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PROCEEDINGS OF NRC ANNUAL PROBABILISTIC FLOOD HAZARD ASSESSMENT RESEARCH WORKSHOPS I-IV

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Part 2: *Second Annual NRC Probabilistic Flood Hazard Assessment Research Workshop*

Research Information Letter
Research Office of Nuclear Regulatory Research

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ABSTRACT

The U.S. Nuclear Regulatory Commission (NRC) Office of Nuclear Regulatory Research (RES) is conducting a multiyear, multi-project Probabilistic Flood Hazard Assessment (PFHA) Research Program to enhance the NRC's risk-informed and performance-based regulatory approach with regard to external flood hazard assessment and safety consequences of external flooding events at nuclear power plants (NPPs). It initiated this research in response to staff recognition of a lack of guidance for conducting PFHAs at nuclear facilities that required staff and licensees to use highly conservative deterministic methods in regulatory applications. Risk assessment of flooding hazards and consequences of flooding events is a recognized gap in NRC's risk-informed, performance-based regulatory framework. The objective, research themes, and specific research topics are described in the RES Probabilistic Flood Hazard Assessment Research Plan. While the technical basis research, pilot studies and guidance development are ongoing, RES has been presenting Annual PFHA Research Workshops to communicate results, assess progress, collect feedback and chart future activities. These workshops have brought together NRC staff and management from RES and User Offices, technical support contractors, as well as interagency and international collaborators and industry and public representatives.

These conference proceedings transmit the agenda, abstracts, presentation slides, summarized questions and answers, and panel discussion for the first four Annual U.S. Nuclear Regulatory Commission (NRC) Probabilistic Flood Hazard Assessment Research Workshops held at NRC Headquarters in Rockville, MD. The workshops took place on October 14–15, 2015; January 23–25, 2017; December 4–5, 2017; and April 30–May 2, 2019. The first workshop was an internal meeting attended by NRC staff, contractors, and partner Federal agencies. The following workshops were public meetings and attended by members of the public; NRC technical staff, management, and contractors; and staff from other Federal agencies. All of the workshops began with an introductory session that included perspectives and research program highlights from the NRC Office of Nuclear Regulatory Research and also may have included perspectives from the NRC Office of New Reactors and Office of Nuclear Reactor Regulation, the Electric Power Research Institute (EPRI), and industry representatives. NRC and EPRI contractors and staff as well as invited Federal and public speakers gave technical presentations and participated in various styles of panel discussion. Later workshops included poster sessions and participation from academic and interested students. The workshops included five focus areas:

(1) leveraging available flood information
(2) evaluating the application of improved mechanistic and climate probabilistic modeling for storm surge, climate and precipitation
(3) probabilistic flood hazard assessment frameworks
(4) potential impacts of dynamic and nonstationary processes
(5) assessing the reliability of flood protection and plant response to flooding events

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ABBREVIATION AND ACRONYMS

σ	sigma, standard deviation
°C	degrees Celsius
°F	degrees Fahrenheit
^{13}C-NMR	carbon-13 nuclear magnetic resonance
^{14}C	carbon-14
17B	Guidelines for Determining Flood Flow Frequency—Bulletin 17B, 1982
17C	Guidelines for Determining Flood Flow Frequency—Bulletin 17C, 2018
1-D	one dimensional
20C	20th Century Reanalysis
2BCMB	Level 2—DPR and GMI Combine
2-D	two dimensional
3-D	three dimensional
AAB	Accident Analysis Branch in NRC/RES/DSA
AB	auxiliary building
AC, ac	alternating current
ACCP	Alabama Coastal Comprehensive Plan
ACE	accumulated cyclone energy, an approximation of the wind energy used by a tropical system over its lifetime
ACM	alternative conceptual model
ACME	Accelerated Climate Modeling for Energy (DOE)
ACWI	Advisory Committee on Water Information
AD	anno Domini
ADAMS	Agencywide Documents Access and Management System
ADCIRC	ADvanced CIRCulation model
AEP	annual exceedance probability
AEP4	Asymmetric Exponential Power distribution
AFW	auxiliary feedwater
AGCMLE	Assistant General Counsel for Materials Litigation and Enforcement in NRC/OGC/GCHA
AGCNRP	Assistant General Counsel for New Reactor Programs in NRC/OGC/GCHA
AGFZ	Azores–Gibraltar Transform Fault
AGL	above ground level
AIC	Akaike Information Criterion

AIMS	assumptions, inputs, and methods
AIRS	Advanced InfraRed Sounder
AIT	air intake tunnel
AK	Alaska
AM	annual maxima
AMJ	April, May, June
AMM	Atlantic Meridional Mode
AMO	Atlantic Multi-Decadal Oscillation
AMS	annual maxima series
AMSR-2	Advance Microwave Scanning Radiometer
AMSU	Advanced Microwave Sounding Unit
ANN	annual
ANO	Arkansas Nuclear One
ANOVA	analysis of variance decomposition
ANS	American Nuclear Society
ANSI	American National Standards Institute
ANVS	Netherlands Authority for Nuclear Safety and Radiation Protection
AO	Assistant for Operations in NRC/OEDO
AOP	abnormal operating procedure
APF	annual probability of failure
APHB	Probabilistic Risk Assessment Operations and Human Factors Branch
API	application programming interface
APLA/APLB	Probabilistic Risk Assessment Licensing Branch A/B in NRC/NRR/DRA
APOB	PRA Oversight Branch in NRC/NRR/DRA
AR	atmospheric river
AR	Arkansas
AR4, AR5	climate scenarios from the 4th/5th Intergovernmental Panel on Climate Change Reports / Working Groups
ARA	Applied Research Associates
ArcGIS	geographic information system owned by ESRI
ARF	areal reduction factor
ARI	average return interval
ARR	Australian Rainfall-Runoff Method
AS	adjoining stratiform
ASM	annual series maxima

ASME	American Society of Mechanical Engineers
ASN	French Nuclear Safety Authority (Autorité de Sûreté Nucléaire)
ASTM	American Society for Testing and Materials
ATMS	Advance Technology Microwave Sounder
ATWS	anticipated transient without scram
AVHRR	Advance Very High Resolution Radiometer
B&A	Bittner & Associates
BATEA	Bayesian Total Error Analysis
BB	backbuilding/quasistationary
BC	boundary condition
Bel V	subsidiary of Belgian Federal Agency for Nuclear Control (FANC)
BHM	Bayesian Hierarchical Model
BIA	Bureau of Indian Affairs
BMA	Bayesian Model Averaging
BQ	Bayesian Quadrature
BWR	boiling-water reactor
CA	California
CAC	common access card
CAPE	Climate Action Peer Exchange
CAPE	convective available potential energy
CAS	corrective action study
CAS2CD	CAScade 2-Dimensional model (Colorado State)
Cat.	category on the Saffir-Simpson Hurricane Wind Scale
CBR	center, body, and range
CC	Clausius-Clapeyron
CC	climate change
CCCR	Center for Climate Change Research
CCDP	conditional core damage probability
CCI	Coppersmith Consulting Inc.
CCSM4	Community Climate System Model version 4
CCW	closed cooling water
CDB	current design basis
CDF	core damage frequency
CDF	cumulative distribution function

CE	common era
CEATI	Centre for Energy Advancement through Technological Innovation
CEET	cracked embankment erosion test
CENRS	National Science and Technology Council Committee on Environment, Natural Resources, and Sustainability
CESM	Community Earth System Model
CFD	computational fluid dynamics
CFHA	comprehensive flood hazard assessment
CFR	*Code of Federal Regulations*
CFSR	Climate Forecast System Reanalysis
CHIPs	Coupled Hurricane Intensity Prediction System
CHiRPs	Climate Hazards Group infraRed Precipitation with Station Data
CHL	Coastal and Hydraulics Laboratory
CHRP	Coastal Hazard Rapid Prediction, part of StormSIM
CHS	Coastal Hazards System
CI	confidence interval
CICS-NC	Cooperative Institute for Climates and Satellites—North Carolina
CIPB	Construction Inspection Management Branch in NRC/NRO/DLSE
CIRES	Cooperative Institute for Research in Environmental Sciences
CL	confidence level
CL-ML	homogeneous silty clay soil
CMC	Canadian Meteorological Center forecasts
CMIP5	Coupled Model Intercomparison Project Phase 5
CMORPH / C-MORPH	Climate Prediction Center Morphing Technique
CNE	Romania Consiliul National al Elevilor
CNSC	Canadian Nuclear Safety Commission
CO	Colorado
CoCoRaHS	Community Collaborative Rain, Hail & Snow Network (NWS)
COE	U.S. Army Corps of Engineers (see also USACE)
COL	combined license
COLA	combined license application
COM-SECY	NRC staff requests to the Commission for guidance
CONUS	Continental United States
COOP	Cooperative Observer Network (NWS)

COR	contracting officer’s representative
CPC	Climate Prediction Center (NOAA)
CPFs	cumulative probability functions
CR	comprehensive review
CRA	computational risk assessment
CRB	Concerns Resolution Branch in NRC/OE
CRL	coastal reference location
CRPS	continuous ranked probability score
CSNI	Committee on the Safety of Nuclear Installations
CSRB	Criticality, Shielding & Risk Assessment Branch in NRC/NMSS/DSFM
CSSR	Climate Science Special Report (by the U.S. Global Change Research Program)
CSTORM	Coastal Storm Modeling System
CTA Note	note to Commissioners’ Assistants
CTXS	Coastal Texas Study
C_V	coefficient of variation
CZ	capture zone
DC	District of Columbia
DAD	depth-area-duration
DAMBRK	Dam Break Flood Forecasting Model (NWS)
DAR	Division of Advanced Reactors in NRC/NRO
DayMet	daily surface weather and climatological summaries
dBz	decibel relative to z, or measure of reflectivity of radar
DCIP	Division of Construction Inspection and Operational Programs in NRC/NRO
DDF	depth-duration-frequency curve
DDM	data-driven methodology
DDST	database of daily storm types
DE	Division of Engineering in NRC/RES
DHSVM	distributed hydrology soil vegetation model, supported by University of Washington
DIRS	Division of Inspection and Regional Support in NRC/NRR
DJF	December, January, February
DLBreach	Dam/Levee Breach model developed by Weiming Wu, Clarkson University
DLSE	Division of Licensing, Siting, and Environmental Analysis in NRC/NRO

DOE	U.S. Department of Energy
Dp	pressure deficit
DPI	power dissipation index
DPR	Division of Preparedness and Response in NRC/NSIR
DPR	Dual Frequency Precipitation Radar
DQO	data quality objective
DRA	Division of Risk Assessment in NRC/NRR
DRA	Division of Risk Analysis in NRC/RES
DREAM	Differential Evolution Adaptive Metropolis
DRP	Division of Reactor Projects in NRC/R-I
DRS	Division of Reactor Safety In NRC/R-I and R-IV
DSA	Division of Systems Analysis in NRC/RES
DSEA	Division of Site Safety and Environmental Analysis, formerly in NRC/NRO, now in DLSE
DSFM	Division of Spent Fuel Management in NRC/NMSS
DSI3240	NCEI hourly precipitation data
DSMS	Dam Safety Modification Study
DSMS	digital surface models
DSPC	USACE Dam Safety Production Center
DSRA	Division of Safety Systems, Risk Assessment and Advanced Reactors in NRC/NRO (merged into DAR)
DSS	Division of Safety Systems in NRC/NRR
DSS	Hydrologic Engineering Center Data Storage System
DTWD	doubly truncated Weibull distribution
DUWP	Division of Decommissioning, Uranium Recovery, and Waste Programs in NRC/NMSS
DWOPER	Operational Dynamic Wave Model (NWS)
dy	day
EAD	expected annual damage
EB2/EB3	Engineering Branch 2/3 in NRC/R-IV/DRS
EBTRK	Tropical Cyclone Extended Best Track Dataset
EC	Eddy Covariance Method
EC	environmental condition
ECC	ensemble copula coupling
ECCS	emergency core cooling systems pump

ECs	environmental conditions
EDF	Électricité de France
EDG	emergency diesel generator
EF	environmental factor
EFW	emergency feedwater
EGU	European Geophysical Union
EHCOE	NRC External Hazard Center of Expertise
EHID	External Hazard Information Digest
EIRL	equivalent independent record length
EIS	environmental impact statement
EKF	Epanechikov kernel function
EMA	expected moments algorithm
EMCWF	European Centre for Medium-Range Weather Forecasts
EMDR	eastern main development region (for hurricanes)
EMRALD	Event Model Risk Assessment using Linked Diagrams
ENSI	Swiss Federal Nuclear Safety Inspectorate
ENSO	El Niño Southern Oscillation
EPA	U.S. Environmental Protection Agency
EPIP	emergency plan implementing procedure
EPRI	Electric Power Research Institute
ER	engineering regulation (USACE)
ERA-40	European ECMWF reanalysis dataset
ERB	Environmental Review Branch in NRC/NMSS/FCSE
ERDC	Engineer Research and Development Center (USACE)
ERL	equivalent record length
ESCC	Environmental and Siting Consensus Committee (ANS)
ESEB	Structural Engineering Branch in NRC/RES/DE
ESEWG	Extreme Storm Events Work Group (ACWI/SOH)
ESP	early site permit
ESRI	Environmental Systems Research Institute
ESRL	Earth Systems Research Lab (NOAA/OAR)
EST	Eastern Standard Time
EST	empirical simulation technique
ESTP	enhanced storm transposition procedure

ET	event tree
ET	evapotranspiration
ET/FT	event tree/fault tree
ETC	extratropical cyclone
EUS	eastern United States
EV4	extreme value with four parameters distribution function
EVA	extreme value analysis
EVT	extreme value theory
EXHB	External Hazards Branch in NRC/NRO/DLSE
Exp	experimental
f	annual probability of failure (USBR, USACE)
F1, F5	tornado strengths on the Fujita scale
FA	frequency analysis
FADSU	fluvial activity database of the Southeastern United States
FAQ	frequently asked question
FAST	Fourier Analysis Sensitivity Test
FBPS	flood barrier penetration seal
FBS	flood barrier system
FCM	flood-causing mechanism
FCSE	Division of Fuel Cycle Safety, Safeguards & Environmental Review in NRC/NMSS
FD	final design
FDC	flood design category (DOE terminology)
FEMA	Federal Emergency Management Agency
FERC	Federal Energy Regulatory Commission
FFA	flood frequency analysis
FFC	flood frequency curve
FHRR	flood hazard reevaluation report
FITAG	Flooding Issues Technical Advisory Group
FL	Florida
FLDFRQ3	U.S. Bureau of Reclamation flood frequency analysis tool
FLDWAV	flood wave model (NWS)
FLEX	diverse and flexible mitigation strategies
Flike	extreme value analysis package developed University of Newcastle, Australia

FLO-2D	two-dimensional commercial flood model
FM Approvals	Testing and Certification Services Laboratories, originally Factory Mutual Laboratories
f-N	annual probability of failure vs. average life loss, N
FOR	peak flood of record
FPM	flood protection and mitigation
FPS	flood penetration seal
FRA	Flood Risk Analysis Compute Option in HEC-WAT
FRM	Fire Risk Management, Inc.
FSAR	final safety analysis report
FSC	flood-significant component
FSG	FLEX support guidelines
FSP	flood seal for penetrations
FT	fault tree
ft	foot
FXHAB	Fire and External Hazards Analysis Branch in NRC/RES/DRA
FY	fiscal year
G&G	geology and geotechnical engineering
GA	generic action
GCHA	Deputy General Counsel for Hearings and Administration in NRC/OGC
GCM	Global Climate Model
GCRP	U.S. Global Change Research Program
GCRPS	Deputy General Counsel for Rulemaking and Policy Support in NRC/OGC
GEFS	Global Ensemble Forecasting System
GeoClaw	routines from Clawpack-5 (“Conservation Laws Package”) that are specialized to depth-averaged geophysical flows
GEO-IR	Geostationary Satellites—InfraRed Imagery
GEV	generalized extreme value
GFDL	Geophysical Fluid Dynamics Lab (NOAA)
GFS	Global Forecast System
GHCN	Global Historical Climatology Network
GHCND	Global Historical Climatology Network-Daily
GIS	geographic information system
GISS	Goddard Institute for Space Studies (NASA)

GKF	Gaussian Kernel Function
GL	generic letter
GLO	generalized logistic distribution
GLRCM	Great Lakes Regional Climate Model
GLUE	generalized likelihood uncertainty estimation
GMAO	Global Modeling and Assimilation Office (NASA)
GMC	ground motion characterization
GMD	geoscientific model development
GMI	GPM microwave imager
GMSL	global mean sea level
GNO	generalized normal distribution
GoF	goodness-of-fit
GPA/GPD	generalized Pareto distribution
GPCP SG	Global Precipitation Climatology Project—Satellite Gauge
GPLLJ	Great Plains lower level jet
GPM	Gaussian process metamodel
GPM	global precipitation measurement
GPO	generalized Pareto distribution
GPROF	Goddard profile algorithm
GRADEX	rainfall-based flood frequency distribution method
Grizzly	simulated component aging and damage evolution events RISMC tool
GRL	Geophysical Research Letters
GRS	Gesellschaft für Anlagen- und Reaktorsicherheit—Global Research for Safety
GSA	global sensitivity analysis
GSFC	Goddard Space Flight Center
GSI	generic safety issue
GUI	graphical user interface
GW-GC	Well-graded gravel with clay and sand
GZA	a multidisciplinary consulting firm
h	second shape parameter of four-parameter Kappa distribution
h/hr	hour
H&H	hydraulics and hydrology
HAMC	hydraulic model characterization

HBV	rainfall runoff model Hydrologiska Byråns Vattenbalansalvdening, supported by the Swedish Meteorological and Hydrological Institute
HCA	hierarchical clustering analysis
HCTISN	Supreme Committee for Transparency and Information on Nuclear Safety (France)
HCW	hazardous convective weather
HDSC	NOAA/NWS/OWP Hydrometeorological Design Studies Center
HEC	Hydrologic Engineering Center, part of USACE/Institute for Water Resources
HEC-1	see HEC-HMS
HEC-FIA	Hydrologic Engineering Center Flood Impact Analysis Software
HEC-HMS	Hydrologic Modeling System
HEC-LifeSim	Hydrologic Engineering Center life loss and direct damage estimation software
HEC-MetVue	Hydrologic Engineering Center Meteorological Visualization Utility Engine
HEC-RAS	Hydrologic Engineering Center River Analysis System
HEC-ResSim	Hydrologic Engineering Center Reservoir System Simulation
HEC-SSP	Hydrologic Engineering Center Statistical Software Package
HEC-WAT	Hydrologic Engineering Center Watershed Analysis Tool
HEP	human error probability
HF	human factors
HFRB	Human Factors and Reliability Branch in NRC/RES/DRA
HHA	hydrologic hazard analysis
HHC	hydrologic hazard curve
HI	Hawaii
HLR	high-level requirement
HLWFCNS	Assistant General Counsel for High-Level Waste, Fuel Cycle and Nuclear Security in NRC/OGC/GCRPS
HMB	Hazard Management Branch in NRC/NRR/JLD, realigned
HMC	hydraulic/hydrologic model characterization
HMR	NOAA/NWS Hydrometeorological Report
HMS	hydrologic modeling system
HOMC	hydrologic model characterization
hPa	hectopascals (unit of pressure)

HR	homogenous region
HRA	human reliability analysis
HRL	Hydrologic Research Lab, University of California at Davis
HRRR	NOAA High-Resolution Rapid Refresh Model
HRRs	Fukushima Hazard Reevaluation Reports (EPRI term)
HRU	hydrologic runoff unit approach
HUC	hydrologic unit code for watershed (USGS)
HUNTER	human actions RISMC tool
HURDAT	National Hurricane Centers HURricane DATabases
Hz	hertz (1 cycle/second)
IA	integrated assessment
IA	Iowa
IAEA	International Atomic Energy Agency
IBTrACS	International Best Track Archive for Climate Stewardship
IC	initial condition
ICOLD	International Commission on Large Dams
ID	information digest
IDF	intensity-duration frequency curve
IDF	inflow design flood
IE	initiating event
IEF	initiating event frequency
IES	Dam Safety Issue Evaluation Studies
IHDM	Institute of Hydrology Distributed Model, United Kingdom
IID	independent and identically distributed
IL	Illinois
IMERG	Integrated Multi-satellitE Retrievals for GPM
IMPRINT	Improved Performance Research Integration Tool
in	inch
IN	information notice
INES	International Nuclear and Radiological Event Scale
INL	Idaho National Laboratory
IPCC	Intergovernmental Panel on Climate Change
IPE	individual plant examination
IPEEE	individual plant examination for external events

IPET	Interagency Performance Evaluation Taskforce for the Performance Evaluation of the New Orleans and Southeast Louisiana Hurricane Protection System
IPWG	International Precipitation Working Group
IR	infrared
IR	inspection report
IRIB	Reactor Inspection Branch in NRC/NRR/DIRS
IRP	Integrated Research Projects (DOE)
IRSN	Institut de Radioprotection et de Sûreté Nucléaire (France’s Radioprotection and Nuclear Safety Institute)
ISG	interim staff guidance
ISI	inservice inspection
ISR	interim staff response
IT	information technology
IVT	integrated vapor transport
IWR	USACE Institute for Water Resources
IWVT	integrated water vapor tendency
J	joule
JJA	June, July, August
JLD	Japan Lesson-learned Directorate or Division in NRC/NRR, realigned
JPA	Joint Powers Authority (FEMA Region II)
JPA	joint probability analysis
JPM	joint probability method
JPM-OS	Joint Probability Method with Optimal Sampling
K	degrees Kelvin
KAERI	Korea Atomic Energy Research Institute
KAP	Kappa distribution
k_d	erodibility coefficient
kg	kilogram
kHz	kilohertz (1000 cycles/second)
km	kilometer
KS	Kansas
LA	Louisiana
LACPR	Louisiana Coastal Protection and Restoration Study
LAR	license amendment request

L-C_v	coefficient of L-variation
LEO	low earth orbit
LER	licensee event report
LERF	large early release frequency
LIA	Little Ice Age
LiDAR	light imaging, detection and ranging; surveying method using reflected pulsed light to measure distance
LIP	local intense precipitation
LMI	lifetime maximum intensity
LMOM / LMR	L-moment
LN4	Slade-type four parameter lognormal distribution function
LOCA	localized constructed analog
LOCA	loss-of-coolant accident
LOOP	loss of offsite power event
LOUHS	loss of ultimate heat sink event
LPIII / LP-III, LP3	Log Pearson Type III distribution
LS	leading stratiform
LS	local storm
LSHR	late secondary heat removal
LTWD	Left-truncated Weibull distribution
LULC	land use and land cover
LWR	light-water reactor
LWRS	Light-Water Reactor Sustainability Program
m	meter
MA	Massachusetts
MA	manual action
MAAP	coupling accident conditions RISMC tool
MAE	mean absolute error
MAM	March, April, May
MAP	mean annual precipitation
MASTODON	structural dynamics, stochastic nonlinear soil-structure interaction in a risk framework RISMC tool
mb	millibar
MCA	medieval climate anomaly
MCC	mesoscale convective complex

MCI	Monte Carlo integration
MCLC	Monte Carlo Life-Cycle
MCMC	Markov chain Monte Carlo method
MCRAM	streamflow volume stochastic modeling
MCS	mesoscale convective system
MCS	Monte Carlo simulation
MCTA	Behrangi Multisatellite CloudSat TRMM Aqua Product
MD	Maryland
MDL	Meteorological Development Laboratory (NWS)
MDR	Main Development Region (for hurricanes)
MDT	Methodology Development Team
MEC	mesoscale storm with embedded convection
MEOW	Maximum Envelopes of Water
MetStorm	storm analysis software by MetStat, second generation of SPAS
MGD	meta-Gaussian distribution
MGS Engineering	engineering consultants
MHS	microwave humidity sounder
MIKE SHE/ MIKE 21	integrated hydrological modeling system
MLC	mid-latitude cyclone
MLE	maximum likelihood estimation
mm	millimeter
MM5	fifth-generation Penn State/NCAR mesoscale model
MMC	mesh-based Monte Carlo method
MMC	meteorological model characterization
MMF	multimechanism flood
MMP	mean monthly precipitation
MN	Minnesota
MO	Missouri
Mode 3	Reactor Operation Mode: Hot Standby
Mode 4	Reactor Operation Mode: Hot Shutdown
Mode 5	Reactor Operation Mode: Cold Shutdown
MOM	Maximum of MEOWs
MOU	memorandum of understanding
MPE	multisensor precipitation estimates

mph	miles per hour
MPS	maximum product of spacings
MRMS	Multi-Radar Multi-Sensor project (NOAA/NSSL)
MS	Mississippi
MSA	mitigating strategies assessment
MSFHI	mitigating strategies flood hazard information
MSL	mean sea level
MSWEP	multisource weighted-ensemble precipitation dataset
MVGC	multivariable Gaussian copula
MVGD	multivariable Gaussian distribution
MVTC	multivariable student’s t copula
N	average life loss (USBR, USACE)
NA14	NOAA National Atlas 14
NACCS	North Atlantic Coast Comprehensive Study
NAEFS	North American Ensemble Forecasting System
NAIP	National Agricultural Imagery Program
NAM-WRF	North American Mesoscale Model—WRF
NAO	North Atlantic Oscillation
NARCCAP	North American Regional Climate Change Assessment Program
NARR	North American Regional Reanalysis (NOAA)
NARSIS	European Research Project New Approach to Reactor Safety Improvements
NASA	National Aeronautics and Space Administration
NAVD88	North American Vertical Datum of 1988
NBS	net basin scale
NCA3/NCA4	U.S. Global Change Research Program Third/Fourth National Climate Assessment
NCAR	National Center for Atmospheric Research
NCEI	National Centers for Environmental Information
NCEP	National Centers for Environmental Prediction (NOAA)
ND	North Dakota
NDFD	National Digital Forecast Database (NWS)
NDSEV	number of days with severe thunderstorm environments
NE	Nebraska
NEA	Nuclear Energy Agency

NEB	nonexceedance bounds
NEI	Nuclear Energy Institute
NESDIS	NOAA National Environmental Satellite, Data, and Information Service
NEUTRINO	a general-purpose simulation and visualization environment including an SPH solver
NEXRAD	next-generation radar
NHC	National Hurricane Center
NI DAQ	National Instruments Data Acquisition Software
NID	National Inventory of Dams
NIOSH	National Institute for Occupational Safety and Health
NLDAS	North American Land Data Assimilation System
nm	nautical miles
NM	New Mexico
NMSS	NRC Office of Nuclear Material Safety and Safeguards
NOAA	National Oceanic and Atmospheric Administration
NOED	notice of enforcement discretion
NPDP	National Performance of Dams Program
NPH	Natural Phenomena Hazards Program (DOE)
NPP	nuclear power plant
NPS	National Park Service
NRC	U.S. Nuclear Regulatory Commission
NRCS	Natural Resources Conservation Service
NRO	NRC Office of New Reactors
NRR	NCEP-NCAR Reanalysis
NRR	NRC Office of Nuclear Reactor Regulation
NSE	Nash-Sutcliffe model efficiency coefficient
NSIAC	Nuclear Strategic Issues Advisory Committee
NSIR	NRC Office of Nuclear Security and Incident Response
NSSL	National Severe Storms Laboratory (NOAA)
NSTC	National Science and Technology Council
NTTF	Near-Term Task Force
NUREG	NRC technical report designation
NUVIA	a subsidiary of Vinci Construction Group, offering expertise in services and technology supporting safety performance in nuclear facilities
NWS	National Weather Service

NY	New York
OAR	NOAA Office of Oceanic and Atmospheric Research
OE	NRC Office of Enforcement
OECD	Organization for Economic Co-operation and Development
OEDO	NRC Office of the Executive Director for Operations
OGC	NRC Office of the General Counsel
OHC	ocean heat content
OK	Oklahoma
OR	Oregon
ORNL	Oak Ridge National Laboratory
OSL	optically stimulated luminescence
OTC	once-through cooling
OWI	Ocean Wind Inc.
OWP	NOAA/NWS Office of Water Prediction
P	present
P/PET	precipitation over PET ratio, aridity
Pa	pascal
PB1	Branch 1 in NRC/R-I/DRP
PBL	planetary boundary layer
PCA	principal component analysis
PCHA	probabilistic coastal hazard assessment
PCMQ	Predictive Capability Maturity Quantification
PCMQBN	Predictive Capability Maturity Quantification by Bayesian Net
PD	performance demand
PDF	probability density function
PDF	performance degradation factor
PDS	partial-duration series
PE3	Pearson Type III distribution
PeakFQ	USGS flood frequency analysis software tool based on Bulletin 17C
PERSIANN-CCS	Precipitation Estimation from Remotely Sensed Information using Artificial Neural Networks—Cloud Classification System (University of California at Irvine Precipitation Algorithm)
PERT	program evaluation review technique
PET	potential evapotranspiration
P-ETSS	Probabilistic Extra-Tropical Storm Surge Model

PF	paleoflood
PF/P-F	precipitation frequency
PFAR	precipitation field area ratio
PFHA	probabilistic flood hazard assessment
PFM	potential failure mode
PI	principal investigator
P-I	pressure-impulse curve
PIF	performance influencing factor
PILF	potentially influential low flood
PM	project manager
PMDA	Program Management, Policy Development & Analysis in NRC/RES
PMF	probable maximum flood
PMH	probable maximum hurricane
PMP	probable maximum precipitation
PMW	passive microwave
PN	product number
PNAS	Proceedings of the National Academy of Sciences of the United States of America
PNNL	Pacific Northwest National Laboratory
POANHI	Process for Ongoing Assessment of Natural Hazard Information
POB	Regulatory Policy and Oversight Branch in NRC/NSIR/DPR
POR	period of record
PPRP	participatory peer review panel
PPS	Precipitation Processing System
PR	Puerto Rico
PRA	probabilistic risk assessment
PRAB	Probabilistic Risk Assessment Branch in NRC/RES/DRA
PRB	Performance and Reliability Branch in NRC/RES/DRA
PRISM	a gridded dataset developed through a partnership between the NRCS National Water and Climate Center and the PRISM Climate Group at Oregon State University, developers of PRISM (the Parameter-elevation Regressions on Independent Slopes Model)
PRMS	USGS Precipitation Runoff Modelling System
Prométhée	IRSN software based on PROMETHEE, the Preference Ranking Organization METhod for Enrichment Evaluation
PRPS	Precipitation Retrieval Profiles Scheme

PS	parallel stratiform
PSA	probabilistic safety assessment, common term for PRA in other countries
PSD	Physical Sciences Division in NOAA/OAR/ESRL
PSF	performance shaping factor
psf	pounds per square foot
PSHA	probabilistic seismic hazard assessment
PSI	paleostage indicators
PSSHA	probabilistic storm surge hazard assessment
P-Surge	probabilistic tropical cyclone storm surge model
PTI	project technical integrator
PVC	polyvinyl chloride
Pw/PW	precipitable water
PWR	pressurized-water reactor
Q	quarter
QA	quality assurance
QC	quality control
QI	Quality Index
QPE	quantitative precipitation estimates
QPF	quantitative precipitation forecast
R	a statistical package
R 2.1	NTTF Report Recommendation 2.1
R&D	research and development
R2	coefficient of determination
RAM	regional atmospheric model
RASP	Risk Assessment of Operational Events Handbook
RAVEN	risk analysis in a virtual environment probabilistic scenario evolution RISMC tool
RC	reinforced concrete
RCP (4.5, 8.5)	representative concentration pathways
RELAP-7	reactor excursion and leak analysis program transient conditions RISMC tool
RENV	Environmental Technical Support Branch in NRC/NRO/DLSE
REOF	rotated empirical orthogonal function
RES	NRC Office of Nuclear Regulatory Research

RF	riverine flooding
RFA	regional frequency analysis
RFC	River Forecast Center (NWS)
RG	regulatory guide
RGB	red, green, and blue imagery (NAIP)
RGB-IF	red, green, blue, and infrared imagery (NAIP)
RGC	regional growth curve
RGGIB	Regulatory Guidance and Generic Issues Branch in NRC/RES/DE
RGS	Geosciences and Geotechnical Engineering Branches now in NRC/NRO/DLSE, formerly in NRC/NRO/DSEA
RHM	Hydrology and Meteorology Branch formerly in NRC/NRO/DSEA
RI	Rhode Island
R-I, R-II, R-III, R-IV	NRC Regions I, II, III, IV
RIC	Regulatory Information Conference, NRC
RIDM	risk-informed decisionmaking
RILIT	Risk-Informed Licensing Initiative Team in NRC/NRR/DRA/APLB
RISMC	risk information safety margin characterization
R_{max}	radius to maximum winds
RMB	Renewals and Materials Branch in NRC/NMSS/DSFM
RMC	USACE Risk Management Center
RMSD	root-mean-square deviation
RMSE	root mean square error
ROM	reduce order modeling
ROP	Reactor Oversight Process
RORB-MC	an interactive runoff and streamflow routing program
RPAC	formerly in NRC/NRO/DSEA
RRTM	Rapid Radiative Transfer Model Code in WRF
RRTMS	RRTM with GCM application
RS	response surface
RTI	an independent, nonprofit institute
RV	return values
SA	storage area
SACCS	South Atlantic Coastal Comprehensive Study
SAPHIR	Sounding for Probing Vertical Profiles of Humidity

SAPHIRE	Systems Analysis Programs for Hands-on Integrated Reliability Evaluations
SBDFA	simulation-based dynamic flooding analysis framework
SBO	station blackout
SBS	simulation-based scaling
SC	safety category (ANS 58.16-2014 term)
SC	South Carolina
SCAN	Soil Climate Analysis Network
SCRAM	immediate shutdown of nuclear reactor
SCS	curve number method
SD	standard deviation
SDC	shutdown cooling
SDP	significance determination process
SDR	Subcommittee on Disaster Reduction
SECY	written issues paper the NRC staff submits to the Commission
SEFM	Stochastic Event-Based Rainfall-Runoff Model
SER	safety evaluation report
SGSEB	Structural, Geotechnical and Seismic Engineering Branch in NRC/RES/DE
SHAC-F	Structured Hazard Assessment Committee Process for Flooding
SHE	Systém Hydrologique Européan
SITES	model that uses headcut erodibility index by USDA-ARS and University of Kansas "Earthen/Vegetated Auxiliary Spillway Erosion Prediction for Dams"
SLC	sea level change
SLOSH	Sea Lake and Overland Surges from Hurricanes (NWS model)
SLR	sea level rise
SMR	small modular reactor
SNOTEL	snow telemetry
SNR	signal-to-noise ratio
SOH	Subcommittee on Hydrology
SOM	self-organizing map
SON	September, October, November
SOP	standard operating pressure
SPAR	standardized plant analysis risk
SPAS	Storm Precipitation Analysis System (MetStat, Inc.)

SPH	smoothed-particle hydrodynamics
SPRA	PRA and Severe Accidents Branch in NRC/NRO/DESR (formerly in DSRA)
SRA	senior reactor analyst
SRES A2	NARCCAP A2 emission scenario
SRH2D/SRH-2D	USBR Sedimentation and River Hydraulics—Two-Dimensional model
SRM	staff requirements memorandum
SRP	standard review plan
SRR	storm recurrence rate
SSAI	Science Systems and Applications, Inc.
SSC	structure, system, and component
SSHAC	Senior Seismic Hazard Assessment Committee
SSM	Swedish Radiation Safety Authority (Strål säkerhets mydigheten)
SSMI	Special Sensor Microwave Imager
SSMIS	Special Sensor Microwave Imager/Sounder
SSPMP	site-specific probable maximum precipitation
SST	sea surface temperature
SST	stochastic simulation technique
SST	stochastic storm transposition
SSURGO	soil survey geographic database
ST4 or Stage IV	precipitation information from multisensor (radar and gauges) precipitation analysis
STEnv	severe thunderstorm environment
STM	stochastic track method
StormSIm	stochastic storm simulation system
STSB	Technical Specifications Branch in NRC/NRR/DSS
STUK	Finland Radiation and Nuclear Safety Authority
STWAVE	STEady-state spectral WAVE model
SÚJB	Czech Republic State Office for Nuclear Safety
SWAN	Simulation Waves Nearshore Model
SWE	snow-water equivalent
SWL	still water level
SWMM	EPA Storm Water Management Model
SWT	Schaefer-Wallis-Taylor Climate Region Method
TAG	EPRI Technical Assessment Guide

TC	tropical cyclone
TCI	TRMM Combined Instrument
Td	daily temperature
TDF	transformed extreme value type 1 distribution function (four parameter)
TDI	technically defensible interpretations
TELEMAC	two-dimensional hydraulic model
TELEMAC 2D	a suite of finite element computer programs owned by the Laboratoire National d'Hydraulique et Environnement (LNHE), part of the R&D group of Électricité de France
T-H	thermohydraulic
TI	technical integration
TI	technology innovation project
TL	training line
TMI	Three Mile Island
TMI	TRMM Microwave Imager
TMPA	TRMM Multisatellite Precipitation Analysis
TN	Tennessee
TOPMODEL	two-dimensional distributed watershed model by Keith Beven, Lancaster University
TOVS	Television-Infrared Observation Satellite (TIROS) Operational Vertical Sounder
TP-#	Test Pit #
TP-29	U.S. Weather Bureau Technical Paper No. 29
TP-40	Technical Paper No. 40, “Rainfall Frequency Atlas of the U.S.,” 1961
TR	USACE technical report
TREX	two-dimensional, runoff, erosion, and export model
TRMM	Tropical Rainfall Measuring Mission
TRVW	Tennessee River Valley Watershed
TS	technical specification
TS	trailing stratiform
TSR	tropical-storm remnant
TUFLOW	two-dimensional hydraulic model
TVA	Tennessee Valley Authority
TX	Texas
U.S. or US	United States
UA	uncertainty analysis

UC	University of California
UH	unit hydrograph
UKF	uniform kernel function
UKMET	medium-range (3- to 7-day) numerical weather prediction model operated by the United Kingdom METeorological Agency
UL	Underwriters Laboratories
UMD	University of Maryland
UNR	user need request
UQ	uncertainty quantification
URMDB	Uranium Recovery and Materials Decommissioning Branch in NRC/NMSS/DUWP
USACE	U.S. Army Corps of Engineers (see also COE)
USACE-NWD	USACE NorthWest Division
USBR	U.S. Bureau of Reclamation
USDA	U.S. Department of Agriculture
USDA-ARS	United State Department of Agriculture—Agricultural Research Service
USFWS	U.S. Fish and Wildlife Service
USGS	United States Geological Survey
UTC	coordinated universal time
VA	Virginia
VDB	validation database
VDMS	Validation Data Management System
VDP	validation data planning
VIC	Variable Infiltration Capacity model
VL-AEP	very low annual exceedance probability
W	watt
WAK	Wakeby distribution
WASH-1400	Reactor Safety Study: An Assessment of Accident Risks in U.S. Commercial Nuclear Power Plants [NUREG-75/014 (WASH-1400)]
WB	U.S. Weather Bureau
WBT	wet bulb temperature
WEI	Weibull distribution
WGEV	Working Group on External Events
WGI	Working Group I
WI	Wisconsin

WinDamC	USDA/NRCS model for estimating erosion of earthen embankments and auxiliary spillways of dams
WL	water level
WMO	World Meteorological Organization
WRB	Willamette River Basin
WRF	Weather Research and Forecasting model
WRR	Water Resources Research (journal)
WSEL / WSL	water surface elevation
WSM6	WRF Single-Moment 6-Class Microphysics Scheme
WSP	USGS Water Supply Paper
XF	external flooding
XFEL	external flood equipment list
XFOAL	external flood operation action list
XFPRA	external flooding PRA
yr	year
yrBP	years before present
Z	Zulu time, equivalent to UTC

INTRODUCTION

Background

The NRC is conducting a multiyear, multi-project Probabilistic Flood Hazard Assessment (PFHA) Research Program. It initiated this research in response to staff recognition of a lack of guidance for conducting PFHAs at nuclear facilities that required staff and licensees to use highly conservative deterministic methods in regulatory applications. The staff described the objective, research themes, and specific research topics in the "Probabilistic Flood Hazard Assessment Research Plan," Version 2014-10-23, provided to the Commission in November 2014 (ADAMS Accession Nos. ML14318A070 and ML14296A442). The PFHA Research Plan was endorsed in a joint user need request by the NRC Office of New Reactors and Office of Nuclear Reactor Regulation (UNR NRO-2015-002, ADAMS Accession No. ML15124A707). This program is designed to support the development of regulatory tools (e.g., regulatory guidance, standard review plans) for permitting new nuclear sites, licensing new nuclear facilities, and overseeing operating facilities. Specific uses of flooding hazard estimates (i.e., flood elevations and associated affects) include flood-resistant design for structures, systems, and components (SSCs) important to safety and advanced planning and evaluation of flood protection procedures and mitigation.

The lack of risk-informed guidance with respect to flooding hazards and flood fragility of SSCs constitutes a significant gap in the NRC's risk-informed, performance-based regulatory approach to the assessment of hazards and potential safety consequences for commercial nuclear facilities. The probabilistic technical basis developed will provide a risk-informed approach for improved guidance and tools to give staff and licensees greater flexibility in evaluating flooding hazards and potential impacts to SSCs in the oversight of operating facilities (e.g., license amendment requests, significance determination processes (SDPs), notices of enforcement discretion (NOEDs)) as well as licensing of new facilities (e.g., early site permit applications, combined license (COL) applications), including proposed small modular reactors (SMRs) and advanced reactors. This methodology will give staff more flexibility in assessing flood hazards at nuclear facilities so the staff will not have to rely on the use of the current deterministic methods, which can be overly conservative in some cases.

The main focus areas of the PFHA Research Program are to (1) leverage available frequency information on flooding hazards at operating nuclear facilities and develop guidance on its use, (2) develop and demonstrate a PFHA framework for flood hazard curve estimation, (3) assess and evaluate application of improved mechanistic and probabilistic modeling techniques for key flood-generating processes and flooding scenarios, (4) assess potential impacts of dynamic and nonstationary processes on flood hazard assessments and flood protection at nuclear facilities, and (5) assess and evaluate methods for quantifying reliability of flood protection and plant response to flooding events. Workshop organizers used these focus areas to develop technical session topics for the workshop.

Workshop Objectives

The Annual PFHA Research Workshops serve multiple objectives: (1) inform and solicit feedback from internal NRC stakeholders, partner Federal agencies, industry, and the public about PFHA research being conducted by the NRC Office of Nuclear Regulatory Research (RES), (2) inform internal and external stakeholders about RES research collaborations with Federal agencies, the Electric Power Research Institute (EPRI) and the French Institute for Radiological and Nuclear

Security (IRNS) and (3) provide a forum for presentation and discussion of notable domestic and international PFHA research activities.

Workshop Scope

Scope of the workshop presentations and discussions included:

- Current and future climate influences on flooding processes
- Significant precipitation and flooding events
- Statistical and mechanistic modeling approaches for precipitation, riverine flooding, and coastal flooding processes
- Probabilistic flood hazard assessment frameworks
- Reliability of flood protection and mitigation features and procedures
- External flooding probabilistic risk assessment

Summary of Proceedings

These proceedings transmit the agenda, abstracts, and slides from presentations and posters presented, and chronicle the question and answer sessions and panel discussions held, at the U.S. Nuclear Regulatory Commission's (NRC's) Annual Probabilistic Flood Hazard Assessment (PFHA) Research Workshops, which take place approximately annually at NRC Headquarters in Rockville, MD. The first four workshops took place as follows:

- 1st Annual NRC PFHA Research Workshop, October 14–15, 2015
- 2nd Annual NRC PFHA Research Workshop, January 23–25, 2017 (Agencywide Documents Access and Management System (ADAMS) Accession No. ML17040A626)
- 3rd Annual NRC PFHA Research Workshop, December 4–5, 2017 (ADAMS Accession No. ML17355A071)
- 4th Annual NRC PFHA Research Workshop, April 30–May 2. 2019 (ADAMS Accession No. ML19156A446)

These proceedings include presentation abstracts and slides and a summary of the question and answer sessions. The first workshop was limited to NRC technical staff and management, NRC contractors, and staff from other Federal agencies. The three workshops that followed were meetings attended by members of the public; NRC technical staff, management, and contractors; and staff from other Federal agencies. Public attendees over the course of the workshops included industry groups, industry members, consultants, independent laboratories, academic institutions, and the press. Members of the public were invited to speak at the workshops. The fourth workshop included more invited speakers from the public than from the NRC and the NRC's contractors.

The proceedings for the second through fourth workshops include all presentation abstracts and slides and submitted posters and panelists' slides. Workshop organizers took notes and audio-recorded the question and answer sessions following each talk, during group panels, and during end-of-day question and answer session. Responses are not reproduced here verbatim and were generally from the presenter or co-authors. Descriptions of the panel discussions identify the speaker when possible. Questions were taken orally from attendees, on question cards, and over the telephone.

Related Workshops

An international workshop on PFHA took place on January 29–31, 2013. The workshop was devoted to sharing information on PFHAs for extreme events (i.e., annual exceedance probabilities (AEPs) much less than 2x10^{-3} per year) from the Federal community). The NRC issued the proceedings as NUREG/CP-302, "Proceedings of the Workshop on Probabilistic Flood Hazard Assessment (PFHA)," in October 2013 (ADAMS Accession No. ML13277A074).

2 SECOND ANNUAL NRC PROBABILISTIC FLOOD HAZARD ASSESSMENT RESEARCH WORKSHOP

2.1 Introduction

This chapter details the 2nd Annual NRC Probabilistic Flood Hazard Assessment (PFHA) Research Workshop held at the U.S. Nuclear Regulatory Commission (NRC) Headquarters in Rockville, MD, on January 23–25, 2017.

The workshop began with an introduction from Mike Weber, Director, NRC Office of Nuclear Regulatory Research (RES). Following the introduction, NRC licensing staff and industry representatives presented their perspectives on PFHA research needs and priorities. Finally, NRC RES and Electric Power Research Institute (EPRI) staff presented descriptions of their flooding research programs.

Following the introduction session, NRC and EPRI contractors and staff gave technical presentations and answered clarifying questions. Partner Federal agencies took part in a panel discussion on their PFHA research and applications. At the end of each day, participants had an opportunity to provide feedback and ask generic questions about research related to PFHA for nuclear facilities.

2.1.1 Organization of Conference Proceedings

Section 2.2 provides the agenda for this workshop. The program is also located at ADAMS Accession No. ML17054C495.

Section 2.3 presents the proceedings from the workshop, including abstract, presentation slides, and summaries of the question and answer session for each of the technical sessions.

The summary document of session abstracts for the technical presentations can be viewed in the PFHA Research Workshop Program at ADAMS Accession No. ML17054C495. The complete workshop presentation package is available at ADAMS Accession No. ML17040A626.

Section 2.4 provides a summary of the workshop and section 1.1 provides a list of the workshop attendees, including remote participants.

2.2 Workshop Agenda

2nd Annual NRC Probabilistic Flood Hazard Assessment Research Workshop at NRC headquarters in Rockville, Maryland

AGENDA: DAY 1: JANUARY 23, 2017

Session 1A - Introduction

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

Session 1B - Storm Surge Research

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

** indicates speaker, ^ indicates remote speaker*

AGENDA: DAY 2, JANUARY 24, 2017

08:00–08:05	Welcome, Day 2	

Session 2A - Climate and Precipitation

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

Session 2B - Leveraging Available Flood Information I

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

Session 2C - Leveraging Available Flood Information II

13:45–14:25	Collection of Paleoflood Evidence *John Weglian, EPRI*	2C-1
14:25–15:05	Paleofloods on the Tennessee River—Assessing the Feasibility of Employing Geologic Records of Past Floods for Improved Flood Frequency Analysis *Tessa Harden*, USGS Oregon Water Science Center*; *and Jim O'Connor*, USGS Geology, Minerals, Energy, and Geophysics Science Center, Portland, OR*	2C-2
15:05–15:20	BREAK	

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

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

AGENDA: DAY 3, JANUARY 25, 2017

08:00–08:05	Welcome, Day 3	

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

08:05–08:45	Effects of Environmental Factors on Manual Actions for Flood Protection and Mitigation at Nuclear Power Plants *Rajiv Prasad*, Garill Coles^, and Angie Dalton^*, *Pacific Northwest National Laboratory; Kristi Branch and Alvah Bittner, Bittner and Associates; and Scott Taylor, Battelle Columbus*	3A-1
08:45–09:25	Modeling Total Plant Response to Flooding Events *Zhegang Ma*, Curtis L. Smith, Steven R. Prescott, Idaho National Laboratory, Risk Assessment and Management Services, and Ramprasad Sampath*, *Centroid PIC, Research and Development*	3A-2

Session 3B - Frameworks I

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

Session 3C - Frameworks II

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

Session 3D - Panel Discussion

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

Session 3E - Future Work in PFHA

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

2.3 Proceedings

2.3.1 Day 1: Session 1A - Introduction

There are no abstracts for this introductory session.

2.3.1.1 Welcome, Michael Weber, Director, Office of Nuclear Regulatory Research, U.S. NRC (Session 1A-1; ADAMS Accession No. ML17054C496)

2.3.1.1.1 Presentation

U.S.NRC

United States Nuclear Regulatory Commission

Protecting People and the Environment

Welcome!

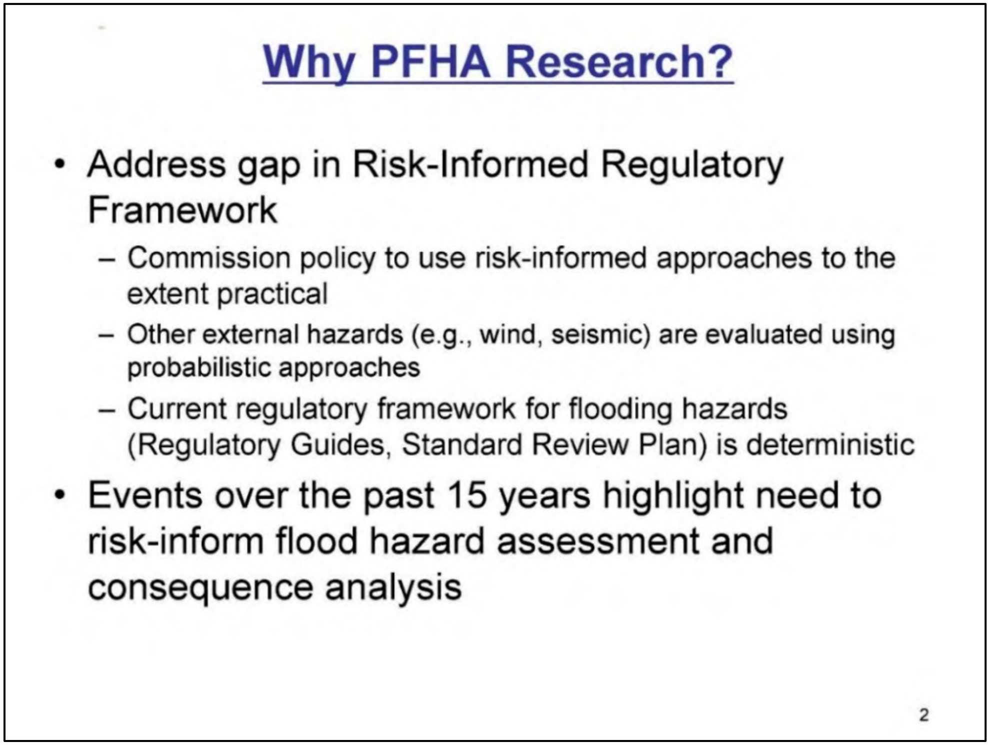
Michael Weber

Director of Nuclear Regulatory Research

2nd PFHA Research Workshop

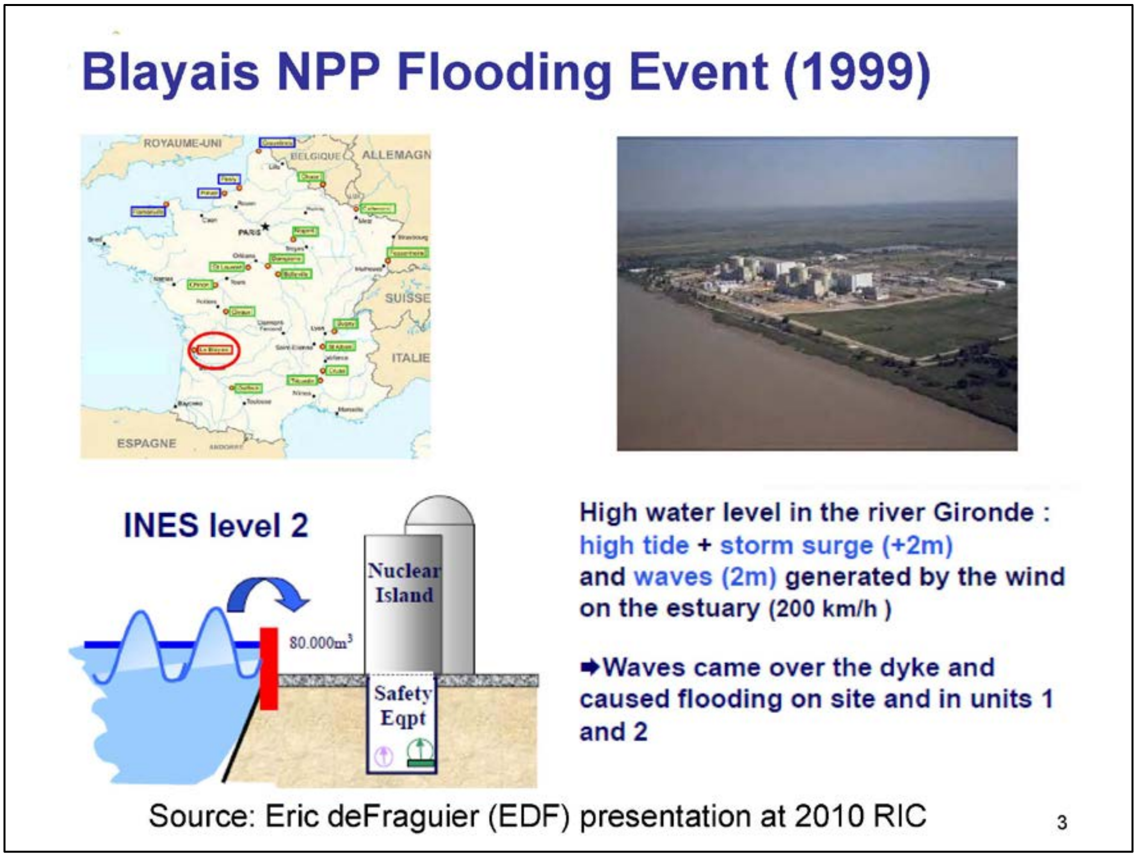
NRC HQ, Rockville, MD

January 23-25, 2017



Why PFHA Research?

