the Taylor Engineering Research Institute and Professor of Ocean Engineering within the College of Computing, Engineering and Construction at the University of North Florida. He conducted meteorological and oceanographic research for over 40 years, leading many efforts that have contributed significantly to improving the predictive state of the art for winds, waves, currents, surges, and coastal evolution due to storms, along with improved methods for the quantification of risk which incorporate alleatory and epistemic uncertainty into a consistent physical framework for coastal hazards. He serves as a US delegate to the United Nations' Joint WMO-IOC Technical Commission for Oceanography and Marine Meteorology (JCOMM) in the area of climate effects and the ocean and is the co-chair of the UN Coastal Inundation and Flooding Demonstration Project. Before coming to UNF, Dr Resio served as Senior Scientist for the ERDC Coastal and Hydraulic Lab.

Victoria Sankovich: Victoria Sankovich is a Meteorologist in the Flood Hydrology and Consequences Group in the Technical Service Center (TSC) of the Bureau of Reclamation in Denver, Colorado. She has served in the TSC for over 3 years, conducting extreme precipitation and storm research and project work. Ms. Sankovich previously studied cloud/precipitation regimes as predicted by numerical weather models using statistical methods. Further, she has operational experience as a meteorologist for the U.S. Antarctic Program. This unique opportunity provided a challenging experience to work directly with weather instrumentation, including LIDAR, sunshine recorders, snow stakes, and rawinsondes. Her principal responsibility is providing expert technical advice on hydrometeorological statistics, including L-moments, and extreme storm analysis to TSC management and staff concerning hydrologic issues for Reclamation and other Department of Interior facilities.

Mel Schaefer: Mel Schaefer is a Surface Water Hydrologist with a Ph.D. in Civil Engineering from the University of Missouri-Rolla. He has over 35-years of experience in hydrologic applications primarily in analysis of extreme storms and floods and was head of the Washington State Dam Safety program for 8-years. He has developed methodologies for conducting regional precipitation-frequency analyses and for stochastic simulation of the spatial and temporal characteristics of storms for use in rainfall-runoff modeling of extreme storms and floods for watersheds throughout the western US and British Columbia. He is co-developer of SEFM, a stochastic flood model for conducting flood simulations for extreme floods. He has conducted studies for extreme floods and provided technical assistance to the USBR, USCOE, BChydro and hydropower utilities on more than 20 dams in developing probabilistic loadings for extreme floods for use in risk analyses for high-consequence dams.

Ray Schneider: Mr. Schneider is a Fellow engineer for the Westinghouse Electric Company. He has more than forty years of experience in the area of Light Water Reactor design and safety analysis, with emphasis on risk informed PSA applications, and severe accident analysis. Over the past several years, Mr. Schneider has represented the PWROG as a member of several NEI task forces, including the NEI Risk based Task Force (RBTF), Risk Informed technical Specifications Task Force (RITSTF), Fire Maintenance Rule task Force (MRTF-Fire) and the NEI FLEX task force supporting the development of the Programmatic Controls section. Mr. Schneider is currently the technical lead for the PWROG supporting the NEI Fukushima Flooding Task Force. ,Mr. Schneider also serves on several Standards development committees including the ANS/ASME Joint Committee on Nuclear Risk Management (JCNRM), ANS/ASME Level 2 PRA Standards working group, and the ANS 2.8 flood hazard development working group. He regularly supports PWR Owner's Groups activities and individual member utilities in Level 1 PSA methods and applications development and Severe Accident Management related activities, and has been the lead individual responsible for over 60 owner's group and individual utility tasks involving PSA methods development, PSA quality improvement, maintenance rule implementation, and risk informed applications.
Mr. Schneider has authored or co-authored over 30 technical publications, and is the recipient of a number of awards including: ASME Engineer of the Year Award, Hartford Chapter, and several division level George Westinghouse Signature Awards.

Timo Schweckendiek: Timo Schweckendiek is a researcher and consultant at Deltares since 2006. His background is hydraulic and geotechnical engineering; he obtained his MSc in Civil Engineering from Delft University of Technology, to which he is affiliated now through his PhD research on risk-based site investigation for levees. His core fields of expertise are flood risk analysis and management and reliability analysis of flood defenses.