- Address gap in Risk-Informed Regulatory Framework
  - Commission policy to use risk-informed approaches to the extent practical
  - Other external hazards (e.g., wind, seismic) are evaluated using probabilistic approaches
  - Current regulatory framework for flooding hazards (Regulatory Guides, Standard Review Plan) is deterministic
- Events over the past 15 years highlight need to risk-inform flood hazard assessment and consequence analysis



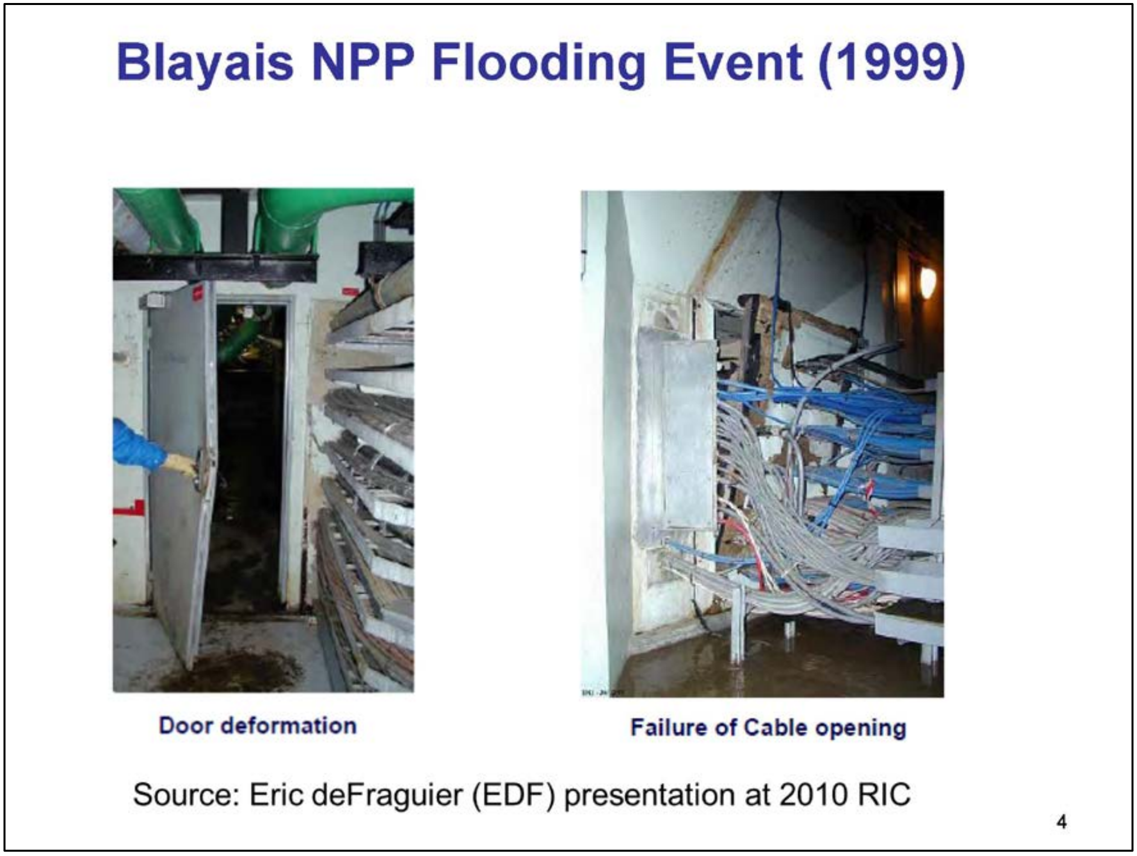
Blayais NPP Flooding Event (1999)

INES level 2

High water level in the river Gironde :
high tide + storm surge (+2m)
and waves (2m) generated by the wind on the estuary (200 km/h)

➡Waves came over the dyke and caused flooding on site and in units 1 and 2

Source: Eric deFraguier (EDF) presentation at 2010 RIC



Blayais NPP Flooding Event (1999)

Door deformation

Failure of Cable opening

Source: Eric deFraguier (EDF) presentation at 2010 RIC

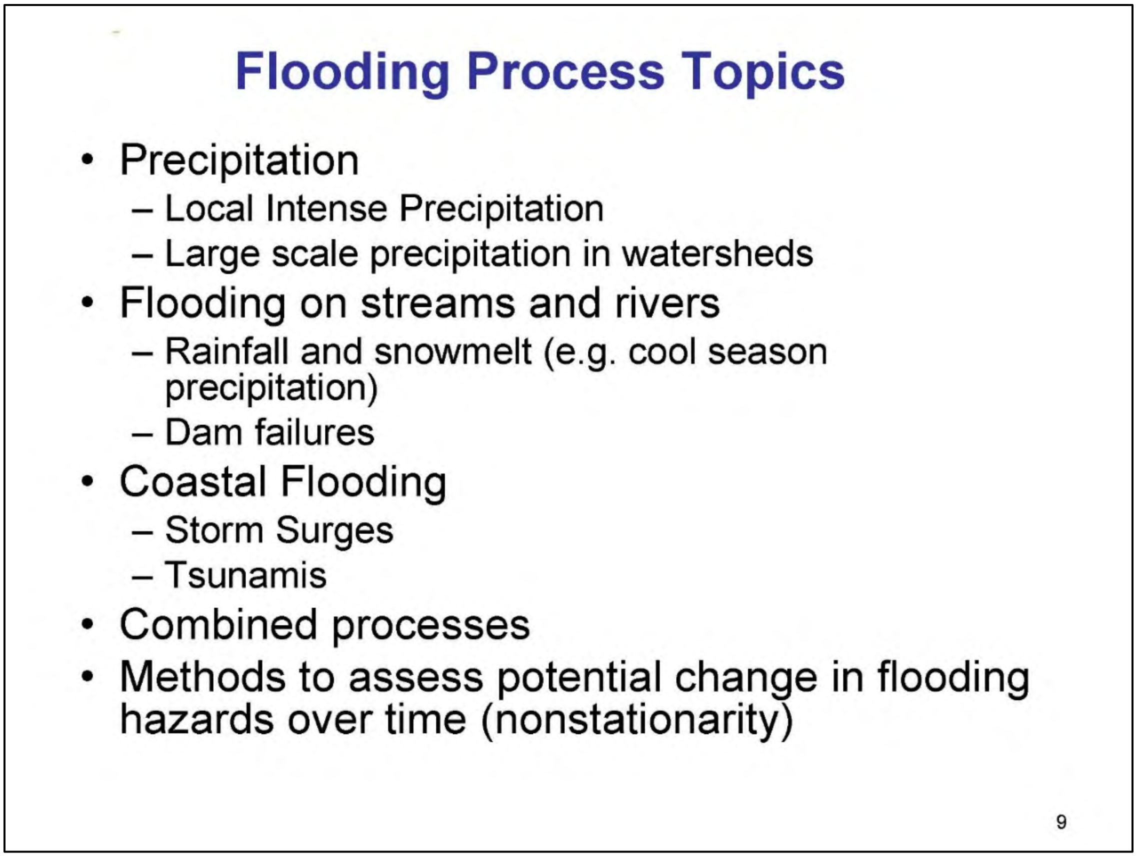
Blayais NPP 1999 Vs. today

Fort Calhoun NPP (2011)

Fukushima (2011)

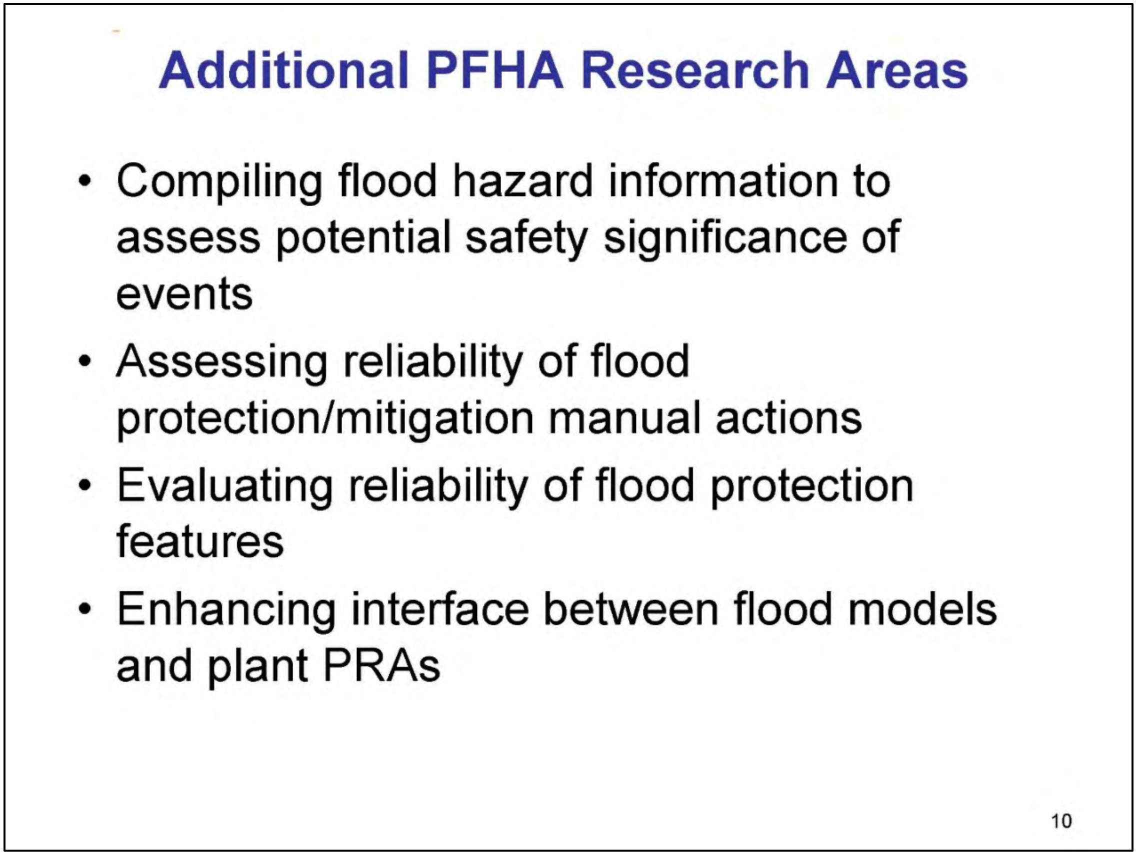
NRC PFHA Research Program Highlights

- Designed to support two NRC programs
  - Oversight of operating reactors
  - New reactor licensing
- Addresses both
  - Flood hazard assessment (magnitude and frequency)
  - Reliability of flood protection and mitigation measures



Flooding Process Topics

- Precipitation
  - Local Intense Precipitation
  - Large scale precipitation in watersheds
- Flooding on streams and rivers
  - Rainfall and snowmelt (e.g. cool season precipitation)
  - Dam failures
- Coastal Flooding
  - Storm Surges
  - Tsunamis
- Combined processes
- Methods to assess potential change in flooding hazards over time (nonstationarity)



Additional PFHA Research Areas

- Compiling flood hazard information to assess potential safety significance of events
- Assessing reliability of flood protection/mitigation manual actions
- Evaluating reliability of flood protection features
- Enhancing interface between flood models and plant PRAs

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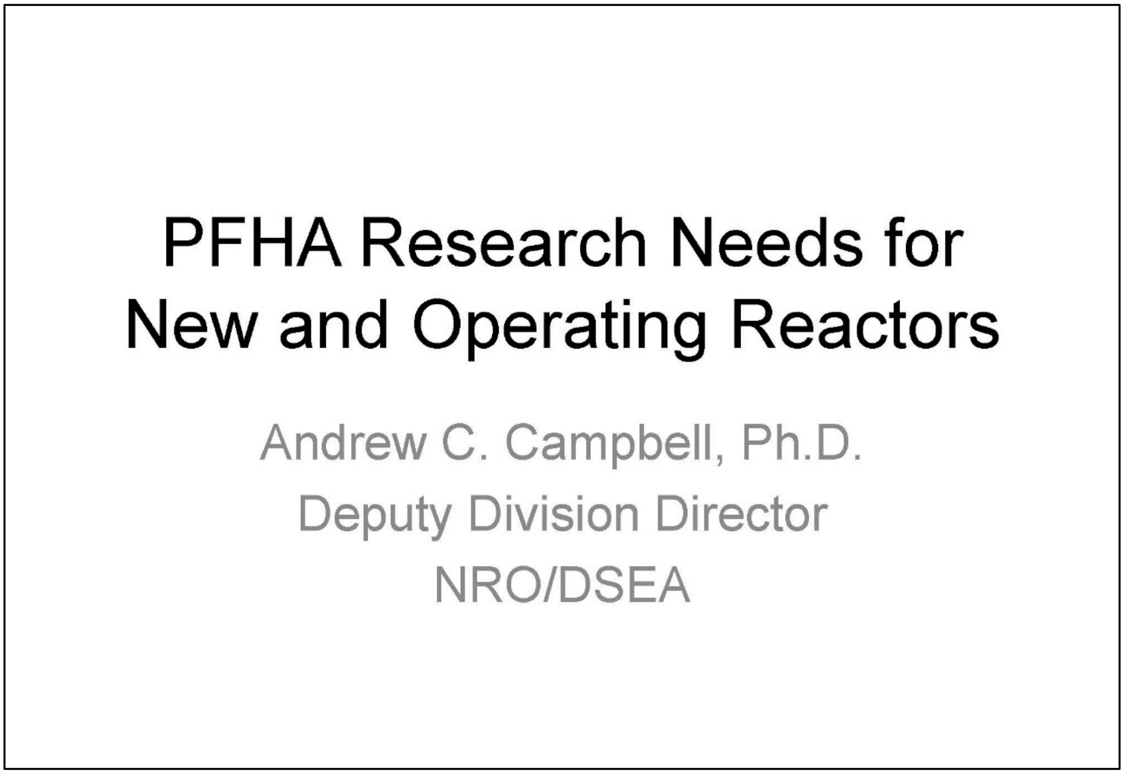
Protecting People and the Environment

Thank You for Your Participation

- Engage
- Collaborate
- Progress

2.3.1.2 PFHA Research Needs for New and Operating Reactors, Andrew C. Campbell, Ph.D., Deputy Director, Division of Site Safety & Environmental Analysis, Office of New Reactors, U.S. NRC (Session 1A-2; ADAMS Accession No. ML17054C497)

2.3.1.2.1 Presentation



PFHA Research Needs for New and Operating Reactors

Andrew C. Campbell, Ph.D.
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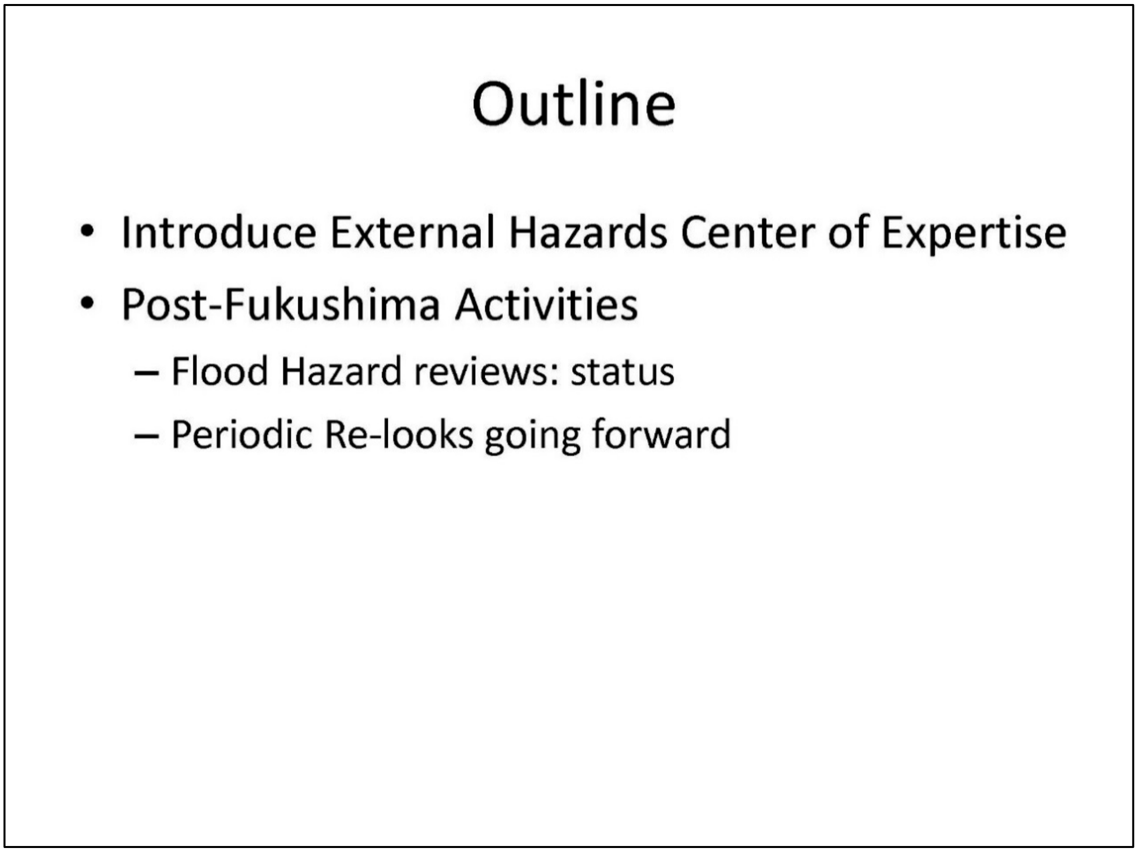
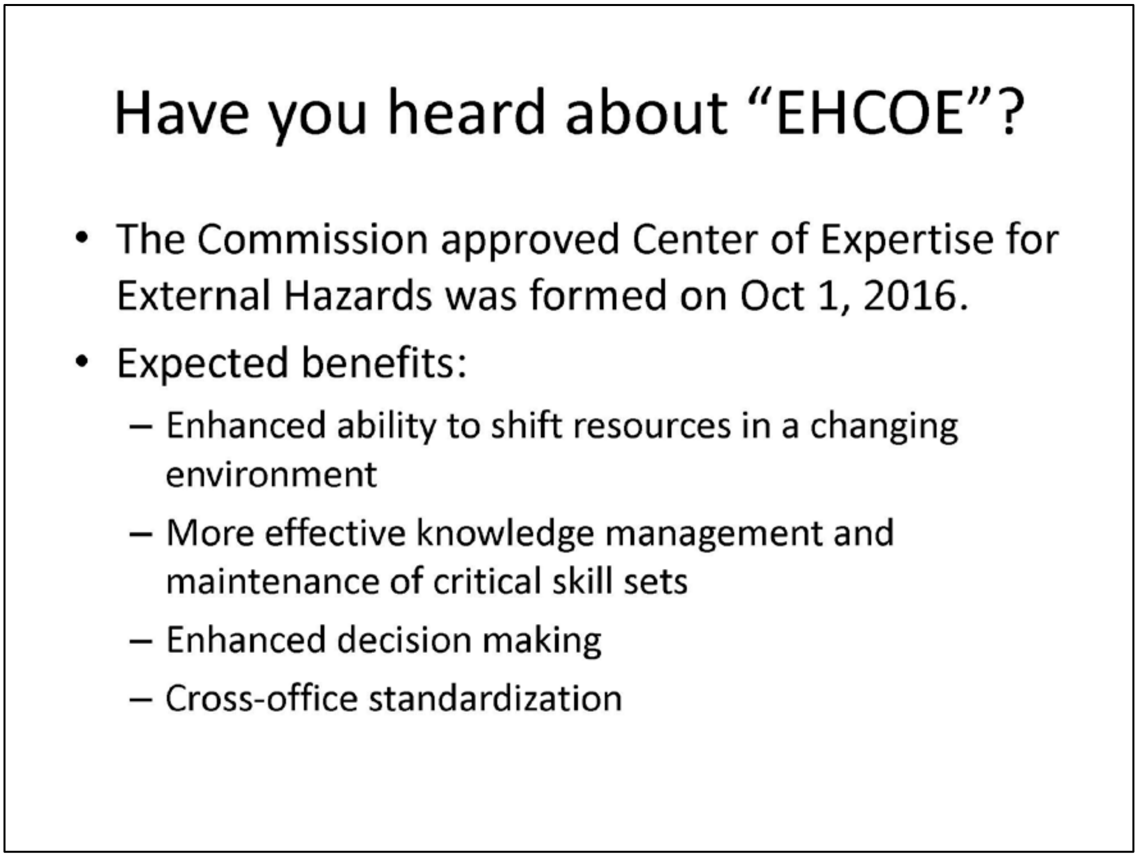


Outline

- Introduce External Hazards Center of Expertise
- Post-Fukushima Activities
  - Flood Hazard reviews: status
  - Periodic Re-looks going forward



Have you heard about “EHCOE”?

- The Commission approved Center of Expertise for External Hazards was formed on Oct 1, 2016.
- Expected benefits:
  - Enhanced ability to shift resources in a changing environment
  - More effective knowledge management and maintenance of critical skill sets
  - Enhanced decision making
  - Cross-office standardization

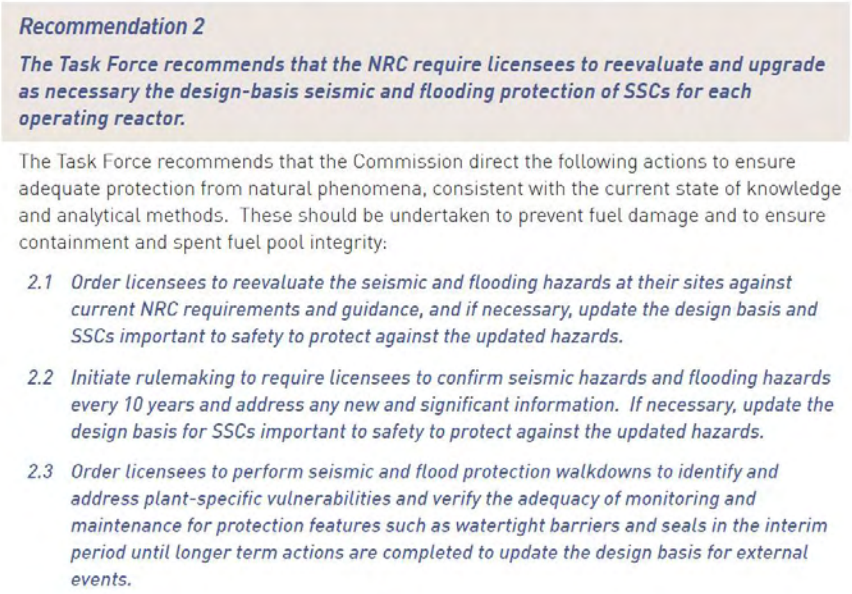
Scope of EHCOE

- All external hazard evaluations associated with reactor licensing (Chapter 2 of the SRP)
- All responsibilities of the NRC's Dam Safety Officer
- Hazards included in the COE:
  - Everything flood-related (external to buildings)
  - Everything climate-driven or climate-related
  - Atmospheric dispersion of radionuclides
  - Everything geology related
  - Everything related to seismic motion
  - Everything related to geotechnical engineering
  - Potential man-made hazards (pipelines, railways, airplanes)

Details Regarding EHCOE

- Located within the Division of Site Safety and Environmental Analysis in New Reactors.
- Approximately 35 staff, including support staff, and transfer of 4 staff Operating Rx Office.
- Work planning and tracking tools in development.
- Commission requested self-assessment of EHCOE creating/implementation due Sept 2017.

Post-Fukushima Response: NTTF Report – Recommendation 2



Recommendation 2

The Task Force recommends that the NRC require licensees to reevaluate and upgrade as necessary the design-basis seismic and flooding protection of SSCs for each operating reactor.

The Task Force recommends that the Commission direct the following actions to ensure adequate protection from natural phenomena, consistent with the current state of knowledge and analytical methods. These should be undertaken to prevent fuel damage and to ensure containment and spent fuel pool integrity:

2.1 *Order licensees to reevaluate the seismic and flooding hazards at their sites against current NRC requirements and guidance, and if necessary, update the design basis and SSCs important to safety to protect against the updated hazards.*

2.2 *Initiate rulemaking to require licensees to confirm seismic hazards and flooding hazards every 10 years and address any new and significant information. If necessary, update the design basis for SSCs important to safety to protect against the updated hazards.*

2.3 *Order licensees to perform seismic and flood protection walkdowns to identify and address plant-specific vulnerabilities and verify the adequacy of monitoring and maintenance for protection features such as watertight barriers and seals in the interim period until longer term actions are completed to update the design basis for external events.*

Post-Fukushima Response: NTTF Report – Recommendation 2

R2.3 – Walkdowns

R2.1 – Hazard Reevaluations

R2.1 – Risk/Plant Response Evaluation

R2.1 – Regulatory Actions (if needed)

R2.2 – Periodic Reevaluations of new and significant information

Post-Fukushima Response: NTTF Report – Recommendation 2

R2.3 – Walkdowns

R2.1 – Hazard Reevaluations

R2.1 – Risk/Plant Response Evaluation

R2.1 – Regulatory Actions (if needed)

R2.2 – Periodic Reevaluations of new and significant information

R2.3 - Walkdowns

- Insights from flooding walkdown have informed activities requested as part of the PFHA research activities
- Examples include:
  - Performance of flood seals
  - Assessment of human actions
  - Assessment of plant response in an integrated manner

Post-Fukushima Response: NTTF Report – Recommendation 2

- R2.3 – Walkdowns
- R2.1 – Hazard Reevaluations
- R2.1 – Risk/Plant Response Evaluation
- R2.1 – Regulatory Actions (if needed)
- R2.2 – Periodic Reevaluations of new and significant information

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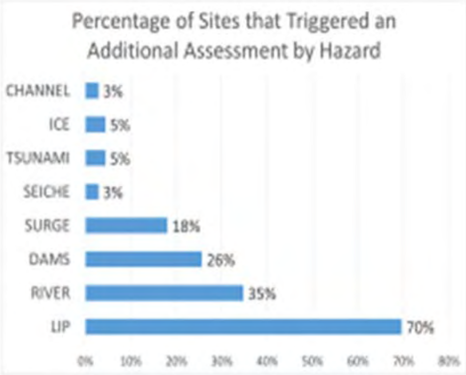
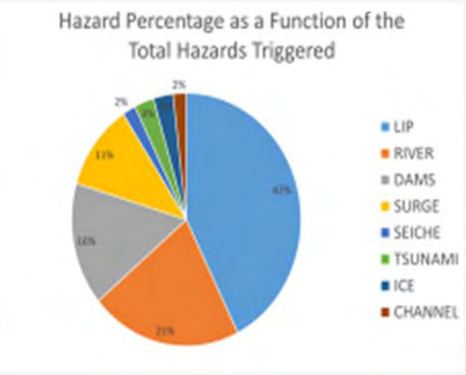
R2.1 – Hazard Reevaluations

- Flooding hazard results for the operating fleet are primarily complete (59 out of 61 ISR letters sent).



Percentage of Sites that Triggered an Additional Assessment by Hazard



Hazard Percentage as a Function of the Total Hazards Triggered

Post-Fukushima Response: NTTF Report – Recommendation 2

R2.3 – Walkdowns

R2.1 – Hazard Reevaluations

R2.1 – Risk/Plant Response Evaluation

R2.1 – Regulatory Actions (if needed)

R2.2 – Periodic Reevaluations of new and significant information

R2.1 – Risk/Plant Response Evaluation

- At sites for which the reevaluated flood is not bounded by the current design basis:
  - Focused evaluations
    - Limited scope evaluations
    - Assess the impact of the reevaluated hazard on the site
    - Ensure appropriate measures (typically protection) are in place and are effective/reasonable

  or
  - Integrated assessments
    - Detailed evaluations
    - Used when hazard exceedance could not be addressed through existing or proposed flood protection
    - Evaluate their capability to protect against and, as necessary, mitigate the effects of reevaluated flooding hazards

Post-Fukushima Response: NTTF Report – Recommendation 2

R2.3 – Walkdowns

R2.1 – Hazard Reevaluations

R2.1 – Risk/Plant Response Evaluation

R2.1 – Regulatory Actions (if needed)

R2.2 – Periodic Reevaluations of new and significant information

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R2.1 – Regulatory Actions (if needed)

- Considers whether additional regulatory actions will be required.
- Per COMSECY-15-0019, additional regulatory actions will be considered at sites that:
  - Experience consequential flooding for hazards with an AEP of **1E-3 to 1E-4/year**
  - Cannot protect against flood hazards with AEP of 1E-3 to 1E-4/year.
- Licensees will provide information about the frequency of consequential flooding as part of the integrated assessments.
- Necessary for licensees/staff to develop estimates of flood hazards associated with an AEP of 1E-3 to 1E-4/year.

R2.1 – Regulatory Actions (if needed)

- NRC staff is currently working to develop case studies to:
  - Support industry in developing estimates of the frequency of consequential flooding
  - Support staff in reviewing estimates or (if necessary) developing independent estimates.
- These are interim products and are consistent with the broader PFHA research plan
- Goal - Develop case studies that…
  - Reflect current state of practice
  - Focus primarily on hazards with AEP in range 1E-3 to 1E-4/year
  - Are guided by the "PFHA attributes" (NEI 16-05)
  - Demonstrate how attributes can be met to develop an "approximately mean" hazard
  - Provide examples, not de facto requirements

Post-Fukushima Response: NTTF Report – Recommendation 2

R2.3 – Walkdowns

R2.1 – Hazard Reevaluations

R2.1 – Risk/Plant Response Evaluation

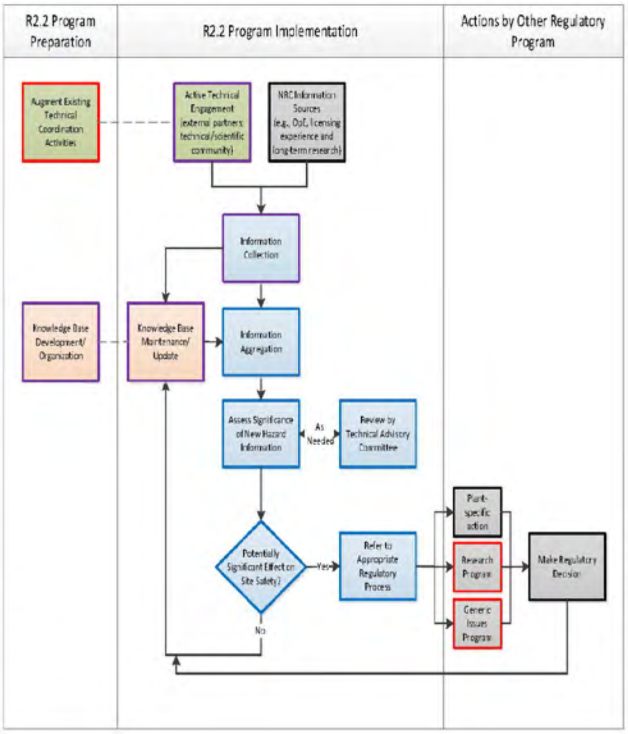
R2.1 – Regulatory Actions (if needed)

R2.2 – Periodic Reevaluations of new and significant information

R2.2 – Periodic Reevaluations of new and significant information

- Complements existing processes for evaluating new information
  - Proactive
  - Systematic
  - Timely/efficient
  - Predictable
- Seeks, aggregates, and interprets new information related to external hazards
- Leverages existing agency capabilities
- Assesses the potential effect of new information on plants and refers issues to appropriate regulatory program
  - May require application of NRC's risk-informed regulatory framework

R2.2 – Periodic Reevaluations



Knowledge Base Activities

- Compiles and organizes existing info/tools
- Incorporates new info/tools

Active Technical Engagement and Coordination

- Periodic engagement with external organizations as well as scientific and technical communities

Assessment Activities

- Collects and integrates new information
- Assesses whether new/aggregated information has a significant effect on site hazard
- [If needed] Refers the issue and associated analyses to appropriate regulatory process

2.3.1.2.2 Questions and Answers

Question:

NUREG-2150, “A Proposed Risk Management Regulatory Framework,” issued April 2012, recommends the risk-informed-based approach and defense in depth. How will this approach involve defense in depth?

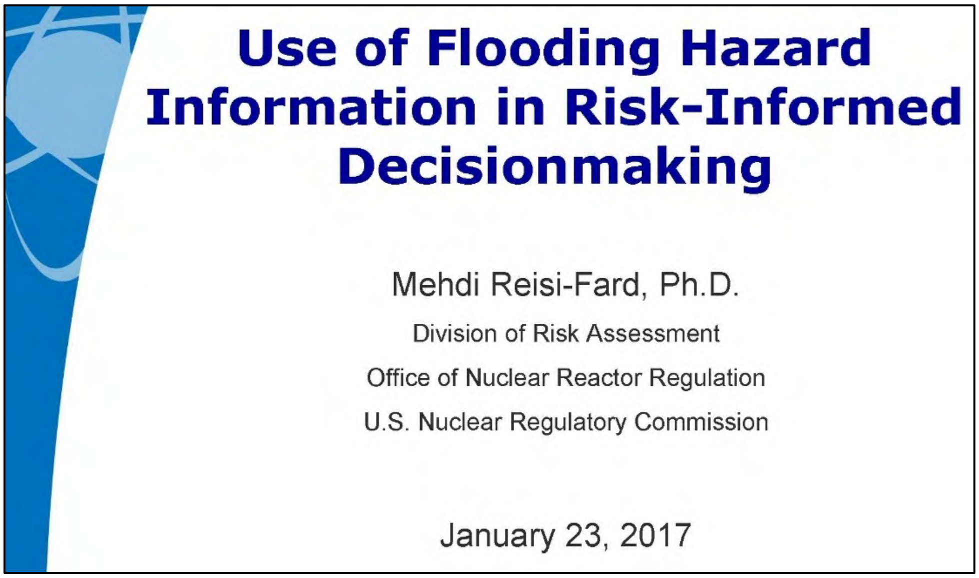
Response:

This is not a risk-based approach but a risk-informed approach. The agency has adhered to that perspective since the policy was developed in the 1990s. In 2006, the NRC developed the probabilistic risk assessment (PRA) policy. It is important that defense in depth be part of that. Recently I was at a plant with a couple of inspectors and staff from the Office of Nuclear Reactor Regulation (NRR), and we looked at all of the plant’s FLEX equipment and the plant has defense in depth. It has multiple ways of pumping water to where it is needed. The facility has multiple ways of providing power to the plant. This is an example of defense in depth. Even if it were possible, on a probability basis, to determine that the likelihood of an event occurring is miniscule, from the plant’s perspective and the NRC’s regulatory perspective defense in depth is not quantifiable directly but it is something that makes a great deal of sense not only in the history of the NRC’s approach to regulation but going forward. The concern with moving to only a probability basis is understandable, but that is not what the NRC is doing. Instead, this is using a risk-informed approach. The NRC believes it is beneficial to have many ways to solve a problem.

2.3.1.3 Use of Flooding Hazard Information in Risk-Informed Decision-making,

Mehdi Reisi-Fard, Ph.D., Reliability and Risk Analyst, PRA Licensing Branch, Division of Risk Assessment, Office of Nuclear Reactor Regulation, U.S. NRC (Session 1A-3; ADAMS Accession No. ML17054C498)

2.3.1.3.1 Presentation



Use of Flooding Hazard Information in Risk-Informed Decisionmaking

Mehdi Reisi-Fard, Ph.D.

Division of Risk Assessment

Office of Nuclear Reactor Regulation

U.S. Nuclear Regulatory Commission

January 23, 2017

Background: NRC Regulations Overview

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- Designed to withstand effects of natural phenomena, such as floods (10 CFR 50 Appendix A)
  - Appropriate consideration of most severe of the natural phenomena that have been historically reported. With sufficient margin for limited accuracy, quantity, and period of time for accumulated_historical data
  - Reflect the importance of the safety functions to be performed
- Current Nuclear Regulatory Commission guidance references deterministic methods for hazard evaluation
  - Reliance on concept of "probable maximum" scenarios

Background: Risk Measures and PRA Policy

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- Safety Goals for the Operations of Nuclear Power Plants Policy Statement (51 FR 30028; August 21, 1986) established goals that broadly define an acceptable level of radiological risk.
- Probabilistic Risk Assessment (PRA) Policy Statement (60 FR 42622; August 16, 1995) formalized the Commission's commitment to risk-informed regulation through the expanded use of PRA.
  - *The use of PRA technology should be increased in all regulatory matters to the extent supported by the state of the art in PRA methods and data, and in a manner that complements the NRC's deterministic approach and supports the NRC's traditional defense-in-depth philosophy.*

Use of Risk-Informed Approaches

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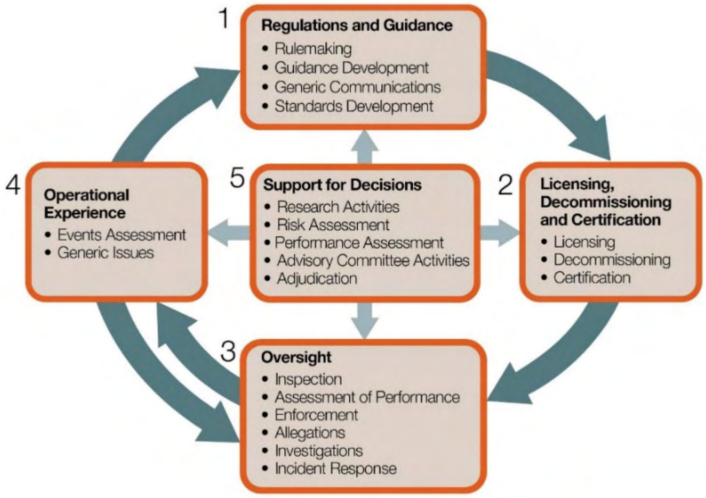

1 **Regulations and Guidance**
- Rulemaking
- Guidance Development
- Generic Communications
- Standards Development

2 **Licensing, Decommissioning and Certification**
- Licensing
- Decommissioning
- Certification

3 **Oversight**
- Inspection
- Assessment of Performance
- Enforcement
- Allegations
- Investigations
- Incident Response

4 **Operational Experience**
- Events Assessment
- Generic Issues

5 **Support for Decisions**
- Research Activities
- Risk Assessment
- Performance Assessment
- Advisory Committee Activities
- Adjudication

Risk-Informed Rules & Policies

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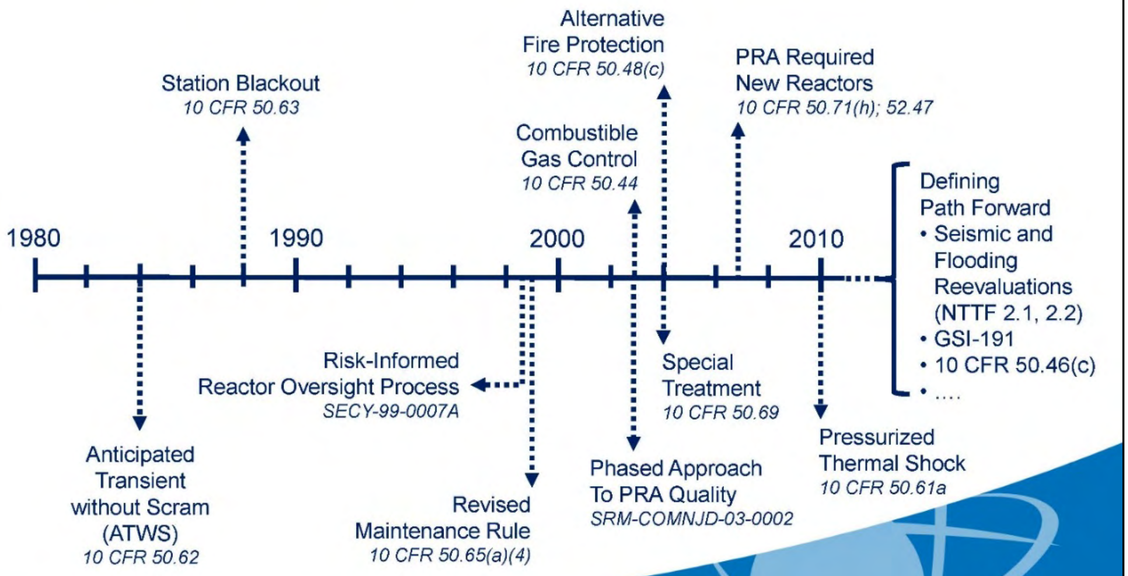

Station Blackout
10 CFR 50.63

Combustible Gas Control
10 CFR 50.44

Alternative Fire Protection
10 CFR 50.48(c)

PRA Required New Reactors
10 CFR 50.71(h); 52.47

Defining Path Forward
- Seismic and Flooding Reevaluations (NTTF 2.1, 2.2)
- GSI-191
- 10 CFR 50.46(c)
- ....

Anticipated Transient without Scram (ATWS)
10 CFR 50.62

Risk-Informed Reactor Oversight Process
SECY-99-0007A

Revised Maintenance Rule
10 CFR 50.65(a)(4)

Phased Approach To PRA Quality
SRM-COMNJD-03-0002

Special Treatment
10 CFR 50.69

Pressurized Thermal Shock
10 CFR 50.61a

Risk-Informed Licensing Activities

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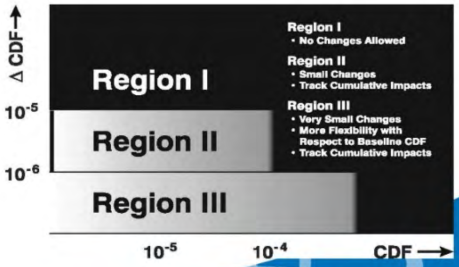
- Regulatory Guide (RG) 1.174 and Standard Review Plan (SRP) 19 provide general guidance for risk-informed licensing basis changes
- Examples of specific guidance:
  - Risk-informed technical specifications (TS) changes: RG 1.177, SRP 16.1
  - Risk-informed inservice inspection (ISI) (piping): RG 1.178, SRP 3.9.8

RG 1.174, Section 2.3.1:
when the risk associated with a particular hazard group would affect the decision being made, it is the Commission's policy that, if a staff-endorsed PRA standard exists for that hazard group, then the risk will be assessed using a PRA that meets that standard



Risk-Informed Oversight

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- Reactor Oversight Process (ROP) is the agency's program to inspect, measure, and assess the safety performance of nuclear power plants (NPPs) and to respond to any decline in performance.
- Performance evaluated by analyzing inspection findings resulting from inspection program and performance indicators.
  - Significance Determination Process (SDP) used to support determination of the safety significance of inspection findings (i.e., performance deficiencies)

PRA Framework

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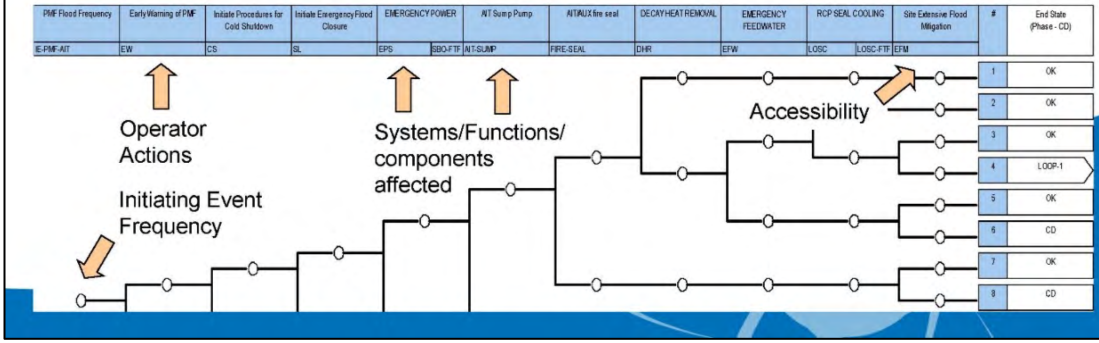
- PRA is a structured, analytical process for identifying potential weaknesses and strengths of a plant design in an integrated fashion
  - provides a framework for explicitly addressing and presenting uncertainties
  - includes all potential accident initiators and mitigation failures (including multiple failures)
  - evaluates responses (physical, automatic and operator response) to perturbations
  - outputs may include core damage frequency, release frequency and radiological consequences
- In using PRA results, sources of uncertainty and assumptions and their impact on results should be understood.



Examples of Pre-Fukushima Flooding Risk Evaluations

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- PRA studies for specific NPPs in 1980s
- A number of Individual Plant Examination of External Events (IPEEE) submittals in response to Supplement 4 to Generic Letter 88-20 in 1990s
  - External flooding was screened from further analyses in many cases using qualitative analyses
- SDP analyses of performance deficiencies (for example Fort Calhoun in 2010)

Source: OPPD Public Presentation (April 4, 2012)

SDP Analyses Following Fukushima Response

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- In light of the effects from the earthquake and tsunami of March 11, 2011, on the NPPs at Fukushima, NRC concluded U.S. NPPs needed to reaffirm their existing ability to resist quakes and flooding.
- On March 2012, NRC requested that all US NPP licensees implement flood protection walkdowns (Recommendation 2.3) to capture any degraded, non-conforming conditions, and cliff-edge effects for flooding
  - Plants completed their walkdowns by November 2012; NRC inspectors have done follow-up inspections and the agency has issued plant-specific assessments of the licensee's walkdown reports.
  - Flooding walkdowns resulted in identification of a number of performance deficiencies associated with external flooding.

Findings Related to External Flooding

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Inadequate Flood Procedures		**Degraded or Missing Flood Barriers/Seals**	
2010 - Fort Calhoun inadequate flood procedure	YELLOW	2004 - Oconee access cover impacting shutdown capability	WHITE
2013 - Watts Bar/Sequoyah inadequate procedures	WHITE	2011 - Brunswick degraded flood barriers	WHITE
2013 - Watts Bar inadequate procedures/plant realignment	YELLOW	2013 - Sequoyah degraded flooding seals	WHITE
2013 - Dresden inadequate flood procedure	WHITE	2013 - Three Mile Island missing flooding seals	WHITE
2013 - Monticello flood protection plan	YELLOW	2013 - Watts Bar protection of safety-related equipment	GREEN
2013 - Point Beach inadequate sandbagging protection	WHITE	2014 - Arkansas Nuclear One inadequate flood protection	YELLOW
		2014 - Ginna unsealed cable penetrations	WHITE
		2014 - St. Lucie unsealed conduits	WHITE
		2014 - Brunswick inadequate flood protection	GREEN

substantial safety significance
low to moderate safety significance
very low safety significance

Some Insights from Recent SDP Analyses

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- Uncertainty associated with flood Frequencies in the range of interest to the NRC is significant. Qualitative insights from plant response and principles of risk-informed decisionmaking should be appropriately considered.
- Full range of hazard curve (containing frequencies of both extreme events and flood elevations below the probable maximum flood) may be needed in some cases for appropriate consideration of impact at various elevations.
- Credit for operator actions as part of human reliability analysis methods for evaluating flood mitigation actions, such as construction of flood protection is a focus area.
- Assumptions about advanced warnings, duration of the events, reliability of components could impact flood mitigation.

NRR Priorities from PFHA User-Need

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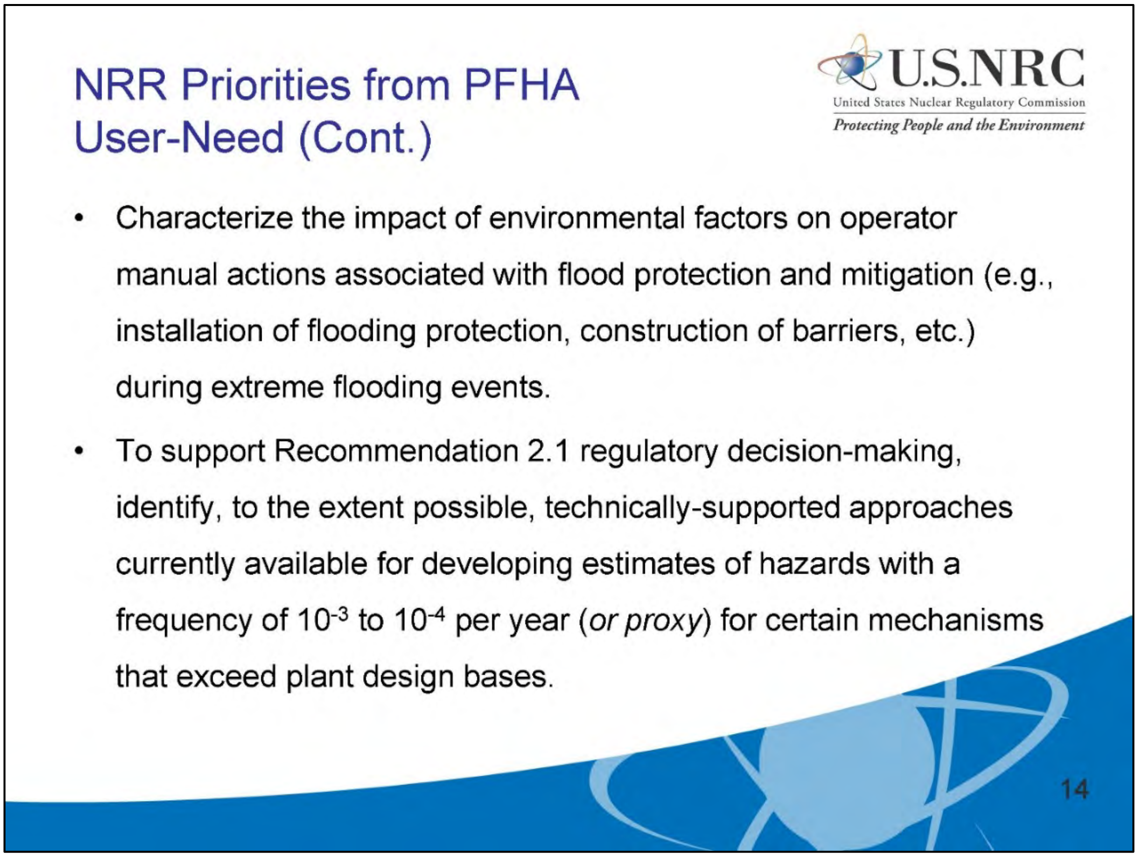
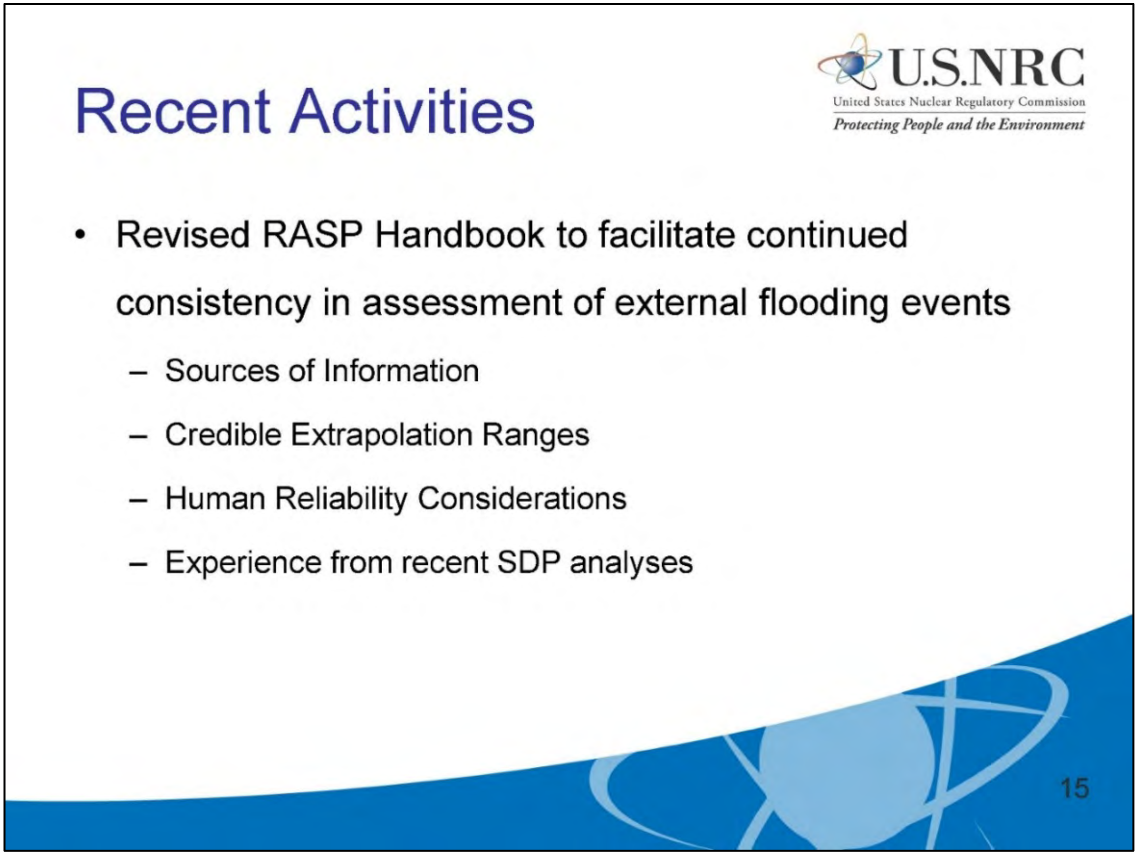
- Provide guidance/develop methods for extending frequency analysis methods to ranges of interest for NRC applications (in many cases beyond current consensus limits for estimating flood frequencies)
- Provide guidance for consistent application of statistically based flood-frequency estimates at sites where historical or paleoflood information may be available (at-site or from regional information)
    - For future updates to Risk Assessment of Operational Events Handbook (known as RASP Handbook)
- Probabilistic treatment of flood protection structures including temporary barriers



NRR Priorities from PFHA User-Need (Cont.)

- Characterize the impact of environmental factors on operator manual actions associated with flood protection and mitigation (e.g., installation of flooding protection, construction of barriers, etc.) during extreme flooding events.
- To support Recommendation 2.1 regulatory decision-making, identify, to the extent possible, technically-supported approaches currently available for developing estimates of hazards with a frequency of 10^{-3} to 10^{-4} per year (*or proxy*) for certain mechanisms that exceed plant design bases.

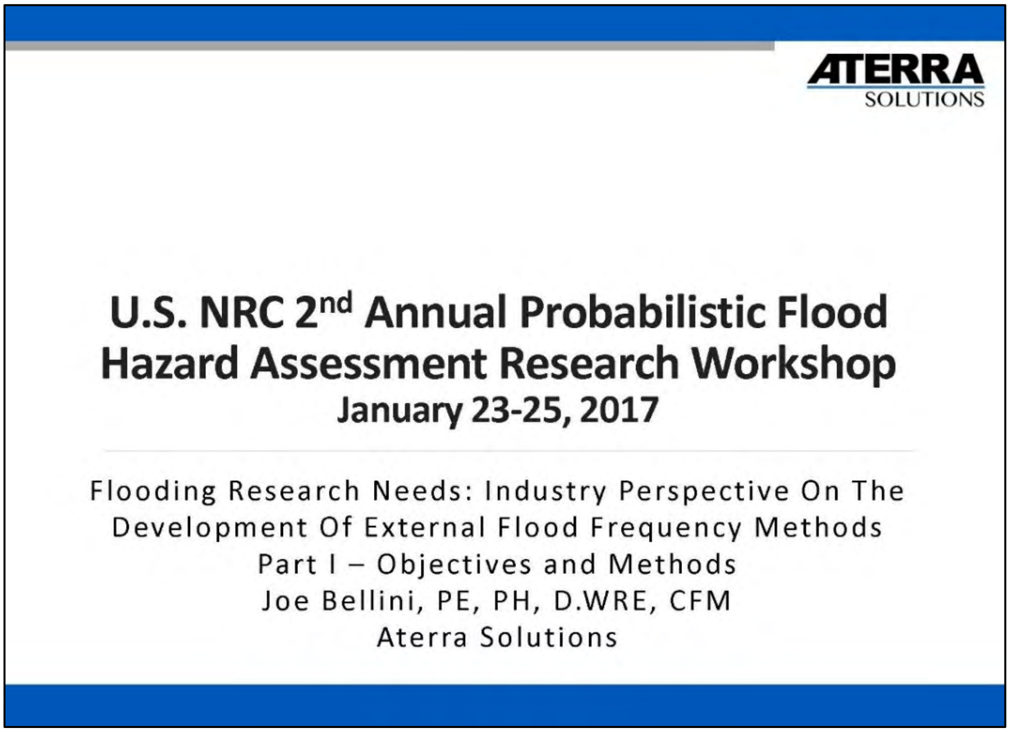


Recent Activities

- Revised RASP Handbook to facilitate continued consistency in assessment of external flooding events
  - Sources of Information
  - Credible Extrapolation Ranges
  - Human Reliability Considerations
  - Experience from recent SDP analyses

2.3.1.4 Flooding Research Needs: Industry Perspectives on Development of External Flood Frequency Methods, Ray Schneider*, Westinghouse Electric Corporation; and Joe Bellini*, P.E., P.H., D.WRE, C.F.M., Aterra Solutions (Session 1A-4; ADAMS Accession No. ML17054C499)

2.3.1.4.1 Presentation



U.S. NRC 2nd Annual Probabilistic Flood Hazard Assessment Research Workshop

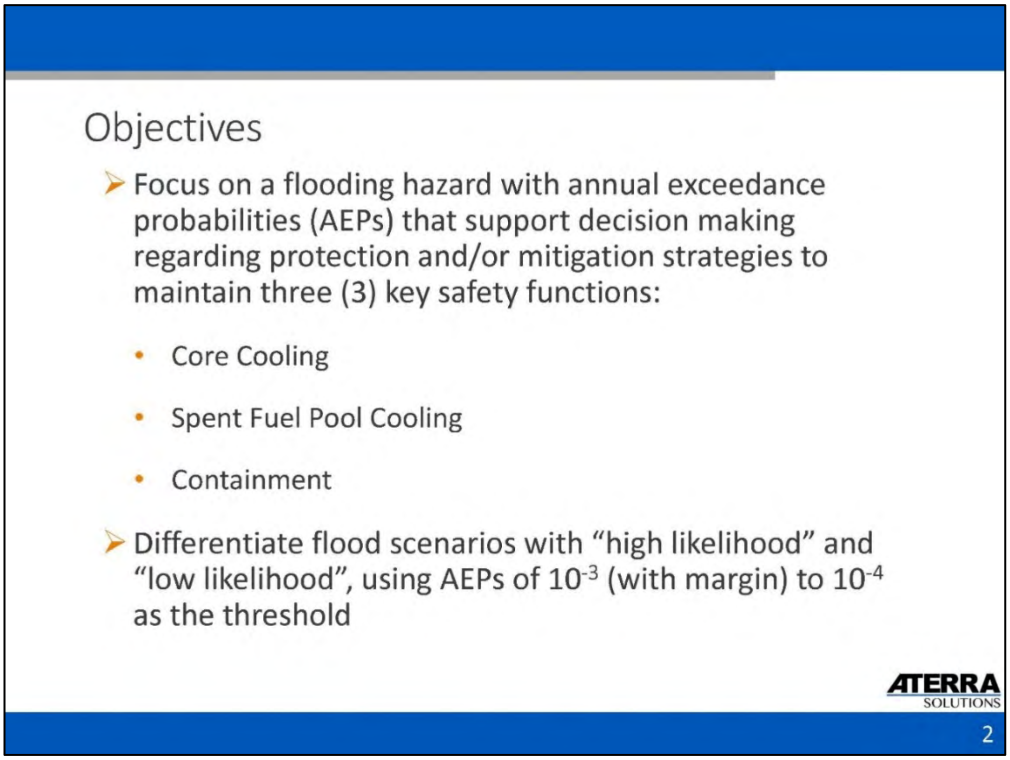
January 23-25, 2017

Flooding Research Needs: Industry Perspective On The Development Of External Flood Frequency Methods

Part I – Objectives and Methods

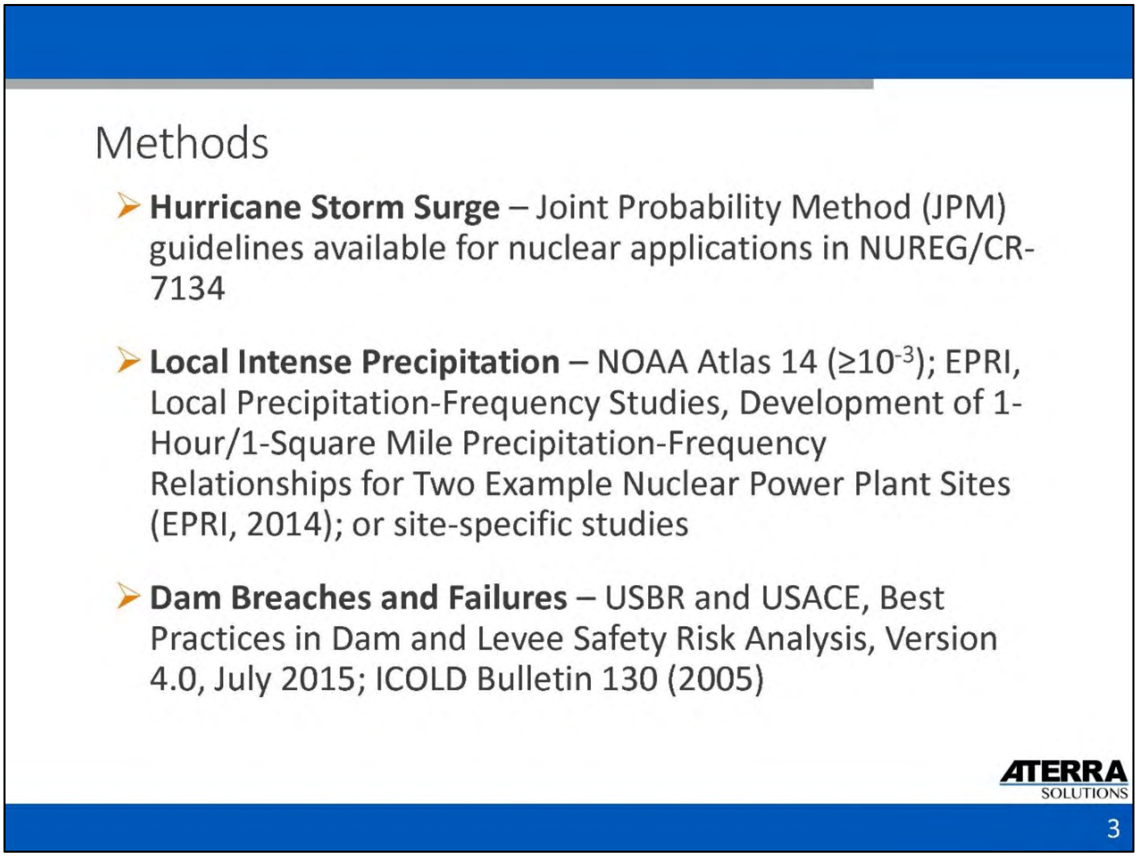
Joe Bellini, PE, PH, D.WRE, CFM

Aterra Solutions



Objectives

- Focus on a flooding hazard with annual exceedance probabilities (AEPs) that support decision making regarding protection and/or mitigation strategies to maintain three (3) key safety functions:
  - Core Cooling
  - Spent Fuel Pool Cooling
  - Containment
- Differentiate flood scenarios with "high likelihood" and "low likelihood", using AEPs of 10^{-3} (with margin) to 10^{-4} as the threshold



Methods

- **Hurricane Storm Surge** – Joint Probability Method (JPM) guidelines available for nuclear applications in NUREG/CR-7134
- **Local Intense Precipitation** – NOAA Atlas 14 ($\geq 10^{-3}$); EPRI, Local Precipitation-Frequency Studies, Development of 1-Hour/1-Square Mile Precipitation-Frequency Relationships for Two Example Nuclear Power Plant Sites (EPRI, 2014); or site-specific studies
- **Dam Breaches and Failures** – USBR and USACE, Best Practices in Dam and Levee Safety Risk Analysis, Version 4.0, July 2015; ICOLD Bulletin 130 (2005)

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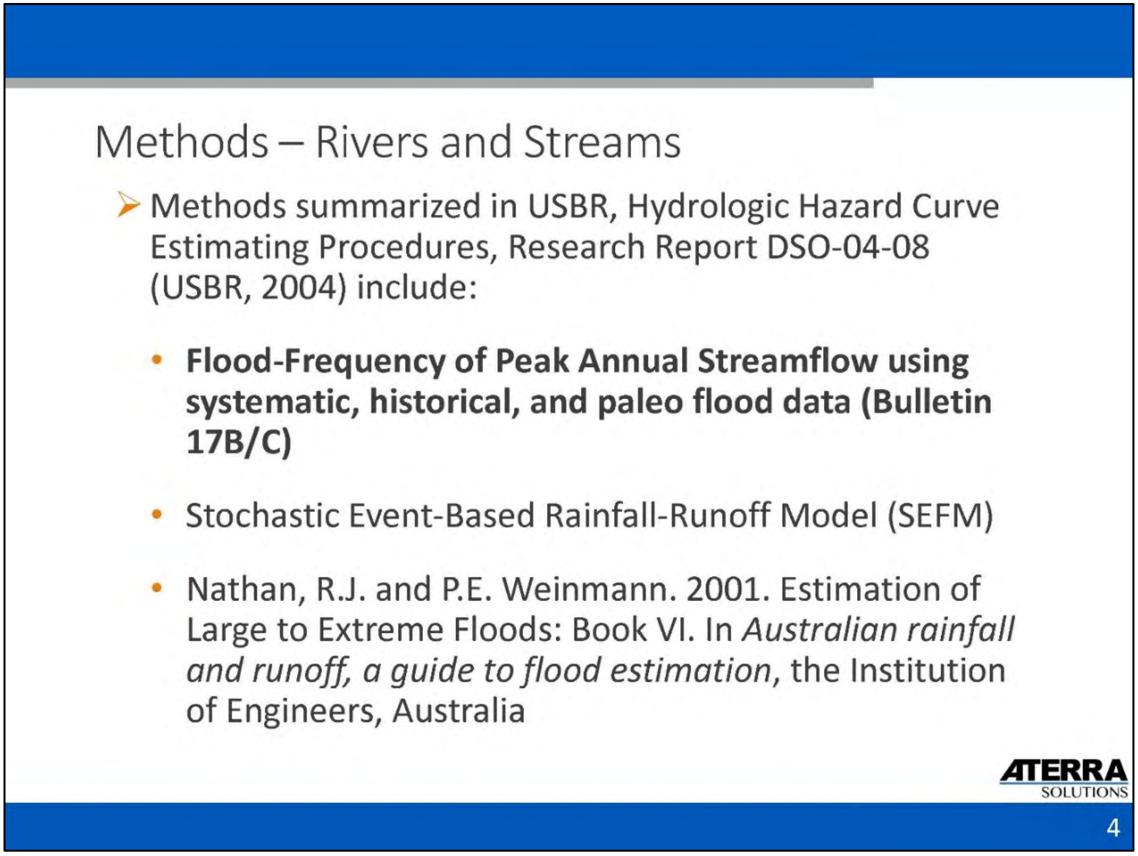

Methods – Rivers and Streams

- Methods summarized in USBR, Hydrologic Hazard Curve Estimating Procedures, Research Report DSO-04-08 (USBR, 2004) include:
  - **Flood-Frequency of Peak Annual Streamflow using systematic, historical, and paleo flood data (Bulletin 17B/C)**
  - Stochastic Event-Based Rainfall-Runoff Model (SEFM)
  - Nathan, R.J. and P.E. Weinmann. 2001. Estimation of Large to Extreme Floods: Book VI. In *Australian rainfall and runoff, a guide to flood estimation*, the Institution of Engineers, Australia

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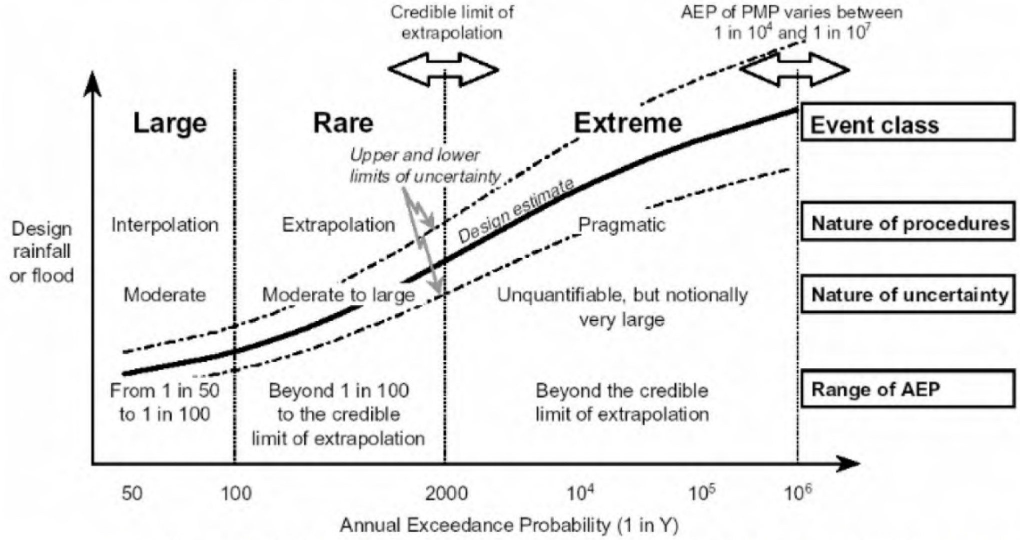
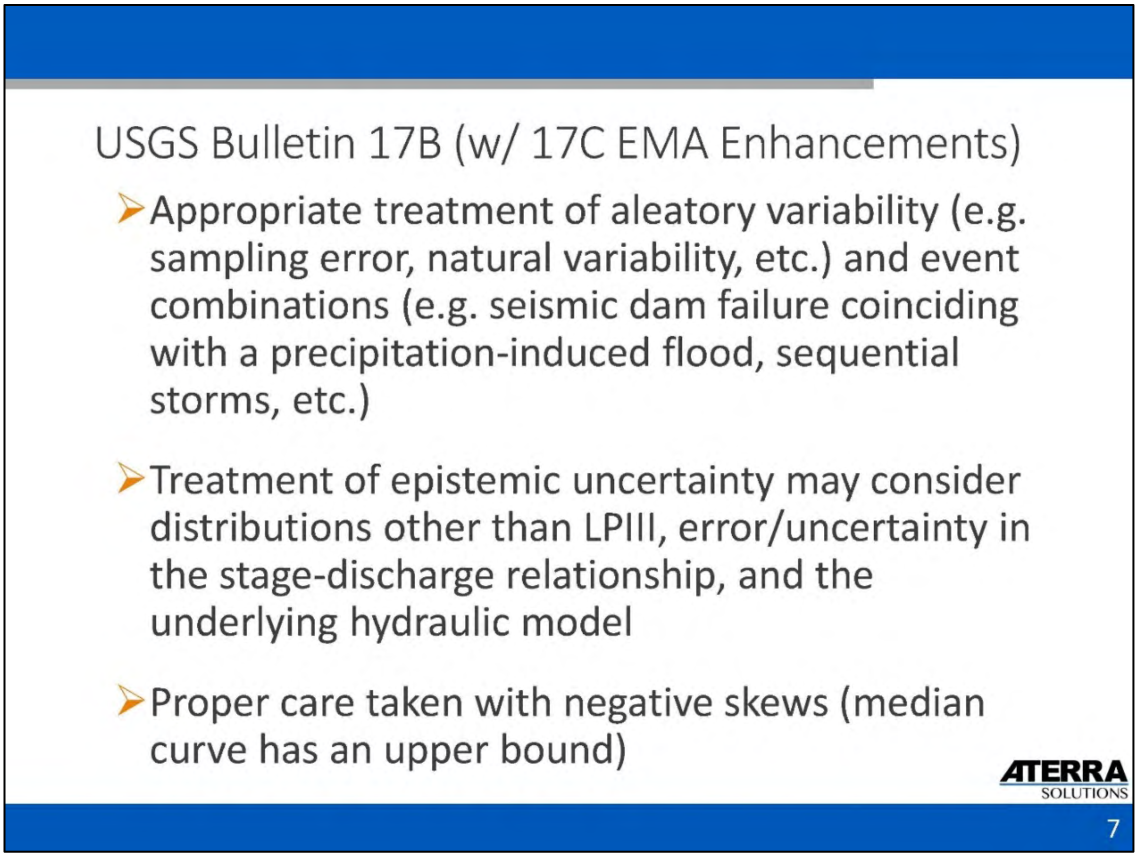
Extrapolation Limits



Characteristics of Notional Floods (Nathan and Weinmann, 2001)

USGS Bulletin 17B (w/ 17C EMA Enhancements)

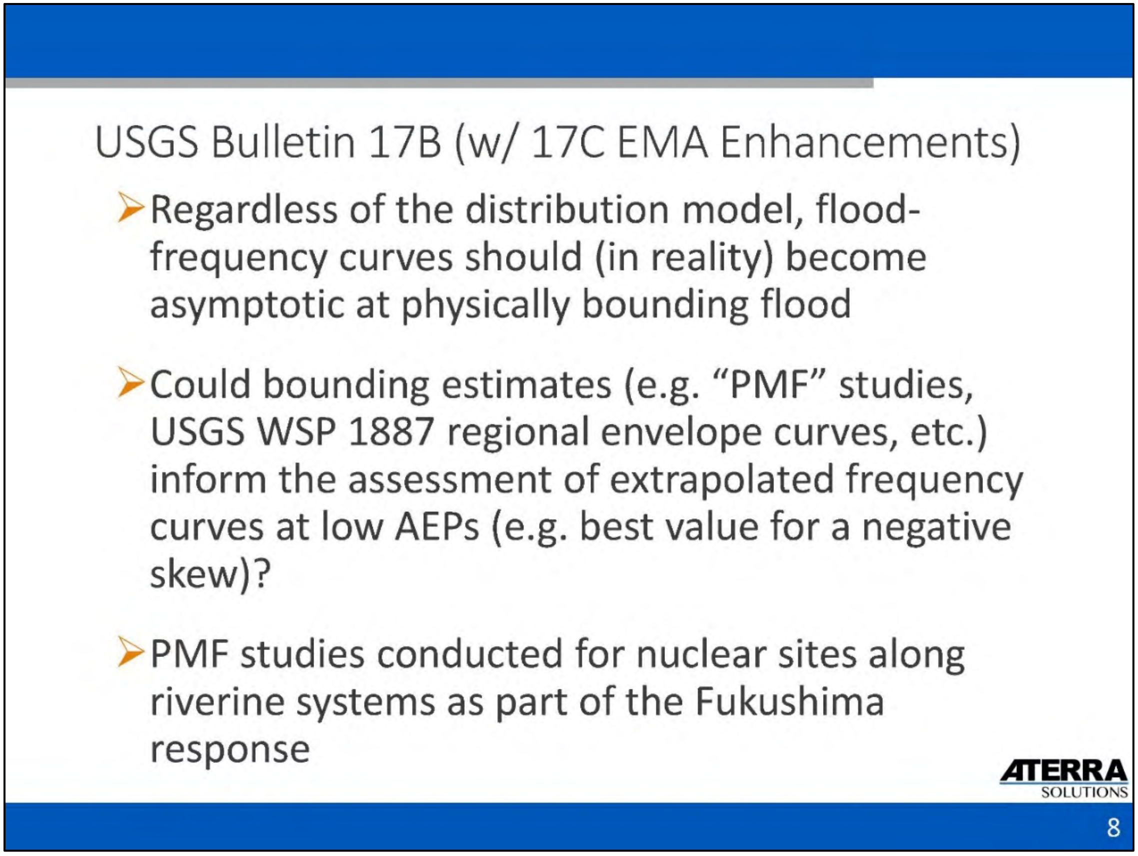
- Pearson Type III probability distribution (using Log_{10} transformation of peak annual streamflow)
- EMA (Expected Moments Algorithm) – Iterative process used to estimate sample moments and LP-III distribution parameters based on observed systematic, historical, and/or paleo flood data and thresholds/ranges for unobserved flood periods → improved accuracy in confidence limits
- Goal is to apply 17B/C for extrapolating to an AEP of 10^{-4} (to be discussed further in Session 2B-2)



USGS Bulletin 17B (w/ 17C EMA Enhancements)

- Appropriate treatment of aleatory variability (e.g. sampling error, natural variability, etc.) and event combinations (e.g. seismic dam failure coinciding with a precipitation-induced flood, sequential storms, etc.)
- Treatment of epistemic uncertainty may consider distributions other than LPIII, error/uncertainty in the stage-discharge relationship, and the underlying hydraulic model
- Proper care taken with negative skews (median curve has an upper bound)

ATERRA SOLUTIONS



USGS Bulletin 17B (w/ 17C EMA Enhancements)

- Regardless of the distribution model, flood-frequency curves should (in reality) become asymptotic at physically bounding flood
- Could bounding estimates (e.g. "PMF" studies, USGS WSP 1887 regional envelope curves, etc.) inform the assessment of extrapolated frequency curves at low AEPs (e.g. best value for a negative skew)?
- PMF studies conducted for nuclear sites along riverine systems as part of the Fukushima response

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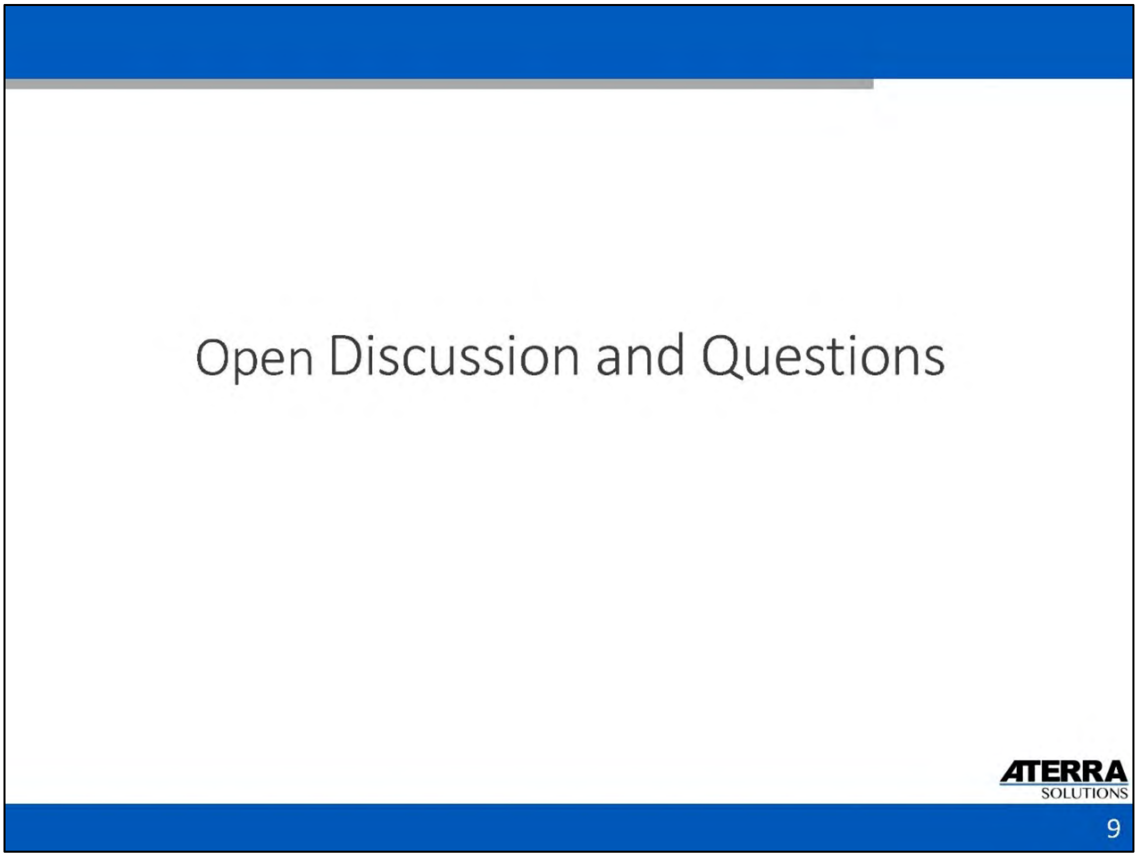
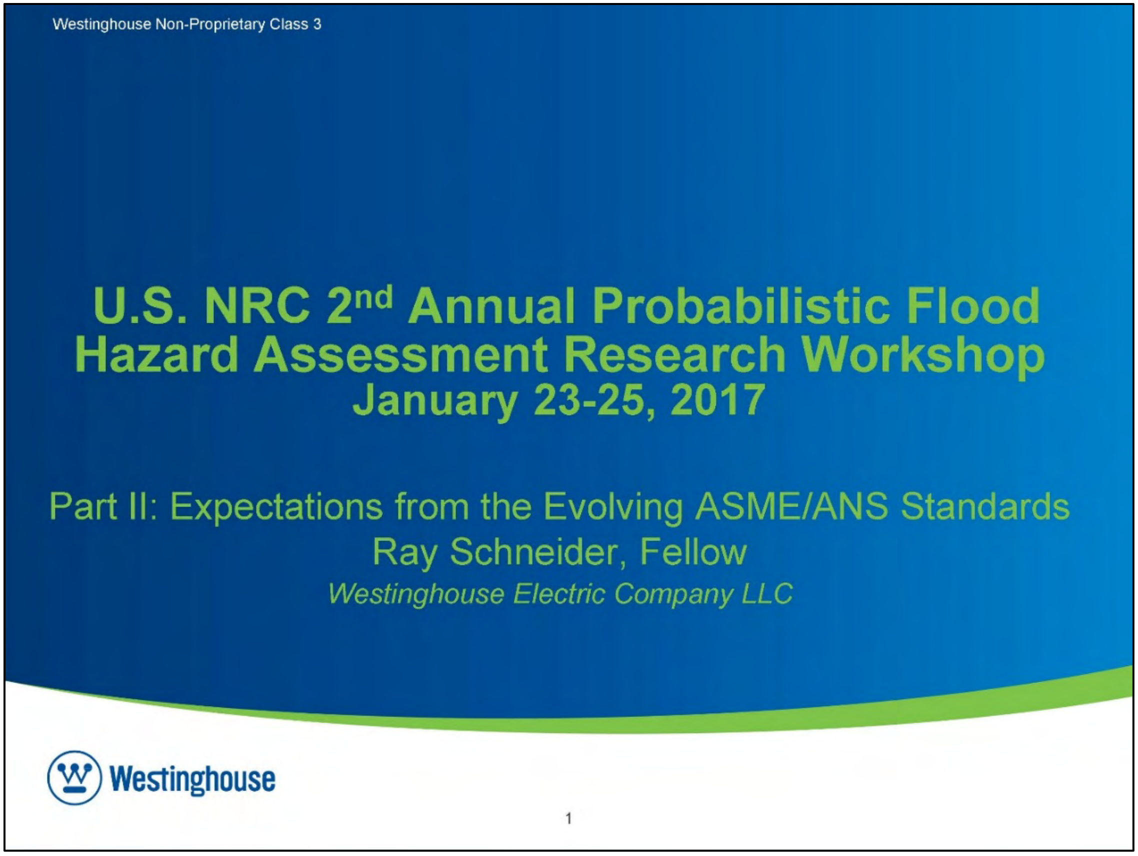


Open Discussion and Questions



Westinghouse Non-Proprietary Class 3

U.S. NRC 2nd Annual Probabilistic Flood Hazard Assessment Research Workshop

January 23-25, 2017

Part II: Expectations from the Evolving ASME/ANS Standards

Ray Schneider, Fellow

Westinghouse Electric Company LLC

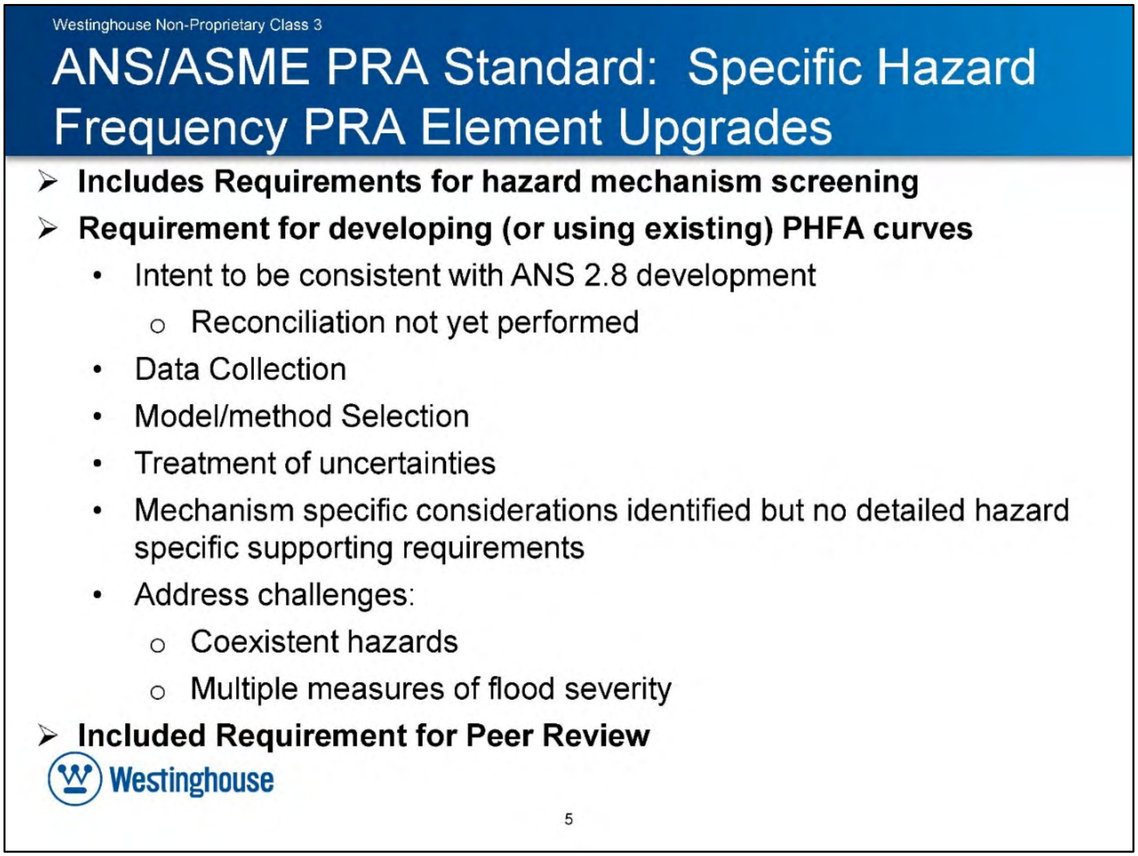
Evolution of Standards Requirement: ANS 2.8

- **External Flood Hazard Frequency Guidance being developed to increase uniformity in treatment of site risks across hazard mechanisms and facility types**
- **ANS 2.8 being refocused from "Probable Maximum" emphasis to provide requirements for performing PFHA Evaluation**
  - Provides high level criteria/process expectations for preparing external flood hazard curve
  - Requirements are not hazard specific
  - Allows flexibility in defining methodology to be used
  - Focus on data collection and use, methodology selection, hazard uncertainty and justification of extrapolations to low frequencies
  - Co-existent hazards not prescriptive
  - Peer review requirements

- **ANS 2.8 being revised to respond to stakeholder comments**
- **Expectation to issue Final in 2017**

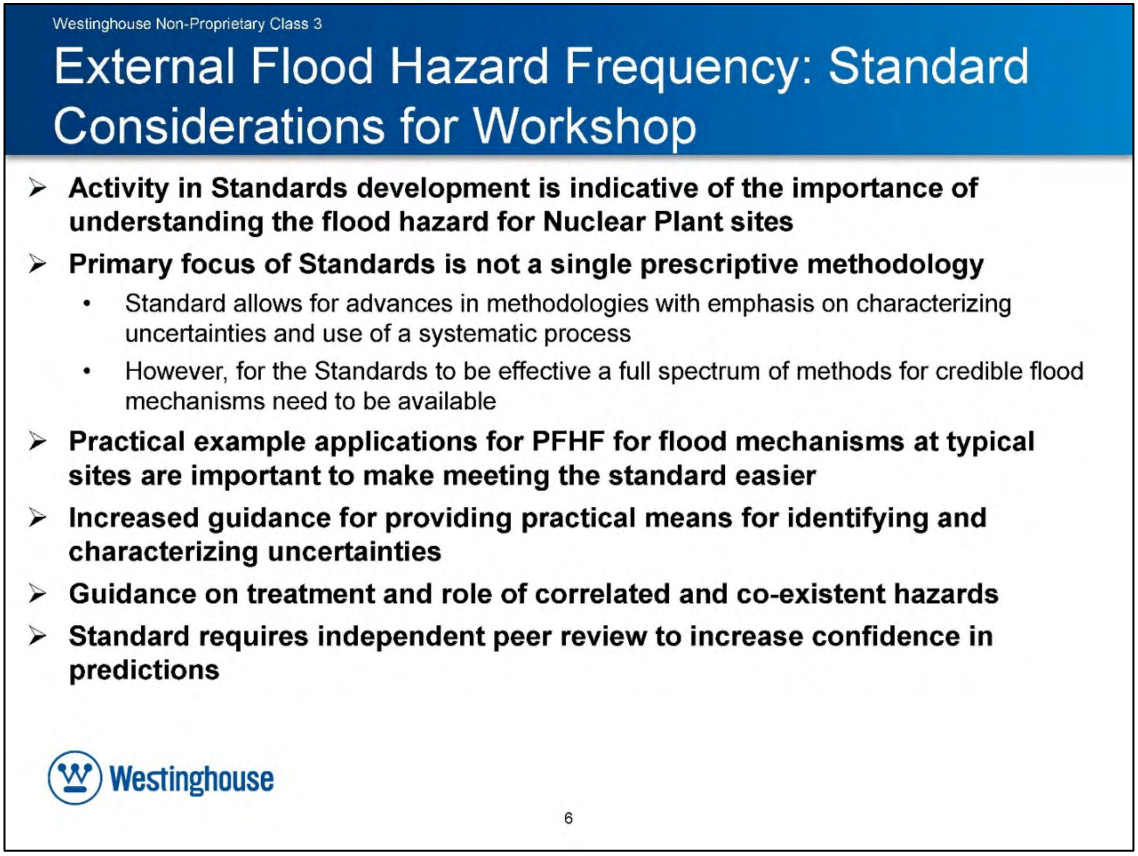
Evolution of Treatment of Flood Hazard Frequency in ASME/ANS PRA Standard

- Known Challenges
  - To date, few external flood PRAs have been performed
  - Diverse nature of flood hazards, measures of severity and associated plant responses
- Proposed guidelines written with cognizance of challenges
  - Requirements ensure that analysts appropriately consider known characteristics, challenges and issues
  - Requirements have been written to afford significant flexibility in how there topics are addressed
- Standard establishes requirements for performing high confidence "mechanism-specific" hazard frequencies and characterizing the challenges posed by that hazard in a manner consistent with the estimation of plant risk.
- From a hazard perspective, primary focus was to develop external flood hazard scenarios suitable for PRA applications, addressing risks of lower frequency flood hazard but recognizing the potential impacts of more frequent flood events
- Standard Part to be incorporated in 2017 Edition of Revised Standard



ANS/ASME PRA Standard: Specific Hazard Frequency PRA Element Upgrades

- **Includes Requirements for hazard mechanism screening**
- **Requirement for developing (or using existing) PHFA curves**
  - Intent to be consistent with ANS 2.8 development
    - Reconciliation not yet performed
  - Data Collection
  - Model/method Selection
  - Treatment of uncertainties
  - Mechanism specific considerations identified but no detailed hazard specific supporting requirements
  - Address challenges:
    - Coexistent hazards
    - Multiple measures of flood severity
- **Included Requirement for Peer Review**



External Flood Hazard Frequency: Standard Considerations for Workshop

- **Activity in Standards development is indicative of the importance of understanding the flood hazard for Nuclear Plant sites**
- **Primary focus of Standards is not a single prescriptive methodology**
  - Standard allows for advances in methodologies with emphasis on characterizing uncertainties and use of a systematic process
  - However, for the Standards to be effective a full spectrum of methods for credible flood mechanisms need to be available
- **Practical example applications for PFHF for flood mechanisms at typical sites are important to make meeting the standard easier**
- **Increased guidance for providing practical means for identifying and characterizing uncertainties**
- **Guidance on treatment and role of correlated and co-existent hazards**
- **Standard requires independent peer review to increase confidence in predictions**

Westinghouse Non-Proprietary Class 3

Open Discussion and Questions

Westinghouse

2.3.1.4.2 *Questions and Answers*

Question:

How big of a watershed or subwatershed can be modeled successfully using the stochastic event-based rainfall runoff model?

Response:

As the watershed increases in size, it becomes more complex because it includes both moving and nonstationary fronts. The only point of reference that I have is that EPRI performed some work primarily considering stationary storms for a power plant in an 8,000-square-mile watershed. That work considered all the different initiating precipitation/snow melt processes but only stationary storms. With only that single example, it is possible that any larger area would be difficult to model in that way.

Question:

What are the most difficult problems with developing the American Nuclear Society flooding standard?

Response:

The biggest problem at present is ensuring consistency among the various sections of the standard. The models and processes that we considered work and the technology that exists is acceptable, so the issue is being consistent through the standard as it is such a wide change.

2.3.1.5 NRC Flooding Research Program Overview, Joseph Kanney*, Ph.D., Meredith Carr, Ph.D., P.E., Thomas Aird, Elena Yegorova , Ph.D., and Mark Fuhrmann, Ph.D., Fire and External Hazards Analysis Branch, Division of Risk Analysis; and Jacob Philip, P.E., Division of Engineering, Structural, Geotechnical and Seismic Engineering Branch, Office of Nuclear Regulatory Research, U.S. NRC (Session 1A-5; ADAMS Accession No. ML17054C500)

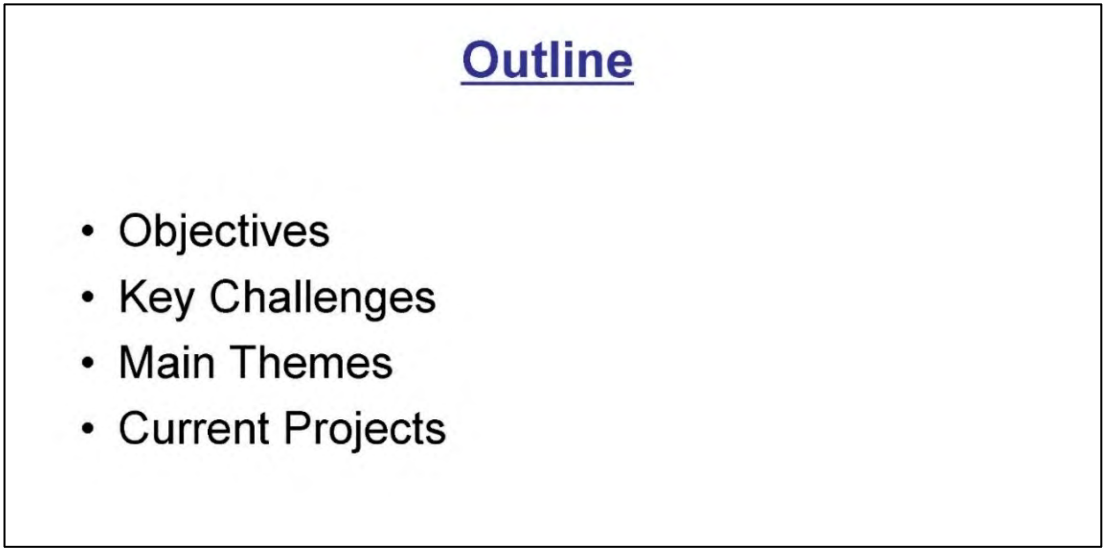
2.3.1.5.1 Presentation

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

Overview of NRC Probabilistic Flood Hazard Assessment Research Program

Meredith Carr, Ph.D.
Mark Fuhrmann, Ph.D.
Joseph Kanney, Ph.D.
Jacob Philip, PE
Elena Yegorova, Ph.D.
Fire and External Hazards Analysis Branch, Division of Risk Analysis
Office of Nuclear Regulatory Research

2nd Annual PFHA Research Workshop
NRC HQ, Rockville, MD
January 23-25, 2017



Outline

- Objectives
- Key Challenges
- Main Themes
- Current Projects

PFHA Research Objectives

- Support development of risk-informed licensing and oversight guidance and tools for assessing flooding hazards and consequences
  - *Addresses significant gap in probabilistic basis for external hazards*
    - Seismic and wind hazard assessments currently have probabilistic basis
- Support both new reactor licensing and oversight of operating reactors
  - *Design basis flood hazard assessments for new facilities*
    - 10 CFR Part 50 - traditional construction permits and operating licenses
    - 10 CFR Part 52 - early site permits (ESPs), combined operating licenses (COLs)
  - *Operating reactor oversight program (ROP)*
    - Significance determination process (SDP) analyses for evaluating deficiencies related to flood protection at operating facilities

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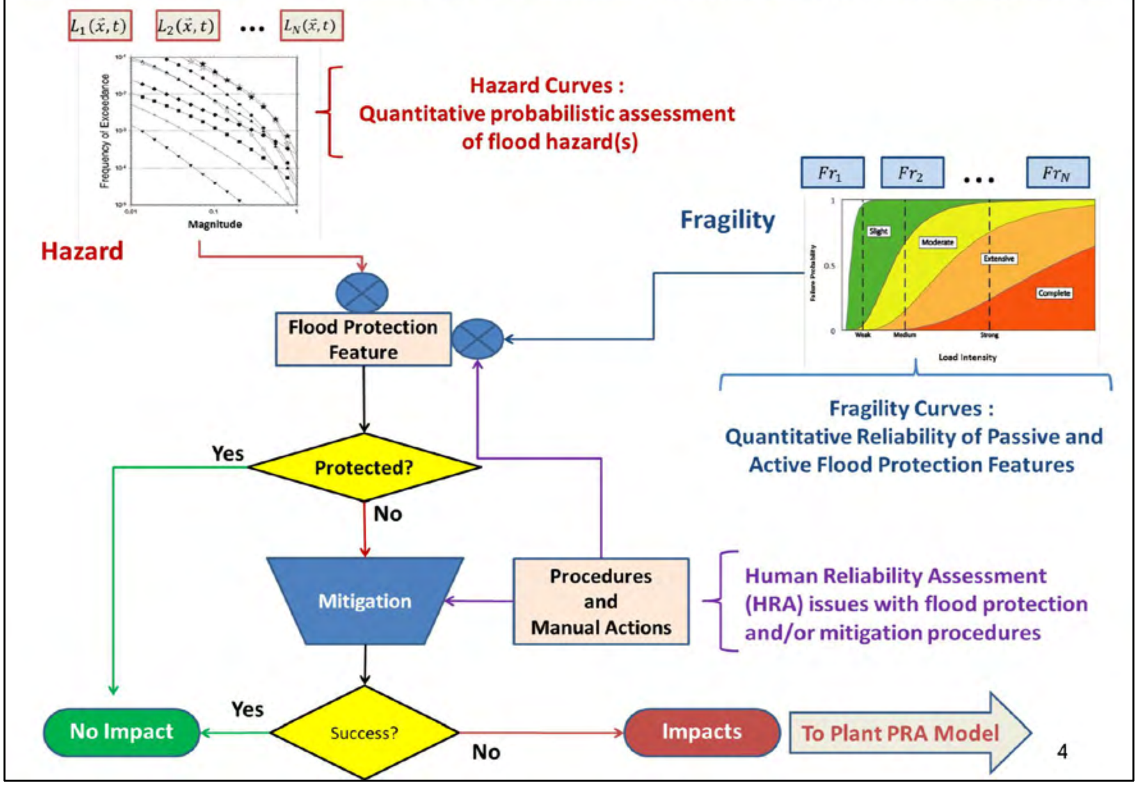
Risk-informed Assessment of Flooding Hazards and Consequences



Hazard Curves :
Quantitative probabilistic assessment of flood hazard(s)

Hazard

Fragility

Fragility Curves :
Quantitative Reliability of Passive and Active Flood Protection Features

Flood Protection Feature

Protected?

Yes

No

Mitigation

Procedures and Manual Actions

Human Reliability Assessment (HRA) issues with flood protection and/or mitigation procedures

Success?

Yes

No

No Impact

Impacts

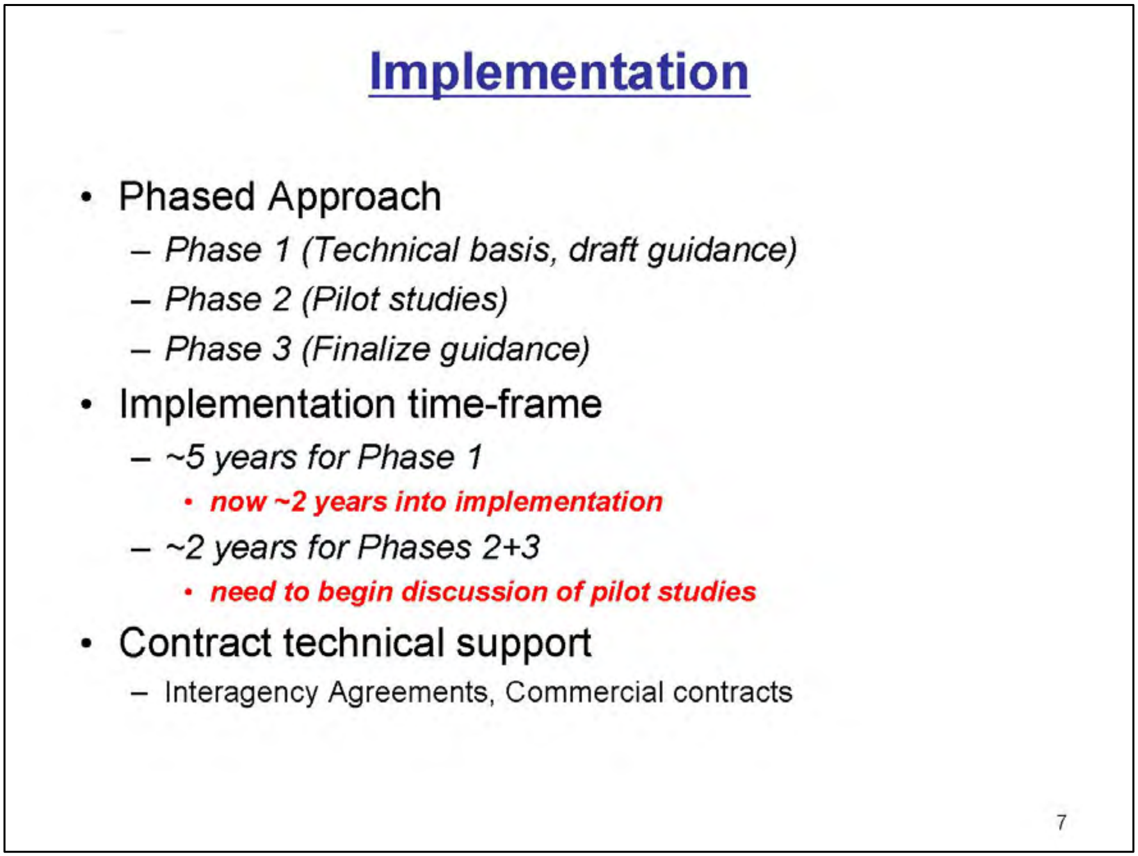
To Plant PRA Model

Key Challenges

- Interested in range of annual exceedance probabilities (AEPs) from moderately rare to extreme floods
  - *Full hazard curves needed*
    - Aleatory and epistemic uncertainties
  - *AEPs in the range 10^{-4} to 10^{-6} desired*
- Coping with large uncertainties
- Component fragility and human reliability information is sparse
- Flooding impacts exhibit cliff-edge effects
- Combined effects and associated effects

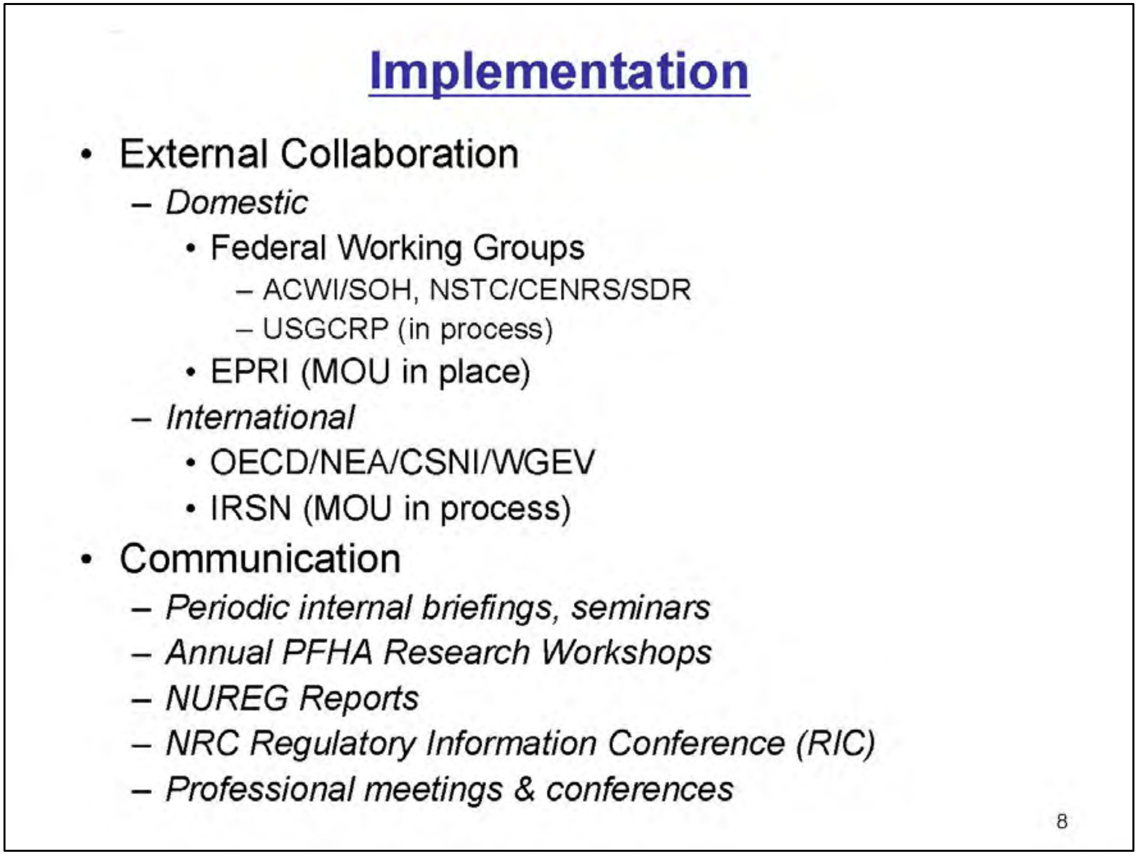
Research Plan Main Themes

- Leverage available flood hazard information
- Develop PFHA framework for range of flooding scenarios and range of AEPs
- Application of improved modeling techniques for processes and mechanisms associated with flooding
- Assess reliability of flood protection, mitigation, and plant response to flooding events
- Assess potential impacts of dynamic and nonstationary processes on flood hazard assessments and flood protection



Implementation

- Phased Approach
  - *Phase 1 (Technical basis, draft guidance)*
  - *Phase 2 (Pilot studies)*
  - *Phase 3 (Finalize guidance)*
- Implementation time-frame
  - *~5 years for Phase 1*
    - ***now ~2 years into implementation***
  - *~2 years for Phases 2+3*
    - ***need to begin discussion of pilot studies***
- Contract technical support
  - Interagency Agreements, Commercial contracts



Implementation

- External Collaboration
  - *Domestic*
    - Federal Working Groups
      - ACWI/SOH, NSTC/CENRS/SDR
      - USGCRP (in process)
    - EPRI (MOU in place)
  - *International*
    - OECD/NEA/CSNI/WGEV
    - IRSN (MOU in process)
- Communication
  - *Periodic internal briefings, seminars*
  - *Annual PFHA Research Workshops*
  - *NUREG Reports*
  - *NRC Regulatory Information Conference (RIC)*
  - *Professional meetings & conferences*

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Protecting People and the Environment

Current Projects

Leverage Available Flooding Information

- **Development of Flood Hazard Information Digests for Operating NPP Sites**
  - *Contractor: Idaho National Laboratory (INL)*
  - *NRC PM: Joseph Kanney*

- **Guidance on Application of State-of-Practice Flood Frequency Analysis Methods and Tools**
  - *Contractor: U.S. Geological Survey (USGS)*
  - *NRC PM: Meredith Carr*

Leverage Available Flooding Information

- **Technical Basis for Extending Frequency Analysis Beyond Current Consensus Limits**
  - *Contractor: U.S. Bureau of Reclamation (USBR)*
  - *NRC PM: Joseph Kanney*
- **Research to Develop Guidance on Extreme Precipitation Frequency in Orographic Regions**
  - *Contractor: USBR*
  - *NRC PM: Joseph Kanney*
- **Eastern US Riverine Flood Geomorphology Feasibility Study**
  - *Contractor: USGS*
  - *NRC PM: Mark Fuhrmann*

PFHA Frameworks

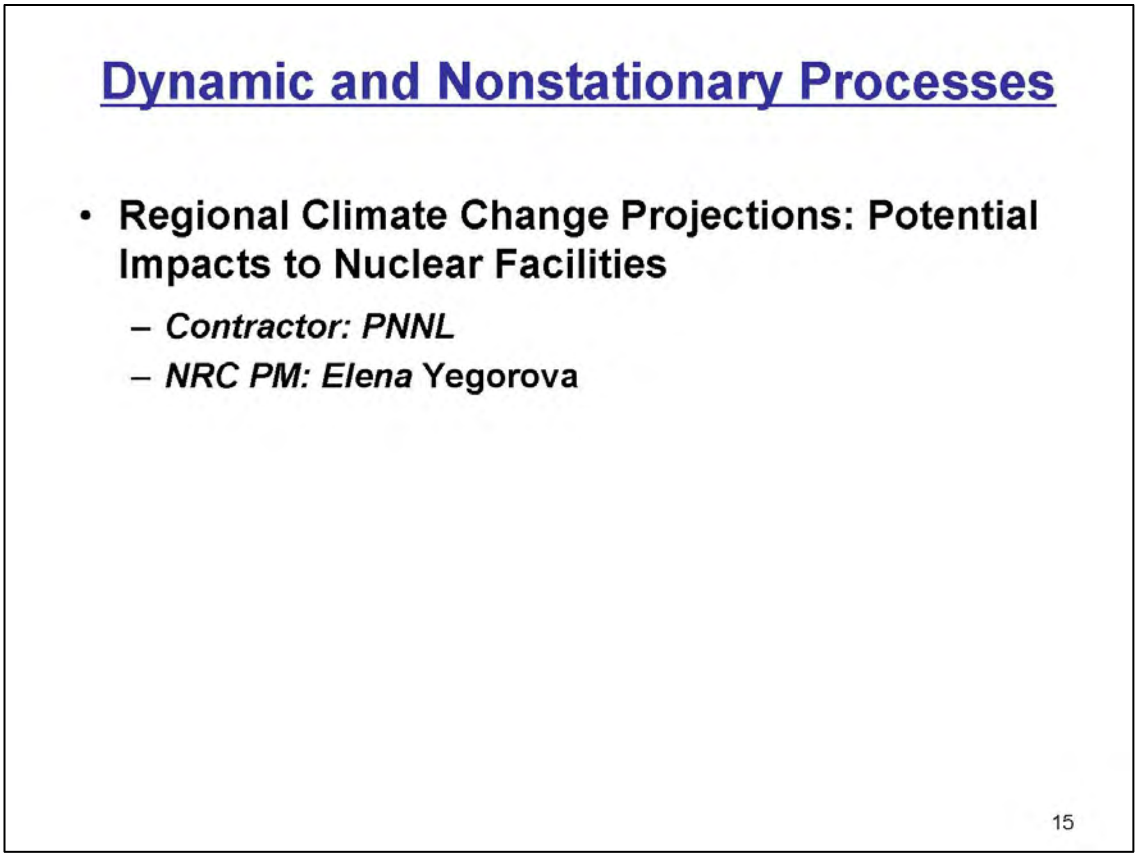
- **Technical Basis for Probabilistic Flood Hazard Assessment – Riverine Flooding**
  - *Contractor: Pacific Northwest National Laboratory (PNNL)*
  - *NRC PM: Joseph Kanney*
- **Probabilistic Flood Hazard Assessment Framework Development**
  - *Contractor: U.S. Army Corps of Engineers (USACE)*
  - *NRC PM: Joseph Kanney*
- **Structured Hazard Assessment Committee Process for Flooding**
  - *Contractor: PNNL*
  - *NRC PM: Joseph Kanney*

Improved Process Modeling

- **Numerical Modeling of Local Intense Precipitation Processes**
  - *Contractor: University of California Davis/USGS*
  - *NRC PM: Elena Yegorova*
- **Quantifying Uncertainties in Probabilistic Storm Surge Models**
  - *Contractor: USACE*
  - *NRC PM: Joseph Kanney*
- **Erosion Processes in Embankment Dams**
  - *Contractor: USBR*
  - *NRC PM: Jacob Philip*

Reliability of Flood Protection and Plant Response to Flooding Events

- **Performance of Flood Penetration Seals at NPPs**
  - *Contractor: Fire Risk Management (FRM)*
  - *NRC PM: Tom Aird*
- **Effects of Environmental Factors on Manual Actions for Flood Protection and Mitigation at NPPs**
  - *Contractor: PNNL*
  - *NRC PM: Meredith Carr*
- **Modeling Total Plant Response to Flooding Events**
  - *Contractor: INL*
  - *NRC PM: Joseph Kanney*



Dynamic and Nonstationary Processes

- **Regional Climate Change Projections: Potential Impacts to Nuclear Facilities**
  - *Contractor: PNNL*
  - *NRC PM: Elena* Yegorova

2.3.1.5.2 Questions and Answers

Comment:

This area is very important with regard to waste management and decommissioning. Would it be possible to work cooperatively with the Office of Nuclear Material Safety and Safeguards (NMSS) by adding NMSS to the review of the documentation?

Response:

We would certainly like to work with you on this issue.

2.3.1.6 ***EPRI Flooding Research Program Overview***, John Weglian, EPRI (Session 1A-6; ADAMS Accession No. ML17054C501)

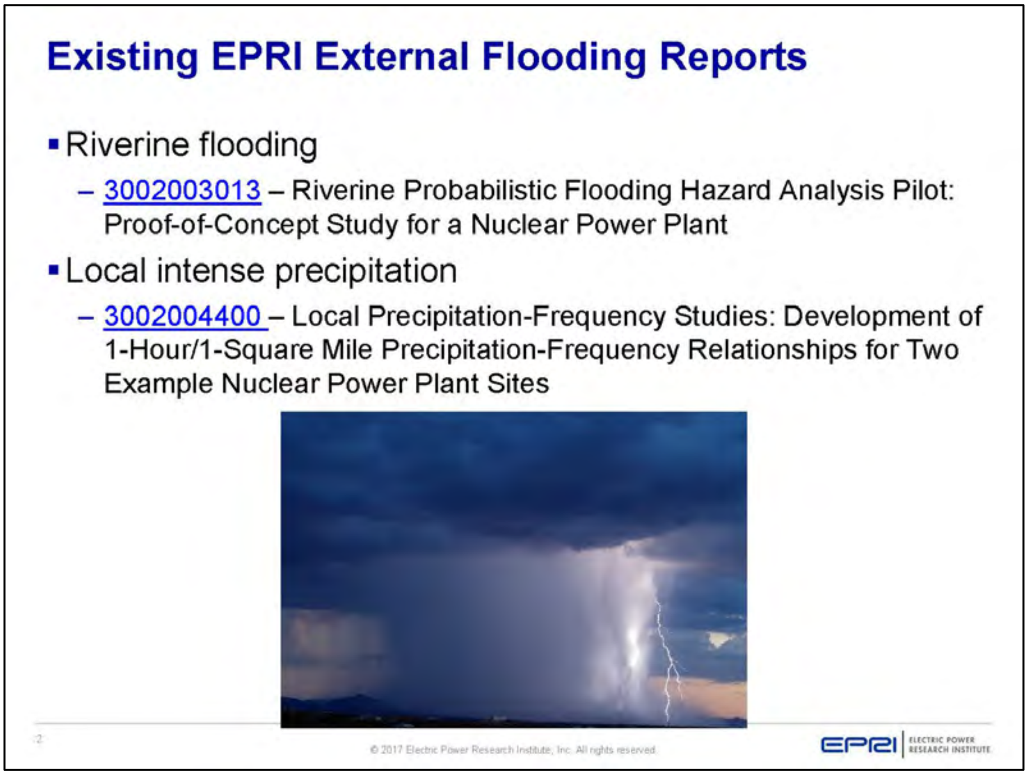
2.3.1.6.1 Presentation

ELECTRIC POWER RESEARCH INSTITUTE

EPRI Flooding Research Program Overview

John E. Weglian
Senior Technical Leader

NRC External Flooding Research Workshop
1/23/2017



Existing EPRI External Flooding Reports

- Riverine flooding
  - 3002003013 – Riverine Probabilistic Flooding Hazard Analysis Pilot: Proof-of-Concept Study for a Nuclear Power Plant
- Local intense precipitation
  - 3002004400 – Local Precipitation-Frequency Studies: Development of 1-Hour/1-Square Mile Precipitation-Frequency Relationships for Two Example Nuclear Power Plant Sites

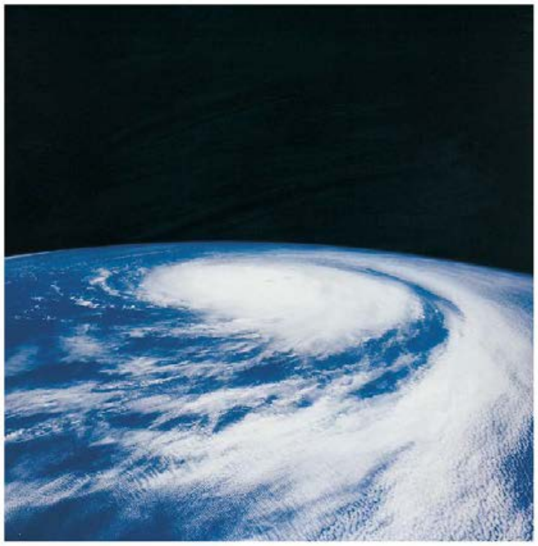
ELECTRIC POWER RESEARCH INSTITUTE

Existing EPRI External Flooding Reports

- Storm surge
  - 3002008111 – Probabilistic Flooding Hazard Assessment for Storm Surge with an Example Based on Historical Water Levels
- Deterministic hazard assessment
  - 3002008113 – Evaluation of Deterministic Approaches to Characterizing Flood Hazards

Near-Term EPRI External Flooding Research

- Collection of paleoflood evidence
  - Report expected in 2017
- Use of paleoflood data in risk-informed approaches
  - Research in 2017-2018
- Estimation of frequency of hurricane-driven storm surge
  - Research in 2017
- Guidance on conducting PRA external flooding walkdowns
  - Research in 2017 or 2018

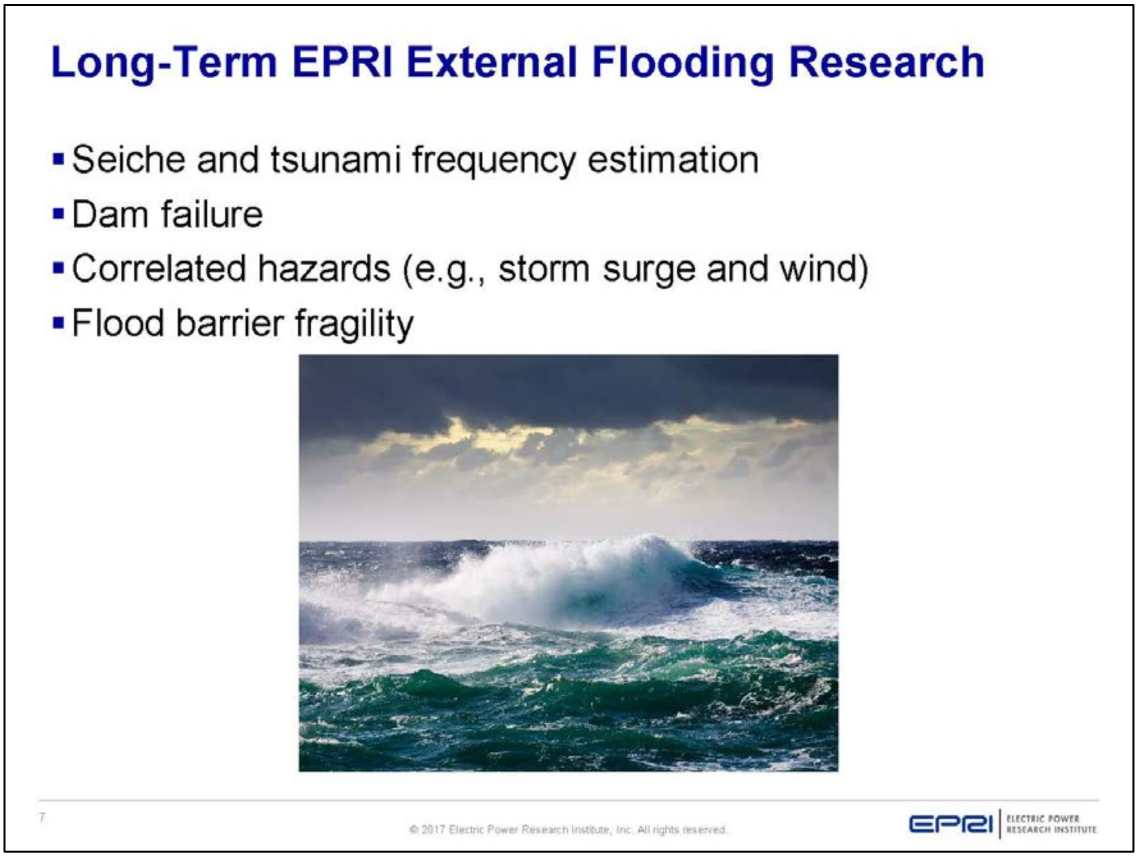


EPRI's NMAC Flood Protection Research

- Flood Protection
  - 3002005423 – Flood Protection Systems Guide
- Follow-on work to identify and communicate good practices in maintaining an external flooding design and licensing basis

EPRI Technology Innovation Research

- Technology Innovation (TI) Projects at EPRI are long-term, high-risk, high-payoff research investigations
- EPRI has a TI project looking at smooth particle hydrodynamics (SPH) for flooding simulations
  - Initial project is focused on an internal flooding scenario
  - Results will be compared to existing flooding assessments
- Goal of the project is to determine if any new risk insights are obtained with this approach
- SPH may be useful for simulating external flooding scenarios
  - Note: Idaho National Labs is investigating the use of SPH for use in dynamic PRA models



Long-Term EPRI External Flooding Research

- Seiche and tsunami frequency estimation
- Dam failure
- Correlated hazards (e.g., storm surge and wind)
- Flood barrier fragility

Together…Shaping the Future of Electricity

John E. Weglian
Senior Technical Leader
jweglian@epri.com
704-595-2763

2.3.2 Day 1: Session 1B - Storm Surge Research

This session covered the development of guidance for the application of improved mechanistic and probabilistic modeling techniques for key flood-generating processes and flooding scenarios.

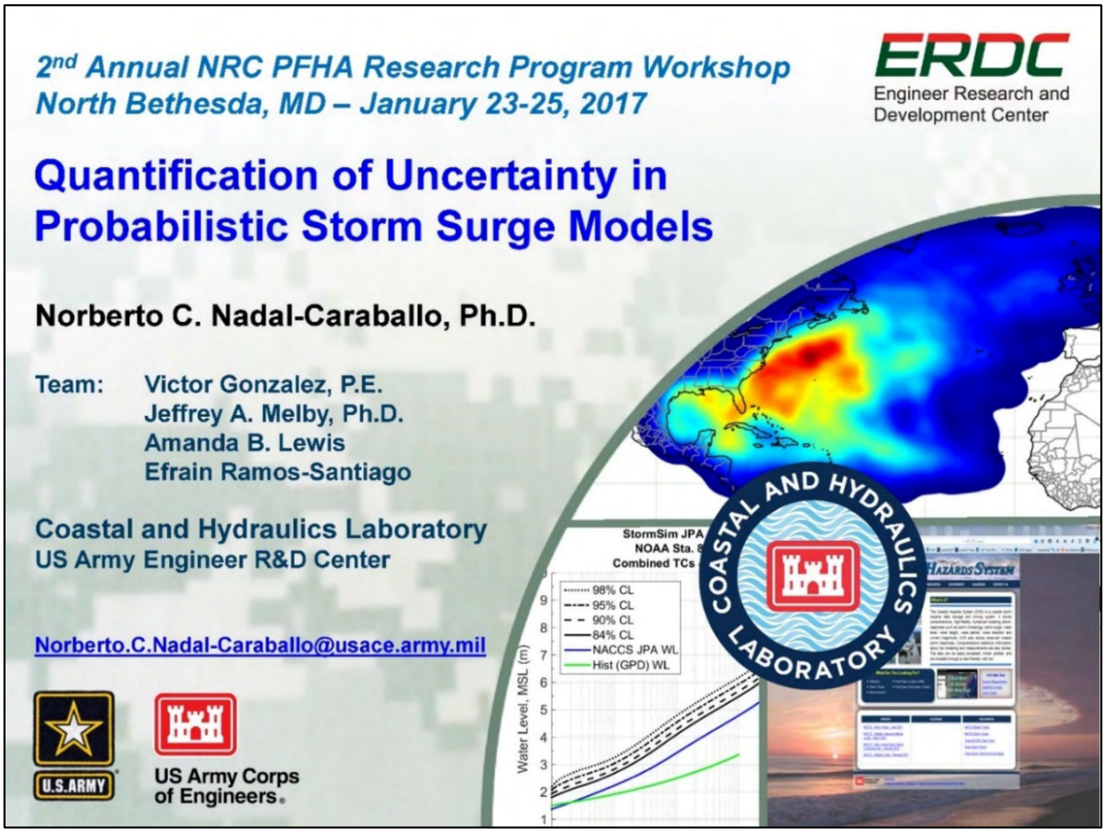
2.3.2.1 *Quantification of Uncertainty in Probabilistic Storm Surge Models*, Norberto C. Nadal-Caraballo*, Ph.D., Victor Gonzalez, P.E., and Jeffrey A. Melby, Ph.D., U.S. Army Corps of Engineers, Engineer Research and Development Center, Coastal and Hydraulics Laboratory (Session 1B-1; ADAMS Accession No. ML17054C502)

2.3.2.1.1 Abstract

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

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

2.3.2.1.2 Presentation



2nd Annual NRC PFHA Research Program Workshop
North Bethesda, MD – January 23-25, 2017

ERDC
Engineer Research and
Development Center

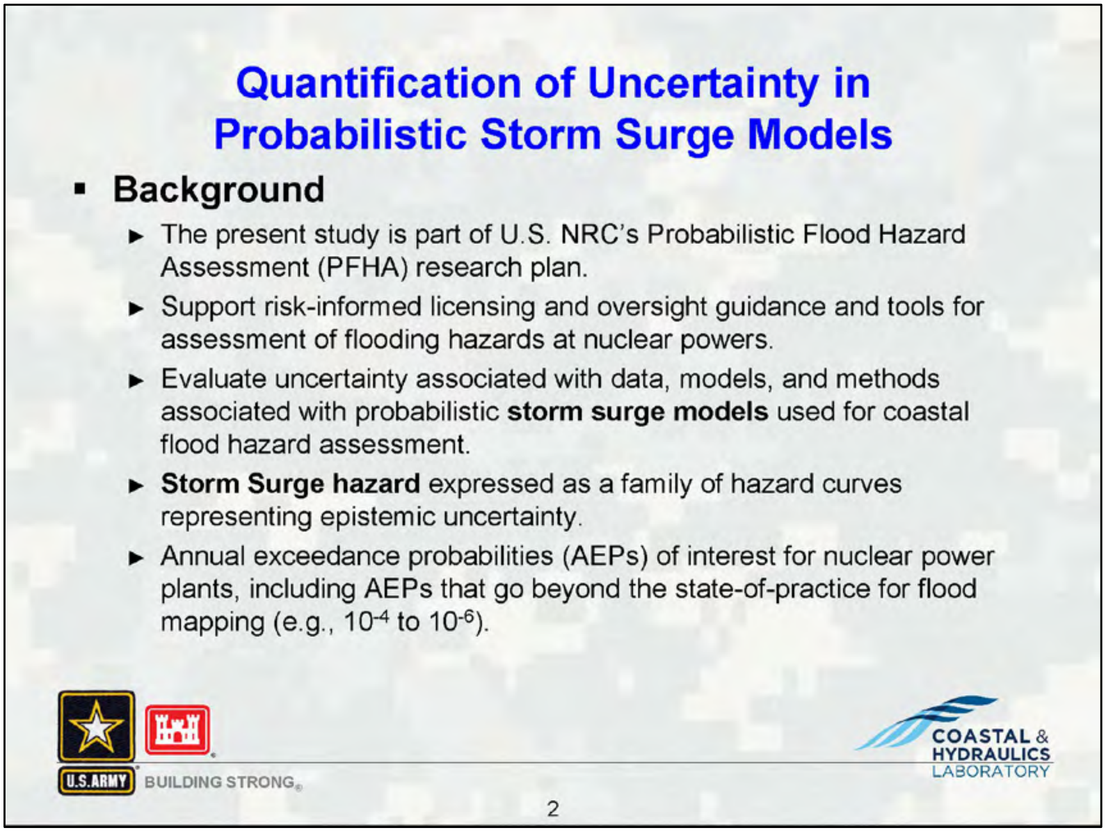
Quantification of Uncertainty in Probabilistic Storm Surge Models

Norberto C. Nadal-Caraballo, Ph.D.

Team: Victor Gonzalez, P.E.
Jeffrey A. Melby, Ph.D.
Amanda B. Lewis
Efrain Ramos-Santiago

Coastal and Hydraulics Laboratory
US Army Engineer R&D Center

Norberto.C.Nadal-Caraballo@usace.army.mil



Quantification of Uncertainty in Probabilistic Storm Surge Models

- **Background**
  - The present study is part of U.S. NRC's Probabilistic Flood Hazard Assessment (PFHA) research plan.
  - Support risk-informed licensing and oversight guidance and tools for assessment of flooding hazards at nuclear powers.
  - Evaluate uncertainty associated with data, models, and methods associated with probabilistic **storm surge models** used for coastal flood hazard assessment.
  - **Storm Surge hazard** expressed as a family of hazard curves representing epistemic uncertainty.
  - Annual exceedance probabilities (AEPs) of interest for nuclear power plants, including AEPs that go beyond the state-of-practice for flood mapping (e.g., 10^{-4} to 10^{-6}).

Quantification of Uncertainty in Probabilistic Storm Surge Models

- **Computation of Storm Surge Hazard**
  - The estimation of storm surge hazard using historical observations in hurricane-prone areas is limited by a lack of adequate data.
  - This has led to the development of methods that rely on the statistical characterization of the tropical cyclone (TC) forcing and subsequent modeling of storm surge response.
  - These methods have evolved into sophisticated joint probability approaches that allow for comprehensive quantification of uncertainty.
  - Joint probability method with optimal sampling (JPM-OS) has become the standard-of-practice for quantifying storm surge hazard in coastal areas affected by TCs.
  - Other methods include global climate models (GCM) with downscaling, and Monte Carlo Simulation (MCS) methods.

General Overview and Logic Tree Approach

JPM Integral

$$\lambda_{r(\hat{x})>r} = \lambda \int P[r(\hat{x}) + \varepsilon > r|\hat{x},\varepsilon]\, f_{\hat{x}}(\hat{x}) f_{\varepsilon}(\varepsilon) d\hat{x} d\varepsilon$$

$$\approx \textstyle\sum_i^n \lambda_i\, P[r(\hat{x}) + \varepsilon > r|\hat{x},\varepsilon]$$

where:

$\lambda_{r(\hat{x})>r}$ = AEP of TC response r due to forcing vector $\hat{x}$

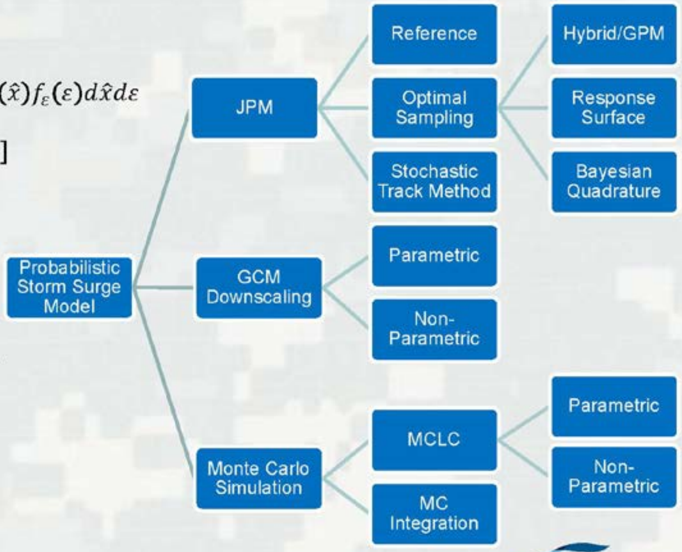
$\hat{x} = f(x_o, \theta, \Delta p, R_{max}, V_t)$

λ = SRR (storms/yr/km)

λ_i = probability mass (storms/yr) or $\lambda\, p_i$, with p_i=product of discrete probability and TC track spacing (km)

$P[r(\hat{x}) + \varepsilon > r|\hat{x},\varepsilon]$ conditional probability that storm i with parameters $\hat{x}_i$ generates a response larger than r

ε = unbiased error of r



Probabilistic Storm Surge Model

JPM

Reference

Optimal Sampling

Stochastic Track Method

Hybrid/GPM

Response Surface

Bayesian Quadrature

GCM Downscaling

Parametric

Non-Parametric

Monte Carlo Simulation

MCLC

MC Integration

Parametric

Non-Parametric

Probabilistic Storm Surge Model Description Example: JPM

- The application of each surge models typically involves the implementation of several types of analyses.
- For each type of analysis several approaches may be available. Using JPM as example:

Model	Method	Data	SRR	Marginal/Conditional	Integration
JPM	JPM-Reference JPM-OS (RS, BQ, Hybrid) JPM-STM	Observed (HURDAT) Reanalysis Synthetic (GCM, STM)	Models (GKF, UKF, EKF) Screening (period of record, intensity)	Parameterization Dependencies Statistical approach (parametric vs. non-parametric)	Distribution error JPM integral (standard discretization, random sampling, Gaussian redistribution)
Task 4		All	Task 2	Task 3	Task 5

Project Tasks

Task 1	**Literature Review**
Task 2	**Investigation of Epistemic Uncertainties in Storm Recurrence Rate Models**
Task 3	**Explore Technically Defensible Data, Models, and Methods for Defining Joint Probability of Storm Parameters**
Task 4	**Explore Technically Defensible Models and Methods for Generating Synthetic Storm Simulation Sets**
Task 5	**Investigate Approaches for Probabilistic Modeling of Numerical Surge Simulation Errors**
Task 6	Synthesis
Task 7	Transfer of Knowledge
Task 8	Final Report Preparation

Classification of Uncertainty

- Two classifications of uncertainty typically recognized:
  - Aleatory – natural randomness of a process; not reducible
  - Epistemic – lack of knowledge about validity of models and data for the representation of real system; can be reduced.
- Classification scheme can be subjective.
- Traditional uncertainty classification in JPM-OS models:
  - The epistemic uncertainty is related to the specific methods and models used in each study.
  - Limited to the inclusion of uncertainty as an error term in the JPM integral.
    - e.g., meteorological modeling, hydrodynamic modeling, idealized storm track variation, and limited variation in wind and pressure profiles.