He is member of the Dutch Expertise Network of Flood Protection, an independent advisory body to the Dutch government on flood defenses and risk issues. Furthermore, he is a Netherlands delegate to the Technical Committee TC304 on "Risk Management in Engineering Practice" of the International Society of Soil Mechanics and Geotechnical Engineering (ISSMGE). Recently, in November 2012 Timo was co-organizer of the FLOODrisk 2012 conference held in Rotterdam.

Jery Stedinger: Dr. Stedinger is Professor of Environmental and Water Resources Systems Engineering, School of Civil and Environmental Engineering, Cornell University. Dr. Stedinger received a B.A. from the Univ. of California at Berkeley in 1972, and a Ph.D. in Environmental Systems Engineering from Harvard in 1977. Since that time he has been a professor in Cornell's School of Civil and Environmental Engineering. Dr. Stedinger's research has focused on statistical and risk issues in hydrology and the operation of water resource systems. Projects have addressed flood frequency analysis including the use of historical and paleoflood data, dam safety, regional hydrologic regression analyses, risk and uncertainty analysis of flood-risk reduction projects, climate change modeling, water resource system simulation, and efficient hydropower system operation and system design.

John Stevenson: Dr. Stevenson is a professional engineer, with many years of engineering experience including the development of structural and mechanical construction criteria, codes and standards used in construction of nuclear power plant and other hazardous civil and mechanical structures, distribution systems and components subjected to postulated extreme environmental and accident loads as a design basis.

He is, or has been since 1970, an active member or chairman of American Nuclear Society, American Society of Civil Engineers, American Society of Mechanical Engineers, American Concrete Institute, American Institute of Steel Construction and the International Atomic Energy Agency where since 1975 he has actively participated in the development of a large number of International Safety Guides, Tech Docs., and Safety Reports concerning siting, civil and mechanical design of nuclear facilities. He currently serves as Chairman of the Technical Advisory Committee to the IAEA International Seismic Safety Center. He is a member of the ASME Boiler and Pressure Vessel Code Committee, Section III, Nuclear Components, various Section III Working Groups, Subgroups and Subcommittees including former Chairman of ASME B&PVC Section III, Division 3 Transportation and Storage Containments for Nuclear Material and Waste. He is a former member of the ASME Board of Nuclear Codes and Standards and is a fellow of the American Society of Mechanical Engineers. He is also a member of the ANS Nuclear Facilities Standards Committee and is, or has been, a member or Chairman of ANS 2.3, 2.8, 2.10, 2.14, 2.26, 2.31 and 58.16 Standards Working Groups who have or are in the process of developing standards in seismic, wind and flood design and safety categorization of structures, systems and components located in nuclear facilities.

His previous work assignments have included Manger of Structural Design and Balance of Plant Engineering Standardization for a major nuclear steam system supplier, Manager of Corporate Quality Assurance for a major architectural/engineering firm, Founder and President of a consulting engineering firm with 5 offices; 2 in the U.S. and 3 in Eastern Europe dedicated to safe design of new and existing nuclear facilities. He is currently a Consulting Engineer providing outside expert consulting services to various organizations involved in the construction of nuclear safety related facilities.

Dr. Stevenson received his B.S. in Civil Engineering from the Virginia Military Institute in 1954, M.S. in Civil Engineering from the Case Institute of Technology in 1962 and Ph.D. in Civil Engineering from Case Western Reserve University in 1968.

Hong Kie Thio: Hong Kie Thio is Principal Seismologist at the Los Angeles office of URS Corporation. He joined the company in 1995 after receiving his PhD in Geophysics at Caltech and has worked on numerous projects including earthquake source studies, real-time earthquake analysis, nuclear monitoring, seismic hazard analysis and tsunami hazard analysis. He is currently serving on the ASCE 7 sub-committee on tsunami loads.