Classification of Uncertainty (cont.)

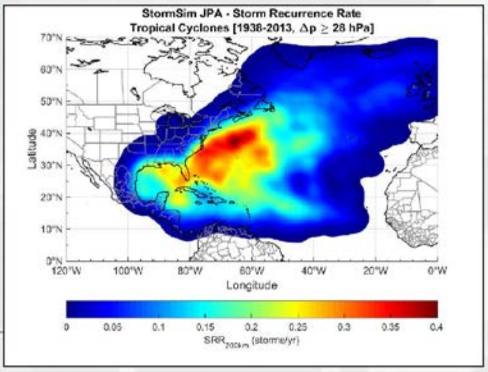
- Treatment of uncertainty in present study:
  - Follows probabilistic seismic hazard analysis (PSHA).
  - Differences between a given numerical model and the natural phenomenon is prevalent (error term) → aleatory
  - It is in the selection and application of alternative data, methods, and models that the uncertainty can be reduced → epistemic
  - Epistemic uncertainty is quantified and propagated through logic tree approach.
  - General study objectives regarding uncertainty:
    - Identification of technically defensible data sources, models, and methods.
    - Assess whether estimates derived from different data, models, and methods need to be carried forward for evaluation of epistemic uncertainty, discarding those not considered technically defensible.

Task 2: Epistemic Uncertainty in SRR Models

- **Task Description**
  - Data sources and methods used for the computation of site-specific storm recurrence rate (SRR) models.
  - Topics:
    - Technically defensible data sources for use in site specific studies (e.g., NOAA's HURDAT).
    - Appropriate models for estimation of SRR, e.g., Gaussian kernel function (GKF), uniform kernel function (UKF), and Epanechnikov kernel function (EKF).
    - Methods for screening historical data and assessing geographic variation in support of site-specific estimation of SRR (e.g., selection of historical period of record and TC binning by intensity).
    - Investigate SRR aleatory uncertainty and whether SRR estimates derived from multiple datasets or methods need to be propagated.

What is an Storm Recurrence Rate ?

- **SRR Definition**
  - Measure of the frequency with which a particular location is expected to be affected by TCs.
  - Typically expressed in units of storms per year per unit distance along the shoreline (e.g., storms/yr/km).
  - Can also be stated as number of storms per year passing within a **radius** of ***x*** km, e.g., $SRR_{200\ km}$ (storms/yr).

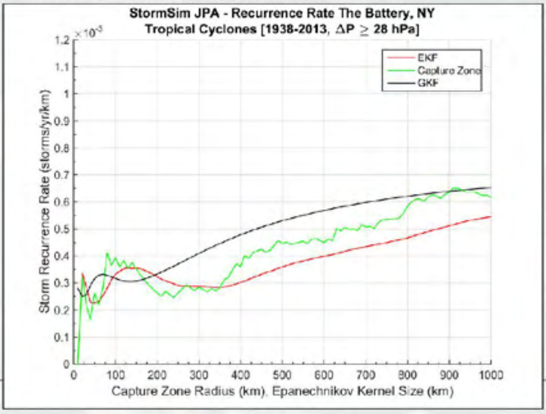


Task 2: Epistemic Uncertainty in SRR Models

- **Numerical Experiments**
  - ► Uncertainty comparison and quantification of three models for the estimation of SRR.
    - Uniform Kernel unction (capture zone approach)
    - Gaussian Kernel Function (Chouinard et al.1997)
    - Epanechnikov Kernel Function
  - ► SRR variability related to selection optimal kernel size.
  - ► SRR variability arising from selection of the period of record.
  - ► SRR variability through the analysis of subsets of data through bootstrap resampling.
  - ► Observation or measurement uncertainty in TC data.
  - ► Effect of data partition (by TC intensity) on SRR uncertainty.

Models for Estimation of SRR

- **Comparison of Kernel Functions**
  - ► UKF estimates tend to be unstable and highly sensitive to data clusters.
  - ► GKF exhibits highest smoothing while EKF curve is closer to UKF curve.
  - ► GKF considers storms past the kernel size distance. Optimal kernel size should be large enough to maximize use of data while avoiding sampling from multiple TC populations.

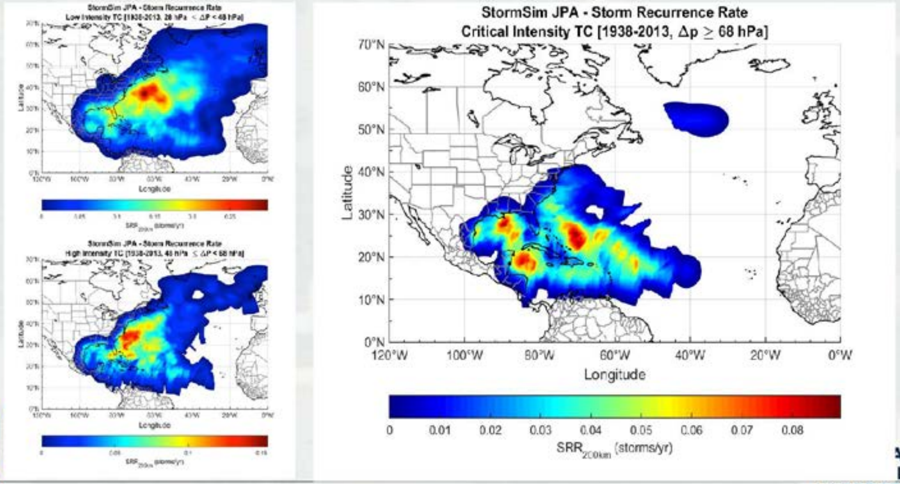


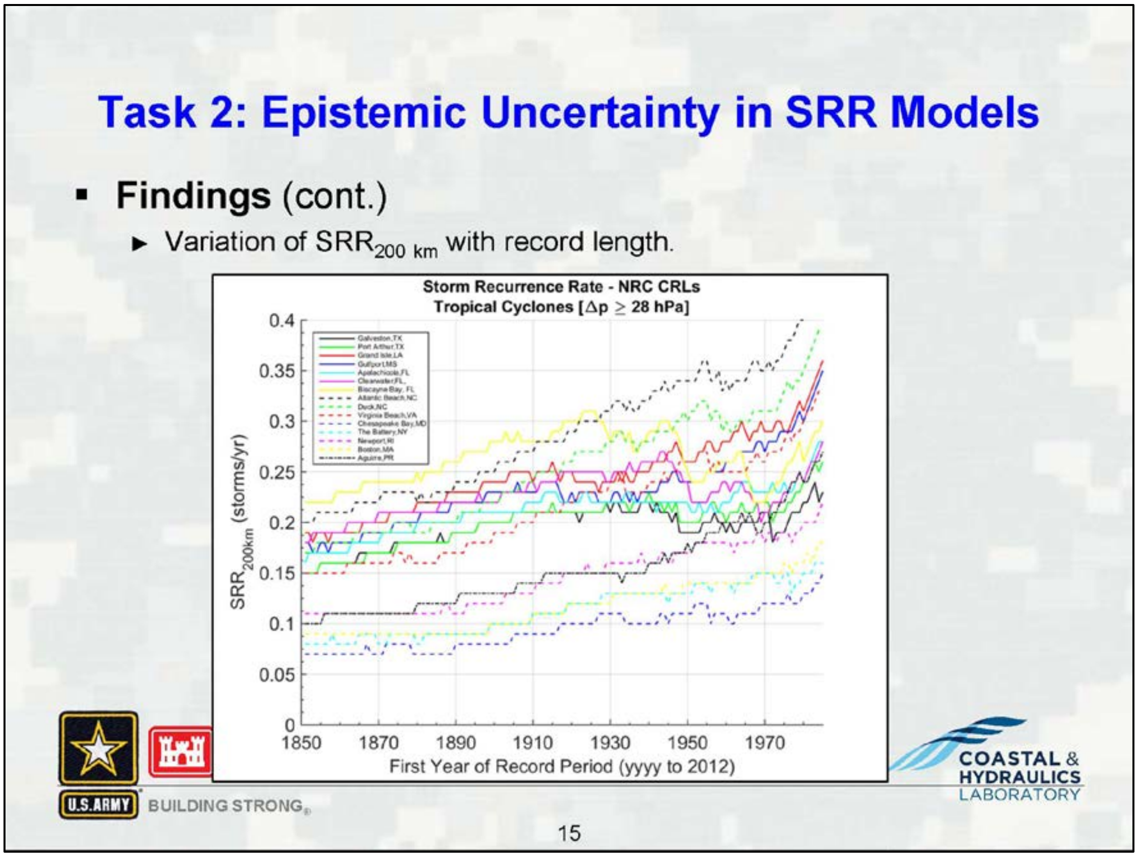
Task 2: Epistemic Uncertainty in SRR Models

- **Findings**
  - The GKF is a better method for estimating SRR compared to UKF (capture zone).
    - GKF can consider larger number of storms than the UKF model.
    - For same ranges of optimal uniform and Gaussian kernel sizes, GKF estimates exhibited reduced coefficient of variation (CV) when compared to UKF.
  - The lowest SRR uncertainty where observed in North Carolina, Florida, Mississippi and Louisiana while the U.S. coast north of Virginia exhibited the largest uncertainties.
  - Typically, larger samples result in a reduction of uncertainty and therefore in reduced sensitivity to model decisions.

Task 2: Epistemic Uncertainty in SRR Models

- **Findings** (cont.)
  - SRR_{200km} for low, high, and critical intensity TCs.
    - Low intensity (28-48 hPa), high intensity (48-68h Pa), critical intensity (≥68 hPa)





Task 2: Epistemic Uncertainty in SRR Models

- **Findings** (cont.)
  - Variation of $SRR_{200\ km}$ with record length.

Task 2: Epistemic Uncertainty in SRR Models

- **Findings** (cont.)
  - Total uncertainty was calculated as

$$\sigma_{\varepsilon} = \sqrt{\sigma_{\varepsilon 1}{}^{2} + \sigma_{\varepsilon 2}{}^{2} + \sigma_{\varepsilon 3}{}^{2} + \cdots + \sigma_{\varepsilon n}{}^{2}}$$

  - In general, sampling uncertainty was the main contributor to total uncertainty, followed by period of record selection; observational uncertainty was the lowest contributor.

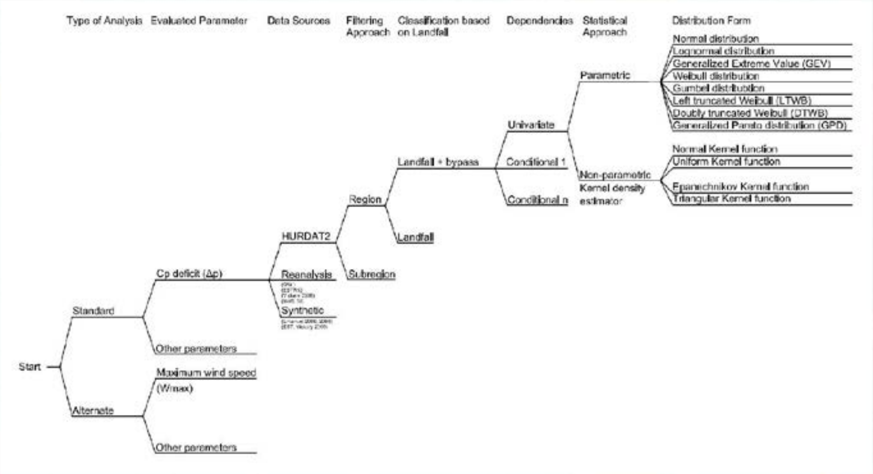
Type of Uncertainty	Percent of Total Uncertainty Δp ≥ 28 hPa	Percent of Total Uncertainty 28 hPa ≤ Δp < 48hPa	Percent of Total Uncertainty 48 hPa ≤ Δp < 68hPa	Percent of Total Uncertainty Δp ≥ 68 hPa
Sampling uncertainty	65	62	71	75
Period of record	19	12	12	7
Gaussian kernel size	15	14	3	4
Observational data	1	12	14	14

Task 3: Data, Models and Methods for Defining Joint Probability of Storm Parameters

- **Task Description**
  - ► Identification of technically defensible TC parameter data sources, screening methods, and parameterization schemes for development of probability distribution.
  - ► Topics:
    - Technically defensible data sources for use in site specific studies, including observational, reanalysis, and synthetic data sources.
    - Data screening methods for development of probability distributions, and evaluation criteria for selecting TCs from historical records or a synthetic datasets.
    - Selection of probability distribution, associated uncertainties, parameter correlations, and adequacy of forcing parameters.
    - Identification of alternate data and methods, and evaluate which of these need to be considered to account for epistemic uncertainty.

Task 3: Data, Models and Methods for Defining Joint Probability of Storm Parameters

- **Example of Logic Tree Approach**

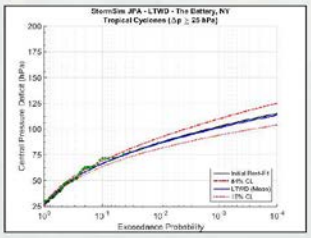


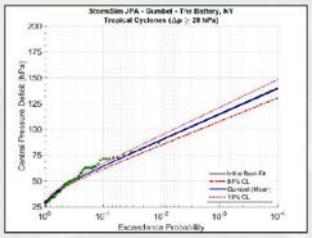
Task 3: Data, Models and Methods for Defining Joint Probability of Storm Parameters

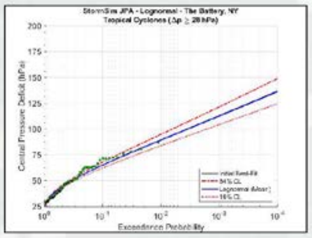
- **Numerical Experiments**
  - Basic unit of analysis: fitting of univariate distributions to TC parameters: $\theta, \Delta p, R_{max}, V_t$
  - The basic analysis (3,500+ fits) was performed to evaluate different methods, models, and data represented in the logic tree branches:
    - Parameterization: standard (*Δp*) or alternate (W_{max})
    - Data source: HURDAT2, GCM synthetics, EBTRK reanalysis
    - Landfalling or bypassing
    - Statistical models: parametric, non-parametric
  - Analysis by intensity: all TCs, high intensity, and low intensity.
  - Assessment of fits: goodness-of-fit tests, RMSD, magnitude of sampling uncertainty, visual inspection of plots.

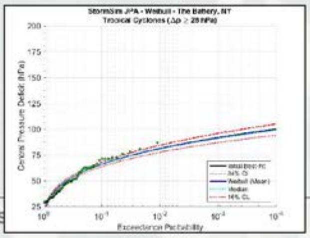
Task 3: Data, Models and Methods for Defining Joint Probability of Storm Parameters

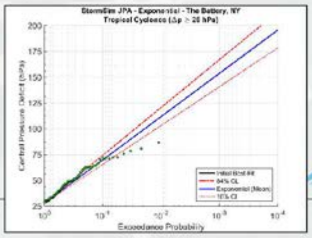
- **Parametric Distributions**
  - TC parameters were fit using Generalized Extreme Value, Generalized Pareto, Gumbel, Normal, Lognormal, Weibull, Gamma, and Exponential distributions; Δp example:

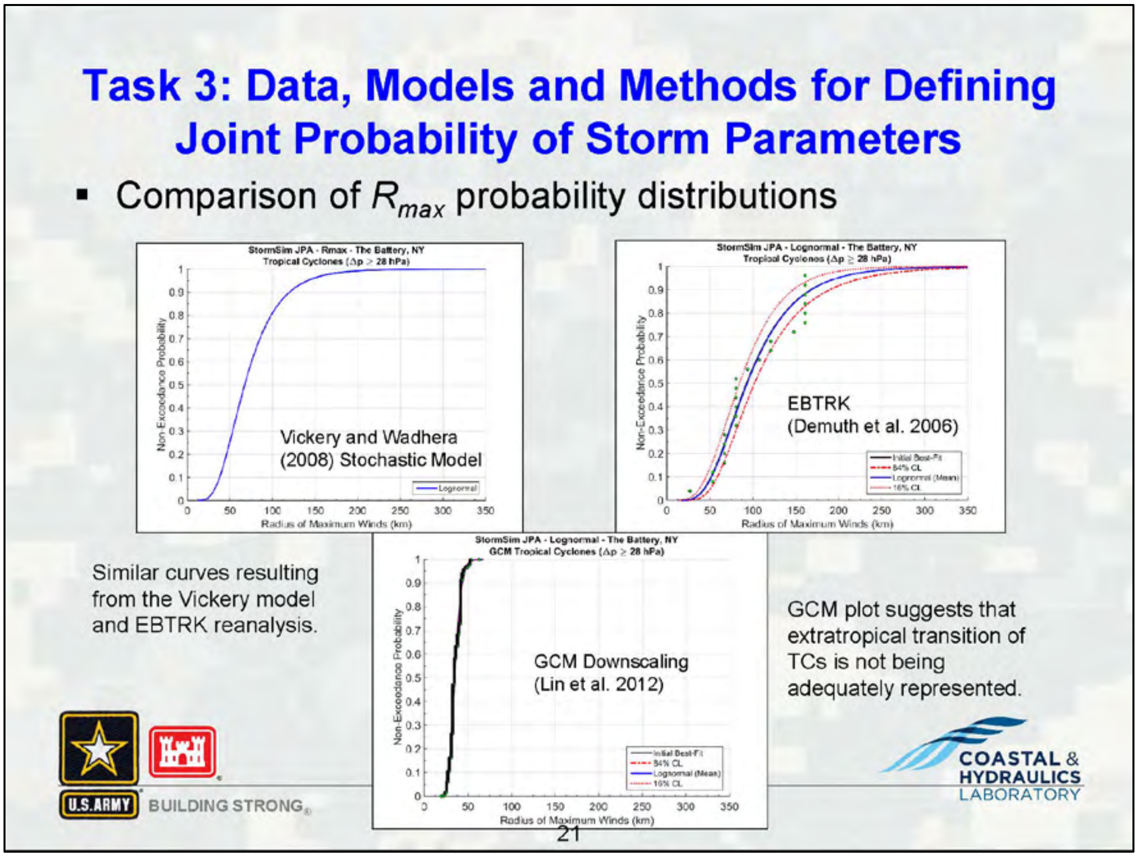












Task 3: Data, Models and Methods for Defining Joint Probability of Storm Parameters

- Comparison of R_{max} probability distributions

Vickery and Wadhera (2008) Stochastic Model

EBTRK (Demuth et al. 2006)

GCM Downscaling (Lin et al. 2012)

Similar curves resulting from the Vickery model and EBTRK reanalysis.

GCM plot suggests that extratropical transition of TCs is not being adequately represented.

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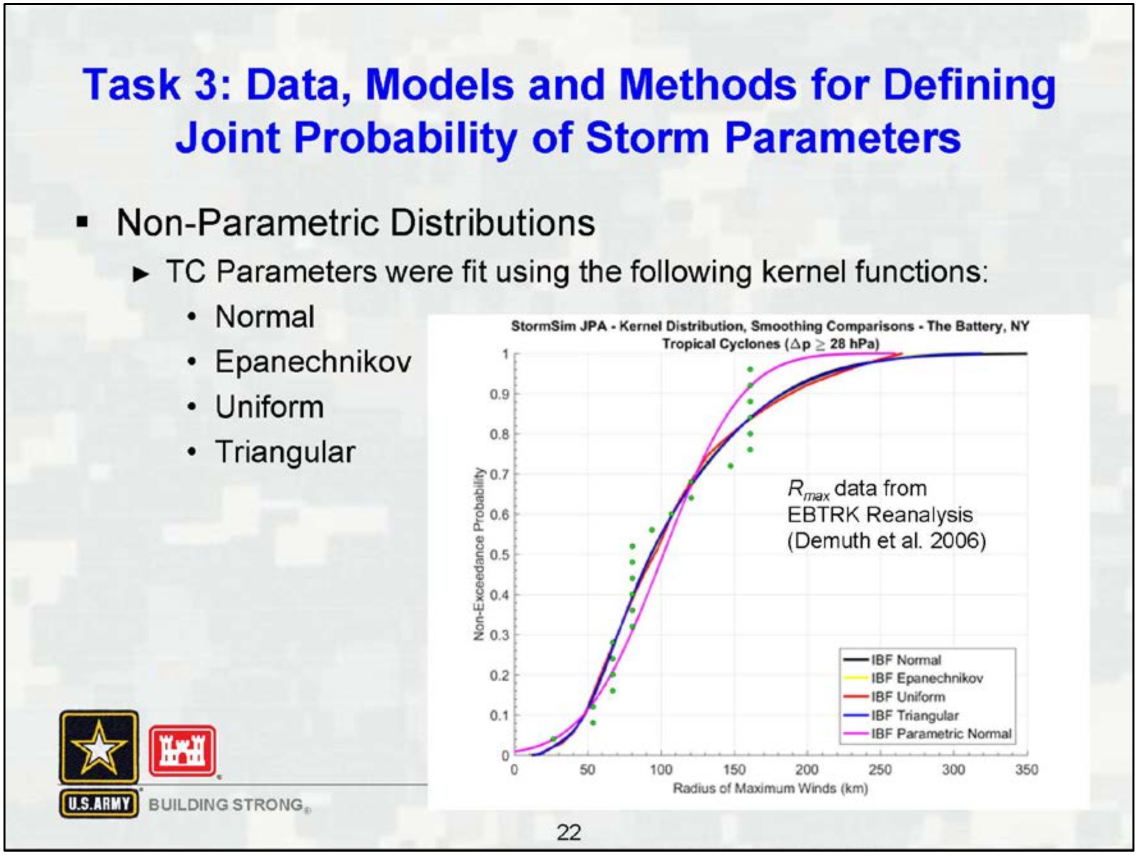

Task 3: Data, Models and Methods for Defining Joint Probability of Storm Parameters

- Non-Parametric Distributions
  - TC Parameters were fit using the following kernel functions:
    - Normal
    - Epanechnikov
    - Uniform
    - Triangular

R_{max} data from EBTRK Reanalysis (Demuth et al. 2006)

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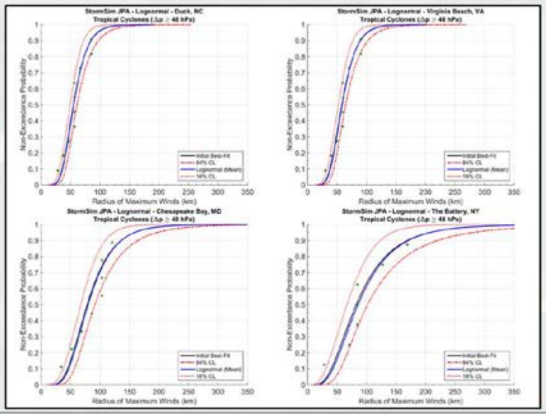
Task 3: Data, Models and Methods for Defining Joint Probability of Storm Parameters

- **General Findings**
  - ► The most relevant factor in choosing distribution type was how well it described the low-frequency tails.
  - ► More than one statistical distribution could be valid for a given TC parameter.
  - ► When more than one distribution was viable, a comparison of the fits usually did not reveal significant differences.
  - ► The sampling technique used for the generation of synthetic TCs may lessen the significance of selecting a given probability distribution for large discretization intervals.
  - ► The judgment of carry forward a given dataset, method, or model was found to be highly dependent on the location.

Task 3: Data, Models and Methods for Defining Joint Probability of Storm Parameters

- **General Findings** (cont.)
  - ► The main contributor to uncertainty associated with the probability distributions was the quantity of data.
    - When TCs were classified as high and low intensity, uncertainty for high intensities TCs increased with latitude.

High intensity lognormal distribution fit of R_{max} EBTRK data for various Atlantic coast locations.



Task 4: Data, Models, and Methods for Generating Synthetic Storm Simulation Sets

- **Task Description**
  - ► Capture full range of technically defensible data and methods for generating synthetic storm sets required to fully characterize and propagate uncertainties in storm surge estimates.
  - ► Topics:
    - Evaluation of discretization methods used to generate synthetic storms for numerical storm surge modeling.
    - Effect of the refinement of the discretization of the parameter space on uncertainty.
    - Analyze the applicability of each method over a wide range of conditions and evaluate whether criteria can be established to assess situations where one method is superior to others.
    - Evaluate the merits of studied approaches and analyze whether estimates derived from different methods need to be considered in the quantification of the epistemic uncertainty.

Task 4: Data, Models, and Methods for Generating Synthetic Storm Simulation Sets

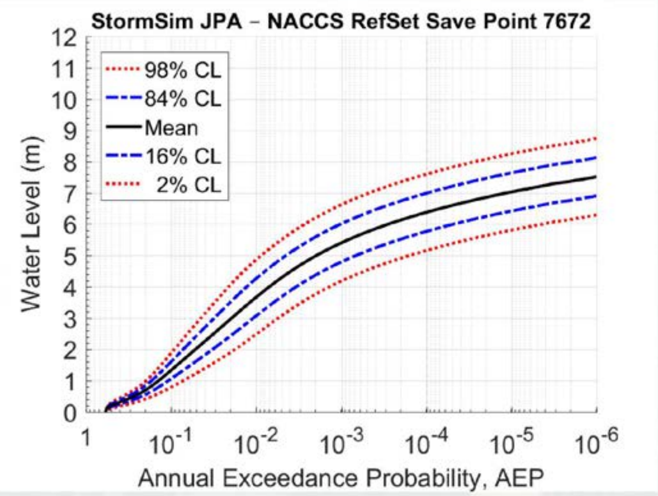
- **Numerical Experiments**
  - ► Use results from North Atlantic Coast Comprehensive Study (Nadal-Caraballo et al. 2015) where hybrid JPM-OS was used.
    - Compare to JPM-OS-RS and JPM-OS-BQ
  - ► Generate JPM "Reference" set or "Gold Standard" as basis for comparison with other methods and TC sets.
  - ► Perform various Monte Carlo simulations for development of storm surge hazard curves:
    - Monte Carlo Life-Cycle (MCLC)
    - Monte Carlo Integration (MCI)
  - ► Develop storm surge hazard curve using TC parameter set from existing GCM downscaling study performed by Lin et al. 2012 for The Battery, NY.

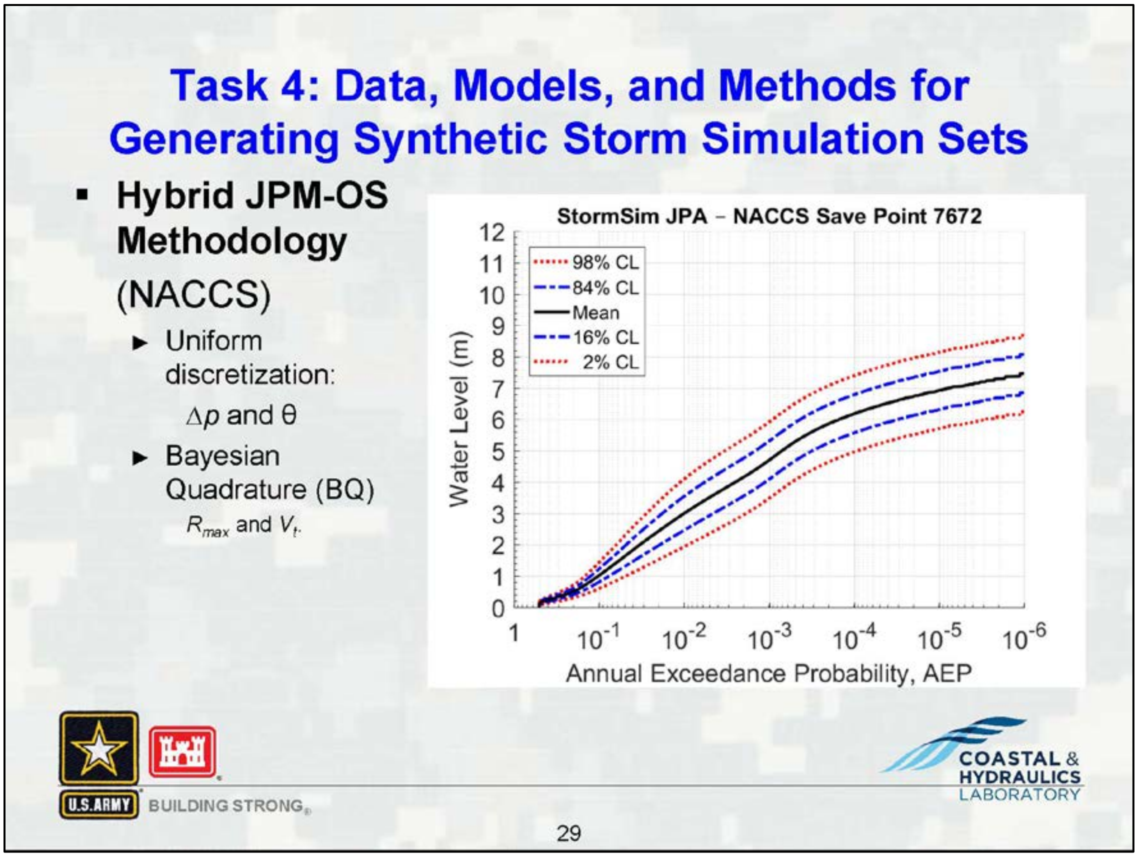
Task 4: Data, Models, and Methods for Generating Synthetic Storm Simulation Sets

- **Reference Set**
  - A large set of synthetic storms was generated to represent the traditional JPM approach.
  - A Gaussian process metamodel (GPM) (Jia et al. 2016) was used to develop tens of hundreds of TCs.
    - The GPM is conceptually similar to the RS approach where the initial discretization of the joint probability distribution is refined by regression or interpolation of storm surge from additional TC parameter combinations.
    - The GPM used in this study was trained using the 1050 synthetic TCs developed as part of the NACCS (Nadal-Caraballo et al. 2015).
  - A total of 74,430 TCs were generated based on refined discretization and using unique parameter combinations.

Task 4: Data, Models, and Methods for Generating Synthetic Storm Simulation Sets

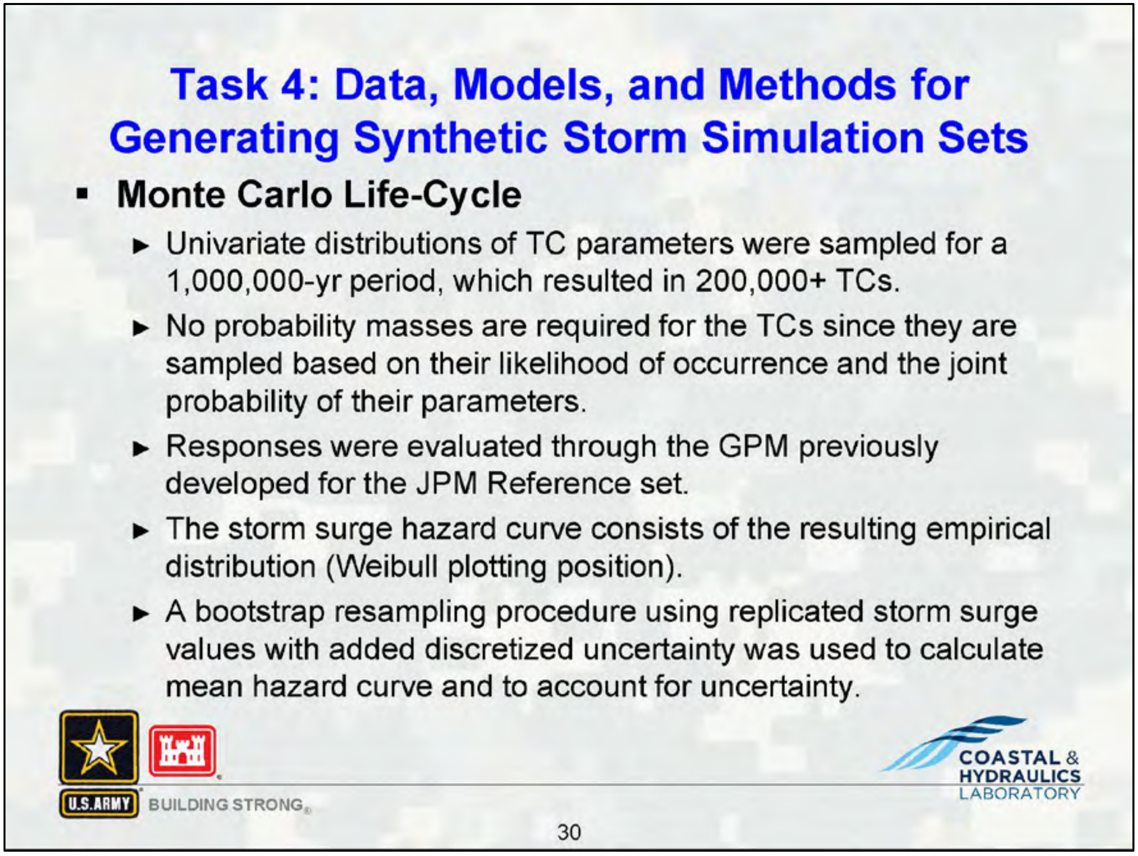
- **Reference Set – Hazard Curve**





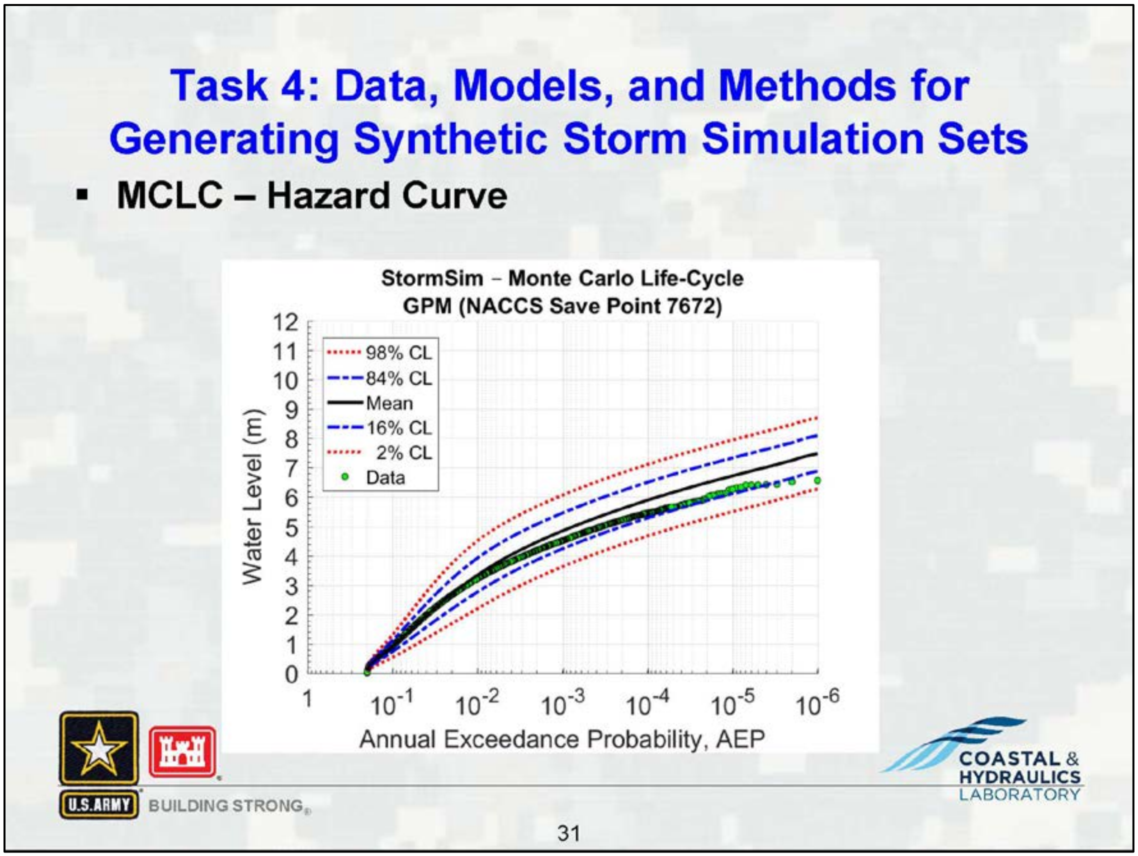
Task 4: Data, Models, and Methods for Generating Synthetic Storm Simulation Sets

- **Hybrid JPM-OS Methodology** (NACCS)
  - Uniform discretization:
    - Δp and θ
  - Bayesian Quadrature (BQ)
    - R_{max} and V_t.



Task 4: Data, Models, and Methods for Generating Synthetic Storm Simulation Sets

- **Monte Carlo Life-Cycle**
  - Univariate distributions of TC parameters were sampled for a 1,000,000-yr period, which resulted in 200,000+ TCs.
  - No probability masses are required for the TCs since they are sampled based on their likelihood of occurrence and the joint probability of their parameters.
  - Responses were evaluated through the GPM previously developed for the JPM Reference set.
  - The storm surge hazard curve consists of the resulting empirical distribution (Weibull plotting position).
  - A bootstrap resampling procedure using replicated storm surge values with added discretized uncertainty was used to calculate mean hazard curve and to account for uncertainty.



Task 4: Data, Models, and Methods for Generating Synthetic Storm Simulation Sets

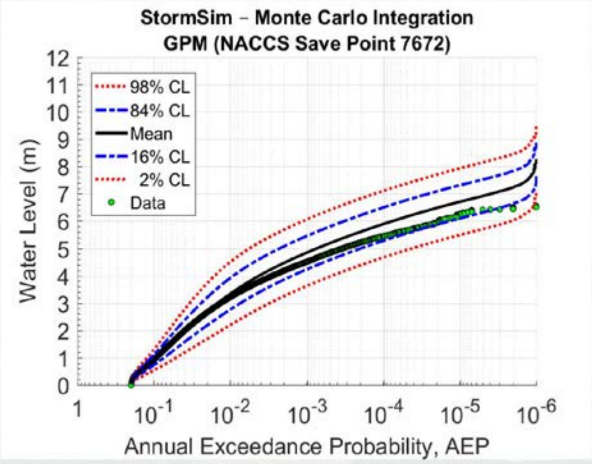
- **MCLC – Hazard Curve**

Task 4: Data, Models, and Methods for Generating Synthetic Storm Simulation Sets

- **Monte Carlo Integration (MCI)** (Wyncoll and Gouldby 2015)
  - Probabilities are calculated as the percent of TCs with response greater than a set of surge elevation bins. No probability masses are were used.
  - $P(C > c) \approx \frac{L_c}{L} * \lambda$, where L_c is the number of Monte Carlo realizations that exceed c, L is the total number of Mote Carlo realizations, and λ is the sample intensity (storms/yr).

Task 4: Data, Models, and Methods for Generating Synthetic Storm Simulation Sets

- MCI – Hazard Curve

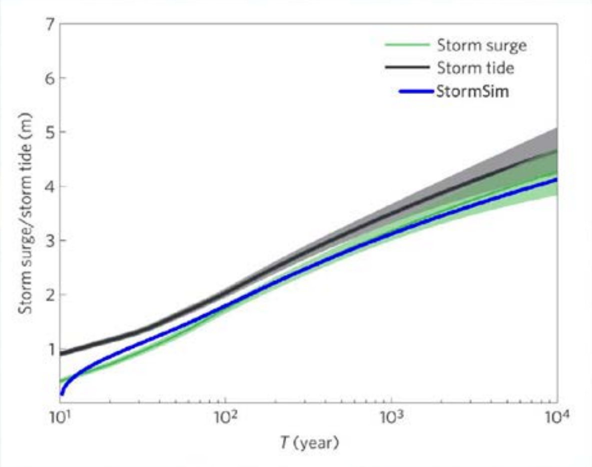


Task 4: Data, Models, and Methods for Generating Synthetic Storm Simulation Sets

- **GCM Downscaling** (Lin et. al 2012)
  - Storm surges are determined using GCM-driven statistical/deterministic hurricane model with hydrodynamic surge models.
  - Synthetic TCs tracks are generated according to large-scale atmospheric and ocean environments rather than historical TCs.
  - The data set consists of 1,470 tracks out of an original number of 5,000 tracks modeled covering a time period from 1970-2010.
  - The storm surge responses were simulated from the forcing parameters of GCM tracks and used as input to the GPM previously trained with NACCS results.
  - Stochastic simulation technique (SST) consisting of combined empirical and GPD fits was applied to the storm surge values.

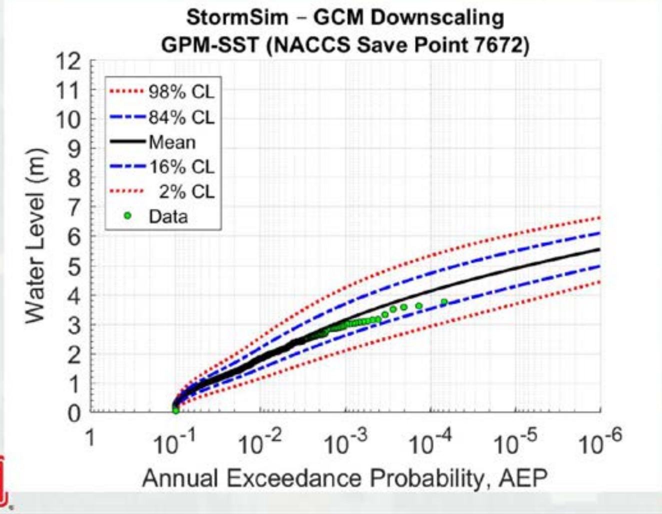
Task 4: Data, Models, and Methods for Generating Synthetic Storm Simulation Sets

- Comparison of Hazard Curves
  - GCM Downscaling results published by Lin et al. 2012
  - TCs simulated from GCM forcing, using NACCS-trained GPM.



Task 4: Data, Models, and Methods for Generating Synthetic Storm Simulation Sets

- **GCM Downscaling – Hazard Curve**



Task 4: Data, Models, and Methods for Generating Synthetic Storm Simulation Sets

- **Comparison of Results**

Storm Surge (m) at The Battery, NY

Method	Annual Exceedance Probability (AEP)				
	10^{-2}	10^{-3}	10^{-4}	10^{-5}	10^{-6}
JPM-Reference (74,430 TCs)	3.7	5.4	6.4	7.0	7.5
JPM-OS (1,050 TCs)	3.0	4.7	6.2	6.9	7.5
MCLC (211,997 TCs)	3.3	4.8	5.9	6.7	7.5
MCI (211,997 TCs)	3.3	4.8	5.9	6.7	8.3
GCM Downscaling (1,470 TCs)	1.8	3.1	4.1	4.9	5.5

All surge only, with uncertainty = max(20%, 0.61m)

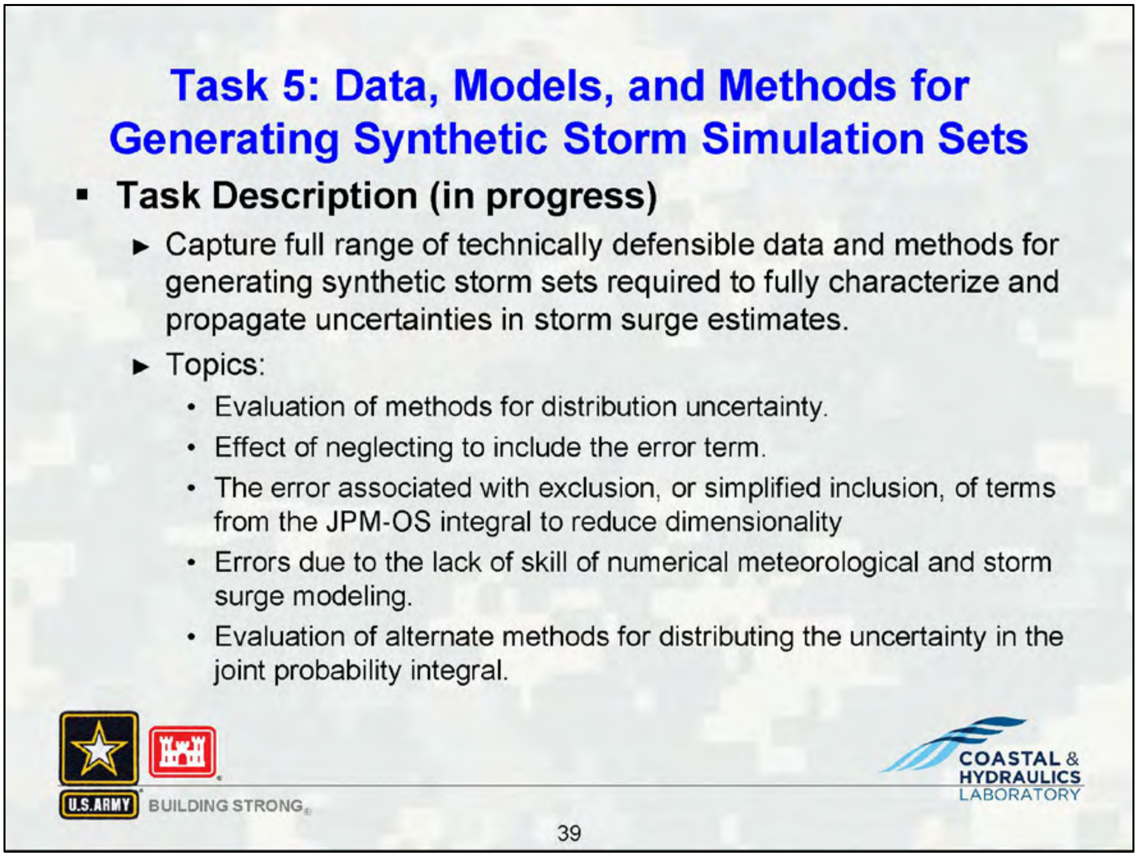
Task 4: Data, Models, and Methods for Generating Synthetic Storm Simulation Sets

- **Comparison of Results**

Percentage Difference in Storm Surge at The Battery, NY

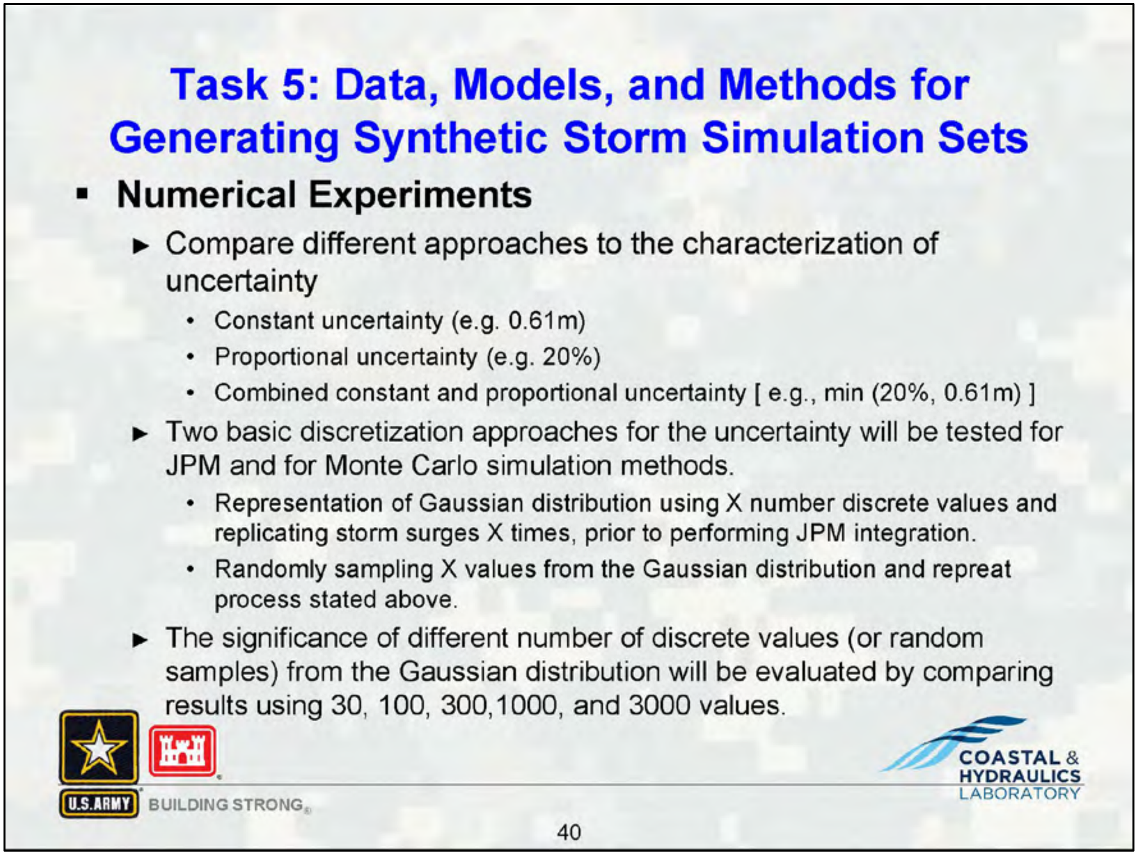
Method	Annual Exceedance Probability (AEP)				
	10^{-2}	10^{-3}	10^{-4}	10^{-5}	10^{-6}
JPM-Reference (74,430 TCs)	-	-	-	-	-
JPM-OS (1,050 TCs)	-18	-13	-3	-2	0
MCLC (211,997 TCs)	-9	-10	-8	-4	0
MCI (211,997 TCs)	-9	-10	-8	-5	10
GCM Downscaling (1,470 TCs)	-50	-42	-35	-30	-26

All surge only, with uncertainty = max(20%, 0.61m)



Task 5: Data, Models, and Methods for Generating Synthetic Storm Simulation Sets

- **Task Description (in progress)**
  - Capture full range of technically defensible data and methods for generating synthetic storm sets required to fully characterize and propagate uncertainties in storm surge estimates.
  - Topics:
    - Evaluation of methods for distribution uncertainty.
    - Effect of neglecting to include the error term.
    - The error associated with exclusion, or simplified inclusion, of terms from the JPM-OS integral to reduce dimensionality
    - Errors due to the lack of skill of numerical meteorological and storm surge modeling.
    - Evaluation of alternate methods for distributing the uncertainty in the joint probability integral.



Task 5: Data, Models, and Methods for Generating Synthetic Storm Simulation Sets

- **Numerical Experiments**
  - Compare different approaches to the characterization of uncertainty
    - Constant uncertainty (e.g. 0.61m)
    - Proportional uncertainty (e.g. 20%)
    - Combined constant and proportional uncertainty [e.g., min (20%, 0.61m)]
  - Two basic discretization approaches for the uncertainty will be tested for JPM and for Monte Carlo simulation methods.
    - Representation of Gaussian distribution using X number discrete values and replicating storm surges X times, prior to performing JPM integration.
    - Randomly sampling X values from the Gaussian distribution and repreat process stated above.
  - The significance of different number of discrete values (or random samples) from the Gaussian distribution will be evaluated by comparing results using 30, 100, 300,1000, and 3000 values.

Task 5: Data, Models, and Methods for Generating Synthetic Storm Simulation Sets

- **Results – Characterization of Uncertainty**

Storm Surge (m) at The Battery, NY

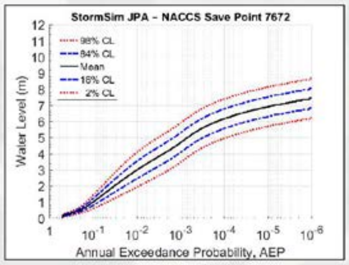
JPM-OS Uncertainty (Gaussian)	Annual Exceedance Probability (AEP)				
	10^{-2}	10^{-3}	10^{-4}	10^{-5}	10^{-6}
max(20%, 0.61m)	**3.0**	**4.7**	**6.2**	**6.9**	**7.5**
Constant (0.61m)	3.1	4.7	6.2	6.9	7.5
Proportional (20%)	3.0	4.7	6.7	8.0	9.0

Percentage Difference in Storm Surge at The Battery, NY

JPM-OS Uncertainty (Gaussian)	Annual Exceedance Probability (AEP)				
	10^{-2}	10^{-3}	10^{-4}	10^{-5}	10^{-6}
max(20%, 0.61m)	-	-	-	-	-
Constant (0.61m)	4	0	0	0	0
Proportional (20%)	0	1	8	15	20

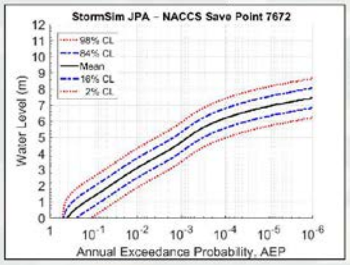
Task 5: Data, Models, and Methods for Generating Synthetic Storm Simulation Sets

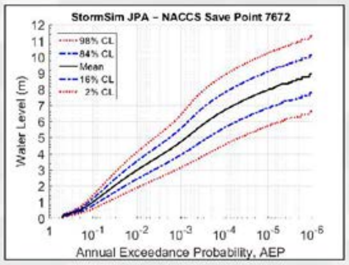
- **Results – Characterization of Uncertainty**



Uncertainty = min(20%, 0.61m)

Constant Uncertainty = 0.61 m





Proportional Uncertainty = 20%

Task 5: Data, Models, and Methods for Generating Synthetic Storm Simulation Sets

- **Results – Integration of Uncertainty**

Storm Surge (m) at The Battery, NY

JPM-OS Uncertainty (Gaussian)	Annual Exceedance Probability (AEP)				
	10^{-2}	10^{-3}	10^{-4}	10^{-5}	10^{-6}
Discrete (444 values)	**3.0**	**4.7**	**6.2**	**6.9**	**7.5**
Discrete (30 values)	3.0	4.7	6.2	7.0	NaN
Discrete (3,000 values)	3.0	4.7	6.2	6.9	7.4
Random (444 values)	3.1	4.8	6.3	7.1	7.7
Random (30 values)	2.9	4.7	6.1	7.5	NaN
Random (3000 values)	3.0	4.7	6.1	6.9	7.4
SurgeStat "Redistribution" (FEMA)	3.0	4.7	6.2	6.9	7.5

Task 5: Data, Models, and Methods for Generating Synthetic Storm Simulation Sets

- **Results – Integration of Uncertainty**

Percentage Difference in Storm Surge at The Battery, NY

JPM-OS Uncertainty (Gaussian)	Annual Exceedance Probability (AEP)				
	10^{-2}	10^{-3}	10^{-4}	10^{-5}	10^{-6}
Discrete (444 values)	-	-	-	-	-
Discrete (30 values)	0	0	0	1	NaN
Discrete (3,000 values)	0	0	0	0	-1
Random (444 values)	2	2	1	2	2
Random (30 values)	-3	0	-1	8	NaN
Random (3000 values)	-1	-1	0	-1	-1
SurgeStat "Redistribution" (FEMA)	0	0	0	0	-1

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2.3.2.1.3 Questions and Answers

Question:

When you performed GCM downscaling, what grid resolution did you consider?

Response:

The set of results that we were given did not directly characterize the extratropical transition storms. The results were from a hurricane model that focused exclusively on tropical cyclones.

Follow-up Question:

Without the proper grid resolution, such storms would not be captured. The presentation mentioned 1,470 storms; from how many GCM projections did this result?

Response:

The researchers simulated 15,000 years and produced 5,000 storms. The reference for this joint study is as follows:

- Lin, Ning, K. Emanuel, M. Oppenhemier, and E. Vanmarcke. 2012. Physically Based Assessment of Hurricane Surge Threat under Climate Change. *Nature Climate Change* 2 (6): 462–467.

Follow-up Question:

There are about 70 GCM projections and if you use each with 100 years, the results would cover about 7,000 years. You had looked at these Monte Carlo simulations and reconciled them with the downscaled data; how do you reconcile them with climate change?

Response:

This study did not specifically consider climate change.

Response from NRC Project Manager:

The focus of this project is not specifically to look at climate change or to look at the change in recurrence rate or change in landfall[1].

Response:

With regard to downscaling, this is a very valid method. This method can be used with JPM-OS to assess tropical cycles, assuming that some issues can be fixed.

Question:

Your presentation alluded to transitioning from a tropical cyclone to an extratropical cyclone and how you condition your model based on the source, for example considering whether it is in the Gulf of Mexico, the South Atlantic, mid-Atlantic, or the North Atlantic and the complications that

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[1] NRC Program Manager indicated that he would get back to the questioner with a more complete response.

arise as you go further north with regard to the synoptic weather. It seems likely that issues would arise with the model as a storm moved from the Gulf to the north, especially over the Atlantic.

Response:

The set of models used for this approach (i.e., the meteorological model and the hydrodynamic model, the Advanced CIRCulation model (ADCIRC)in this case) only see tropical cyclones. Therefore, we need to characterize the extratropical transition by reflecting that in our synthetic storm surge. For example, when we move to the north and storms go through the extratropical transition, they tend to increase in their translational speed and size, so we need to make sure that the synthetic storms that we are generating are also comparable with those changes. If we develop a set for the Gulf of Mexico versus for the North Atlantic, the parameters will reflect those differences. The historical occurrences in those individual seasons inform the individual characteristics that we have those storms carry.

2.3.2.2 Probabilistic Flood Hazard Assessment—Storm Surge, John Weglian, EPRI (Session 1B-2; ADAMS Accession No. ML17054C503)

2.3.2.2.1 Abstract

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

Many storm surge methods and analyses are focused on assessing the flooding impacts from a tropical storm making landfall; however, other types of storms can also cause storm surges, and these events can occur on large lakes as well as oceans. EPRI has published a technical report, on the subject, “Probabilistic Flooding Hazard Assessment for Storm Surge with an Example Based on Historical Water Levels,” EPRI ID 3002008111, dated August 31, 2016 (http://www.epri.com/abstracts/Pages/ProductAbstract.aspx?ProductId=000000003002008111). The report describes multiple methods for performing a PSSHA ; however, the detailed example is based on the assessment of a storm surge at an inland lake site based on historical water levels and wave heights.

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

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

2.3.2.2.2 Presentation

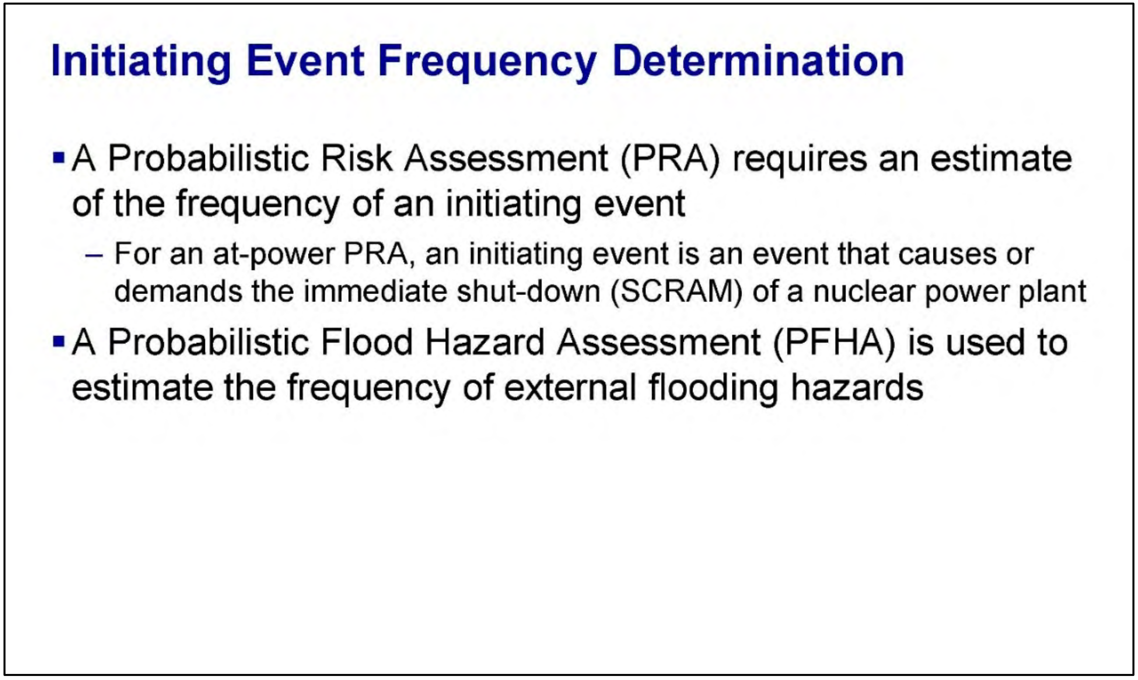
ELECTRIC POWER RESEARCH INSTITUTE

Probabilistic Flood Hazard Assessment

Storm Surge

John E. Weglian
Senior Technical Leader

NRC External Flooding Research Workshop
1/23/2017



Initiating Event Frequency Determination

- A Probabilistic Risk Assessment (PRA) requires an estimate of the frequency of an initiating event
  - For an at-power PRA, an initiating event is an event that causes or demands the immediate shut-down (SCRAM) of a nuclear power plant
- A Probabilistic Flood Hazard Assessment (PFHA) is used to estimate the frequency of external flooding hazards

Extrapolation

- Historical records are limited to a few hundred years at best
- Extrapolation to extremely low frequencies is required to assess risk to nuclear power plants
  - PRA models assess risks down to a frequency of 10^{-7}/yr or lower
  - The PFHA may be required to assess the hazard frequency down to 10^{-6}/yr – equivalent to an Annual Exceedance Probability (AEP) of 10^{-6}
- Design basis analyses use the concept of a Probable Maximum Flood (PMF), but make no attempt to calculate the frequency of occurrence of such a flood

Frequency Analysis as Part of a PFHA

- Extrapolation beyond twice the historical record is not considered to be credible
- A variety of methods are used to extend the effective historical record
  - Use of independent, but applicable measurements (e.g., rain gauges)
  - Transposition of observed storms from one location to another
  - Development of synthetic storms to simulate flooding impact with Monte Carlo analysis
  - Use of paleo (i.e., outside of the historical observation) evidence to inform the data
- All of these techniques involve uncertainty, so it is important to characterize the uncertainty
- Independent peer reviewers lend credence to the analysis

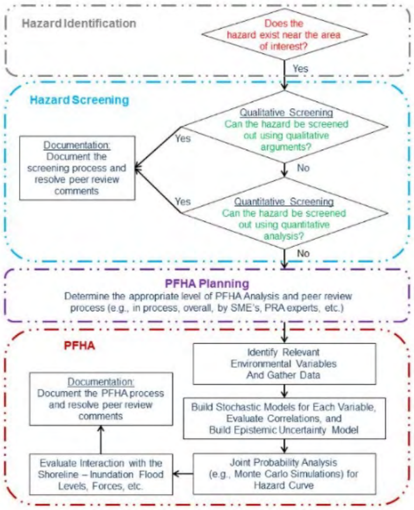
EPRI Report on Storm Surge

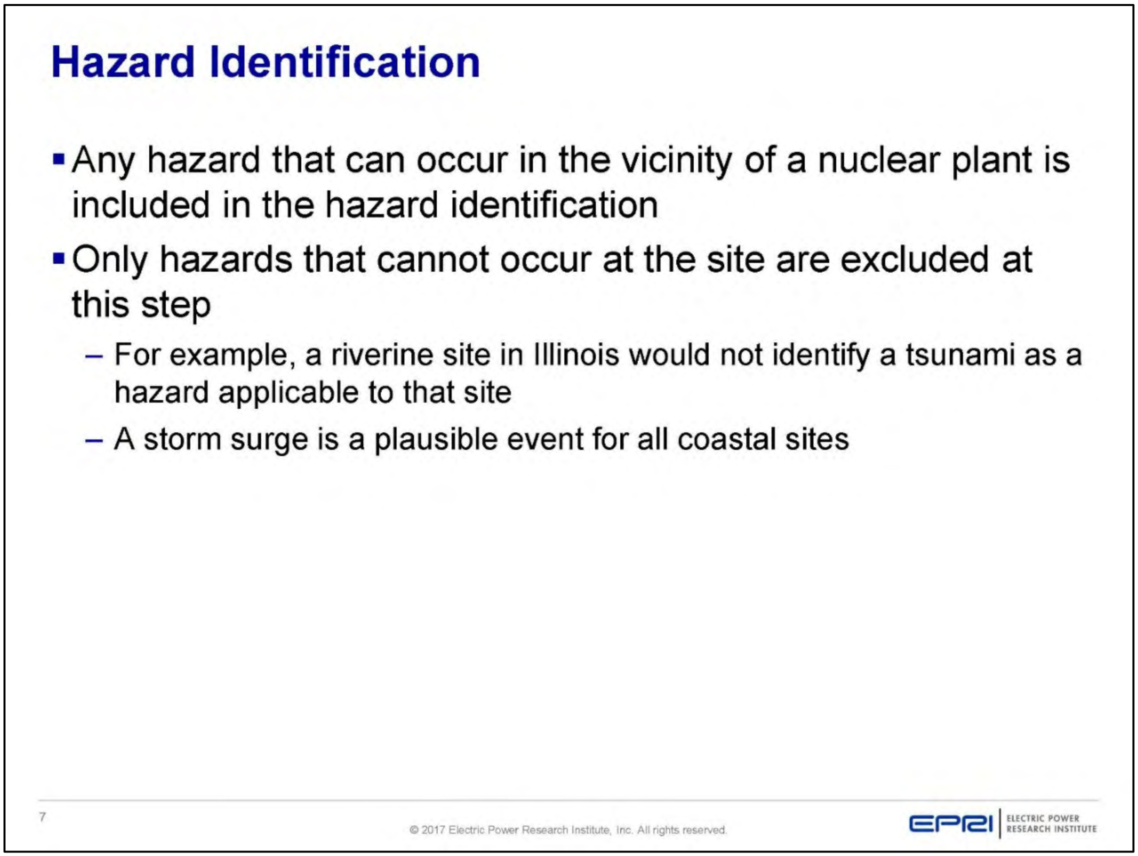
- ERPI report 3002008111, Probabilistic Flooding Hazard Assessment for Storm Surge with an Example Based on Historical Water Levels
- Provides generic PFHA process as applied to Storm Surge
- Available data and storm type that leads to storm surges for site of interest determines the simulation approach
  - Controlling storm is a hurricane: atmospheric parameters such as central pressure deficit, radius of maximum wind, and maximum wind speed as well as tidal levels can be modeled in the Monte Carlo simulation
  - Controlling storm is not hurricane: historical water levels can be utilized to determine mean sea level or average lake level, storm surge level, and wind-wave effects using Monte Carlo simulation techniques

---

Probabilistic Flood Hazard Assessment (PFHA)

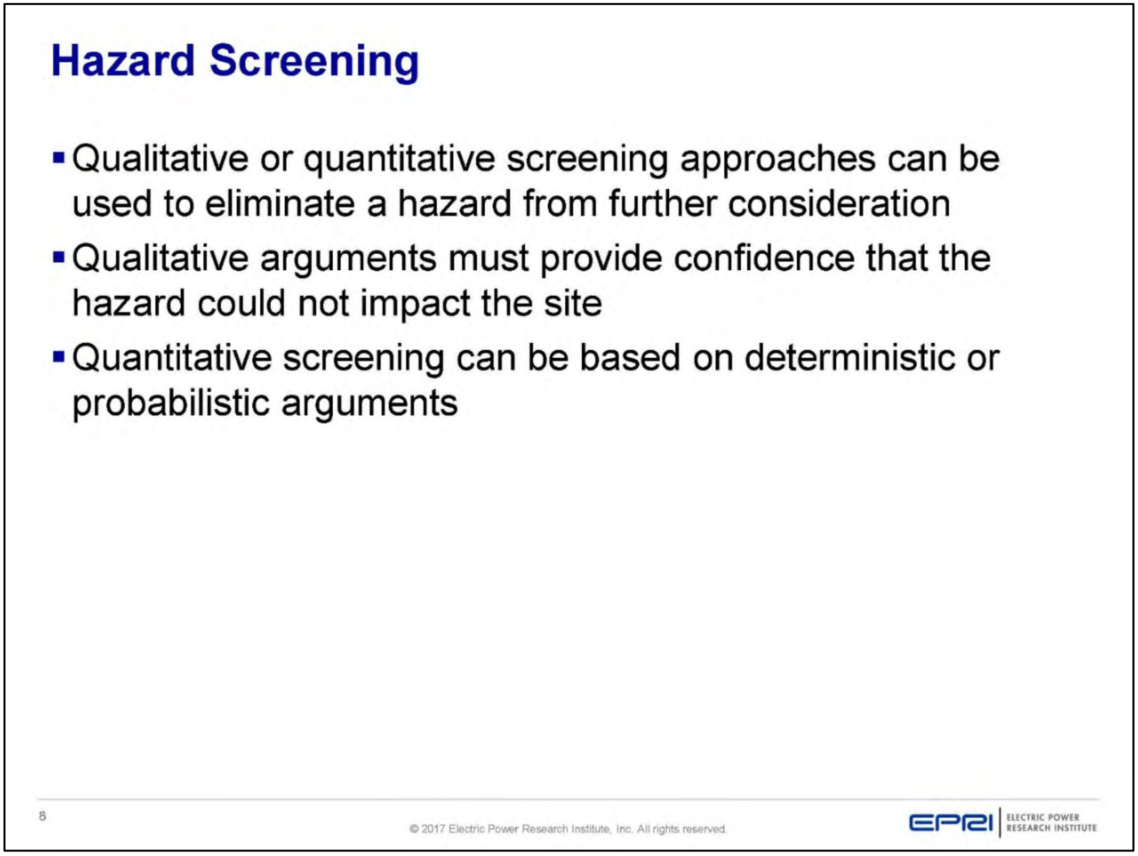
- A PFHA is used to assess a potential external flooding hazard to a site
- Steps of the process include:
  - Hazard identification – Which hazards are applicable to a site?
  - Hazard screening – Can the hazard be screened from analysis?
  - PFHA planning (e.g., determine the appropriate approach)
  - Conducting the PFHA





Hazard Identification

- Any hazard that can occur in the vicinity of a nuclear plant is included in the hazard identification
- Only hazards that cannot occur at the site are excluded at this step
  - For example, a riverine site in Illinois would not identify a tsunami as a hazard applicable to that site
  - A storm surge is a plausible event for all coastal sites



Hazard Screening

- Qualitative or quantitative screening approaches can be used to eliminate a hazard from further consideration
- Qualitative arguments must provide confidence that the hazard could not impact the site
- Quantitative screening can be based on deterministic or probabilistic arguments

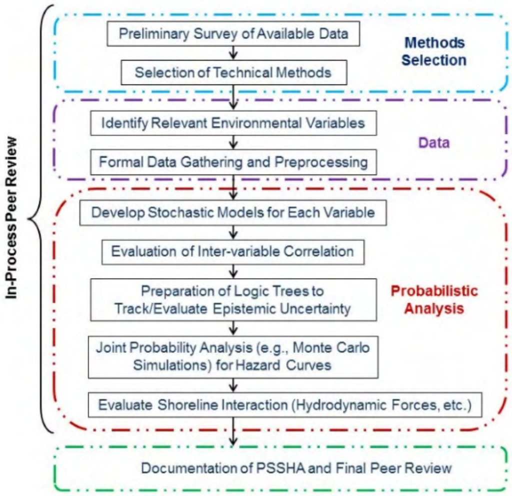
PFHA Planning

- Determine PFHA approach
  - For storm surge, the analysis could be based on synthetic modeling of the controlling storm (typically a hurricane) or based on the use of historical water levels to generate probability density functions for use in Monte Carlo analysis
- Determine peer review participation
  - Involving a peer review team throughout the process can prevent significant re-work if they find an issue that invalidates the analyses at the end

---

Performing the PFHA

- Create the statistical model
  - Correlation of variables
  - Treatment of uncertainty
- Perform the analysis
- Generate the hazard frequency curve
- Validate the analysis with independent peer review



In-Process Peer Review

Methods Selection

Preliminary Survey of Available Data

Selection of Technical Methods

Data

Identify Relevant Environmental Variables

Formal Data Gathering and Preprocessing

Probabilistic Analysis

Develop Stochastic Models for Each Variable

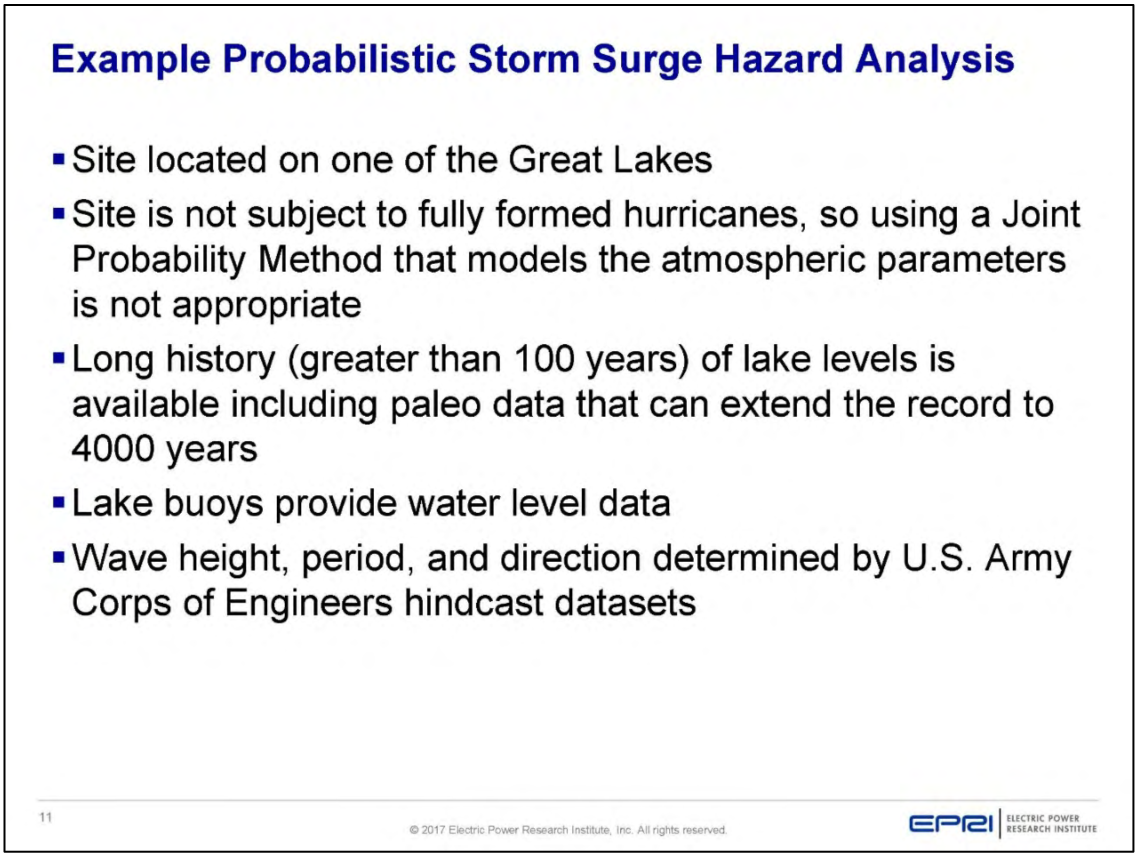
Evaluation of Inter-variable Correlation

Preparation of Logic Trees to Track/Evaluate Epistemic Uncertainty

Joint Probability Analysis (e.g., Monte Carlo Simulations) for Hazard Curves

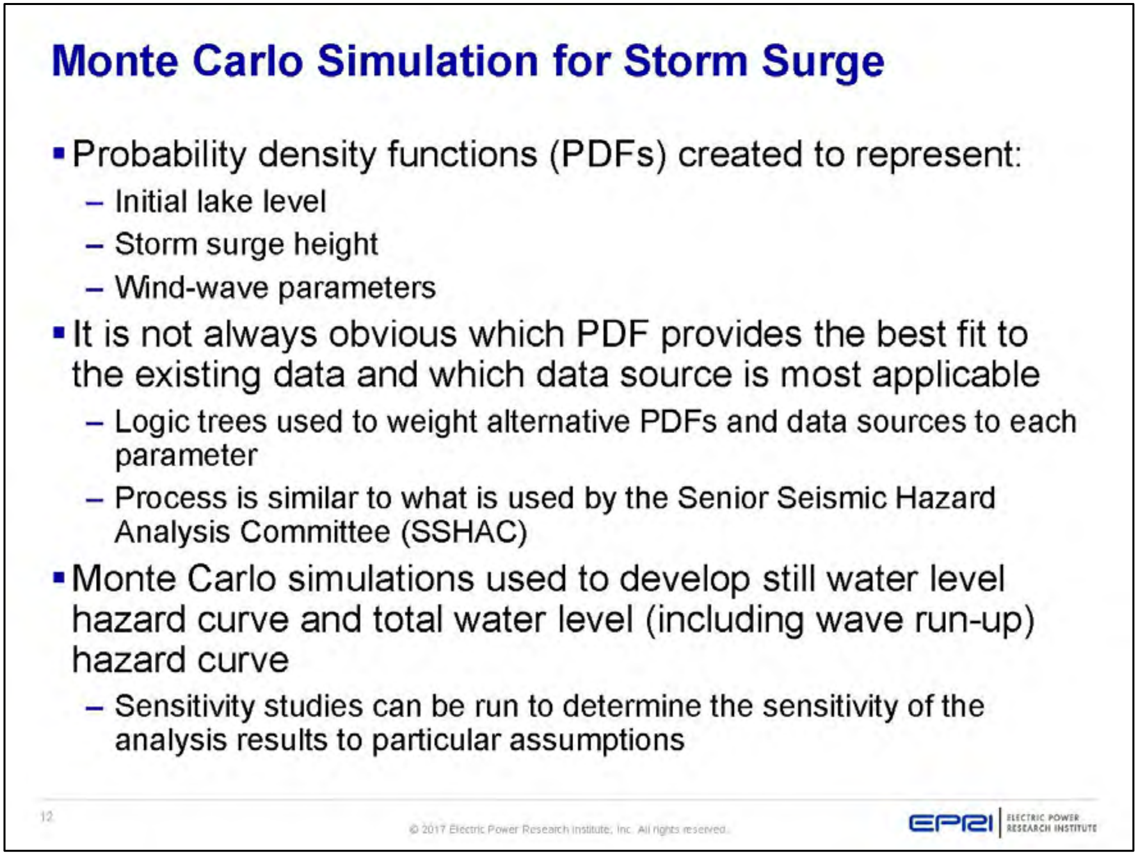
Evaluate Shoreline Interaction (Hydrodynamic Forces, etc.)

Documentation of PSSHA and Final Peer Review



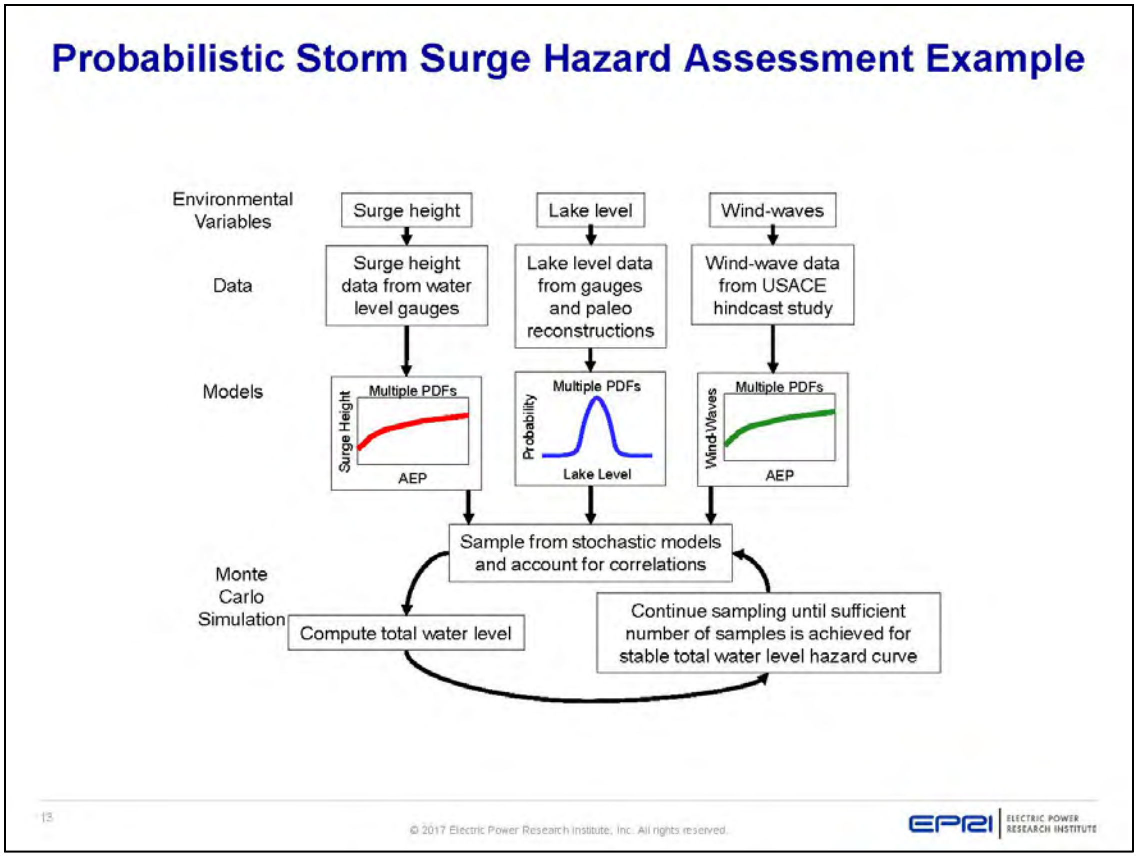
Example Probabilistic Storm Surge Hazard Analysis

- Site located on one of the Great Lakes
- Site is not subject to fully formed hurricanes, so using a Joint Probability Method that models the atmospheric parameters is not appropriate
- Long history (greater than 100 years) of lake levels is available including paleo data that can extend the record to 4000 years
- Lake buoys provide water level data
- Wave height, period, and direction determined by U.S. Army Corps of Engineers hindcast datasets



Monte Carlo Simulation for Storm Surge

- Probability density functions (PDFs) created to represent:
  - Initial lake level
  - Storm surge height
  - Wind-wave parameters
- It is not always obvious which PDF provides the best fit to the existing data and which data source is most applicable
  - Logic trees used to weight alternative PDFs and data sources to each parameter
  - Process is similar to what is used by the Senior Seismic Hazard Analysis Committee (SSHAC)
- Monte Carlo simulations used to develop still water level hazard curve and total water level (including wave run-up) hazard curve
  - Sensitivity studies can be run to determine the sensitivity of the analysis results to particular assumptions



Probabilistic Storm Surge Hazard Assessment Example

Environmental Variables

Surge height

Lake level

Wind-waves

Data

Surge height data from water level gauges

Lake level data from gauges and paleo reconstructions

Wind-wave data from USACE hindcast study

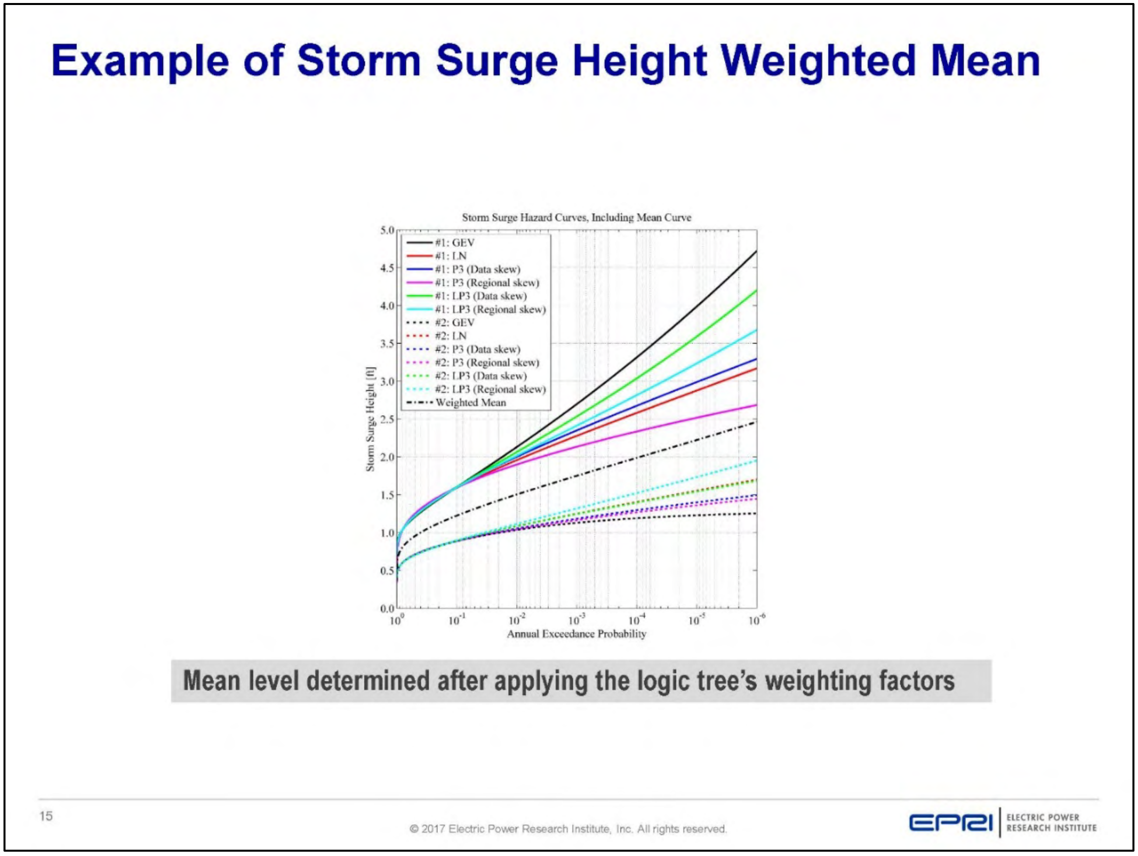
Models

Sample from stochastic models and account for correlations

Monte Carlo Simulation

Compute total water level

Continue sampling until sufficient number of samples is achieved for stable total water level hazard curve

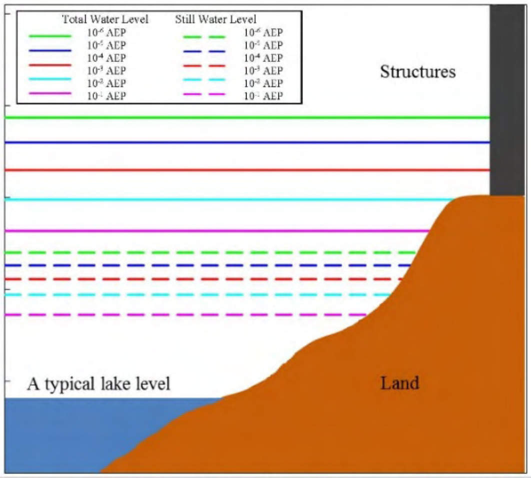


Example of Storm Surge Height Weighted Mean

Storm Surge Hazard Curves, Including Mean Curve

Mean level determined after applying the logic tree's weighting factors

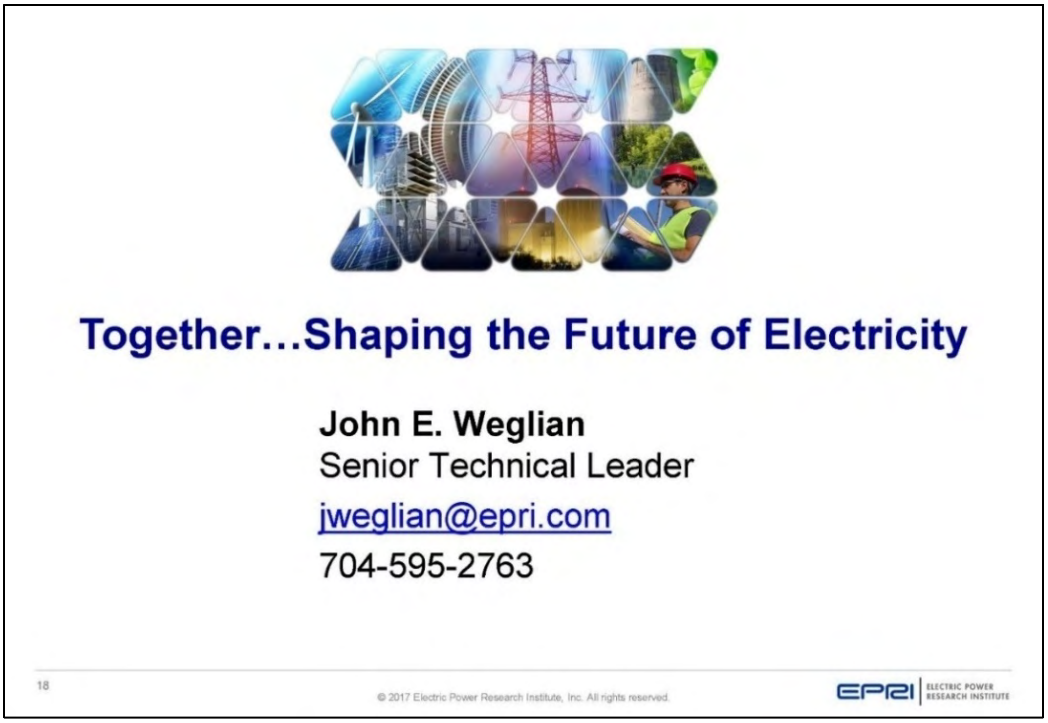
Example Still Water and Total Water Levels



Structures may be impacted by waves at a frequency of about $1X10^{-3}$/year

Uncertainty and Peer Review

- Two important aspects of a PFHA are uncertainty analysis and peer review
- Uncertainty analysis attempts to characterize the range of uncertainty in the analysis
  - Logic trees and sensitivity studies are techniques to control and characterize the uncertainty
- Peer reviews lends credibility to the analysis by getting independent experts to provide comments and findings
  - Engaging a peer review team early and often in the PFHA process helps prevent significant re-work if the peer review team identifies an important issue that needs to be resolved



Together…Shaping the Future of Electricity

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2.3.2.2.3 Questions and Answers

Question:

How did you use the paleoflood data to extrapolate for 4,000 years? The timeframe for glaciation is much longer, and the performance period for waste management ranges from 10,000 to 20,000 years. Would you be able to extrapolate further given the large amount of data?

Response:

The paleo data available did go back beyond 4,000 years; however, the data before 4,000 years was judged not to be applicable to the current time. The lake levels were significantly different than those currently observed. Therefore, the researchers limited the analysis to 4,000 years.

Question:

The paleoflood data were used only for the lake level. There is an assumption that, given the paleo elevation 4,000 years ago, this would still be a potential initiating level for the lake for the next 60 years of operation.

Response:

The lake level is different from paleoflood because it considered the average lake level during that timeframe rather than surge levels. Two different reports cover that topic in different ways. The assumption is that weather patterns can add more or less water to the lakes. It is possible that a storm event in the last 4,000 years added significantly more water to the lakes than what we have seen in our historical measurement, which would be reflected in the higher lake level. This is an attempt to capture that portion of the uncertainty based on the starting point for the storm surge itself.

Follow-up Question:

When testing the resulting lake level statistically, was the level 10 or 20 or 30 feet higher? Was it in a reasonable range that you could expect?

Response:

Although paleo data were available beyond 4,000 years, the researchers did not deem them to be applicable for the current effort.

Question:

What input did the peer reviewers provide?

Response:

I was not involved in that activity and do not know the answer.

2.3.3 Day 2: Session 2A - Climate and Precipitation

This session continued to consider the development of guidance for the application of improved mechanistic and probabilistic modeling techniques for key flood-generating processes and flooding scenarios.

It also included an assessment of the potential impacts of dynamic and nonstationary processes on flood hazard assessments and flood protection at nuclear facilities.

2.3.3.1 Regional Climate Change Projections: Potential Impacts to Nuclear Facilities,

L. Ruby Leung^, Ph.D., Rajiv Prasad*, Ph.D., and Lance Vail, Pacific Northwest National Laboratory (Session 2A-1; ADAMS Accession No. ML17054C504)

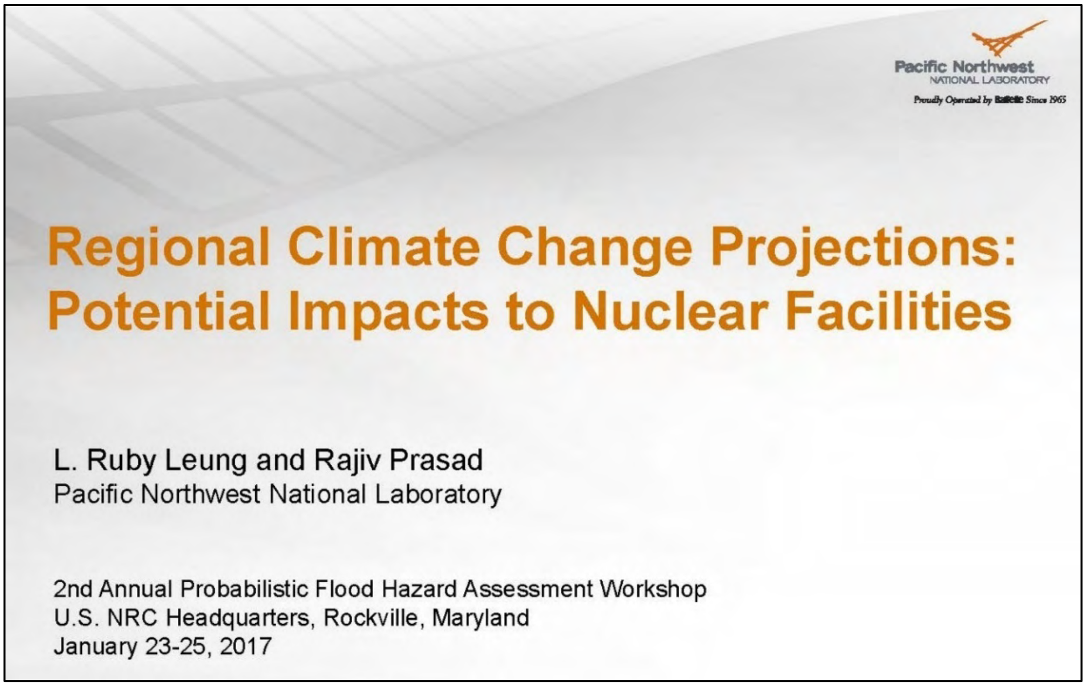
2.3.3.1.1 Abstract

This research project is part of the NRC's PFHA research plan in support of developing a risk-informed licensing framework for flood hazards and design standards at proposed new facilities and significance determination tools for evaluating potential deficiencies related to flood protection at operating facilities. The PFHA plan aims to build upon recent advances in deterministic, probabilistic, and statistical modeling of extreme precipitation events to develop regulatory tools and guidance for NRC staff with regard to PFHA for nuclear facilities. An improved understanding of large-scale climate pattern changes such as changes in the occurrence of extreme precipitation, flood/drought, storm surge, and severe weather events can help inform the probabilistic characterization of extreme events for the NRC's safety reviews. This project provides a literature review, focusing on recent studies that improve understanding of the mechanisms of how the climate parameters relevant to the NRC may change in a warmer climate, including discussions of the robust and uncertain aspects of the changes and future directions for reducing uncertainty in projecting those changes. The current focus is on the southeast region, consisting of 11 southeastern States in the conterminous United States. Except for Kentucky, all these States have currently operating NPPs. New nuclear power reactor permit and license

applications submitted to the NRC in the recent past were for sites located in several of the southeastern States (Virginia, North Carolina, South Carolina, and Florida).

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

2.3.3.1.2 Presentation



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Regional Climate Change Projections: Potential Impacts to Nuclear Facilities

L. Ruby Leung and Rajiv Prasad
Pacific Northwest National Laboratory

2nd Annual Probabilistic Flood Hazard Assessment Workshop
U.S. NRC Headquarters, Rockville, Maryland
January 23-25, 2017

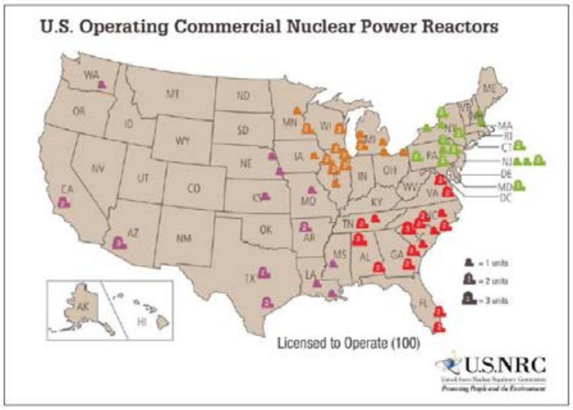
Project overview

- Objective: develop documents to summarize
  - Recent scientific findings on climate change and its impacts
  - Activities of federal agencies with direct responsibility on climate change science
  - Quality assessment of the above relevant to NRC concerns on regional level
- Progress:
  - Delivered first annual letter report focusing on recent scientific findings on climate change and regional impacts in the US - "Potential Impacts of climate change to NPPs" available in ADAMS (#ML16208A282)
  - Second year efforts focus on climate change and hydrologic impacts in southeastern US
  - Major sources of information:
    - Governmental reports (e.g., IPCC AR5, Third National Climate Assessment (NCA3) (Melilo et al. 2014); Regional Technical Input Report Series for the Southeast United States (Ingram et al. 2013); NOAA Technical Report NESDIS 142-2 (Kunkel et al. 2013); U.S. GCRP Climate Science Special Report (CSSR) (Wuebbles et al. 2017))
    - Literature in peer-reviewed journals
    - Websites (e.g., NOAA, National Hurricane Center, Southeast Regional Climate Center)

Background and context

- All Southeast states except for Kentucky, Puerto Rico, and the Virgin Islands have operating nuclear power plants
- Permit and license applications for new reactors applications proposed sites in Virginia, North Carolina, South Carolina, and Florida

Southeast Region for the National Climate Assessment



U.S. Operating Commercial Nuclear Power Reactors

Past changes in temperature and precipitation (1986-2015 minus 1901-1960)

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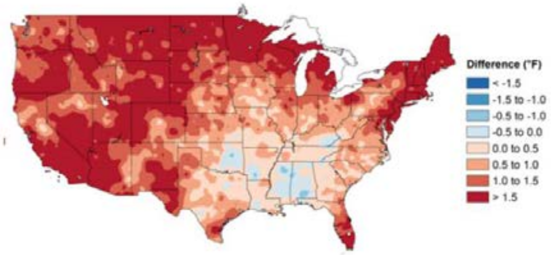
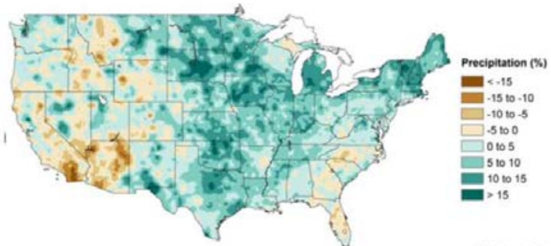
The Southeast is part of a "warming hole"

Annual Temperature

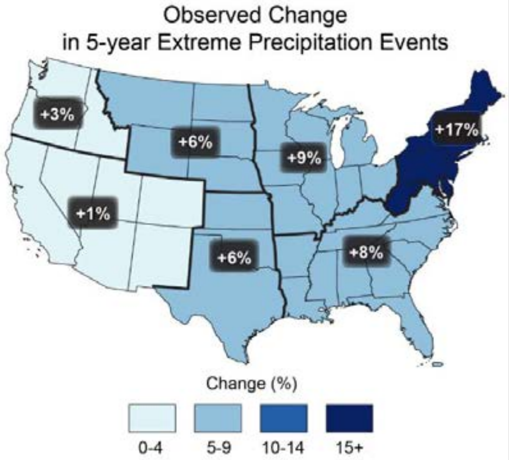


Insignificant change in mean precipitation

Annual Precipitation



8% increase in 5-year extreme precipitation



(Wuebbles et al. 2017 CSSR)

High percentile of tornadoes per outbreak has increased over time

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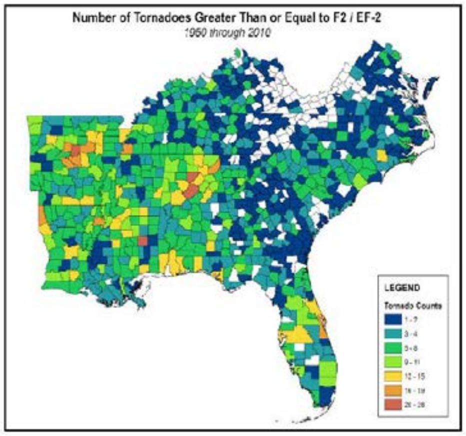
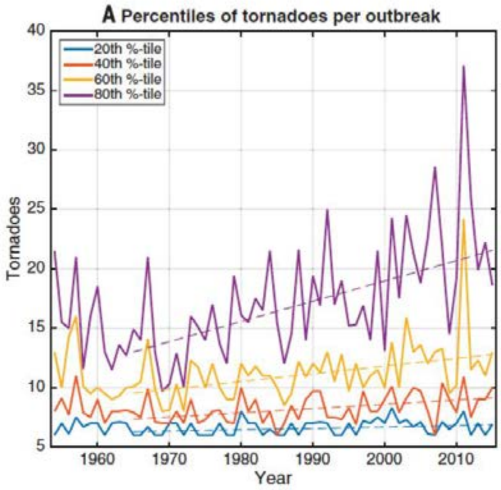
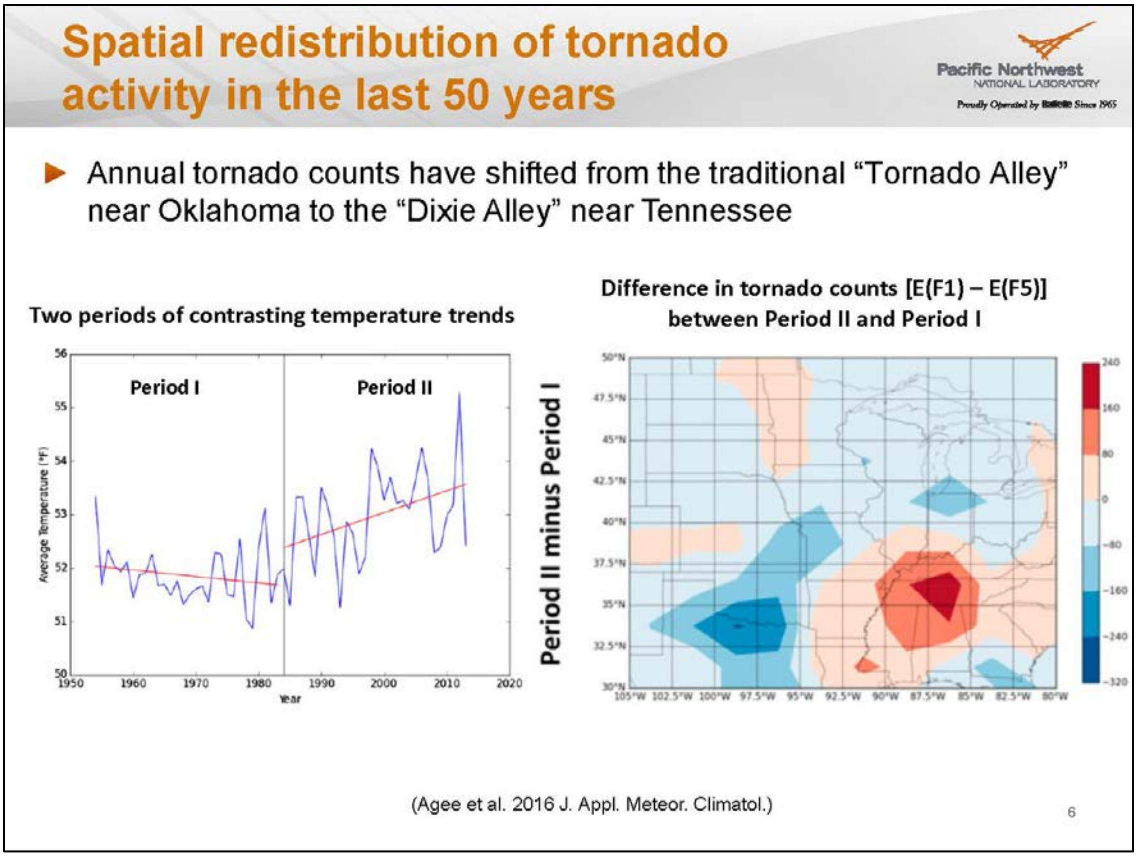
- Frequency of tornado outbreaks (sequences of six or more tornadoes rated F1 and greater) has increased in the past decades



(Kunkel et al. 2013 NOAA Technical Report)



(Tippet et al. 2016 Nature Climate Change)



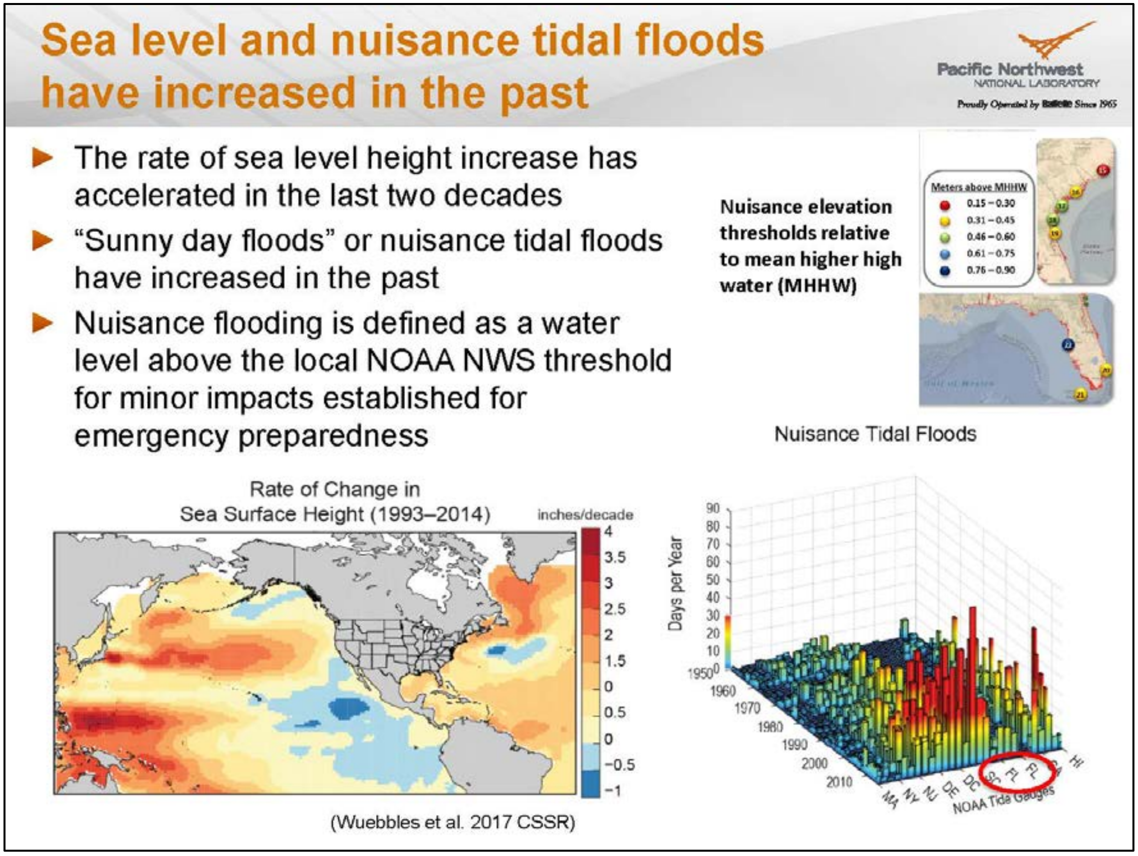
Spatial redistribution of tornado activity in the last 50 years

- Annual tornado counts have shifted from the traditional "Tornado Alley" near Oklahoma to the "Dixie Alley" near Tennessee

Two periods of contrasting temperature trends

Difference in tornado counts [E(F1) – E(F5)] between Period II and Period I

(Agee et al. 2016 J. Appl. Meteor. Climatol.)



Sea level and nuisance tidal floods have increased in the past

- The rate of sea level height increase has accelerated in the last two decades
- "Sunny day floods" or nuisance tidal floods have increased in the past
- Nuisance flooding is defined as a water level above the local NOAA NWS threshold for minor impacts established for emergency preparedness

Nuisance elevation thresholds relative to mean higher high water (MHHW)

Nuisance Tidal Floods

Rate of Change in Sea Surface Height (1993–2014)

(Wuebbles et al. 2017 CSSR)

Scenarios for climate projections

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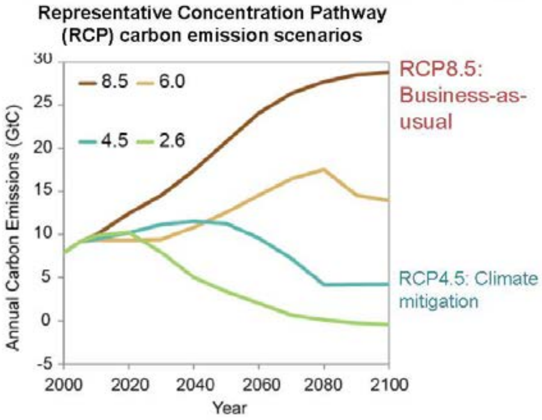
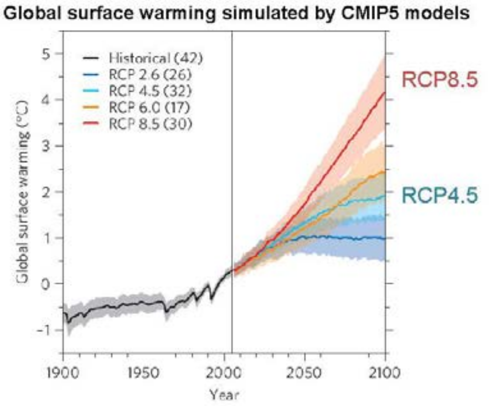
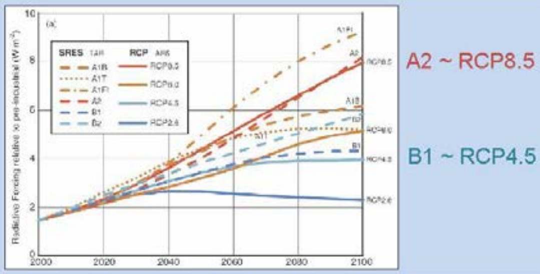




Comparison of scenarios used in IPCC AR4 and AR5:

Business-as-usual: A2 – RCP8.5

Climate mitigation: B1 – RCP4.5



Frequency of high temperature projected to increase

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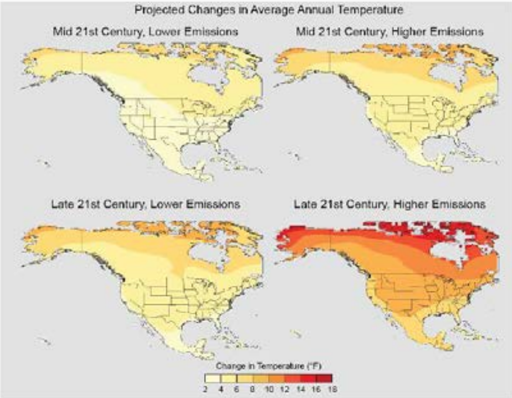
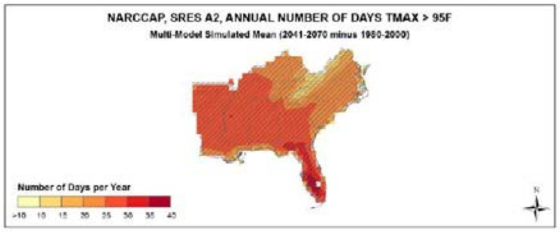
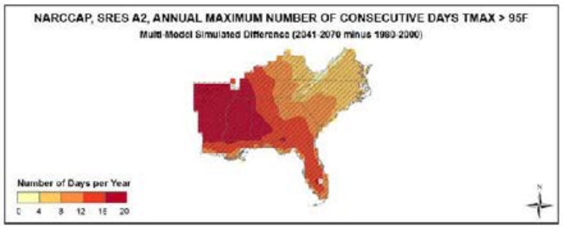
No "warming hole" in future projections
Milder warming along the coast compared to inland



(Wuebbles et al. 2017 CSSR)

Multi-model mean changes from 8 NARCCAP simulations for A2 scenario

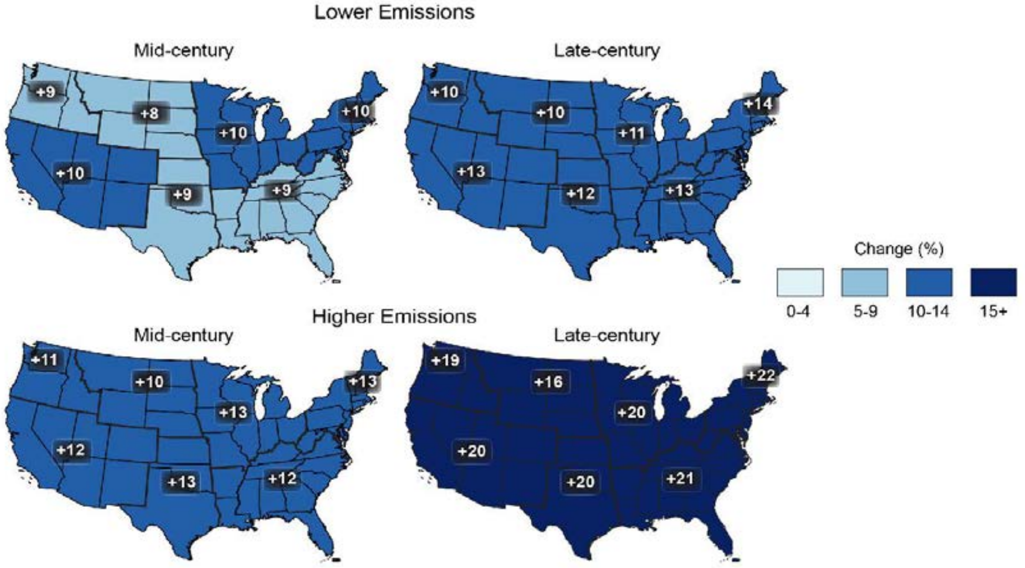




(NOAA NESDIS Technical Report 2013)

Extreme precipitation projected to increase in the future

Projected change in daily, 20-year extreme precipitation: scales with the magnitude of warming

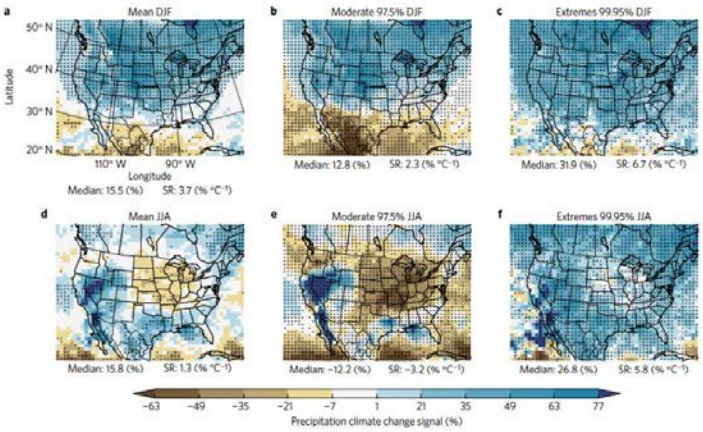


(Wuebbles et al. 2017 CSSR)

Exceedance probability of 99.95% hourly precipitation may increase by fourfold

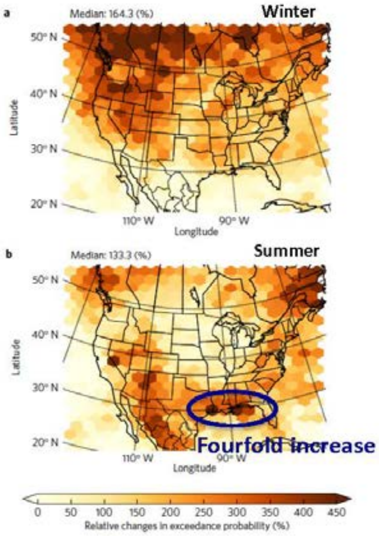
- Convection permitting modeling shows dominant increases in 99.95% extreme hourly precipitation across the US

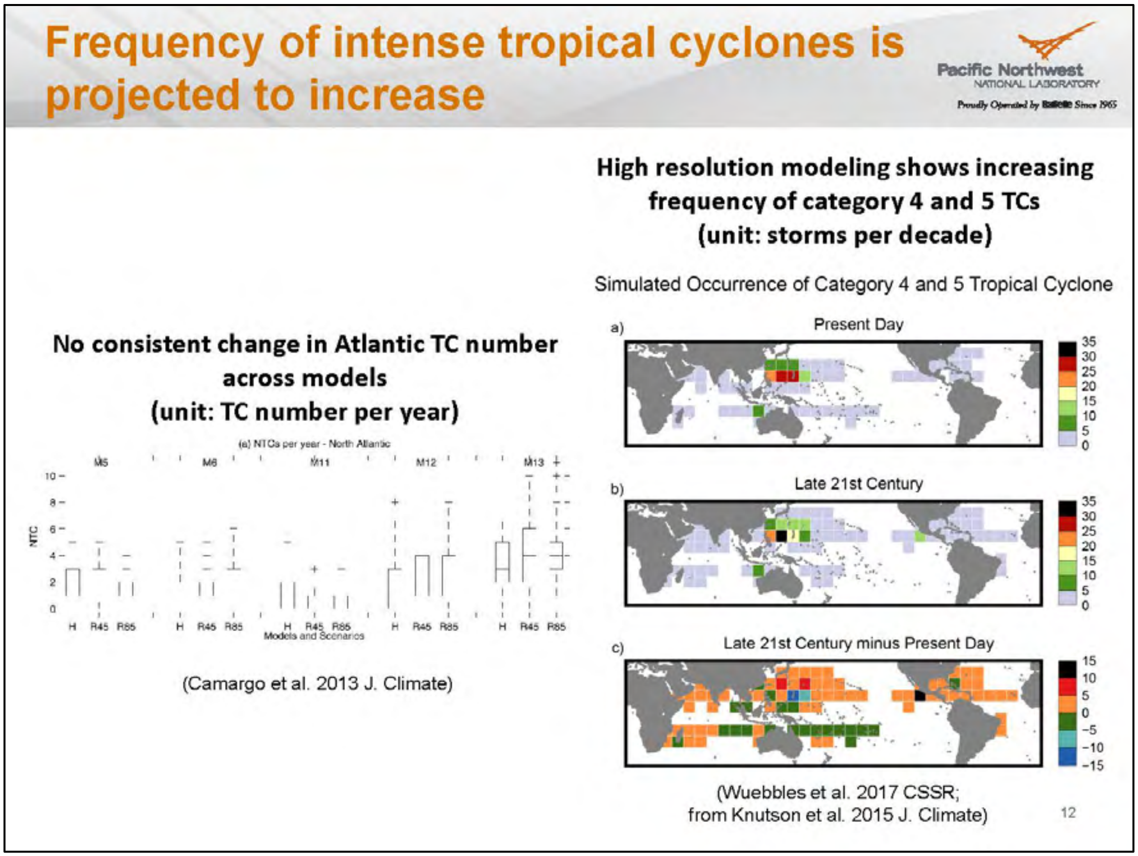
Precipitation change (%) for 2071-2100 relative to 1976-2005: increase in 99.95% everywhere



(Prein et al. 2016 Nature Climate Change)

Relative change in exceedance probability of the present day 99.95% hourly precipitation





Frequency of intense tropical cyclones is projected to increase

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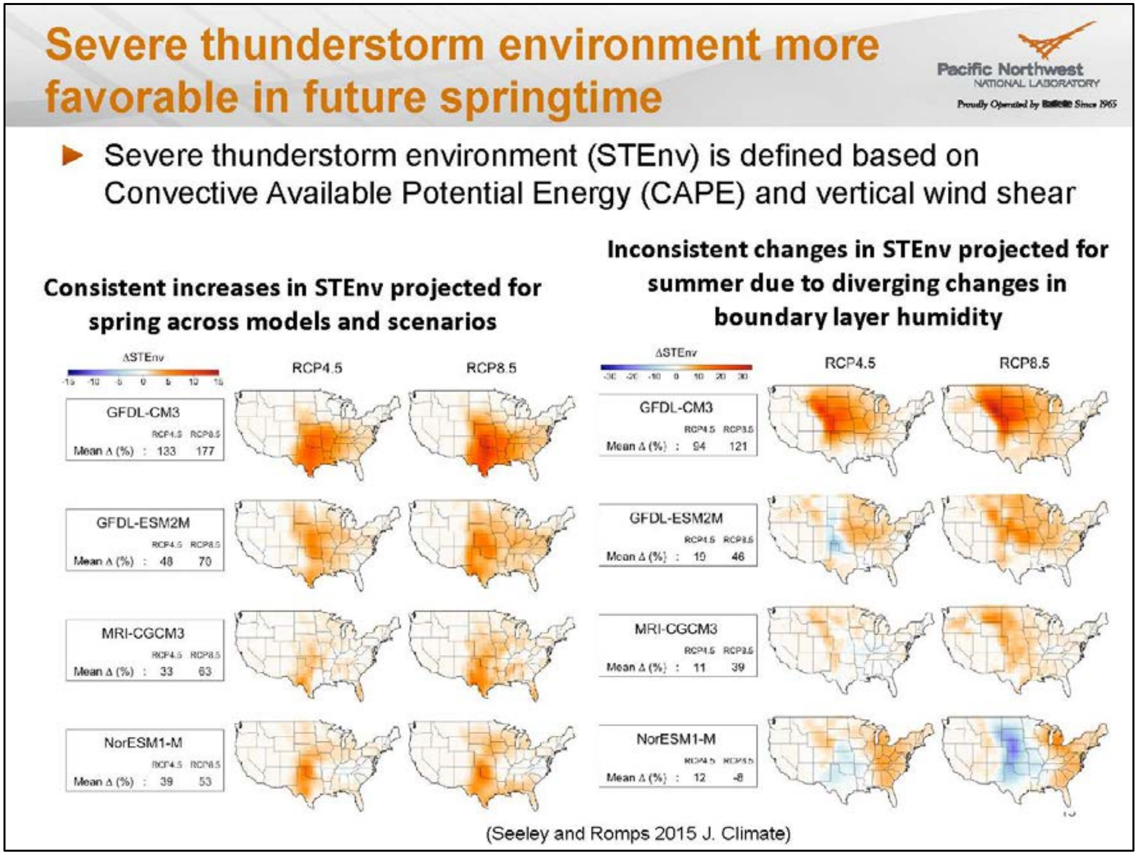
No consistent change in Atlantic TC number across models (unit: TC number per year)

(Camargo et al. 2013 J. Climate)

High resolution modeling shows increasing frequency of category 4 and 5 TCs (unit: storms per decade)

Simulated Occurrence of Category 4 and 5 Tropical Cyclone

(Wuebbles et al. 2017 CSSR; from Knutson et al. 2015 J. Climate)



Severe thunderstorm environment more favorable in future springtime

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- Severe thunderstorm environment (STEnv) is defined based on Convective Available Potential Energy (CAPE) and vertical wind shear

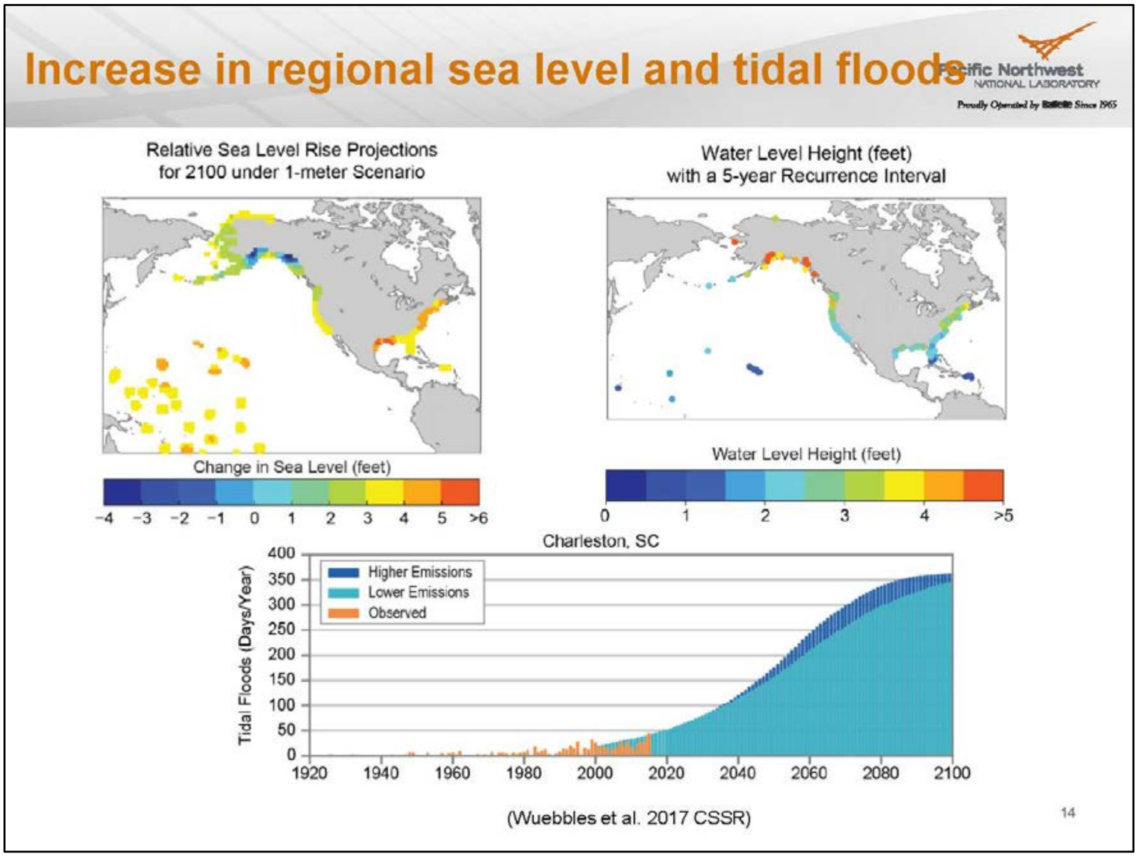
Consistent increases in STEnv projected for spring across models and scenarios