Wilbert O. Thomas, Jr.: Mr. Thomas is a Senior Technical Consultant with Michael Baker Jr., Inc. in Manassas, Virginia. He reviews and performs hydrologic analyses for flood insurance studies and participates in special projects sponsored by FEMA and other clients such as the Maryland State Highway Administration. Mr. Thomas worked for the U.S. Geological Survey for 30 years and has worked for Michael Baker, Jr., Inc., since April 1995. Mr. Thomas is a registered professional hydrologist with over 47 years of specialized experience in conducting water resources projects and analyzing water resources data. Mr. Thomas is the author of more than 75 papers and abstracts on a variety of surface water hydrologic topics. As an U.S. Geological Survey employee, Mr. Thomas participated in the development of Bulletin 17B, Guidelines For Determining Flood Flow Frequency, published in 1982 and still used by all Federal agencies for flood frequency analysis for gaged streams. Mr. Thomas is the current chair of the Hydrologic Frequency Analysis Work Group (http://acwi.gov/hydrology/Frequency/) that is evaluating revisions to Bulletin 17B.

Tony Wahl: Tony Wahl is a Hydraulic Engineer with 23 years experience in the Bureau of Reclamation Hydraulics Laboratory at Denver, Colorado, working in the areas of flow measurement and canal control, turbine hydraulics, fish screening, dam breach modeling, and laboratory modeling and field testing of hydraulic structures. Since 1995 he has been engaged in research related to embankment dam breach modeling. Since about 2004 he has been the technical coordinator for an international collaboration through the CEATI Dam Safety Interest Group that is focused on developing better methods for modeling embankment dam erosion and breach processes. He has led studies to evaluate competing methods for quantifying the erodibility of cohesive soils, a key input to newer dam erosion and breach models. Mr. Wahl's recent research also includes physical scale modeling and numerical modeling of breach processes associated with canal embankments. Mr. Wahl is a registered professional engineer and earned a B.S. and M.S. in Civil Engineering from Colorado State University. In 2005, he was selected as the Bureau of Reclamation's Federal Engineer of the Year. Mr. Wahl is the author of more than 90 technical papers and is presently serving on ASCE task committees studying flow measurement at canal gates and the uncertainties and errors associated with hydraulic measurements and experimentation.

Ty V. Wamsley: Dr. Ty Wamsley is Chief of the Storm and Flood Protection Division in the Coastal and Hydraulics Laboratory at the U.S. Army Engineer Research and Development Center in Vicksburg, MS. He leads a team of engineers and scientists in the execution of research and development and engineering support services in the areas of storm and flood risk reduction project design and maintenance; sediment management; groundwater and watershed engineering and management; operation and maintenance of navigation projects; and regional-scale databases and information systems. He has received a Department of the Army Superior Civilian Service Award for his leadership and technical contribution to the Corps' flood and storm damage reduction mission.

Yong Wei: Dr. Yong Wei is a senior research scientist in tsunami modeling, coastal hazard mitigation, and geophysical data analysis. He has more than 10 years of research experience on tsunami modeling, methodology, and associated geophysics. He has developed extensive skills and proficiencies in various computer models dealing with the hydrodynamics of long waves. He also specializes in analysis of the tsunami source mechanism from seismic data and ocean observations. He joined Pacific Marine Environmental Laboratory and University of

Washington in 2006. He is currently the leading scientist in NOAA's tsunami modeling team in a multi-year effort to develop high-resolution tsunami inundation models for U.S. coasts.

Daniel Wright: Daniel Wright is a 4th year Ph.D. candidate in Environmental Engineering and Water Resources at Princeton University, focusing on flood risk estimation in urban environments. At Princeton, he is also a participant in the Science, Technology, and Environmental Policy certificate program, looking at climate and land use impacts on flood hazards. He has Bachelor's and Master's degrees in Civil and Environmental Engineering from the University of Michigan where he focused on water resources engineering. From 2006-2008 Daniel served as a Regional Sanitation Engineer in the Peace Corps in Monteagudo, and later as a hydraulic engineer Daniel at an engineering firm in Concepción, Chile developing low-impact hydroelectric power projects. He is interested in the intersection of engineering, policy, and development in water resources and climate adaptation.