	RCP4.5	RCP8.5
GFDL-CM3 Mean Δ (%)	133	177
GFDL-ESM2M Mean Δ (%)	48	70
MRI-CGCM3 Mean Δ (%)	33	63
NorESM1-M Mean Δ (%)	39	53

Inconsistent changes in STEnv projected for summer due to diverging changes in boundary layer humidity

	RCP4.5	RCP8.5
GFDL-CM3 Mean Δ (%)	94	121
GFDL-ESM2M Mean Δ (%)	19	46
MRI-CGCM3 Mean Δ (%)	11	39
NorESM1-M Mean Δ (%)	12	-8

(Seeley and Romps 2015 J. Climate)



Increase in regional sea level and tidal floods

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(Wuebbles et al. 2017 CSSR)

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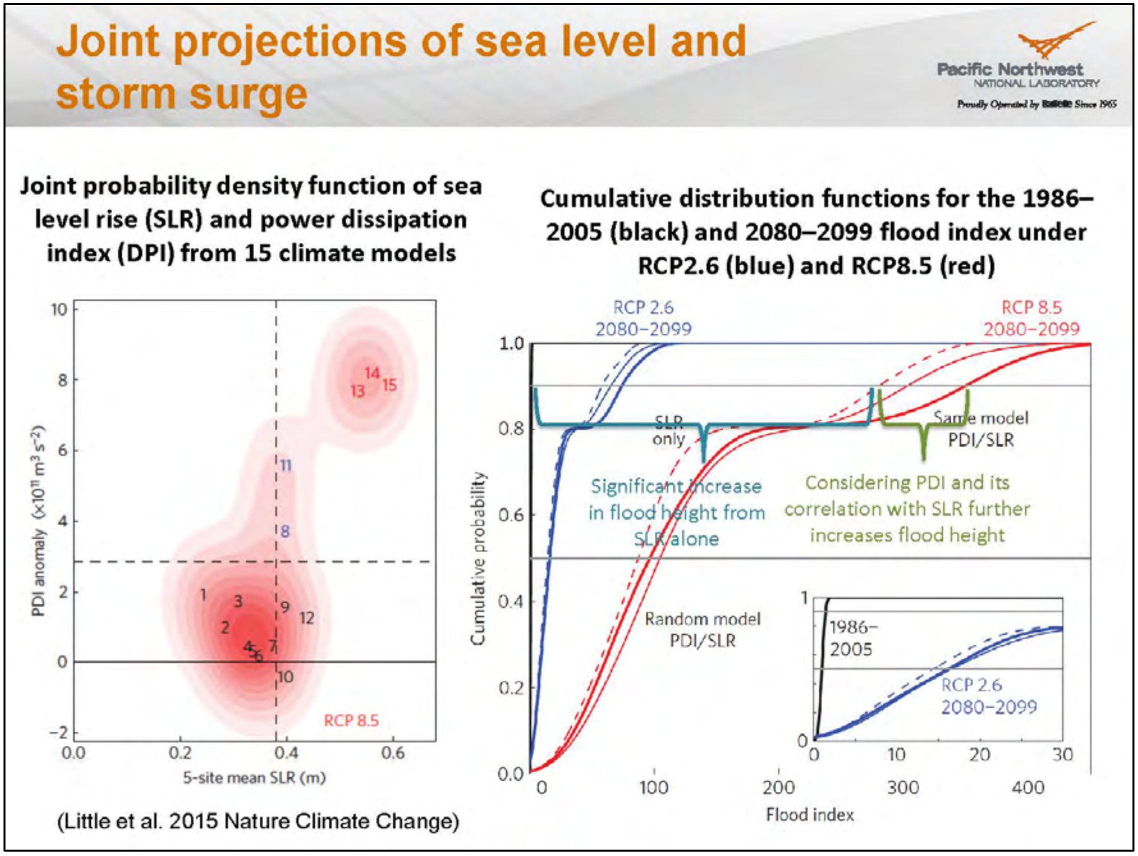

Joint projections of sea level and storm surge

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Joint probability density function of sea level rise (SLR) and power dissipation index (DPI) from 15 climate models

Cumulative distribution functions for the 1986–2005 (black) and 2080–2099 flood index under RCP2.6 (blue) and RCP8.5 (red)

Significant increase in flood height from SLR alone

Considering PDI and its correlation with SLR further increases flood height

(Little et al. 2015 Nature Climate Change)

Hydrologic characteristics of the Southeast region

- Floods in the southeast region can be produced by
  - locally heavy precipitation
  - slow-moving extratropical cyclones during the cool season
  - tropical cyclones during summer and fall
  - late spring rainfall on snowpack
  - storm surge near coastal areas from hurricanes, and
  - occasional large releases from upstream dams.
- Examples of recent floods
  - The August 2016 Louisiana floods
  - The March 2016 southern floods
  - The October 2016 Hurricane Matthew floods
- Droughts in the southeast region
  - relatively short duration (one to three years)
  - recent episodes: 1998-2002 and 2007-2008
- Projected changes in soil moisture and runoff in the southeast region are not statistically significant

---

Hydrologic impacts to Southeast region

- Several studies
  - Effects of urbanization and climate change on freshwater resources
    - Hay et al. (2011), Viger et al. (2011), Bastola (2013), Sun et al. (2015)
- Bastola (2013)
  - Assessed 28 southeast US watersheds

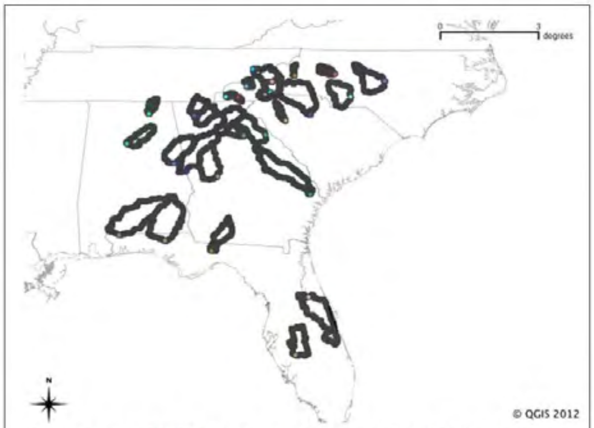

Figure 1. Location of the 28 watersheds within the southeastern United States used in this study

Hydrologic impacts to Southeast region

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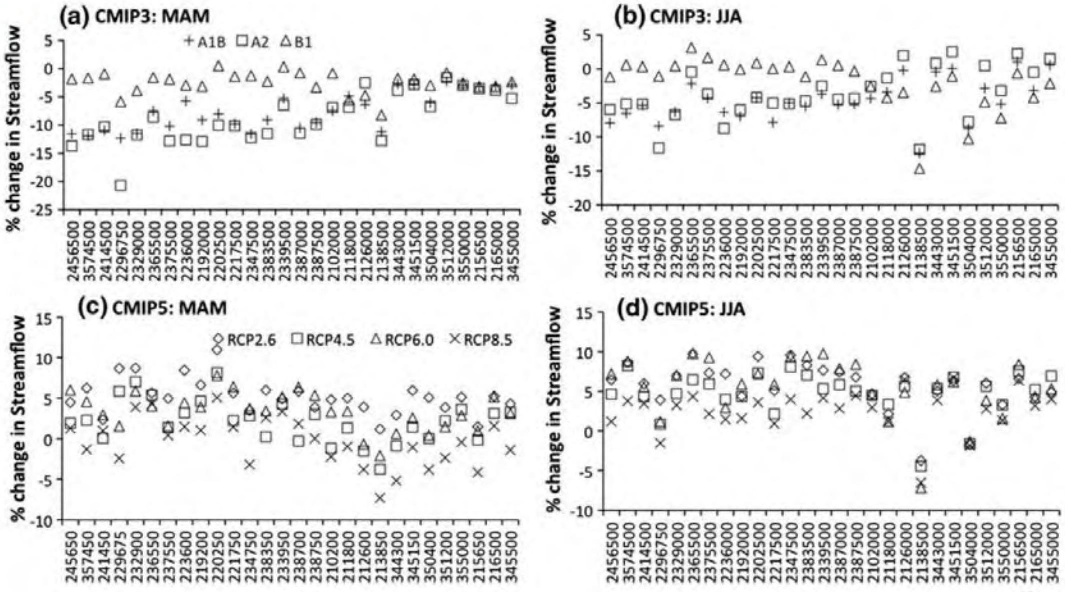
- Results from Bastola (2013)



Hydrologic impacts to Southeast region

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- Hay et al. (2011) and Viger et al. (2011)

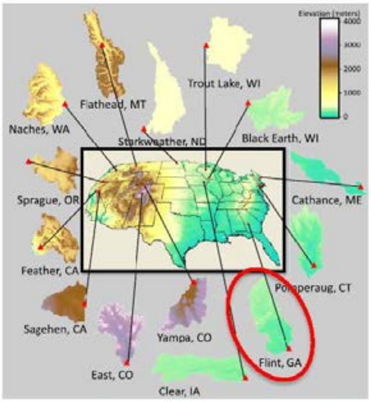


Figure 1. Location map of the United States showing the sites of the 14 selected basins. PRMS models were developed for the basin areas shown. Red triangle denotes location of stream gauge for model calibration (note that basins are not to scale; see Table 1 for relative scales).

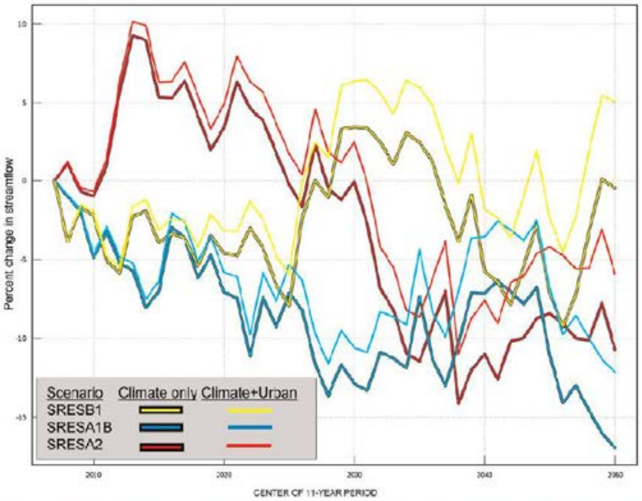


Figure 11. Percent change in 11-yr moving mean daily values of streamflow derived from the five GCMs, with (solid lines) and without (outlined in black) urbanization forecasts, grouped by climate-change scenario.

Insights for floods in Southeast region

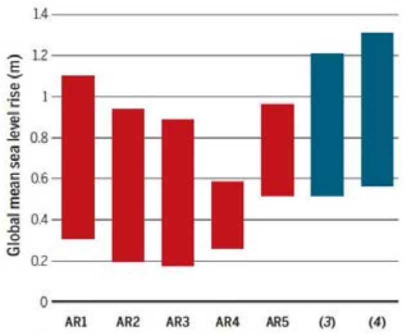
- Many hydrometeorologic parameters that influence floods are not directly addressed in NCA3
- Studies typically investigate the impacts of climate change on runoff characteristics
  - Mean annual, seasonal, or monthly flows
- Floods of interest to the NRC, particularly for safety analysis and review
  - Significantly shorter time-scales (hours to days)
  - Almost always are in the tails of the distribution, away from the mean
  - Typically need complete hydrographs
  - With existing studies, direct conclusions are difficult to draw
- Insights of interest
  - A site -specific analysis should be performed
  - A change in the mean behavior of floods can also reflect a change in the behavior in the tails
  - Further investigations are needed to couple the outputs of GCMs to hydrologic models
  - Exploring dynamical downscaling and nesting of hydrological models
  - Significant uncertainty in predictions of hydrologic models will exist; a framework is needed
  - Site-specific flood protection and mitigation assessment under risk-informed approach

Insights for droughts in Southeast region

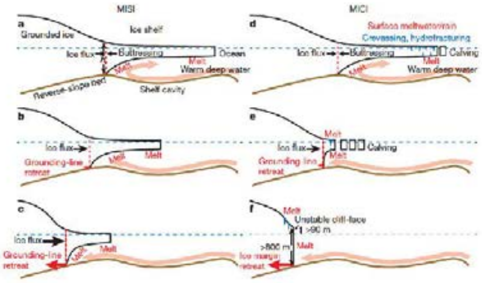
- Many hydrometeorologic parameters that influence droughts are not directly addressed in NCA3
- Studies typically investigate the impacts of climate change on runoff characteristics
  - Mean annual, seasonal, or monthly flows
  - These metrics are useful to the NRC in the review for water use and environmental impacts of plants
- Additional low-flow metrics that are useful to NRC
  - Persistence and frequency of low flows, both seasonally and in the context of multi-year droughts
  - Not directly addressed in current studies
- Insights of interest
  - Site-specific drought assessments
  - Regional and local characteristics may be important
    - Bermuda/Azores high
    - Urbanization and population growth
    - Water management practices
  - Significant uncertainties in all aspects of climate-hydrology assessments is expected to exist
    - Framework needed
    - Periodic refinement of site-specific low-flow assessments

Uncertainty: the evolving SLR projections

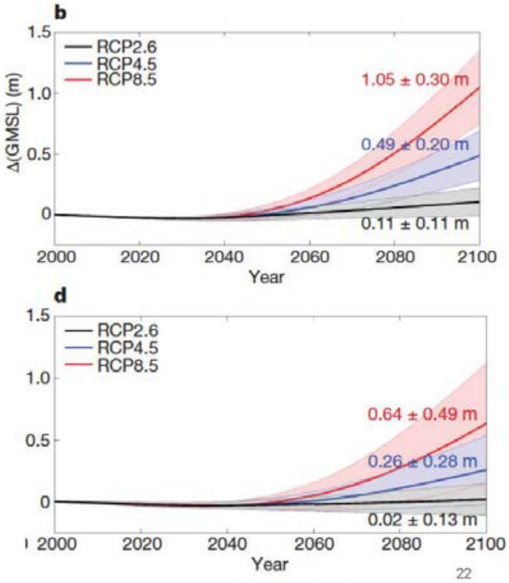
The fall and rise of projected sea level rises



(Oppenheimer and Alley 2016 Science)



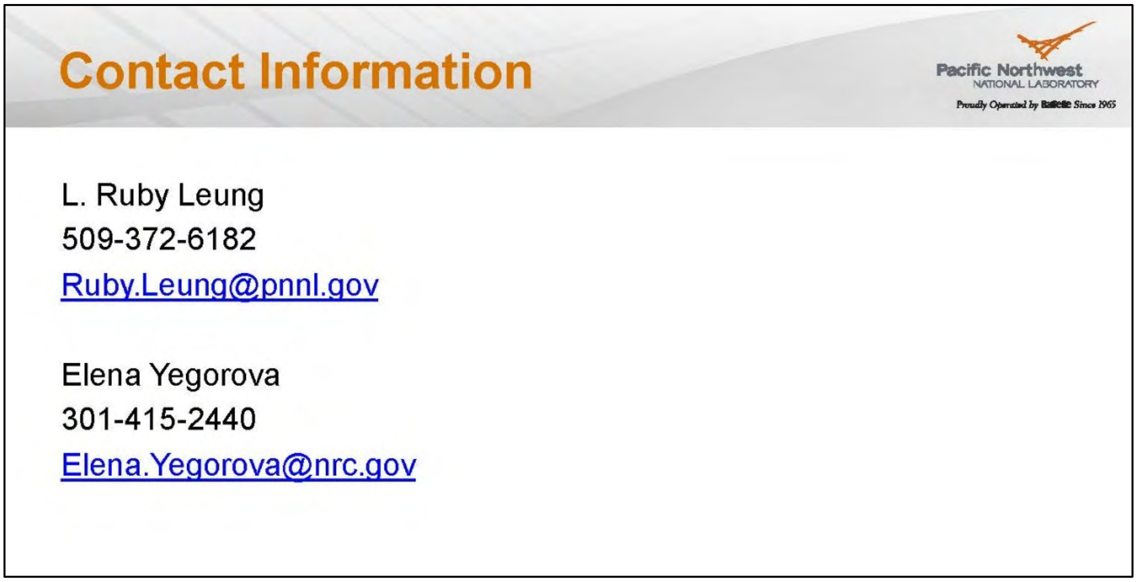
Projections of GMSL change with model parameters constrained by geologic criteria (Pliocene and Last Interglacial)



(DeConto and Pollard 2016 Nature)

Summary

- The US Southeast experiences large subseasonal-to-decadal climate variability that partly obscures the long term trends
- The region is vulnerable to extremes related to hurricanes, severe thunderstorms, storm surge, and flooding and drought
- Despite insignificant changes in mean temperature and precipitation, observational records have revealed past changes in extreme events over the Southeast
- Climate models projected significant changes in extremes in the future (extreme heat and precipitation, intense TCs, severe thunderstorms, SLR, storm surge)
- Multi-model and large ensemble modeling as well as high resolution modeling are becoming more computationally feasible, which may provide opportunities for characterizing and reducing uncertainties
- Potential surprises may arise from tipping elements and compound extreme events that are not well understood/modeled



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2.3.3.1.3 Questions and Answers

Comment:

Fort Calhoun and St. Lucie experienced profound effects from flood, but neither were extreme events. It’s important to emphasize that in addition to considering extreme events, those with 50–100-year return periods also need to be taken into account.

Comment:

Be cautious as the term “extreme event” has a different meaning for hydrologists than for climatologists.

2.3.3.2 Numerical Modeling of Local Intense Precipitation Processes, M. Lev Kavvas*, Ph.D., Kei Ishida*, Ph.D., and Mathieu Mure-Ravaud*, Hydrologic Research Laboratory, Department of Civil and Environmental Engineering, University of California, Davis (Session 2A-2; ADAMS Accession No. ML17054C505)

2.3.3.2.1 Abstract

As population and infrastructure continue to increase, our society has become more vulnerable to extreme events. A flood is an example of a hydrometeorological disaster that has a strong societal impact. Tropical cyclones and mesoscale convective systems are recognized for their ability to generate intense precipitation that may in turn create disastrous floods. Tropical cyclones are intense atmospheric vortices that form over the warm tropical oceans, while mesoscale convective systems are organized collections of several cumulonimbus clouds that interact at the mesoscale (regional scale) to form an extensive and nearly contiguous region of precipitation.

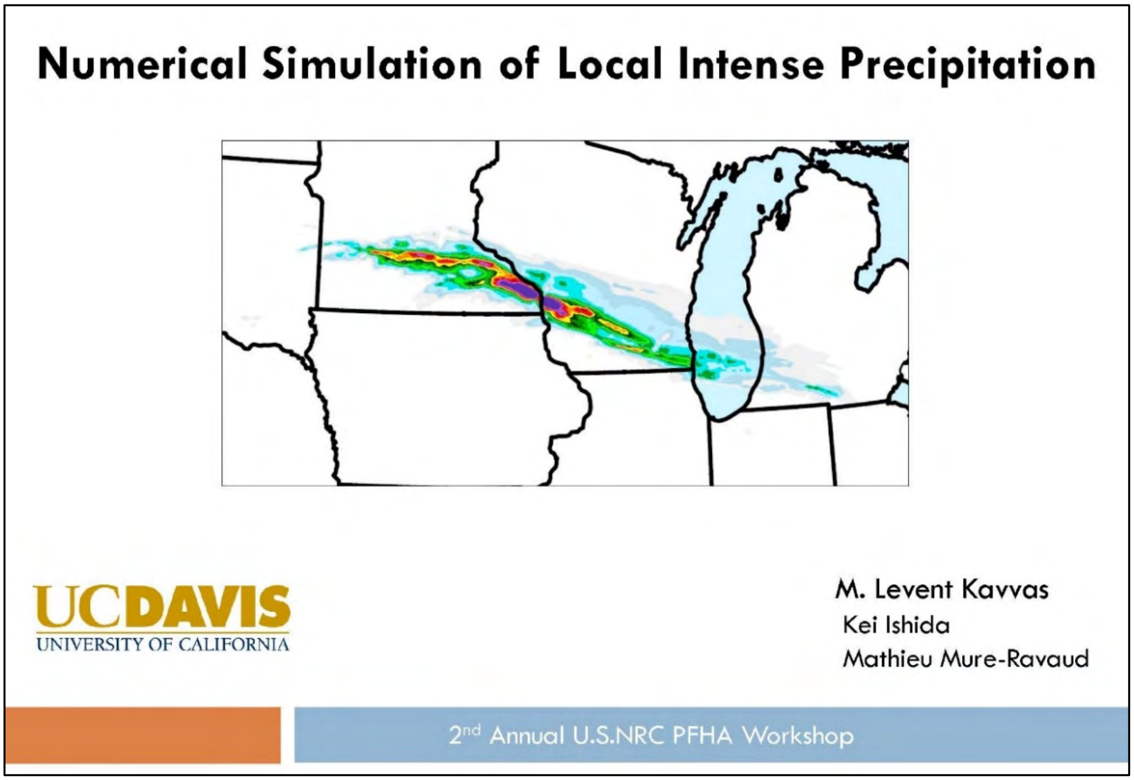
This study assessed the suitability of a regional numerical weather model to simulate local intense precipitation processes within intense tropical cyclones and mesoscale convective systems. More specifically, the study used the Weather Research and Forecasting (WRF) model at 5-kilometer resolution in order to reconstruct the intense precipitation fields associated with several historical tropical cyclones and mesoscale convective systems that affected the United States. The WRF model was run in the simulation mode, which means that it was only subject to the influence of its initial and boundary conditions, and no observation was used to improve the simulations through nudging or other data assimilation techniques.

Numerous studies have shown that regional numerical weather models perform relatively well in reconstructing such storms in the forecasting mode where such techniques are used to improve the model's performances. However, in the context of climate change where one may be interested in simulating the storms of the future, it is important to evaluate the performances of regional numerical weather models in the simulation mode, since no observation is available for the future that would allow using nudging or data assimilation. The storm systems that were simulated were selected within the time period from 2002 to present, based on the National Centers for Environmental Prediction (NCEP) Stage IV precipitation dataset, which is a mosaic of regional multisensor analysis generated by National Weather Service (NWS) River Forecast Centers since 2002. These storms correspond to the most severe storms, in terms of the generation of an intense precipitation field containing pockets of extreme rainfall.

The initial and boundary conditions for the simulations were obtained from the Climate Forecast System Reanalysis (CFSR) dataset, which is provided by NCEP at 0.5 x 0.5 degree spatial resolution and 6-hour temporal resolution. For the simulations of the mesoscale convective systems, the model's simulation nested domains were set up over a region in the Midwest so that the innermost domain covered the severe precipitation areas caused by these storm systems. However, several sets of simulation nested domains were prepared for the simulations of the tropical cyclones because of the diversity in the paths of these systems. More precisely, while the outer domain was the same for all cases and was chosen so as to cover the paths of all the identified severe tropical cyclones, different inner domains were set up so as to include the severe precipitation areas caused by each individual tropical cyclone. With these sets of simulation nested domains, the WRF model was configured to obtain the best results for the simulation of each of the selected severe mesoscale convective system and tropical cyclone storm events with respect to the simulated and observed precipitation fields.

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

2.3.3.2.2 Presentation

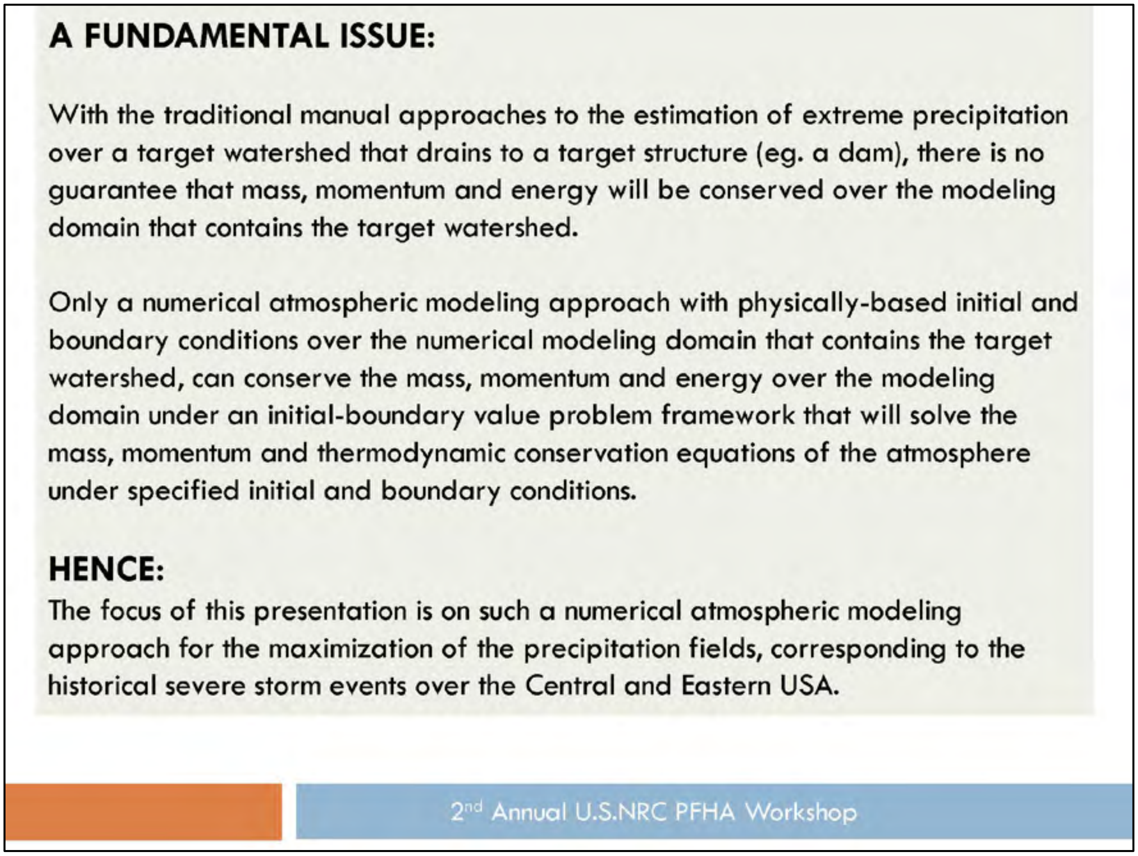


Numerical Simulation of Local Intense Precipitation

UCDAVIS
UNIVERSITY OF CALIFORNIA

M. Levent Kavvas
Kei Ishida
Mathieu Mure-Ravaud

2nd Annual U.S.NRC PFHA Workshop



A FUNDAMENTAL ISSUE:

With the traditional manual approaches to the estimation of extreme precipitation over a target watershed that drains to a target structure (eg. a dam), there is no guarantee that mass, momentum and energy will be conserved over the modeling domain that contains the target watershed.

Only a numerical atmospheric modeling approach with physically-based initial and boundary conditions over the numerical modeling domain that contains the target watershed, can conserve the mass, momentum and energy over the modeling domain under an initial-boundary value problem framework that will solve the mass, momentum and thermodynamic conservation equations of the atmosphere under specified initial and boundary conditions.

HENCE:

The focus of this presentation is on such a numerical atmospheric modeling approach for the maximization of the precipitation fields, corresponding to the historical severe storm events over the Central and Eastern USA.

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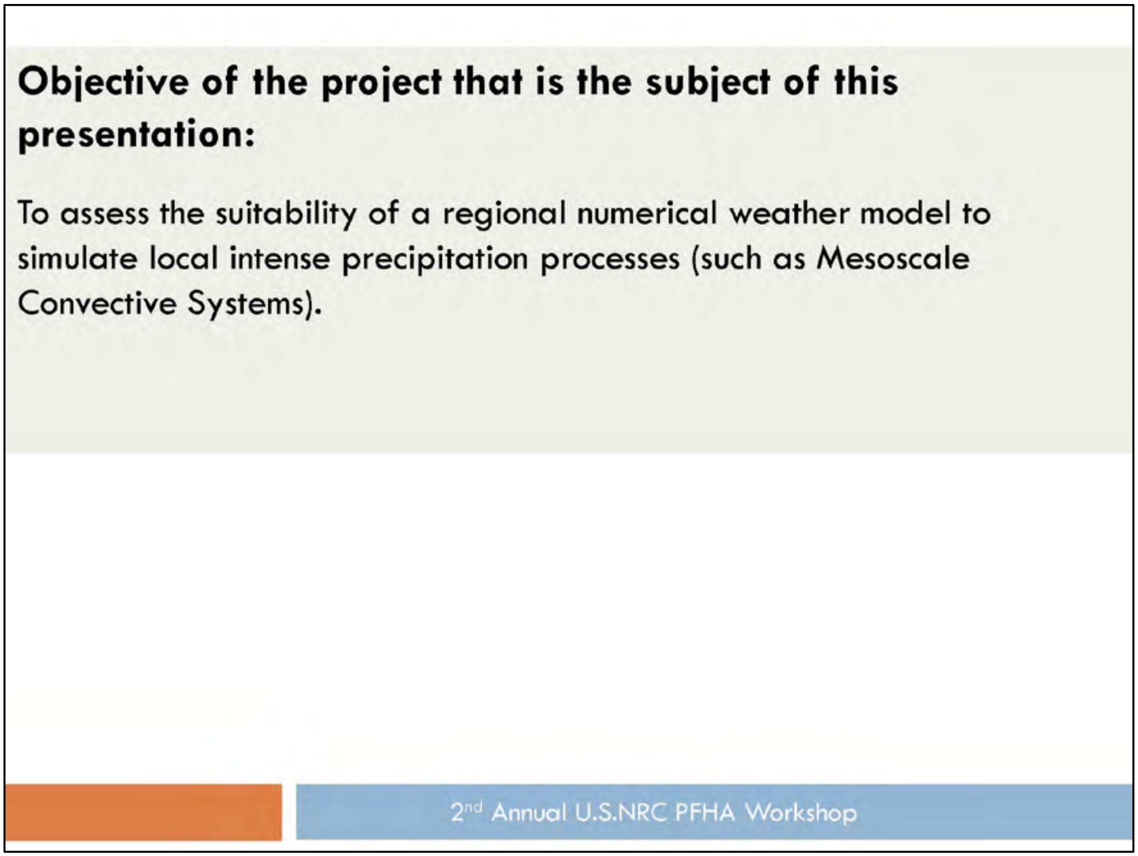
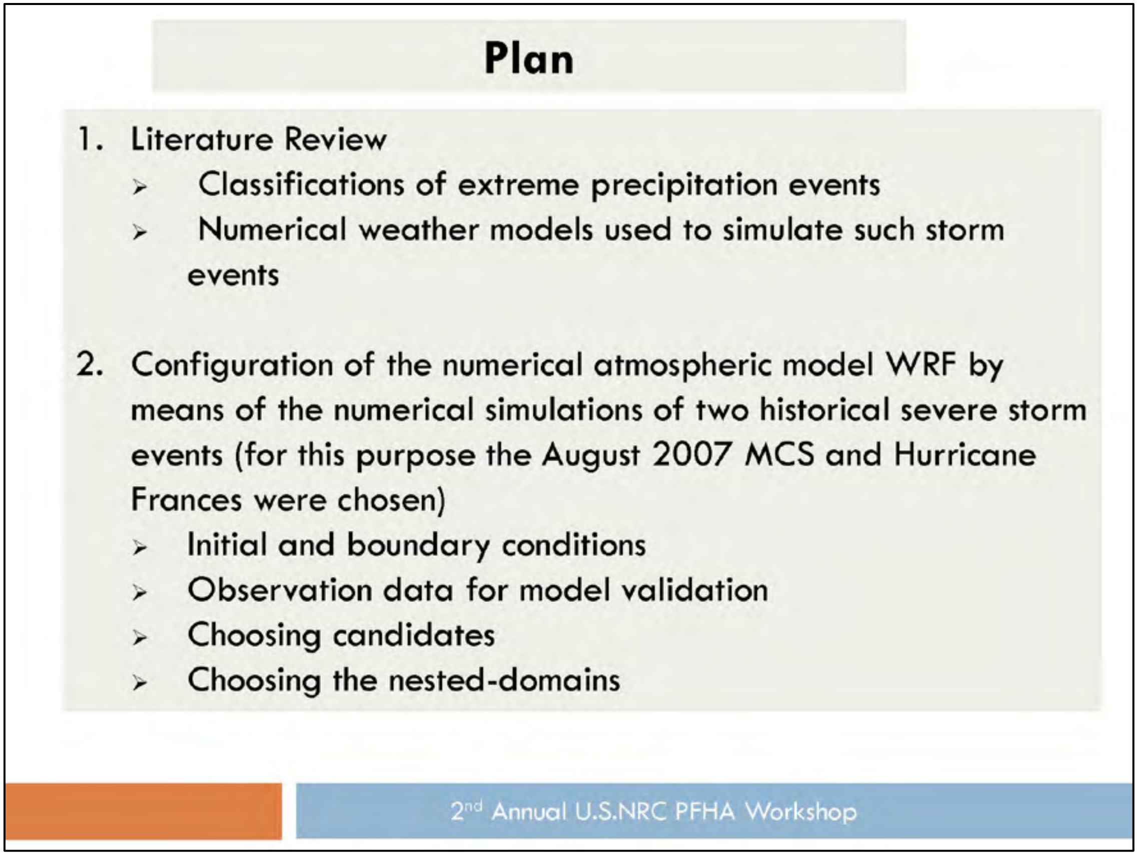


Objective of the project that is the subject of this presentation:

To assess the suitability of a regional numerical weather model to simulate local intense precipitation processes (such as Mesoscale Convective Systems).



Plan

1. Literature Review
    - Classifications of extreme precipitation events
    - Numerical weather models used to simulate such storm events

2. Configuration of the numerical atmospheric model WRF by means of the numerical simulations of two historical severe storm events (for this purpose the August 2007 MCS and Hurricane Frances were chosen)
    - Initial and boundary conditions
    - Observation data for model validation
    - Choosing candidates
    - Choosing the nested-domains

Classifications of extreme precipitation events in USA

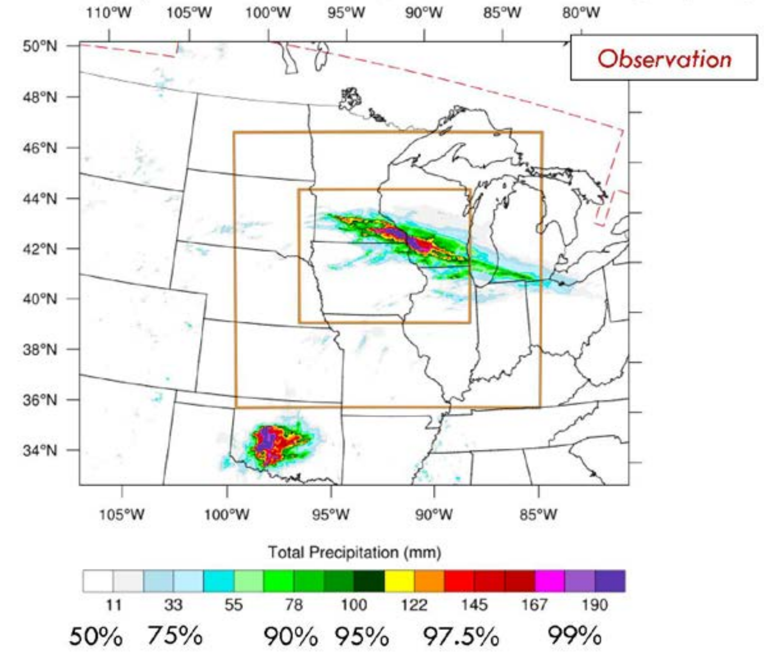
- Various classifications of extreme precipitation events in the literature
- In general, a distinction between tropical and non-tropical origin
- Classification proposed by Schumacher and Johnson (2005) and Stevenson and Schumacher (2014):
  - ✓ Mesoscale Convective Systems: *convective systems with areal extents greater than 100 km and with durations between 3 and 24 h*
  - ✓ Synoptic Systems: *events characterized by the strong large-scale ascent commonly associated with synoptic-scale features (i.e., extratropical cyclones) and/or lasting longer than 24 h*
  - ✓ Tropical Systems (hurricanes)

Evaluation of Model Performance with respect to placing the intense precipitation field in the correct location

- In order to assess the ability of the model to place the intense part of the precipitation field we used the percentage of overlapping, i.e. the number of grid points where both the observation and the simulation are above the threshold, divided by the number of points where the observation is above the threshold. For example, 25% overlapping means that the intense part of the simulated field overlaps with the intense part of the observed field at 25%.

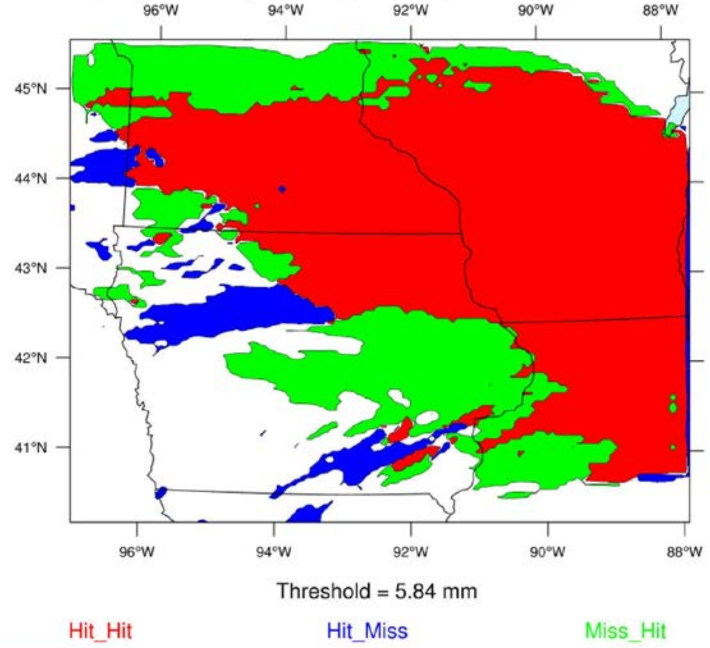
2007 August Mesoscale Convective System

Total accumulated precipitation starting on 2007-08-18_19h and ending on 2007-08-19_18h (ST4-1h)



MCS: 50th percentile
% overlap = 88%

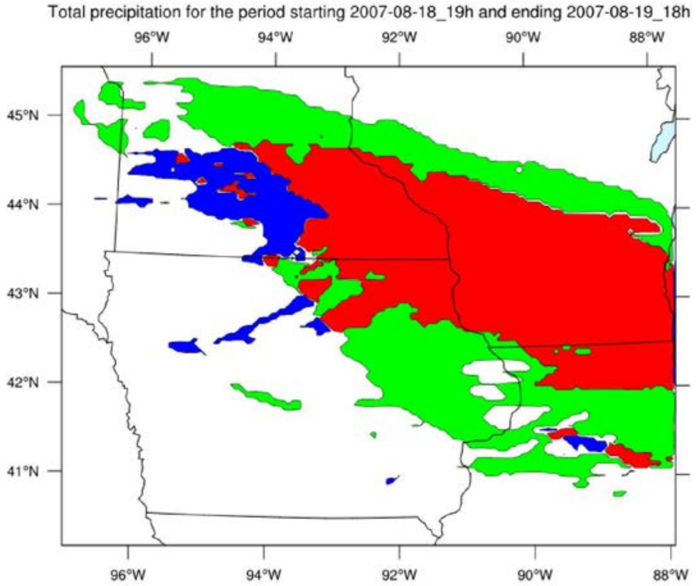
Total precipitation for the period starting 2007-08-18_19h and ending 2007-08-19_18h



Simu 095

MCS: 75th percentile

% overlap = 83%



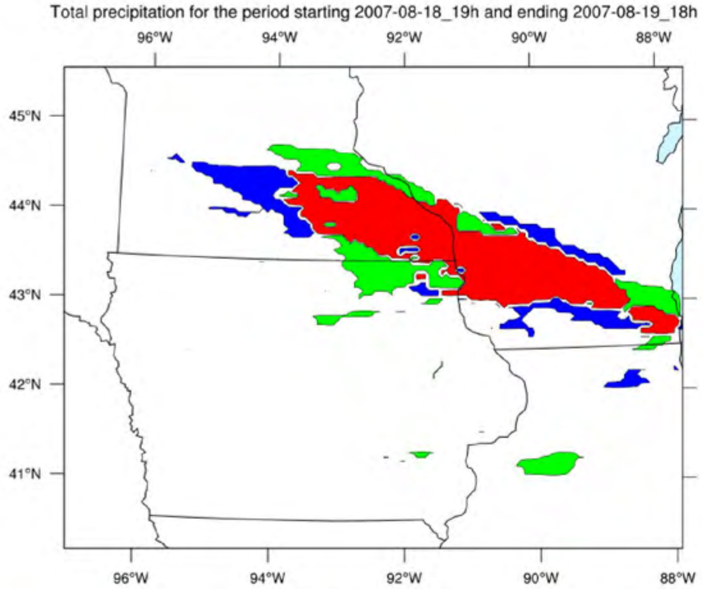
Threshold = 31.3 mm

Hit_Hit Hit_Miss Miss_Hit

Simu 095

MCS: 90th percentile

% overlap = 68%

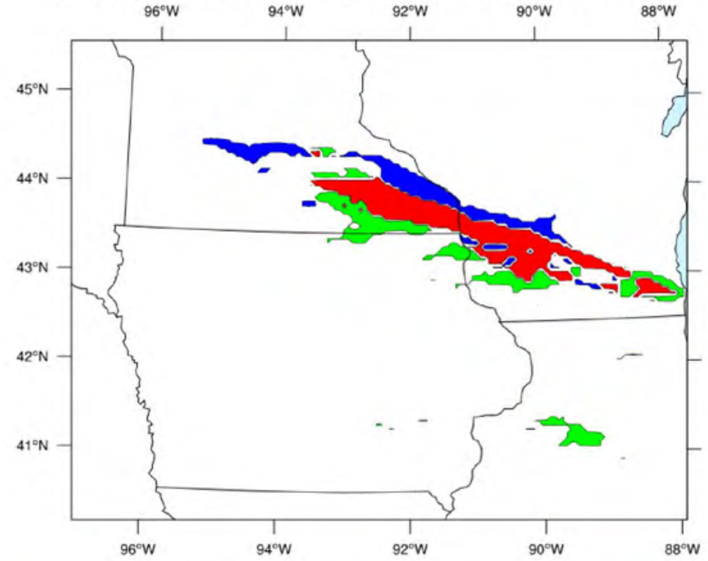


Threshold = 78.2 mm

Hit_Hit Hit_Miss Miss_Hit

Simu 029

MCS: 95th percentile
% overlap = 60%



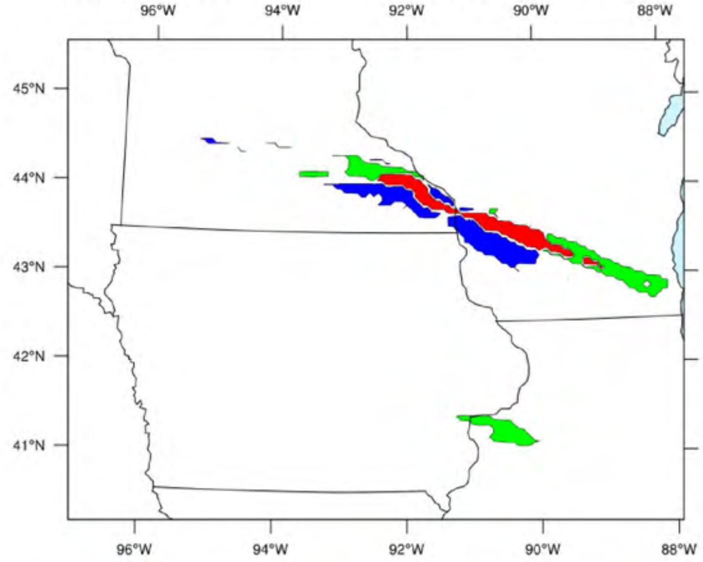
Total precipitation for the period starting 2007-08-18_19h and ending 2007-08-19_18h

Threshold = 104 mm

Hit_Hit Hit_Miss Miss_Hit

Simu 027

MCS: 97.5th percentile
% overlap = 39%

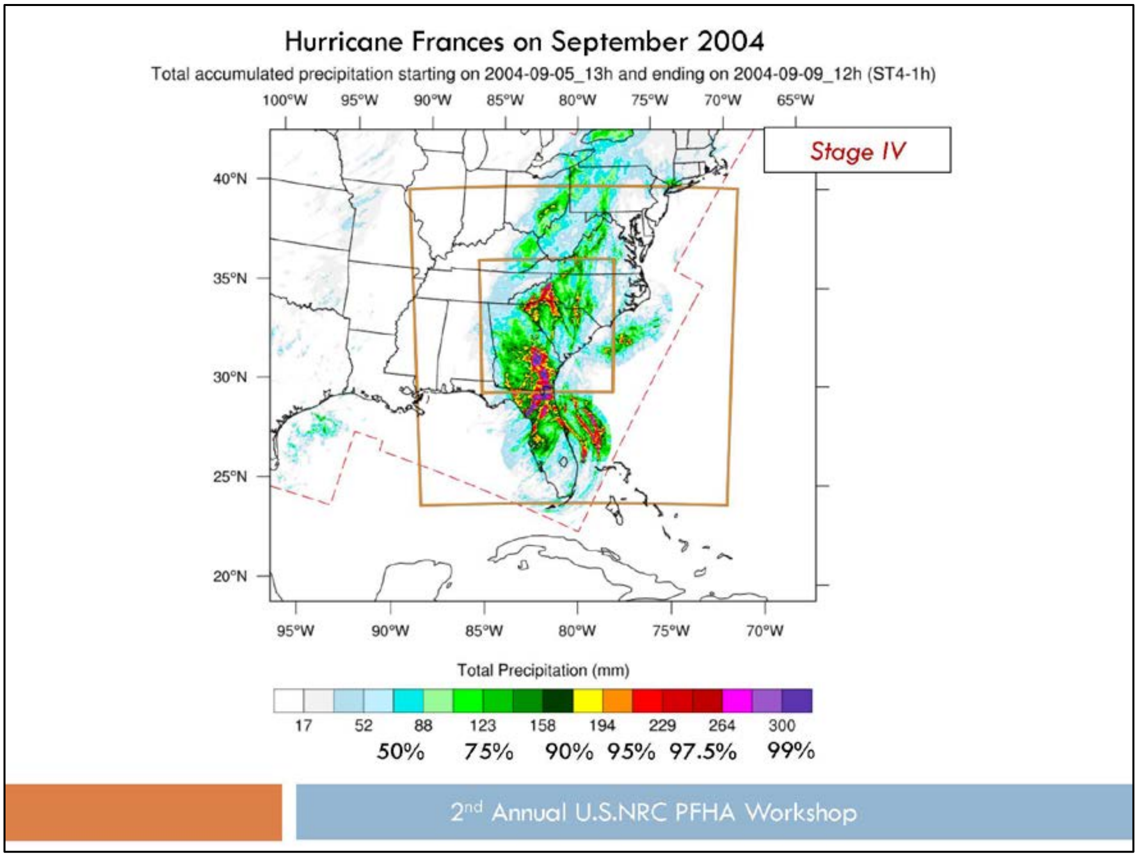


Total precipitation for the period starting 2007-08-18_19h and ending 2007-08-19_18h

Threshold = 134 mm

Hit_Hit Hit_Miss Miss_Hit

Simu 028



Hurricane Frances on September 2004

Total accumulated precipitation starting on 2004-09-05_13h and ending on 2004-09-09_12h (ST4-1h)

50% 75% 90% 95% 97.5% 99%

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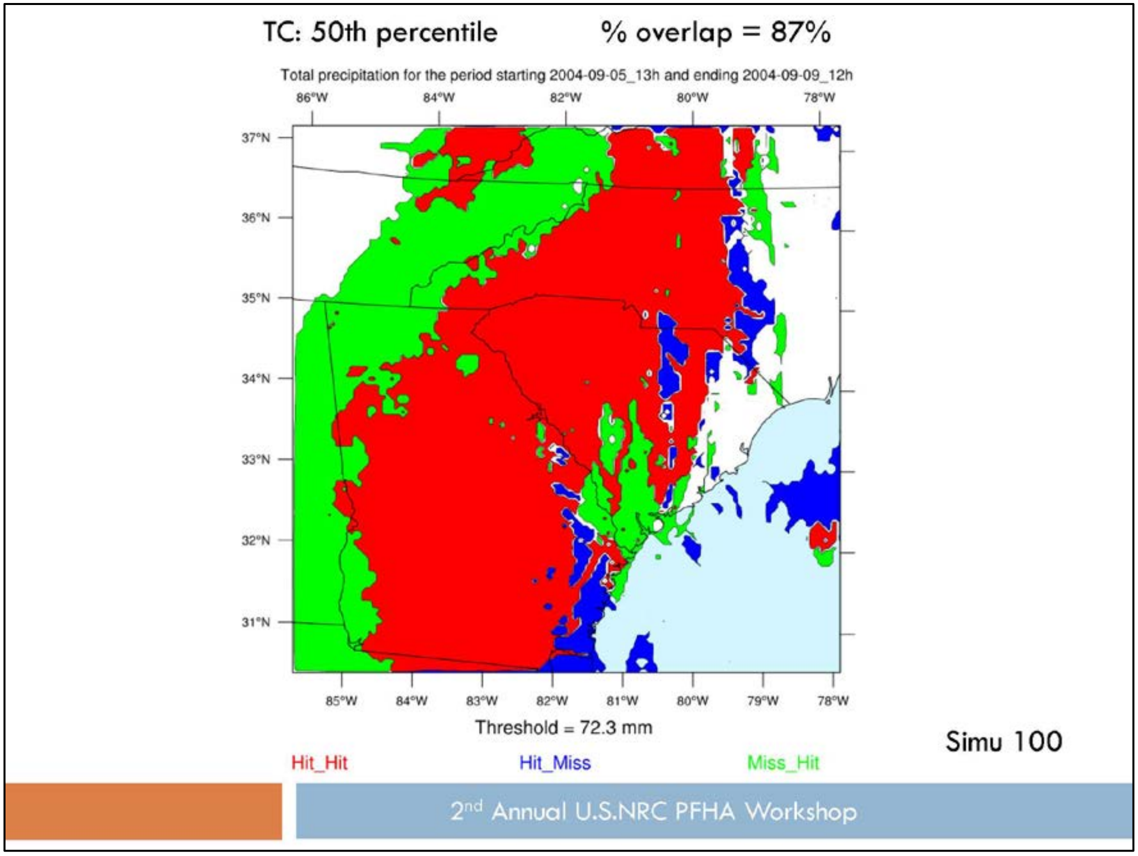

TC: 50th percentile % overlap = 87%

Total precipitation for the period starting 2004-09-05_13h and ending 2004-09-09_12h

Simu 100

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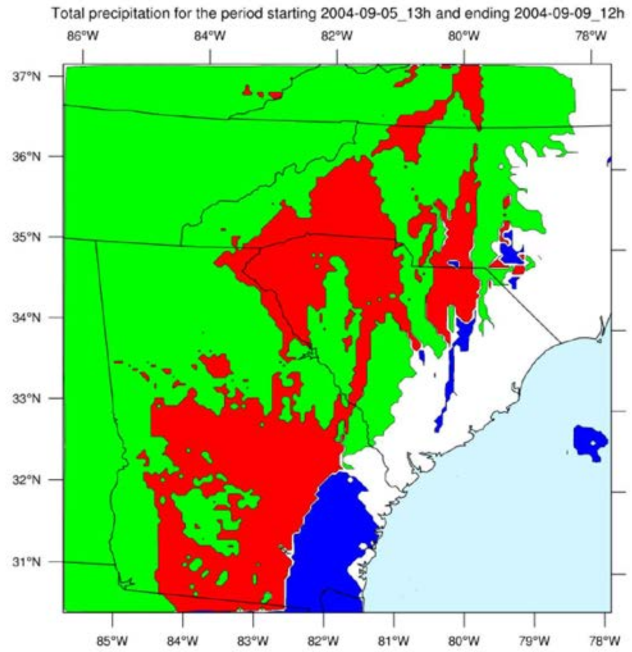
TC: 75th percentile % overlap = 83%



Threshold = 122 mm

Hit_Hit Hit_Miss Miss_Hit

Simu 095

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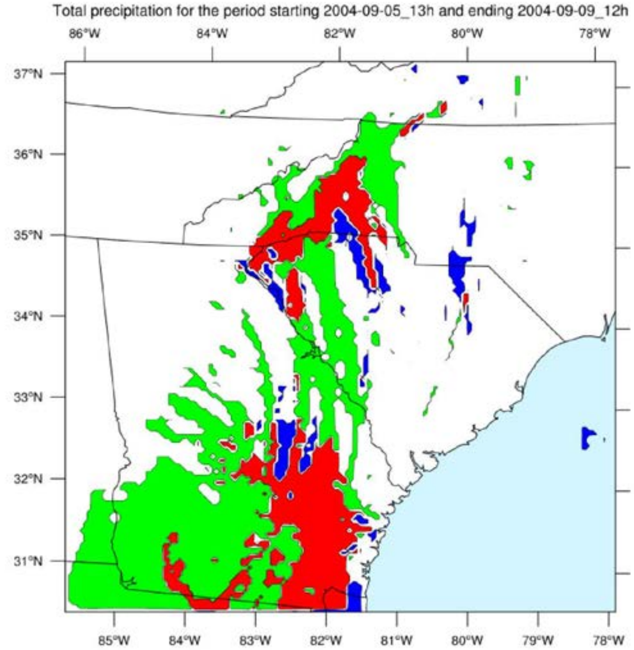
TC: 90th percentile % overlap = 73%



Threshold = 172 mm

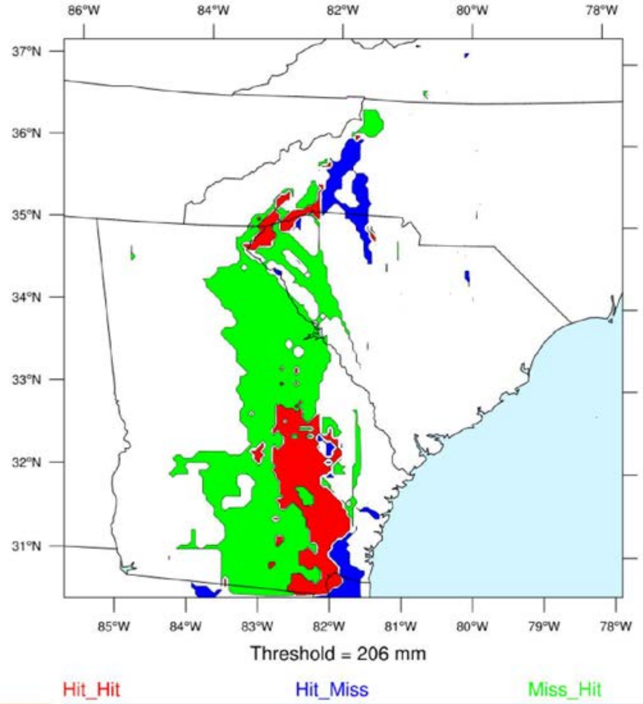
Hit_Hit Hit_Miss Miss_Hit

Simu 093

2nd Annual U.S.NRC PFHA Workshop

TC: 95th percentile % overlap = 62%

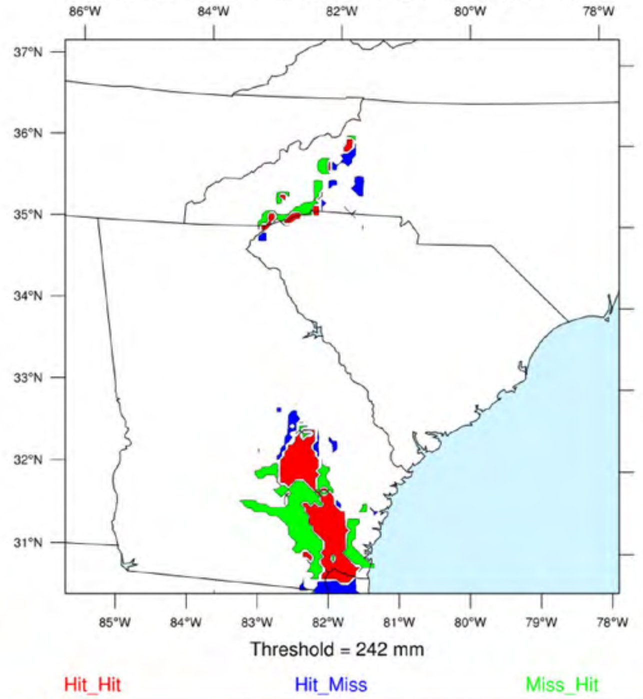
Total precipitation for the period starting 2004-09-05_13h and ending 2004-09-09_12h



Simu 116

TC: 97.5th percentile % overlap = 66%

Total precipitation for the period starting 2004-09-05_13h and ending 2004-09-09_12h



Simu 140

Work Plan

1. Determine the intense MCSs and TCs in the Stage-IV dataset (2002-present) that realized within the simulation inner-domains;
2. Validate the model for each of these storms; then for each of these storms construct the underlying wind and moisture fields;
3. Perform a transposition exercise for one historical MCS and for one historical Hurricane using 2 target areas;
4. Determine the most intense future storm event for each of the two modeling inner domains (one for MCS and one for TC) by dynamicallly downscaling the Community Climate System Model version 4 (CCSM4) climate projection by WRF model over the two domains.

- We determined and simulated the intense Tropical Cyclones that affected the Eastern US from 2002 to present. *Tropical Cyclones are intense atmospheric vortices that form over the warm tropical oceans.*

- We determined and simulated the intense Mesoscale Convective Systems that affected the Midwestern US from 2002 to present. *Mesoscale Convective Systems are organized collections of several cumulonimbus clouds which interact at regional scale to form an extensive and nearly contiguous region of precipitation.*

- Both storm systems are recognized for their ability to generate intense precipitation that may in turn create disastrous floods.

- Storms were selected from the NCEP Stage-IV precipitation analyses, a mosaic of regional multi-sensor analysis generated by National Weather Service River Forecast Centers (RFCs). They combine rain gauge data and radar-estimated rainfall. They are provided at 4 km resolution and three time resolutions: 1-h, 6-h, and 24-h time intervals.

- We used the website http://schumacher.atmos.colostate.edu/precip_monitor/ from the Precipitation Systems Research Group in Colorado State University in order to identify intense precipitation events.

- This website lists every event for which a given threshold (e.g. 100 year, 24 hour) was exceeded at at least one grid cell in Stage IV observation data.

- We analyzed all events and we selected 11 Tropical Cyclones (TCs), and 7 Mesoscale Convective Systems (MCSs) which generated intense precipitation fields.

- We used the Weather Research and Forecasting (WRF) model at 5-km resolution in order to reconstruct their intense precipitation fields.

- Climate Forecast System Reanalysis (CFSR) was used for initial and boundary conditions. The provided spatial and temporal resolutions of CFSR are 0.5 x 0.5 degree and 6-hourly.

- The WRF model was run in the simulation mode: it was only subject to the influence of its initial and boundary conditions, and no observation was used to improve the simulations through nudging or other data assimilation techniques.

- In the context of climate change where one may be interested in simulating the storms of the future, it is important to evaluate the performances of regional numerical weather models in the simulation mode, since no observation is available for the future which would allow using nudging or data assimilation.

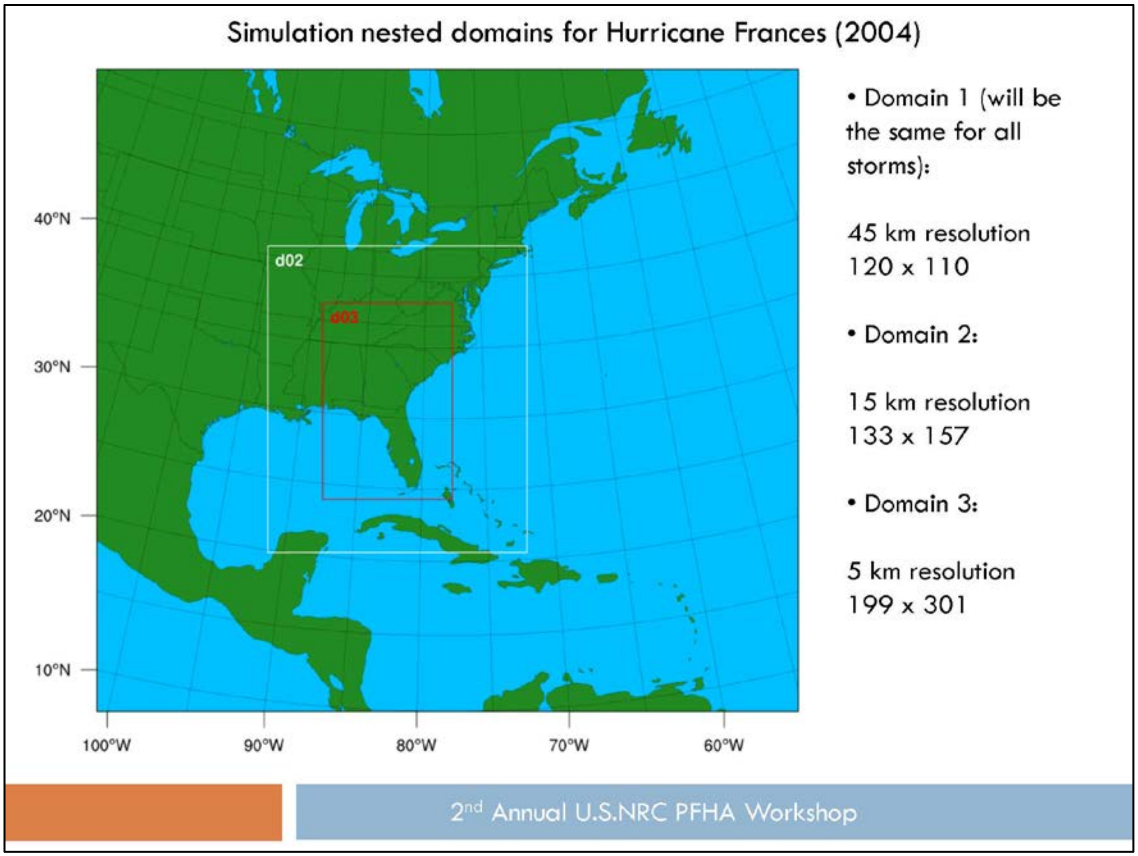
- The WRF model was configured to obtain the best results for the simulation of each of the selected severe MCS and TC storm events with respect to precipitation fields by trying many sets of the model's options:
    - parameterization schemes such as microphysics, cumulus parameterization, planetary boundary layer physics, long wave and short wave radiation physics, etc.
    - vertical resolution (number of layers)
    - initial date for the simulation
    - time step
    - other options related to the physics and dynamics.

1. Simulations of the intense Tropical Cyclones

2. Simulations of the intense Mesoscale Convective Systems

Simulated Tropical Cyclones

□ Hurricane Floyd (1999)
□ Hurricane Isodore (2002)
□ Hurricane Frances (2004)
□ Hurricane Ivan (2004)
□ Hurricane Jeanne (2004)
□ Hurricane Ernesto (2006)
□ Tropical Storm Fay (2008)
□ Hurricane Gustav (2008)
□ Hurricane Irene (2011)
□ Tropical Storm Lee (2011)
□ Hurricane Isaac (2012)
□ Hurricane Sandy (2012)
□ Hurricane Matthew (2016)



Simulation nested domains for Hurricane Frances (2004)

- Domain 1 (will be the same for all storms):

45 km resolution
120 x 110

- Domain 2:

15 km resolution
133 x 157

- Domain 3:

5 km resolution
199 x 301

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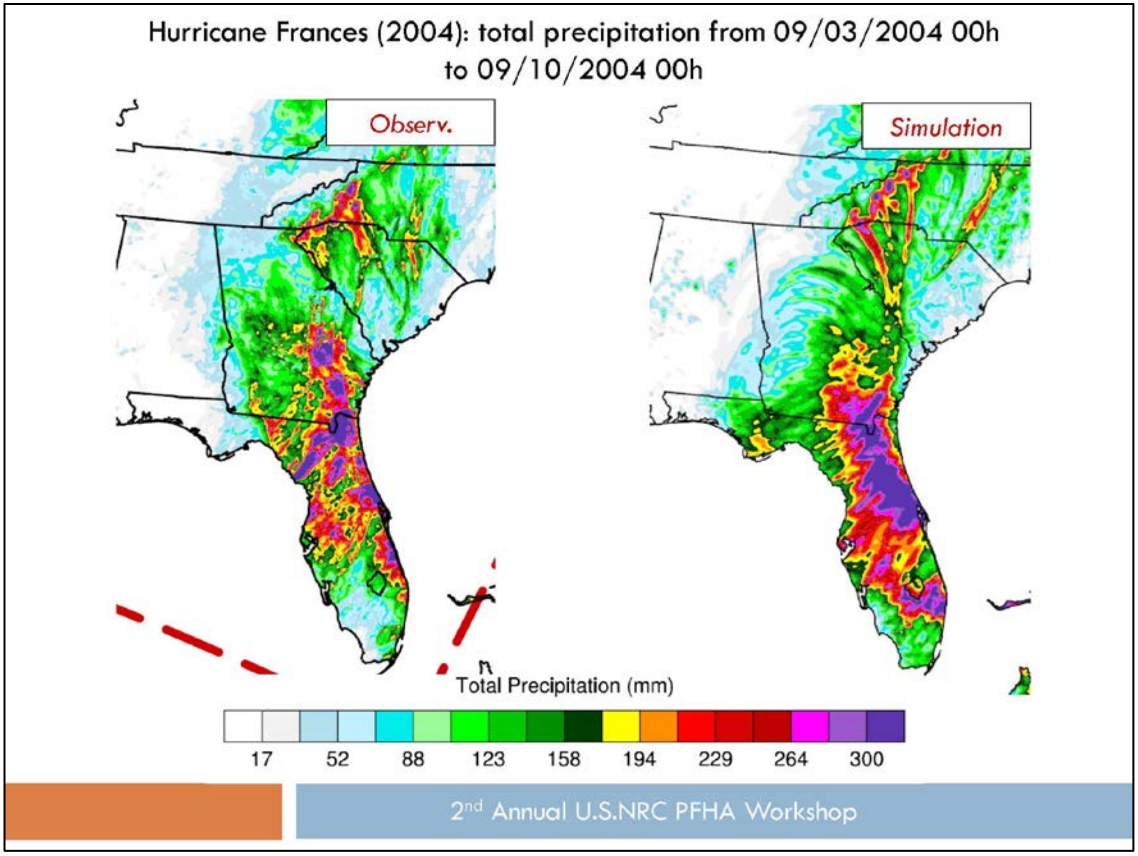

Hurricane Frances (2004): total precipitation from 09/03/2004 00h to 09/10/2004 00h

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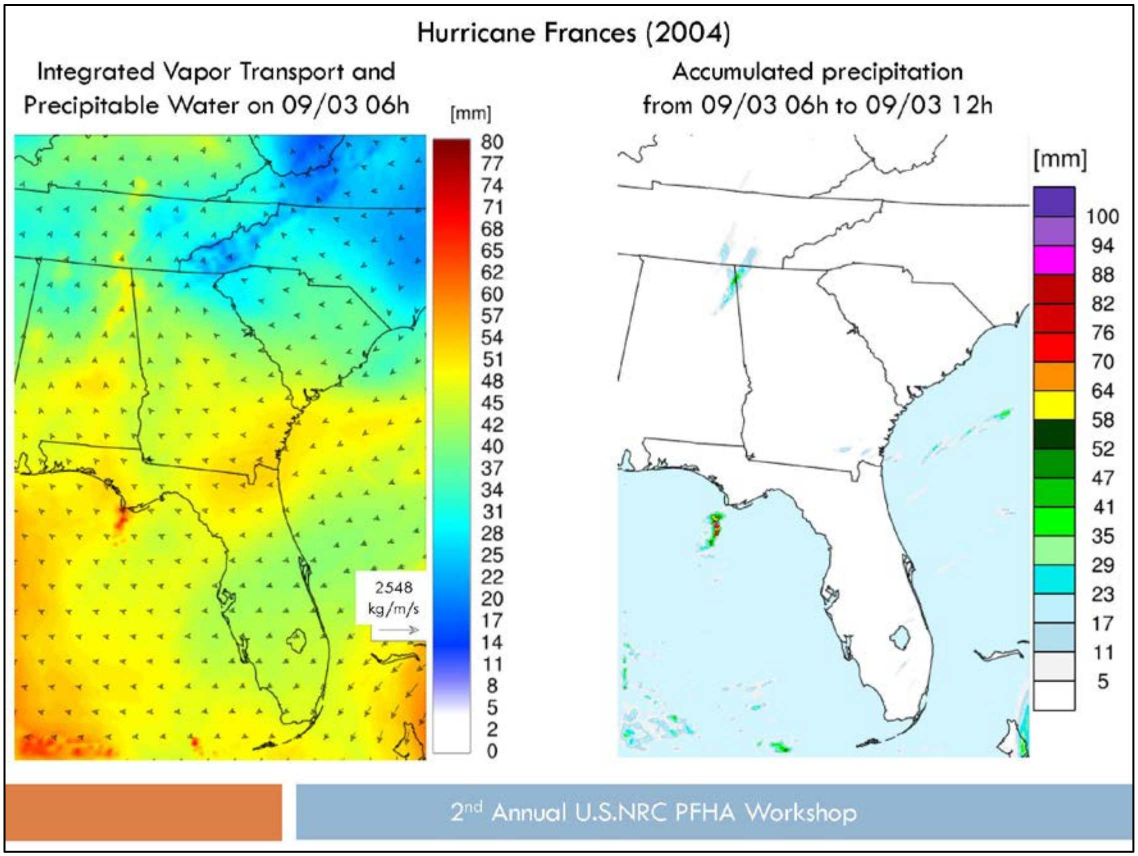

Hurricane Frances (2004)

Integrated Vapor Transport and Precipitable Water on 09/03 06h

Accumulated precipitation from 09/03 06h to 09/03 12h

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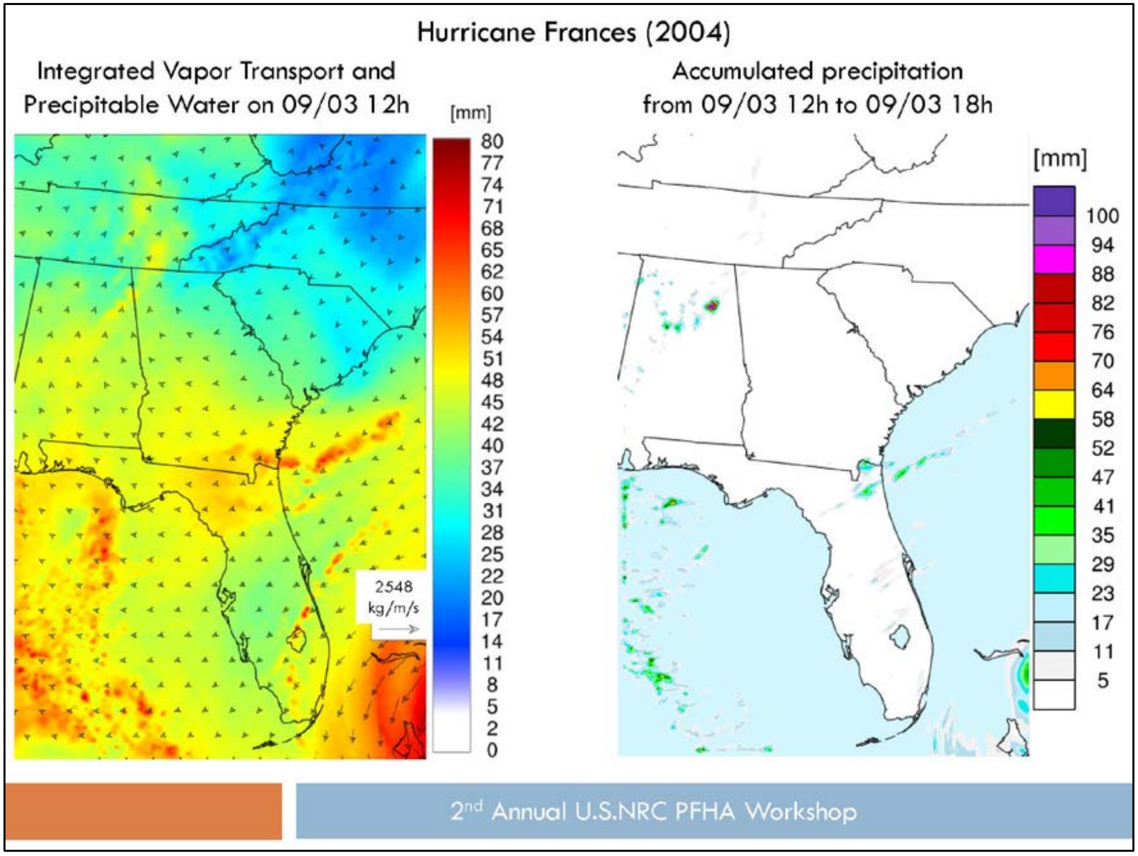

Hurricane Frances (2004)

Integrated Vapor Transport and Precipitable Water on 09/03 12h

Accumulated precipitation from 09/03 12h to 09/03 18h

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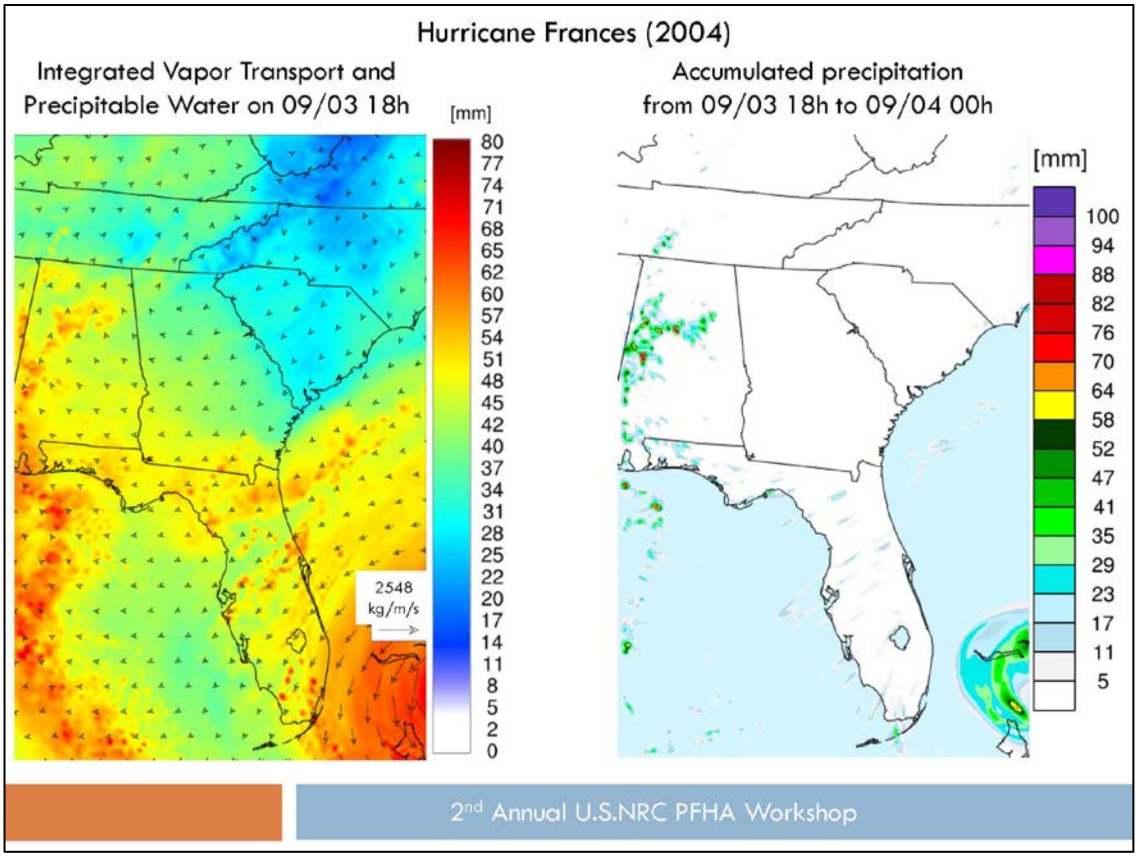

Hurricane Frances (2004)

Integrated Vapor Transport and Precipitable Water on 09/03 18h

Accumulated precipitation from 09/03 18h to 09/04 00h

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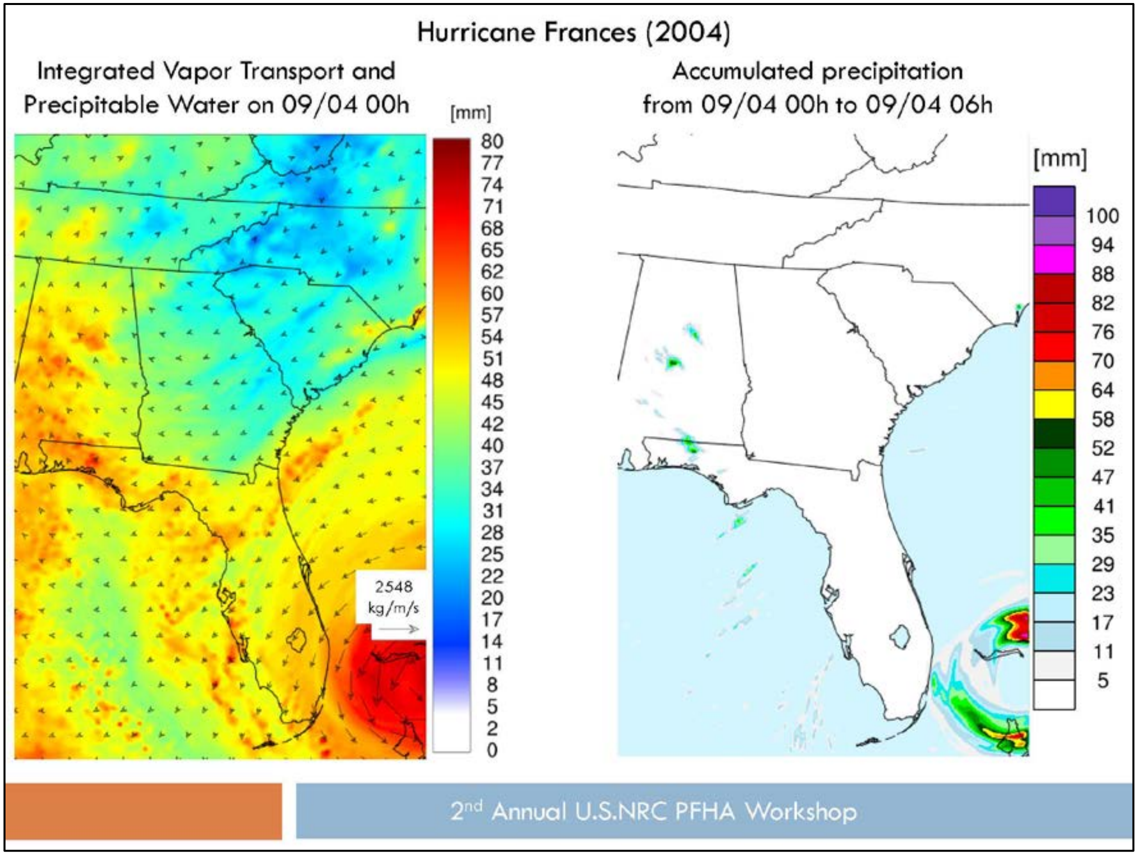

Hurricane Frances (2004)

Integrated Vapor Transport and Precipitable Water on 09/04 00h

Accumulated precipitation from 09/04 00h to 09/04 06h

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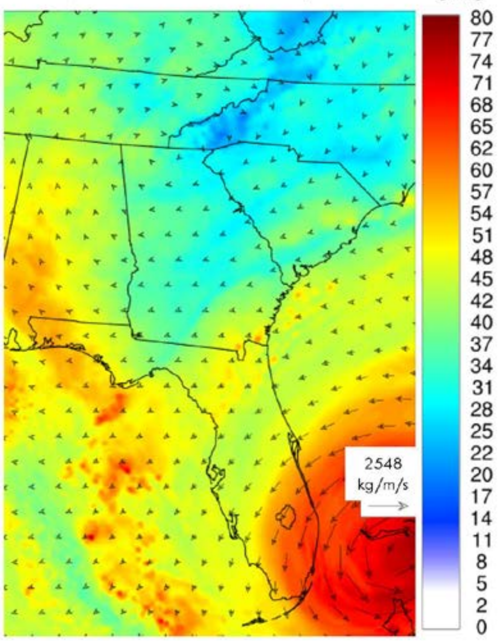
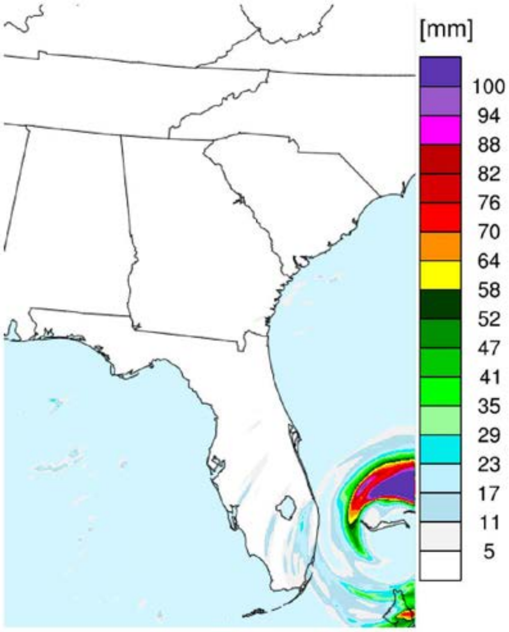
Hurricane Frances (2004)

Integrated Vapor Transport and Precipitable Water on 09/04 06h

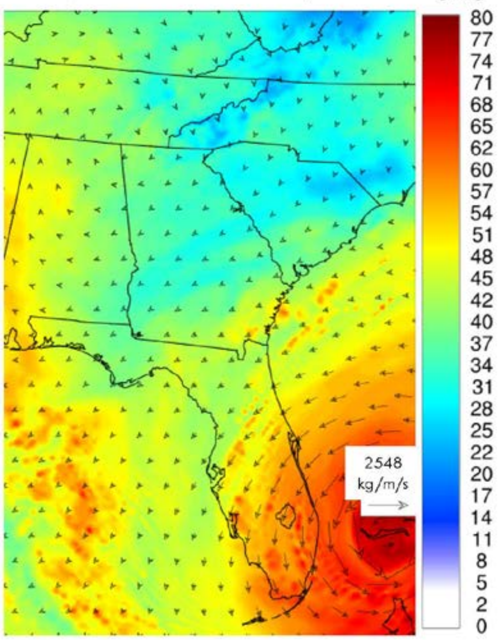


Accumulated precipitation from 09/04 06h to 09/04 12h

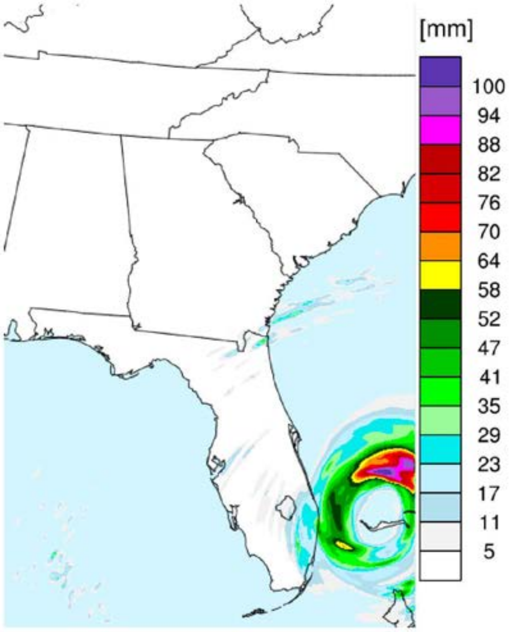


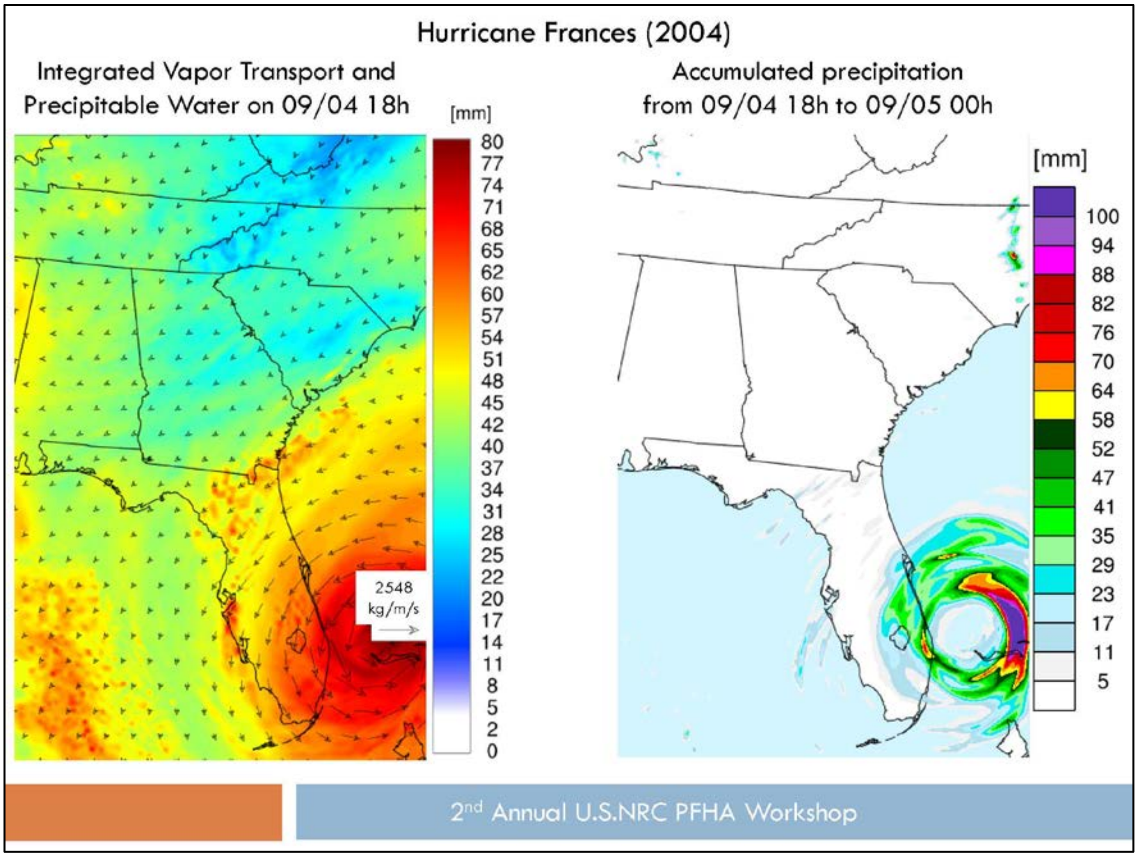
Hurricane Frances (2004)

Integrated Vapor Transport and Precipitable Water on 09/04 12h



Accumulated precipitation from 09/04 12h to 09/04 18h





Hurricane Frances (2004)

Integrated Vapor Transport and Precipitable Water on 09/04 18h

Accumulated precipitation from 09/04 18h to 09/05 00h

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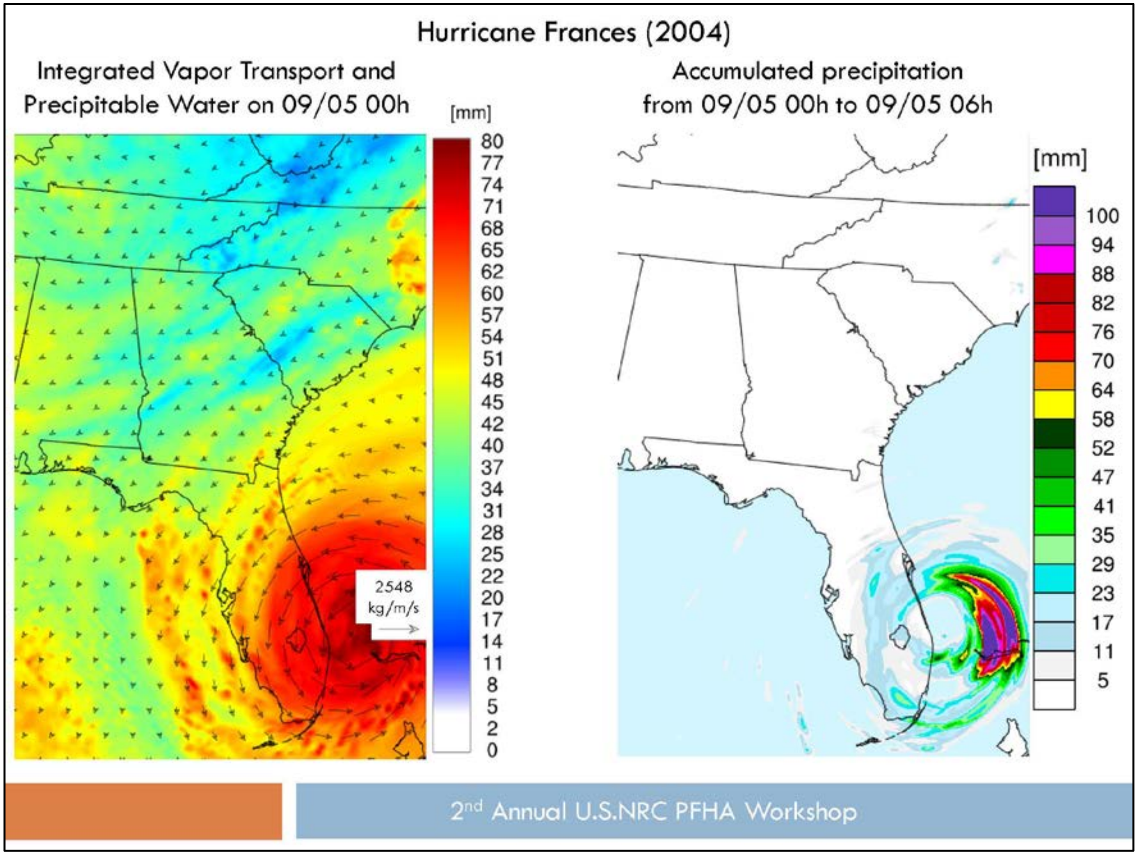

Hurricane Frances (2004)

Integrated Vapor Transport and Precipitable Water on 09/05 00h

Accumulated precipitation from 09/05 00h to 09/05 06h

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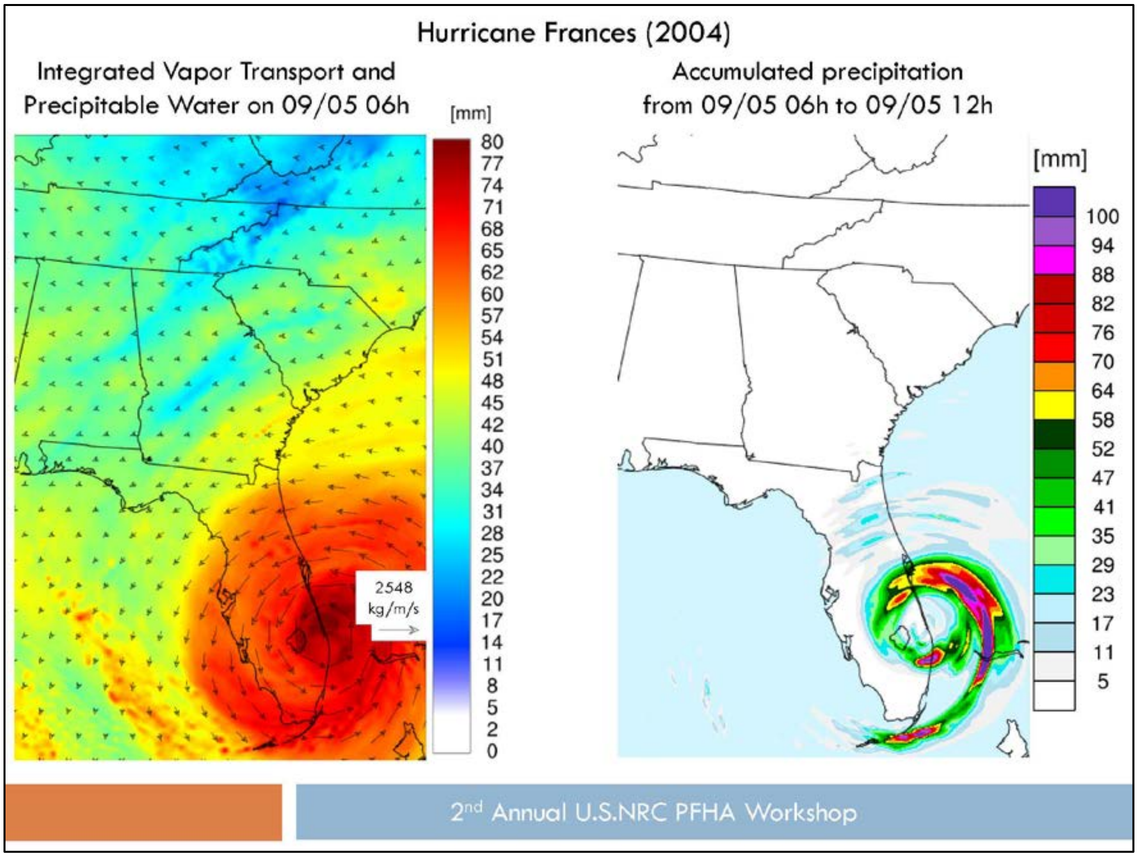
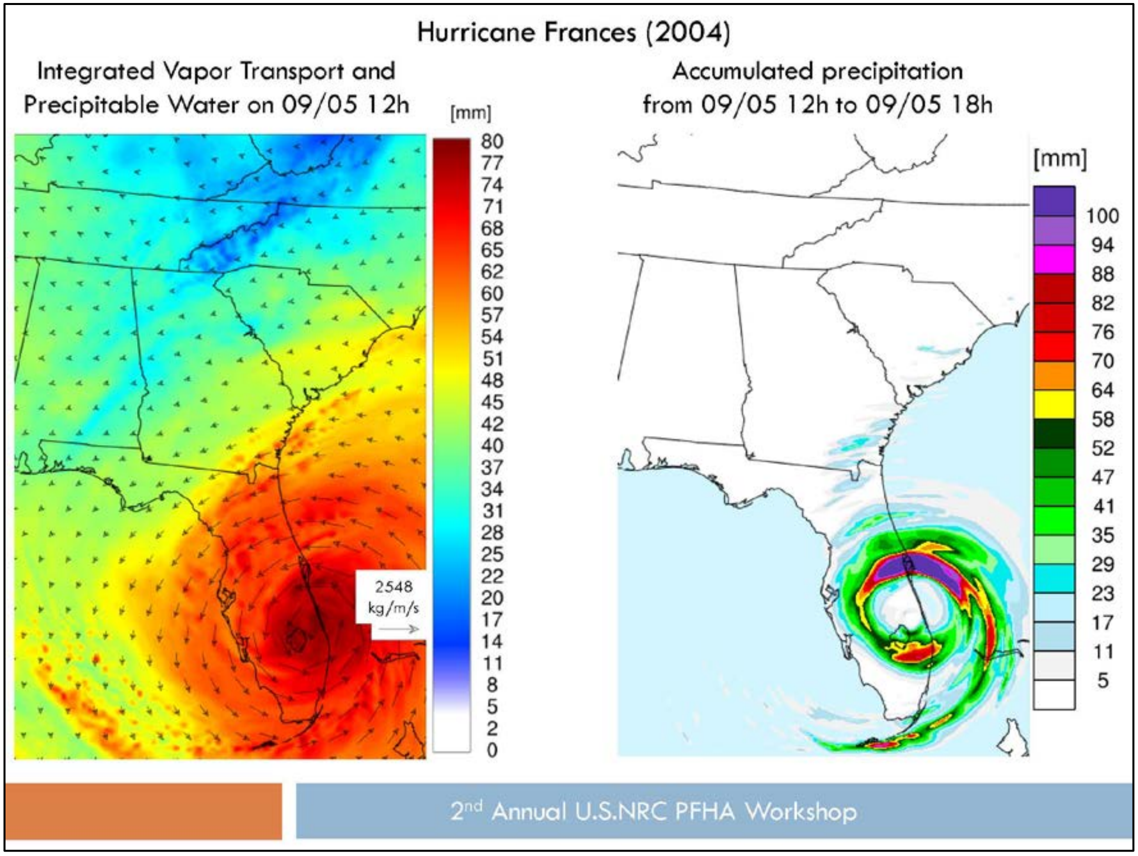


Hurricane Frances (2004)

Integrated Vapor Transport and Precipitable Water on 09/05 06h

Accumulated precipitation from 09/05 06h to 09/05 12h

2nd Annual U.S.NRC PFHA Workshop



Hurricane Frances (2004)

Integrated Vapor Transport and Precipitable Water on 09/05 12h

Accumulated precipitation from 09/05 12h to 09/05 18h

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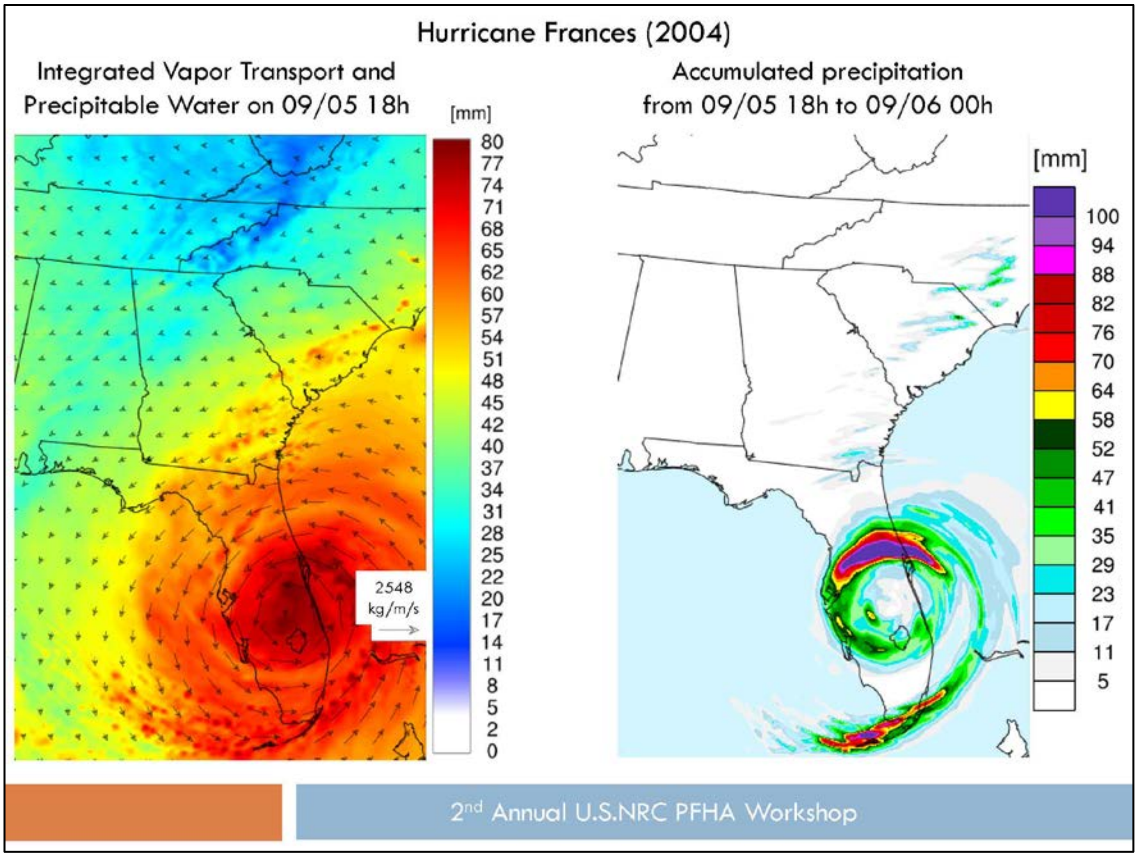

Hurricane Frances (2004)

Integrated Vapor Transport and Precipitable Water on 09/05 18h

Accumulated precipitation from 09/05 18h to 09/06 00h

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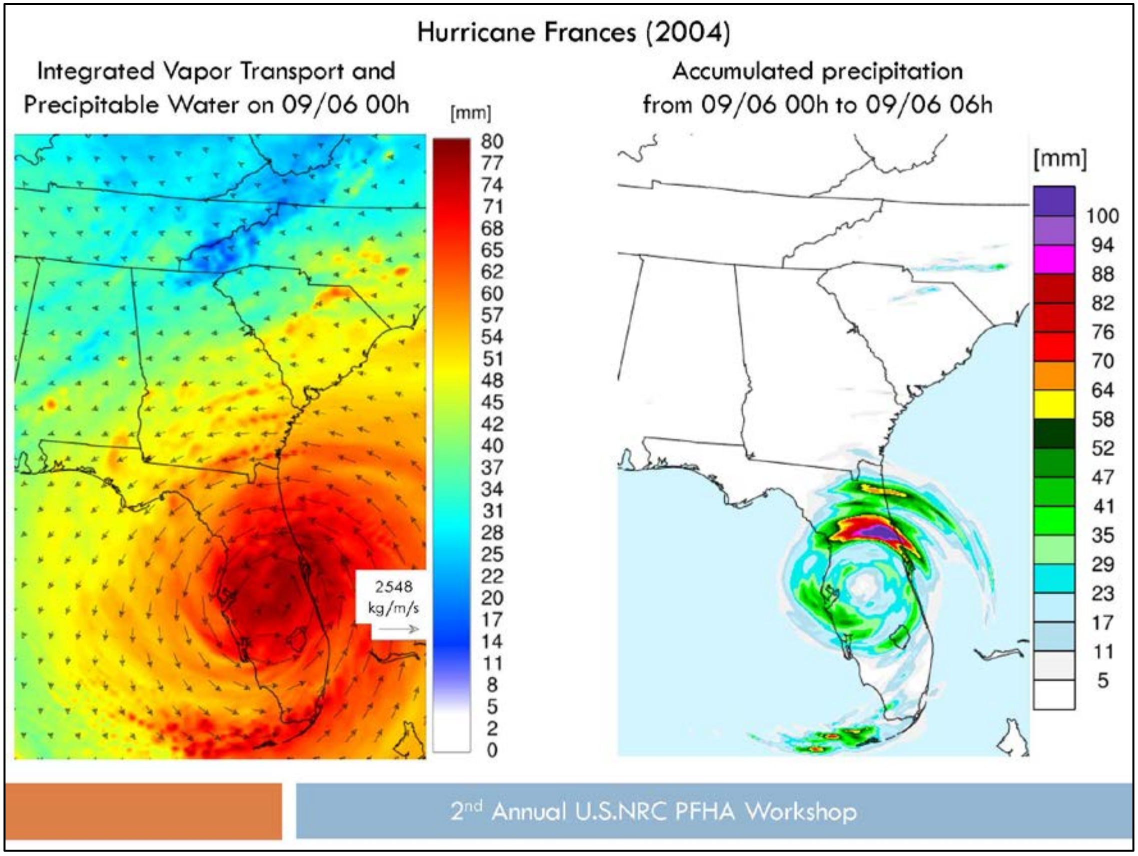

Hurricane Frances (2004)

Integrated Vapor Transport and Precipitable Water on 09/06 00h

Accumulated precipitation from 09/06 00h to 09/06 06h

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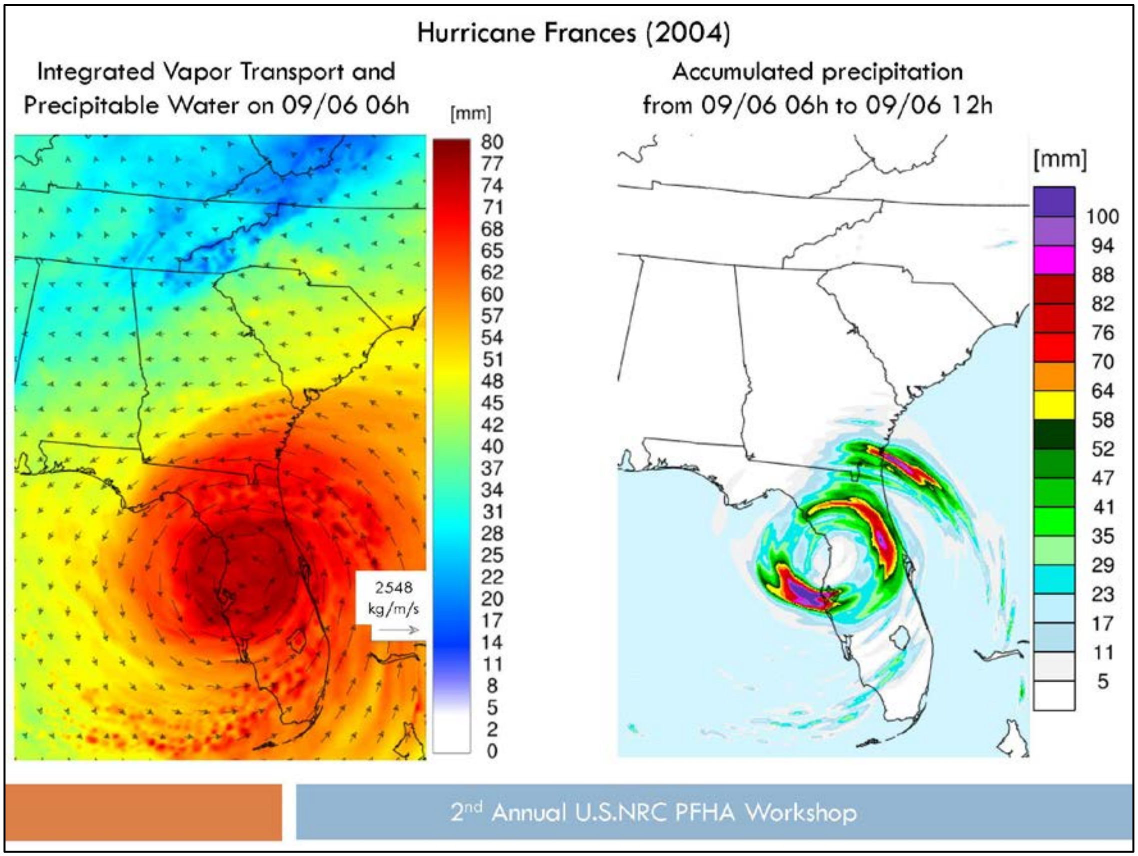

Hurricane Frances (2004)

Integrated Vapor Transport and Precipitable Water on 09/06 06h

Accumulated precipitation from 09/06 06h to 09/06 12h

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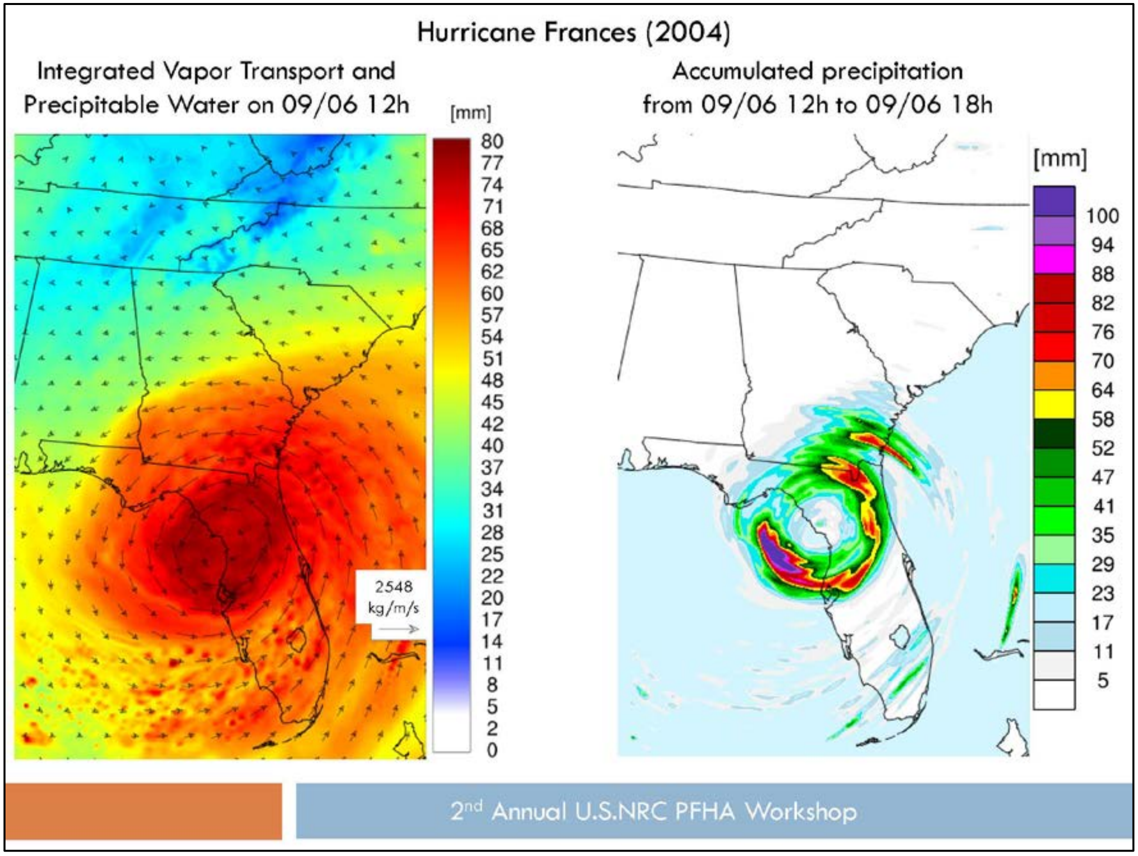

Hurricane Frances (2004)

Integrated Vapor Transport and Precipitable Water on 09/06 12h

Accumulated precipitation from 09/06 12h to 09/06 18h

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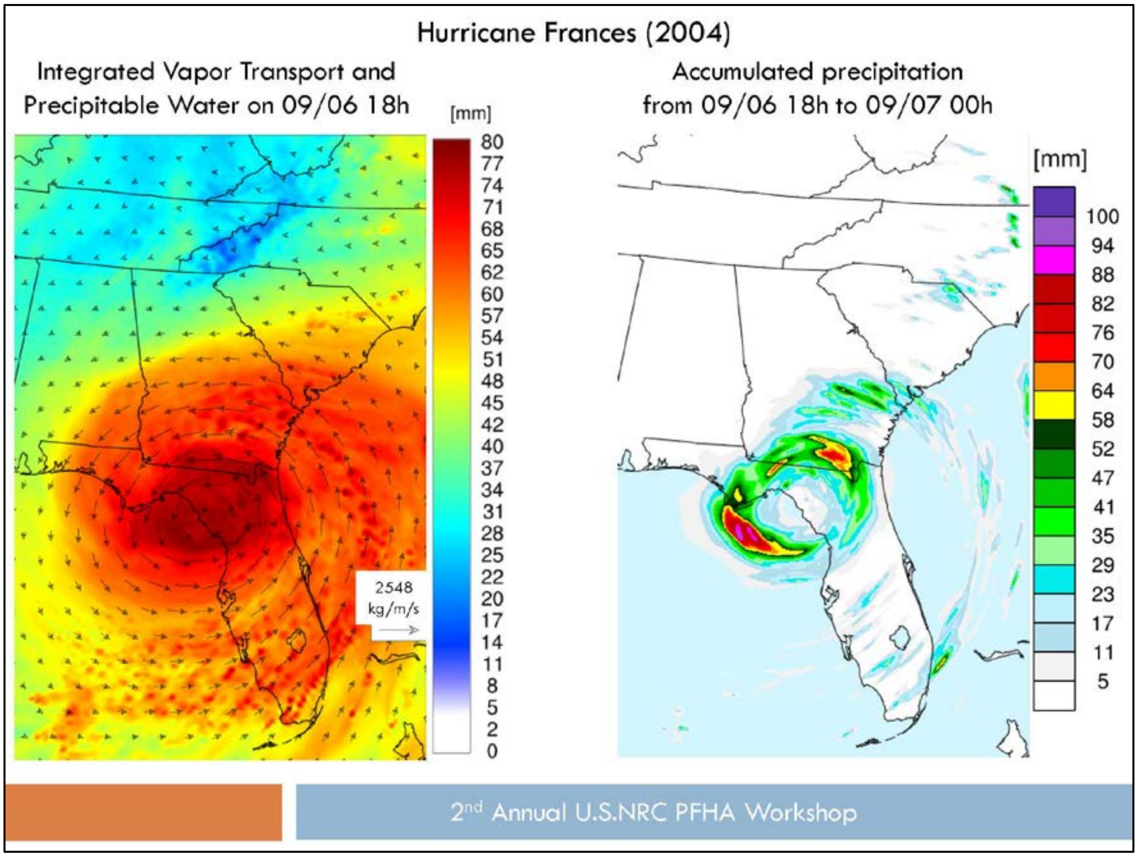

Hurricane Frances (2004)

Integrated Vapor Transport and Precipitable Water on 09/06 18h

Accumulated precipitation from 09/06 18h to 09/07 00h

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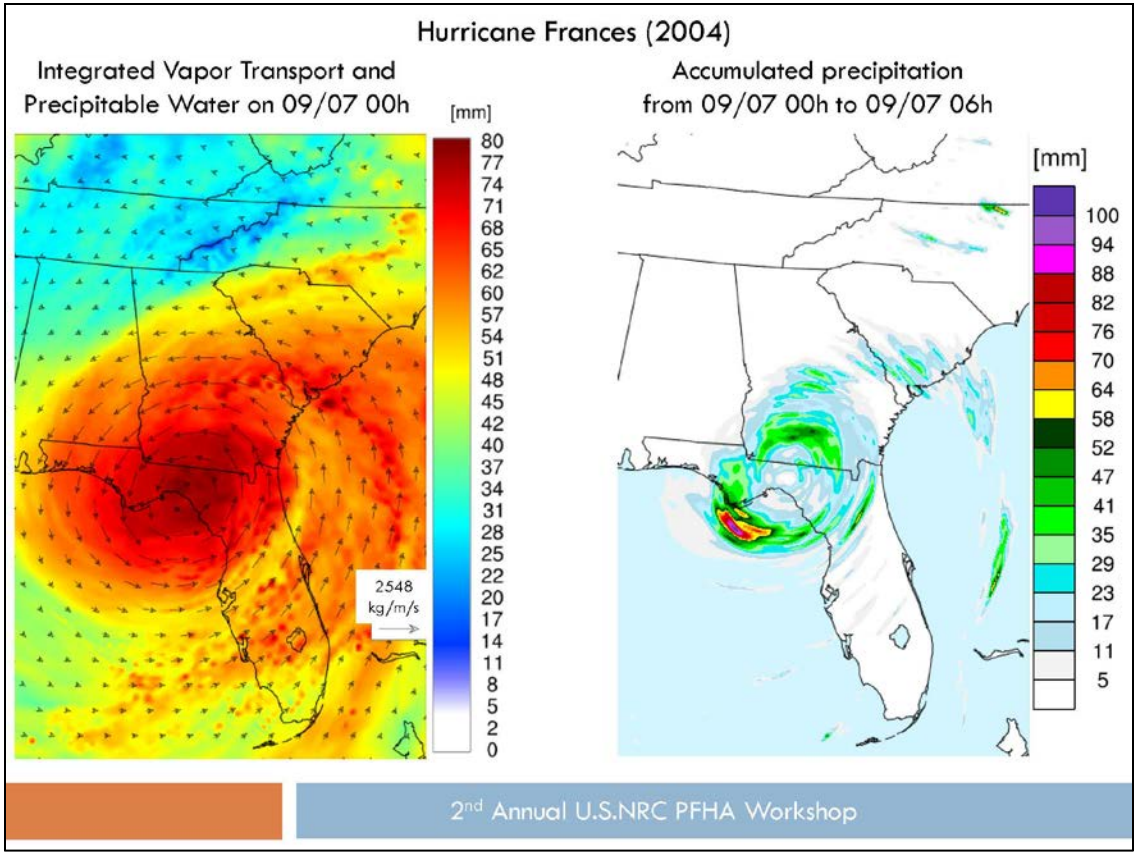

Hurricane Frances (2004)

Integrated Vapor Transport and Precipitable Water on 09/07 00h

Accumulated precipitation from 09/07 00h to 09/07 06h

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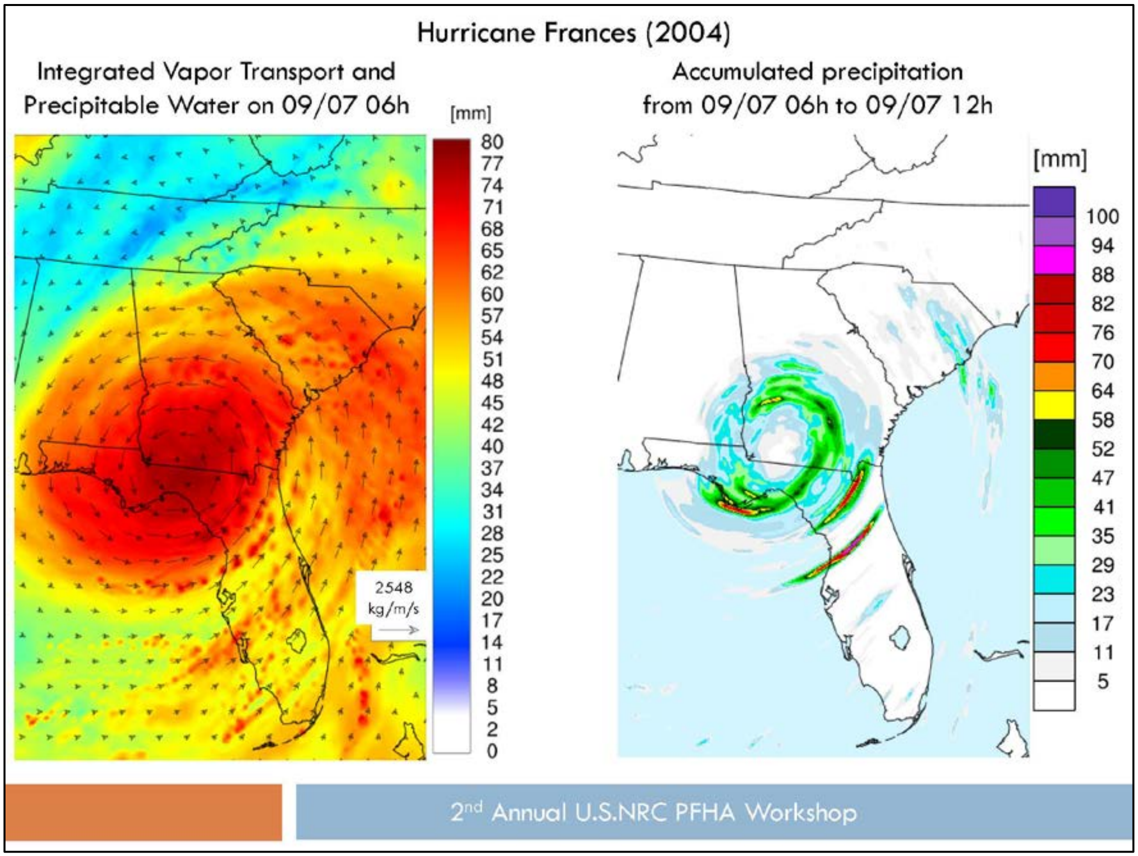
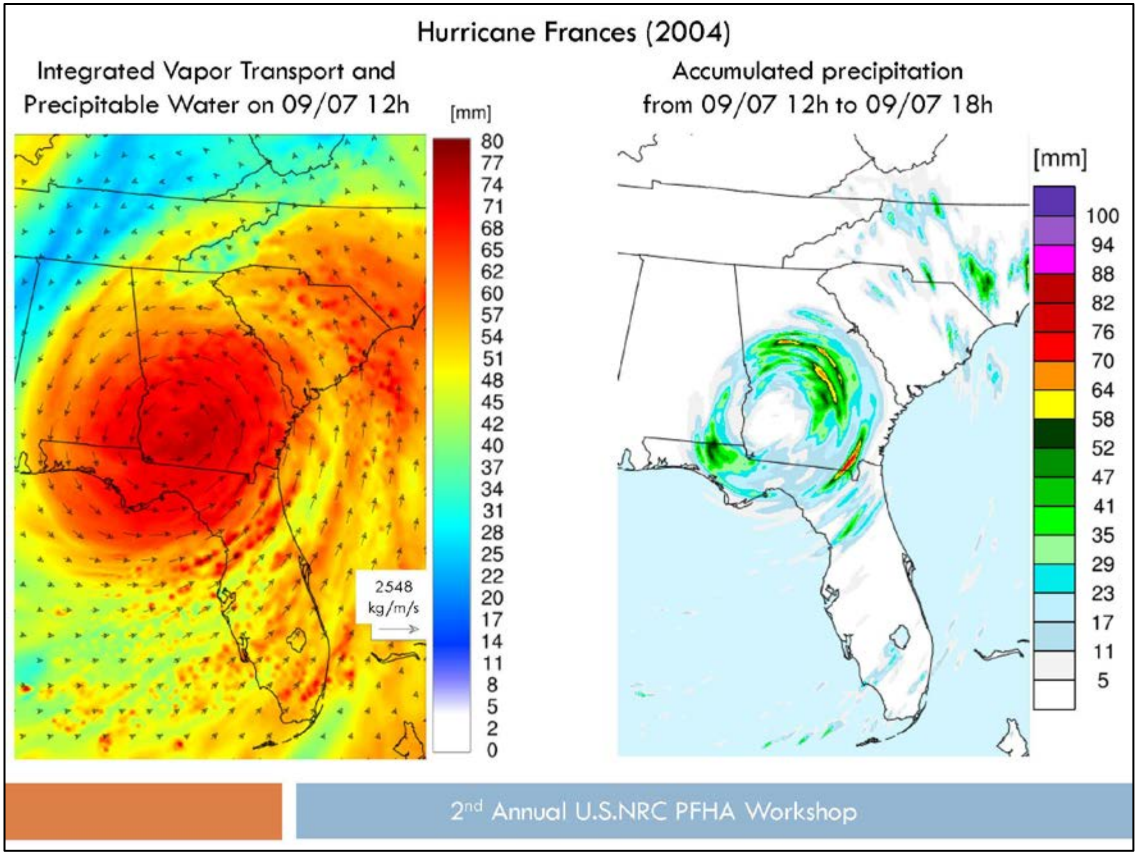


Hurricane Frances (2004)

Integrated Vapor Transport and Precipitable Water on 09/07 06h

Accumulated precipitation from 09/07 06h to 09/07 12h

2nd Annual U.S.NRC PFHA Workshop



Hurricane Frances (2004)

Integrated Vapor Transport and Precipitable Water on 09/07 12h

Accumulated precipitation from 09/07 12h to 09/07 18h

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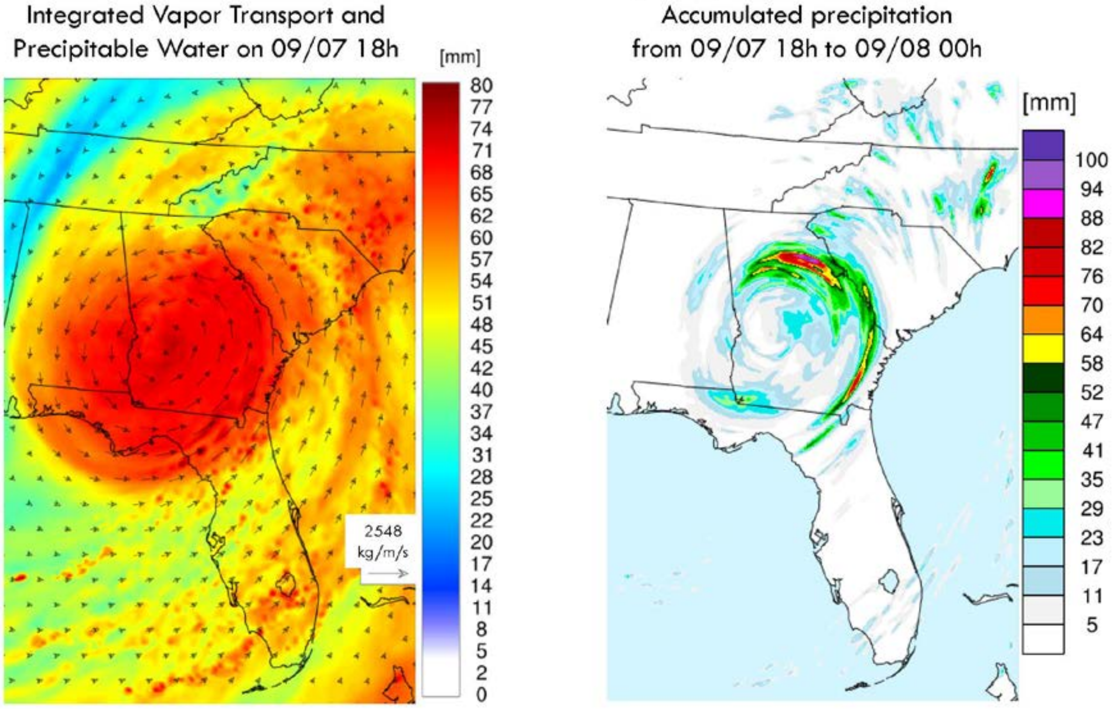
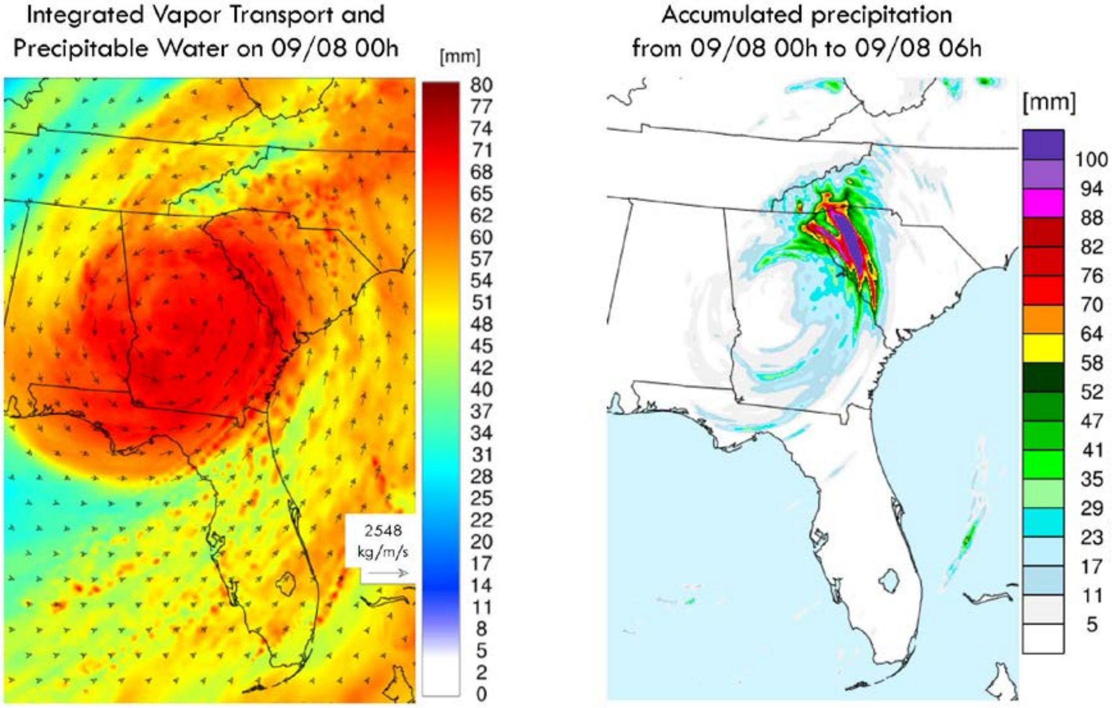
Hurricane Frances (2004)

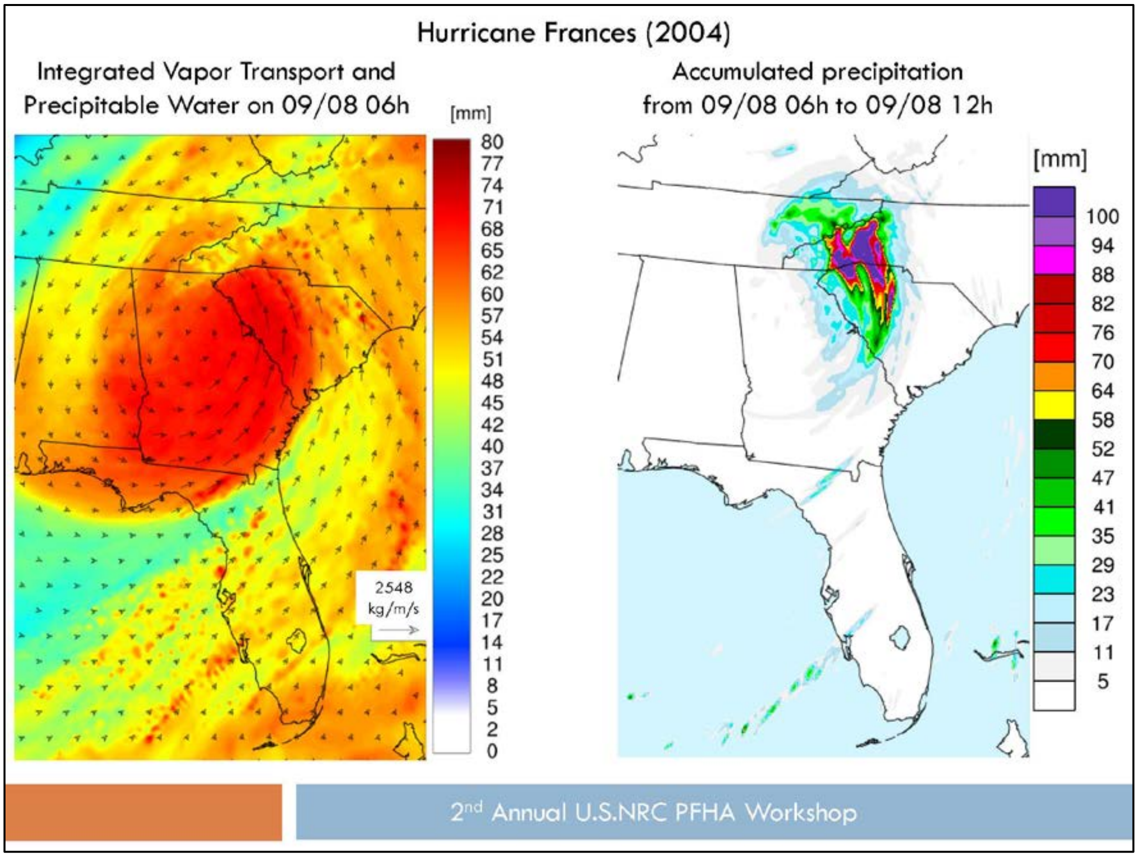

Integrated Vapor Transport and Precipitable Water on 09/07 18h

Accumulated precipitation from 09/07 18h to 09/08 00h

Hurricane Frances (2004)


Integrated Vapor Transport and Precipitable Water on 09/08 00h

Accumulated precipitation from 09/08 00h to 09/08 06h



Hurricane Frances (2004)

Integrated Vapor Transport and Precipitable Water on 09/08 06h

Accumulated precipitation from 09/08 06h to 09/08 12h

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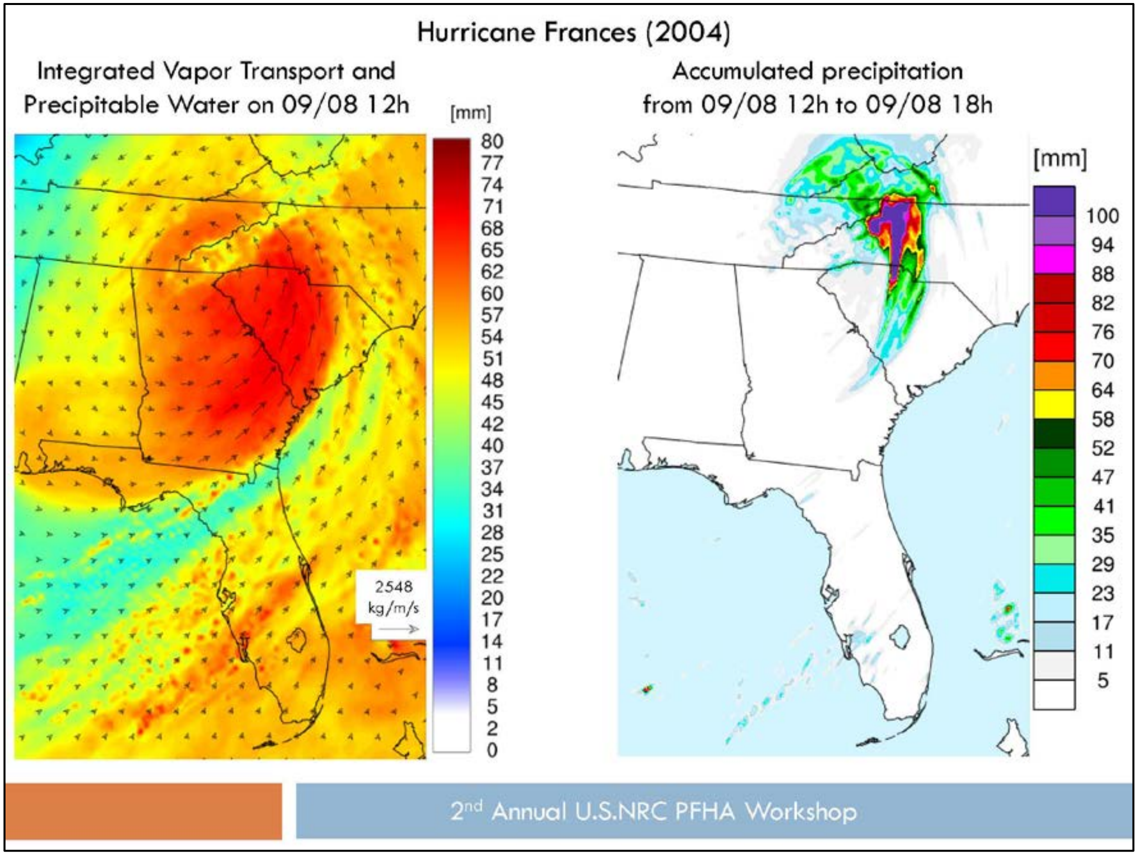
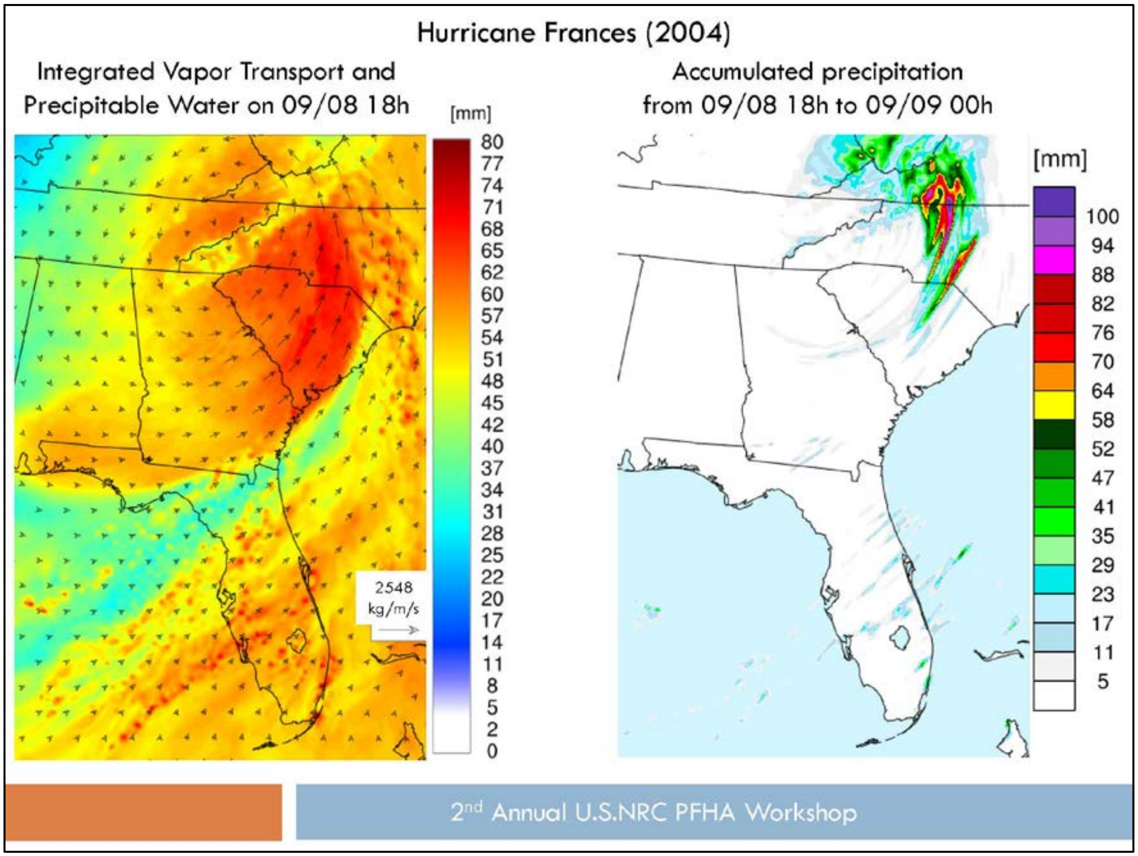


Hurricane Frances (2004)

Integrated Vapor Transport and Precipitable Water on 09/08 12h

Accumulated precipitation from 09/08 12h to 09/08 18h

2nd Annual U.S.NRC PFHA Workshop



Hurricane Frances (2004)

Integrated Vapor Transport and Precipitable Water on 09/08 18h

Accumulated precipitation from 09/08 18h to 09/09 00h

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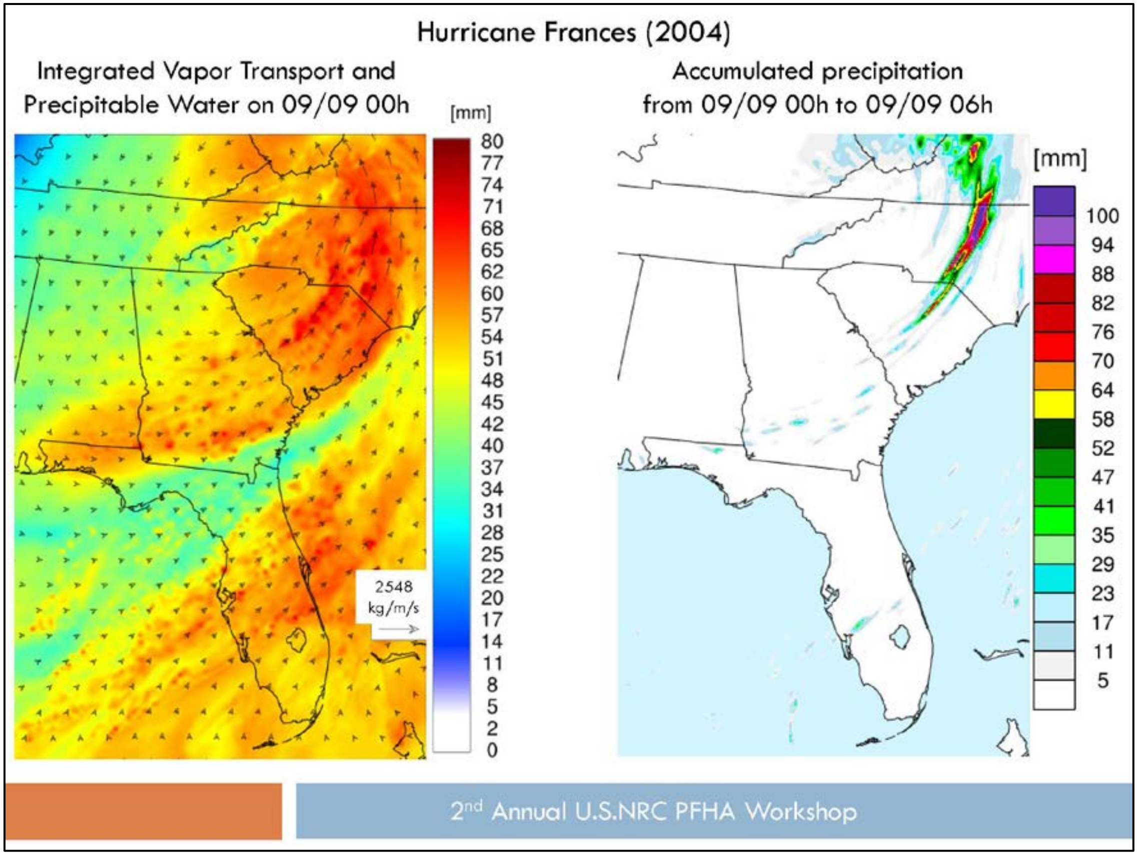

Hurricane Frances (2004)

Integrated Vapor Transport and Precipitable Water on 09/09 00h

Accumulated precipitation from 09/09 00h to 09/09 06h

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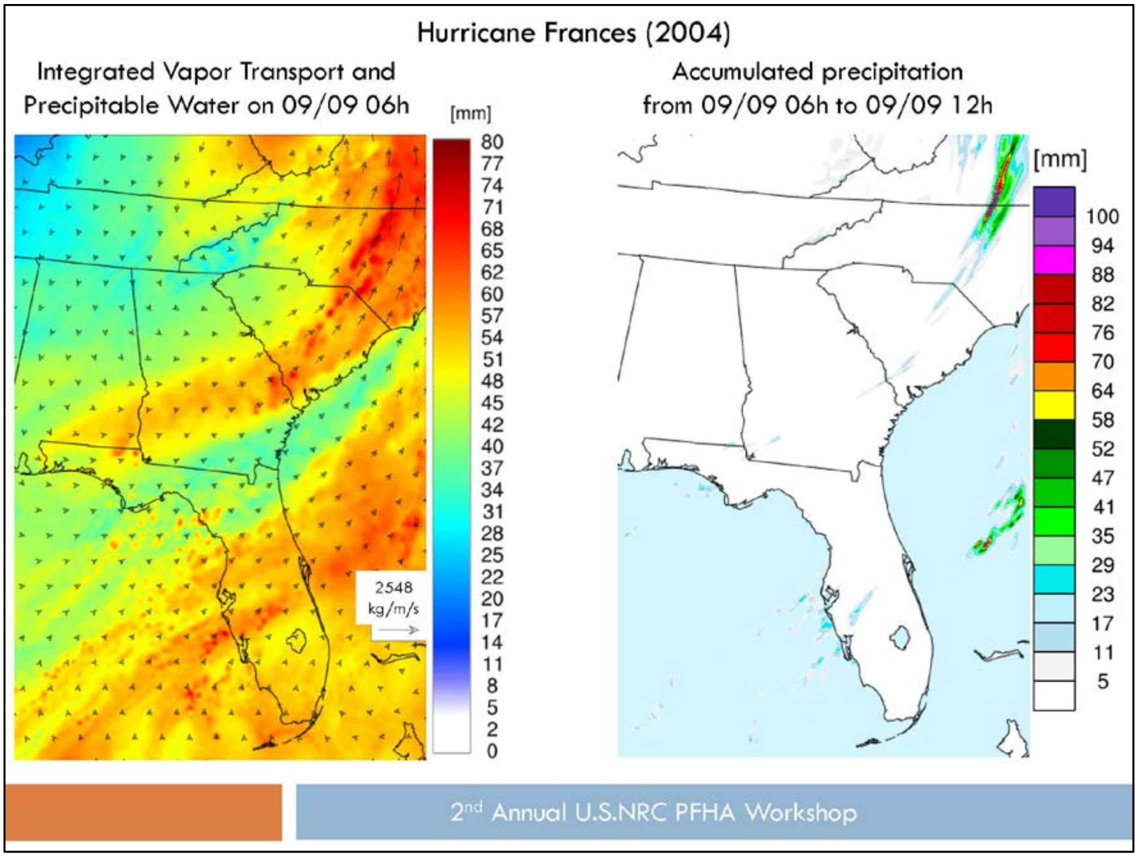
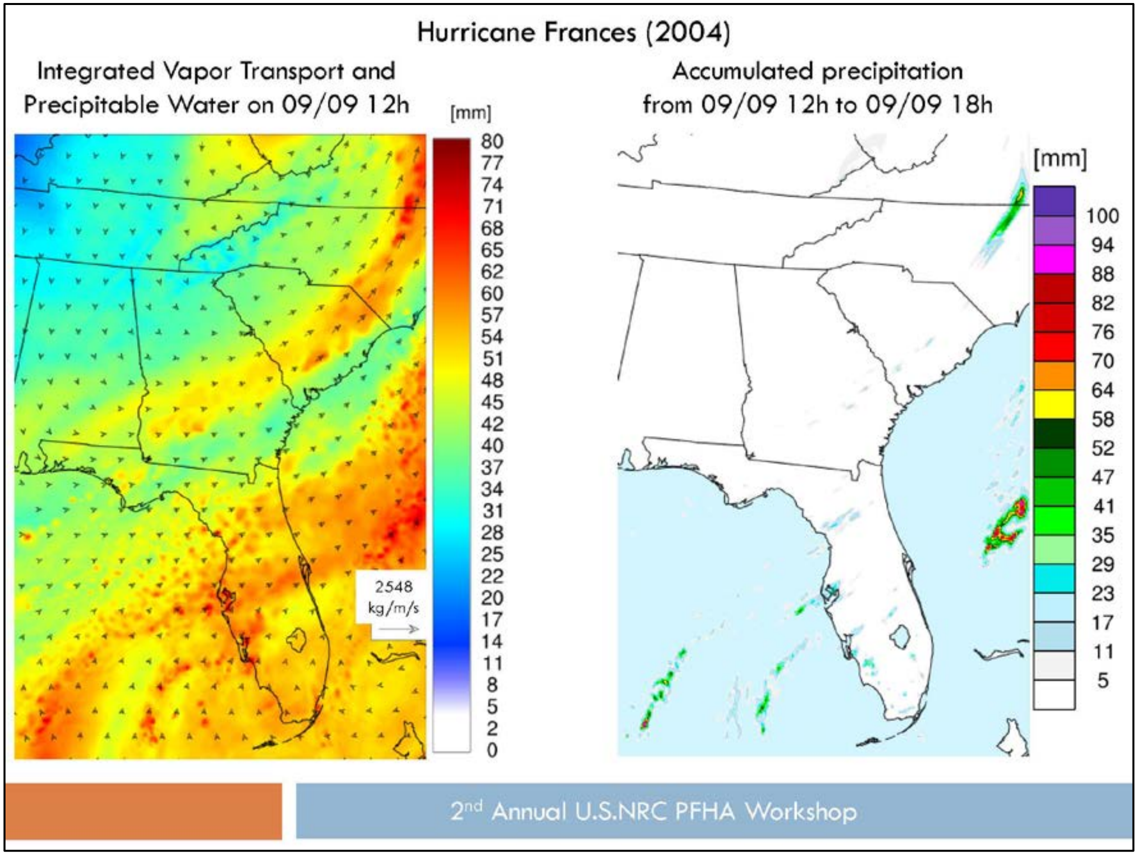


Hurricane Frances (2004)

Integrated Vapor Transport and Precipitable Water on 09/09 06h

Accumulated precipitation from 09/09 06h to 09/09 12h

2nd Annual U.S.NRC PFHA Workshop



Hurricane Frances (2004)

Integrated Vapor Transport and Precipitable Water on 09/09 12h

Accumulated precipitation from 09/09 12h to 09/09 18h

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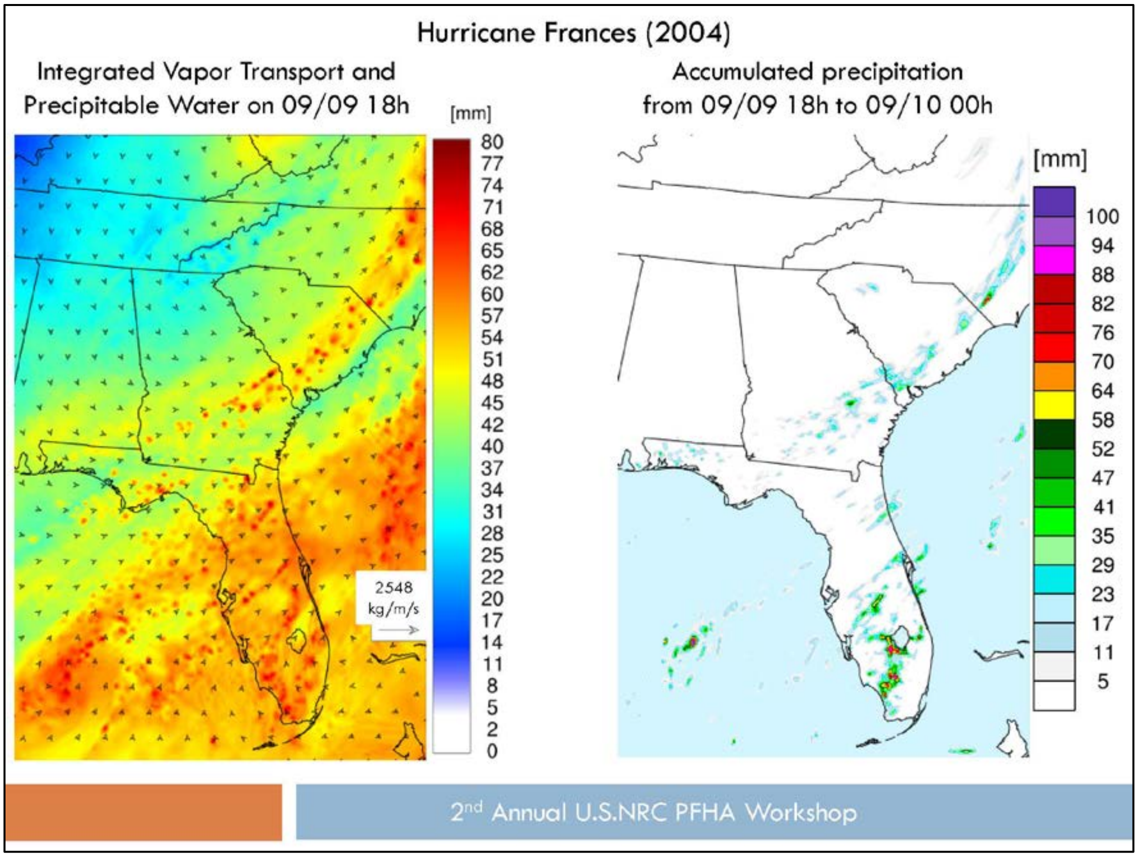

Hurricane Frances (2004)

Integrated Vapor Transport and Precipitable Water on 09/09 18h

Accumulated precipitation from 09/09 18h to 09/10 00h

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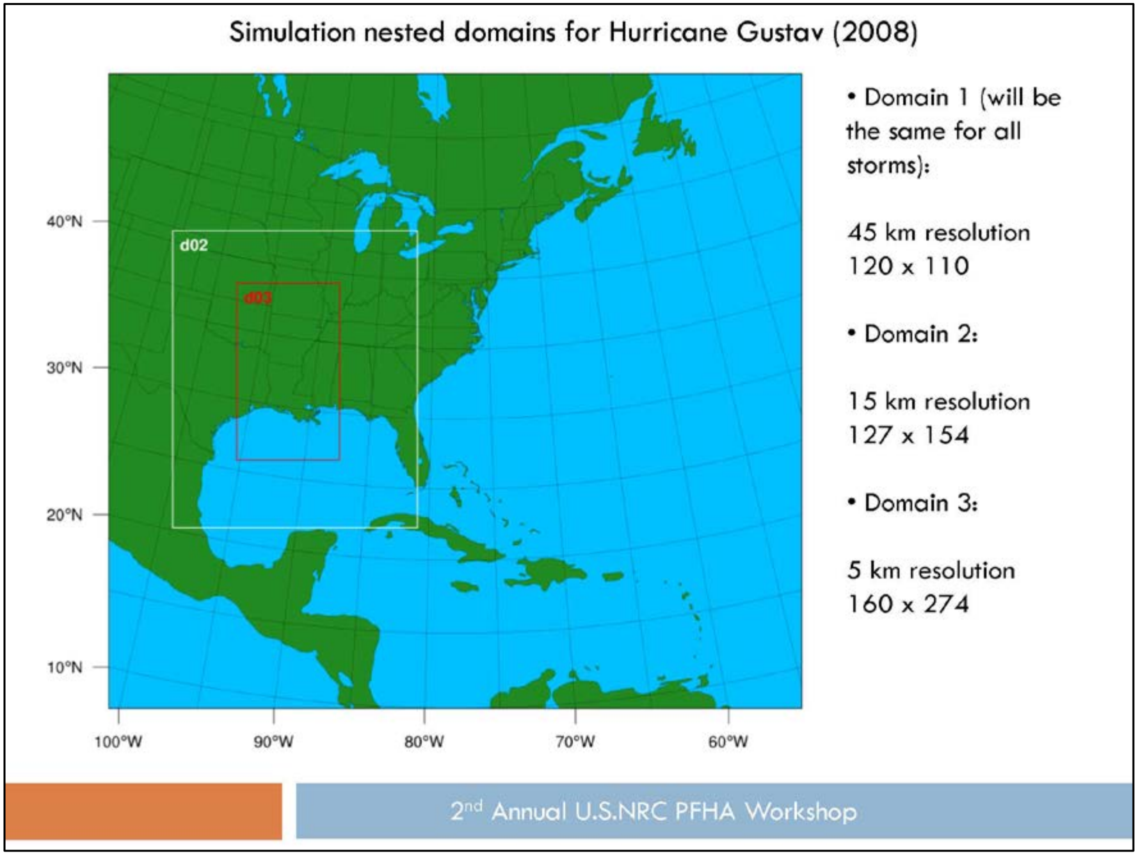

Simulation nested domains for Hurricane Gustav (2008)

- Domain 1 (will be the same for all storms):

45 km resolution
120 x 110

- Domain 2:

15 km resolution
127 x 154

- Domain 3:

5 km resolution
160 x 274

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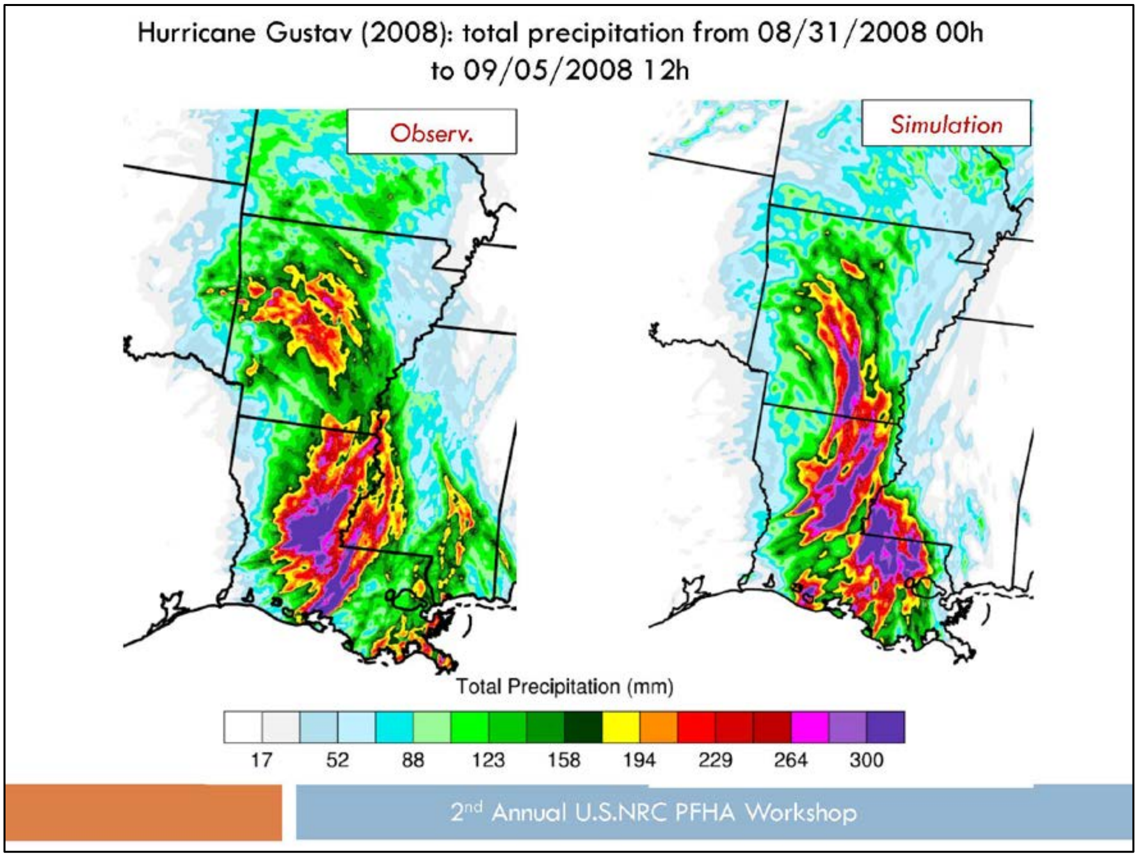

Hurricane Gustav (2008): total precipitation from 08/31/2008 00h to 09/05/2008 12h

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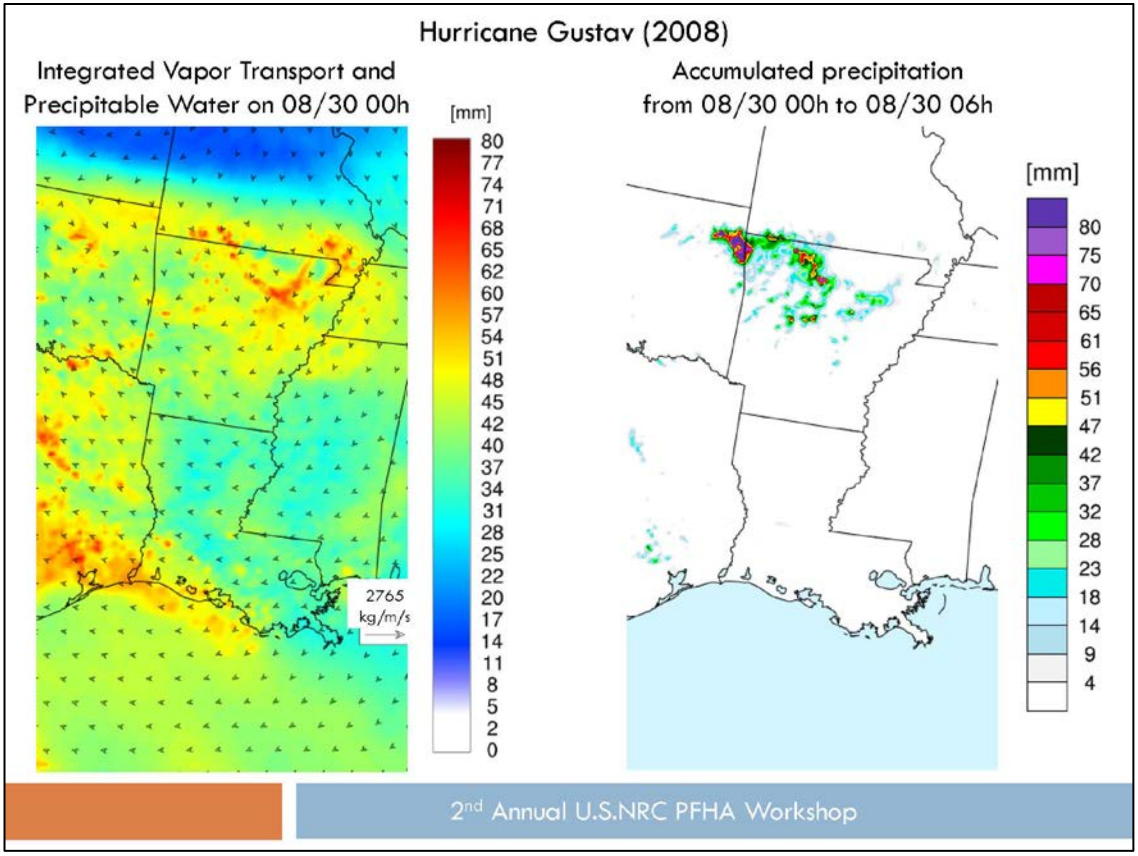

Hurricane Gustav (2008)

Integrated Vapor Transport and Precipitable Water on 08/30 00h

Accumulated precipitation from 08/30 00h to 08/30 06h

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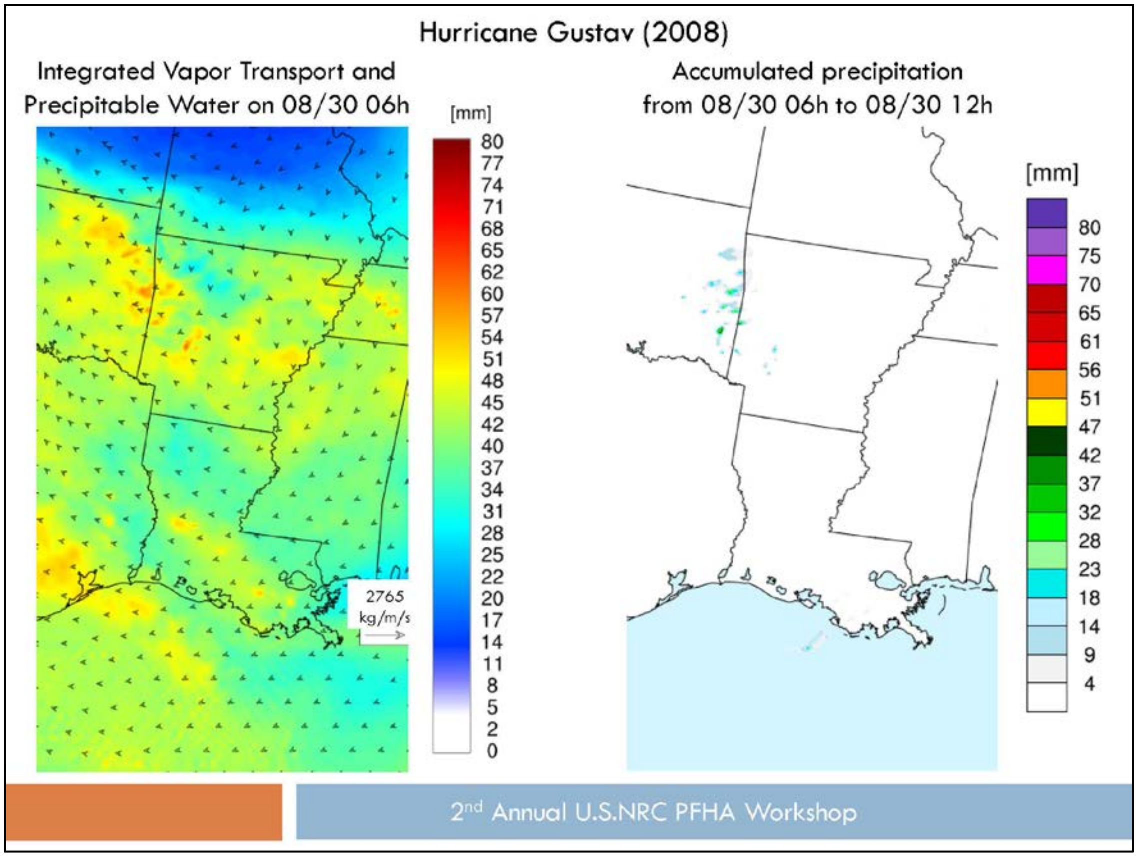

Hurricane Gustav (2008)

Integrated Vapor Transport and Precipitable Water on 08/30 06h

Accumulated precipitation from 08/30 06h to 08/30 12h

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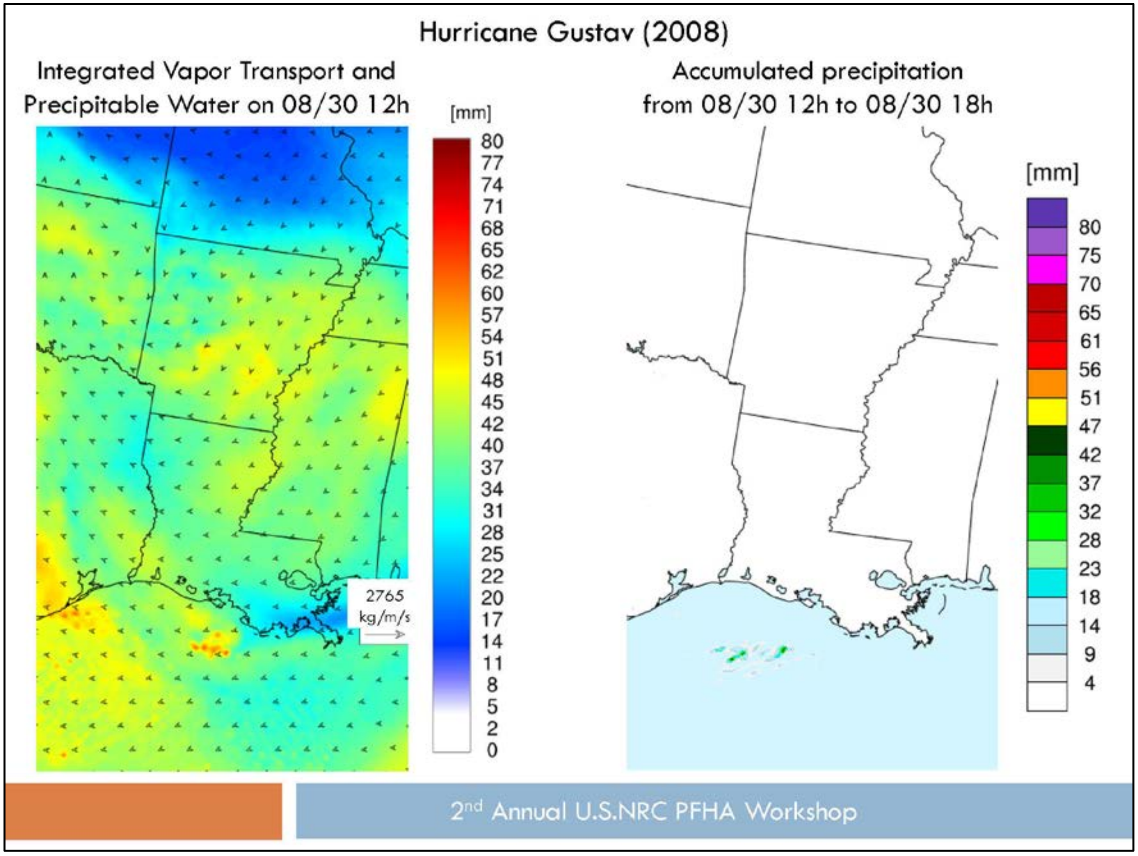

Hurricane Gustav (2008)

Integrated Vapor Transport and Precipitable Water on 08/30 12h

Accumulated precipitation from 08/30 12h to 08/30 18h

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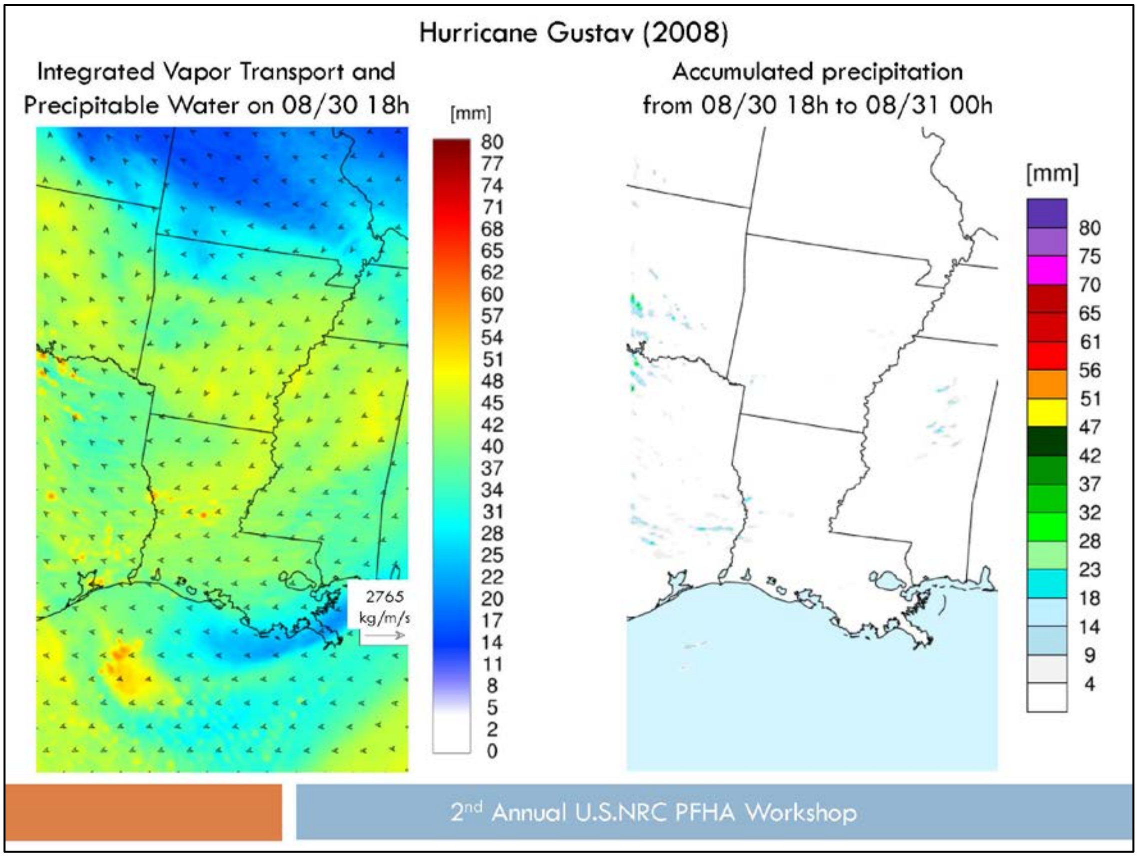

Hurricane Gustav (2008)

Integrated Vapor Transport and Precipitable Water on 08/30 18h

Accumulated precipitation from 08/30 18h to 08/31 00h

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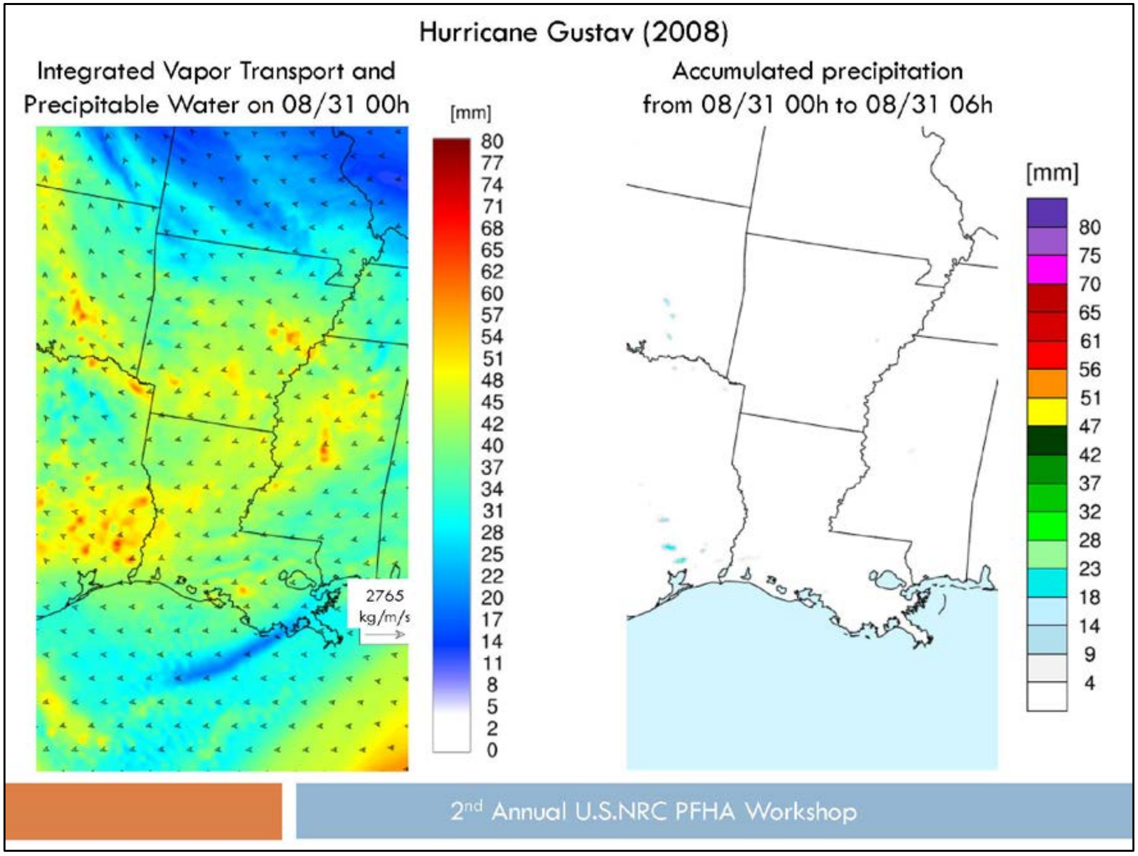

Hurricane Gustav (2008)

Integrated Vapor Transport and Precipitable Water on 08/31 00h

Accumulated precipitation from 08/31 00h to 08/31 06h

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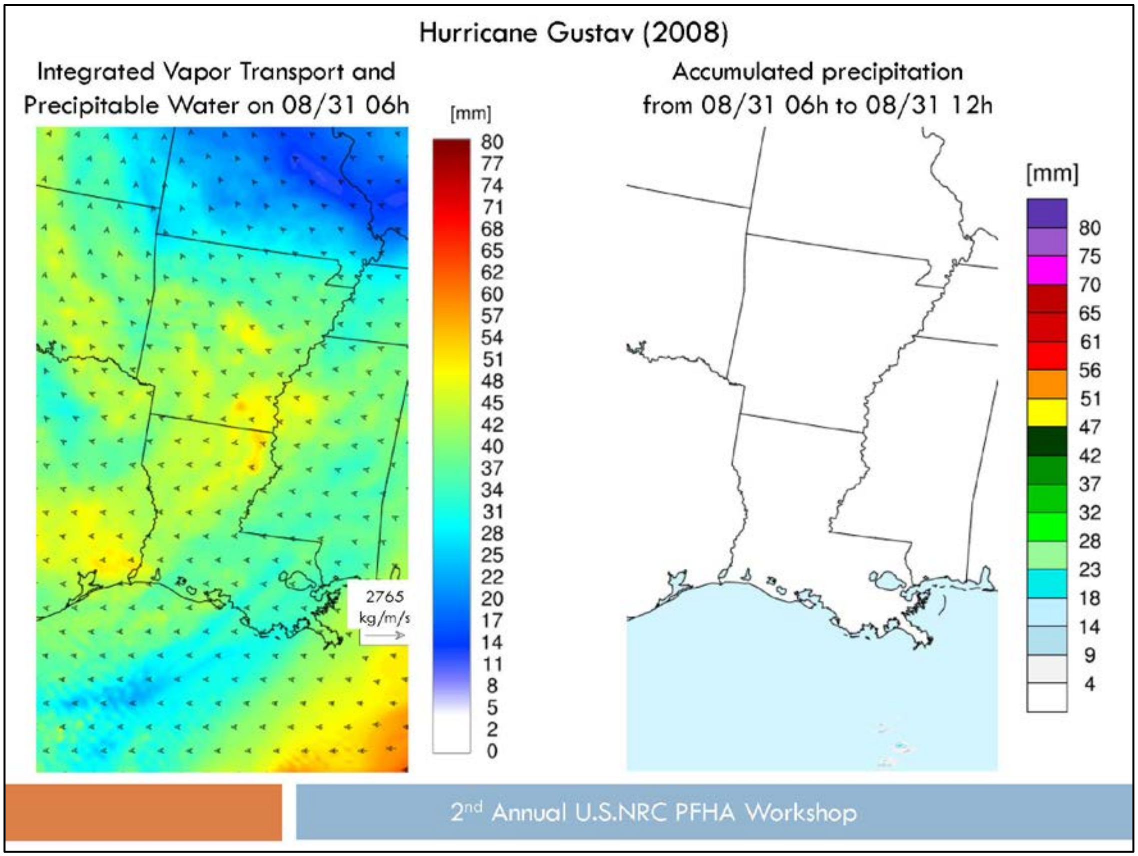

Hurricane Gustav (2008)

Integrated Vapor Transport and Precipitable Water on 08/31 06h

Accumulated precipitation from 08/31 06h to 08/31 12h

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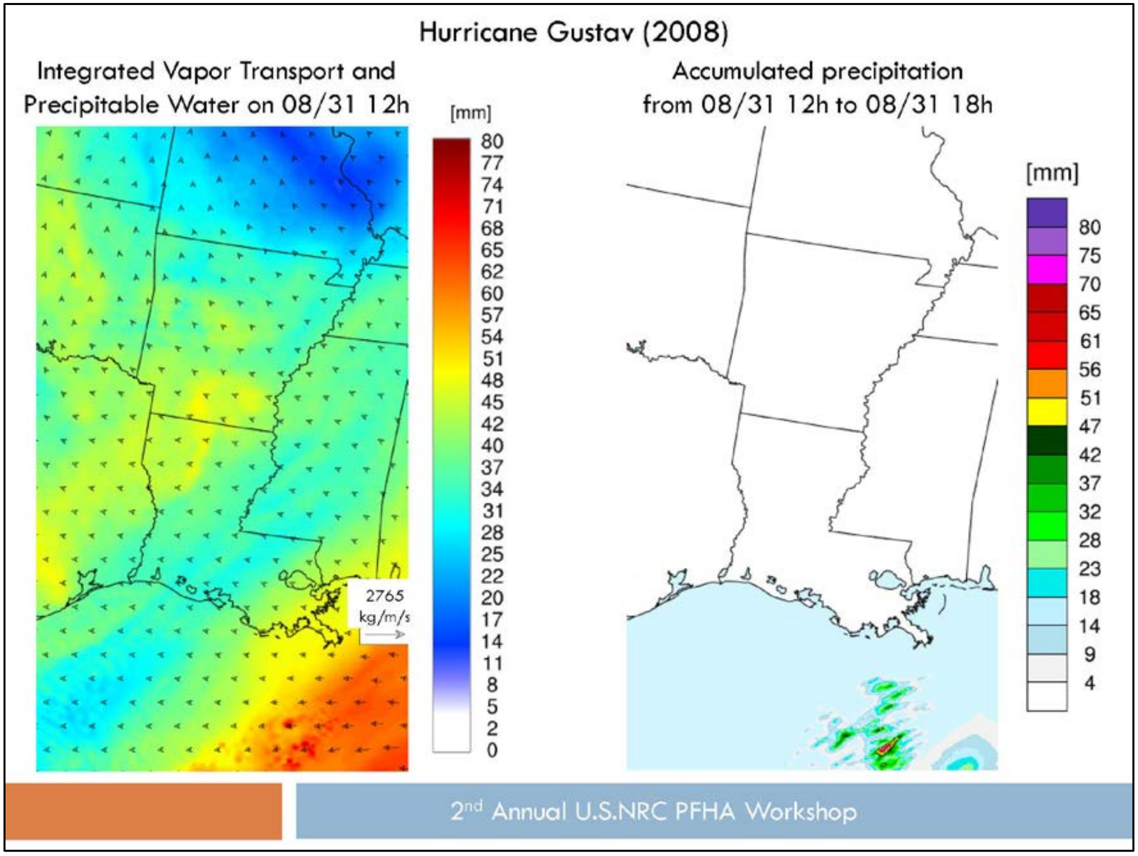

Hurricane Gustav (2008)

Integrated Vapor Transport and Precipitable Water on 08/31 12h

Accumulated precipitation from 08/31 12h to 08/31 18h

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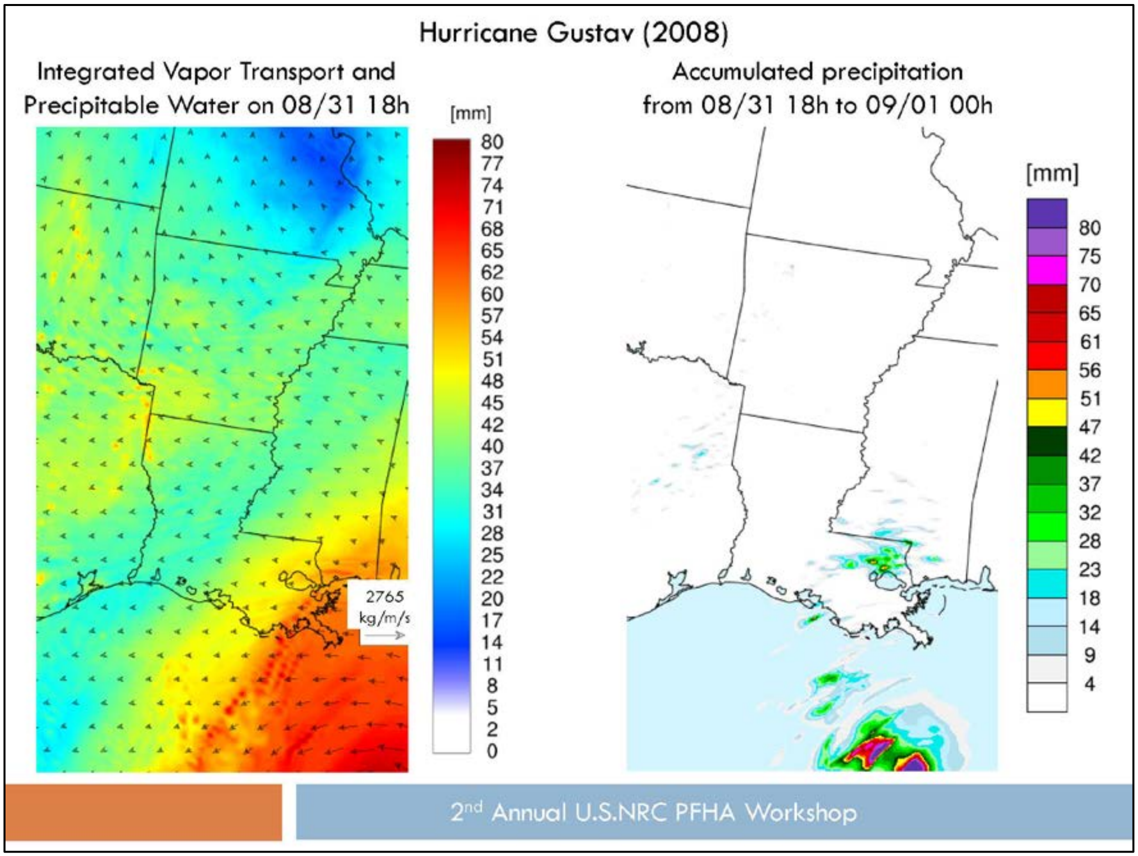

Hurricane Gustav (2008)

Integrated Vapor Transport and Precipitable Water on 08/31 18h

Accumulated precipitation from 08/31 18h to 09/01 00h

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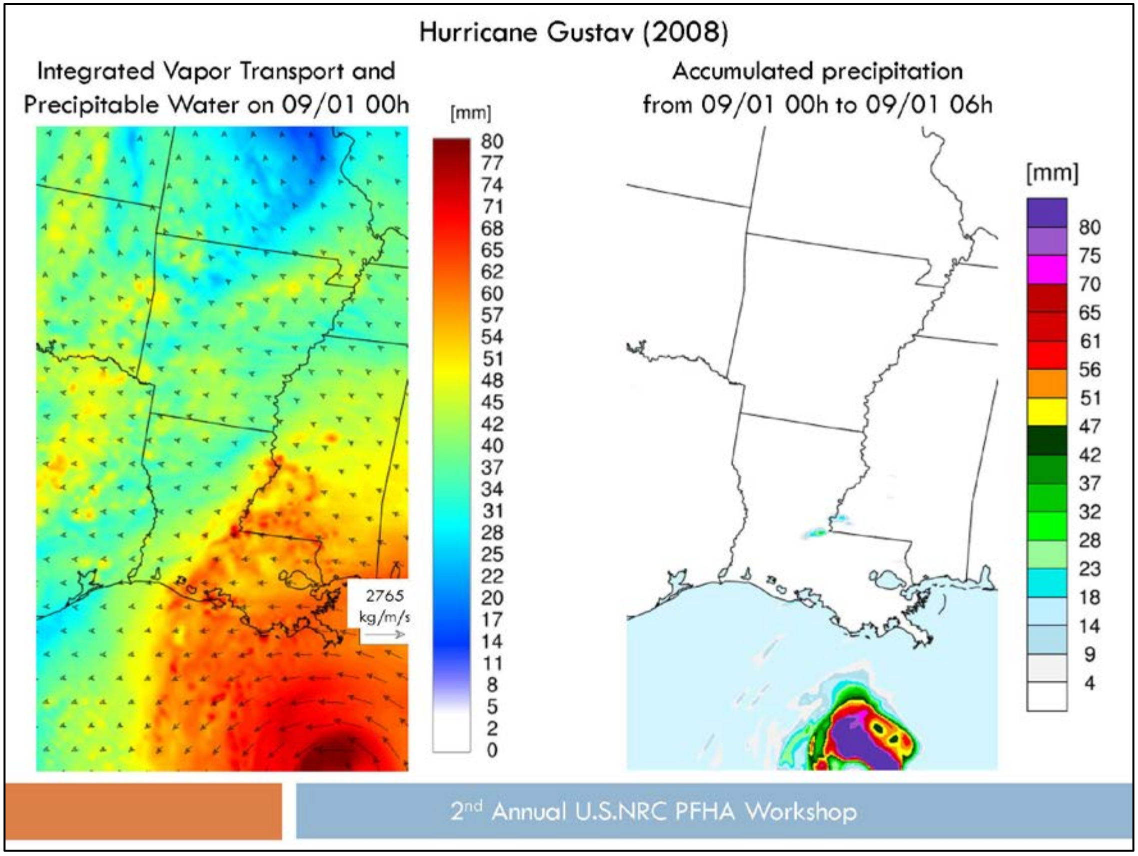

Hurricane Gustav (2008)

Integrated Vapor Transport and Precipitable Water on 09/01 00h

Accumulated precipitation from 09/01 00h to 09/01 06h

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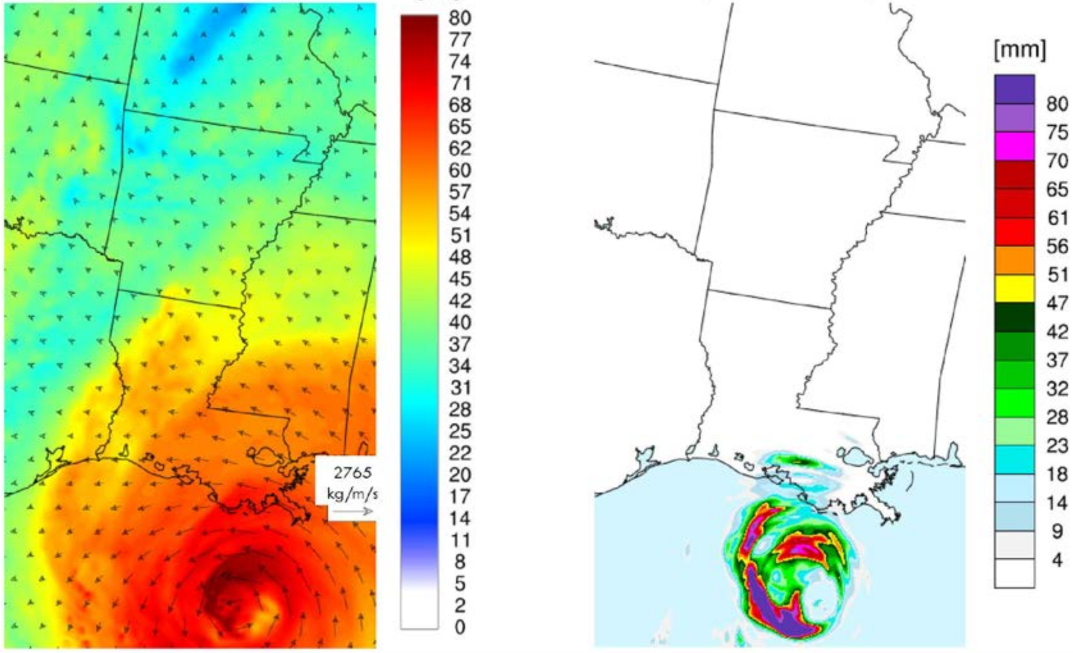
Hurricane Gustav (2008)

Integrated Vapor Transport and Precipitable Water on 09/01 06h

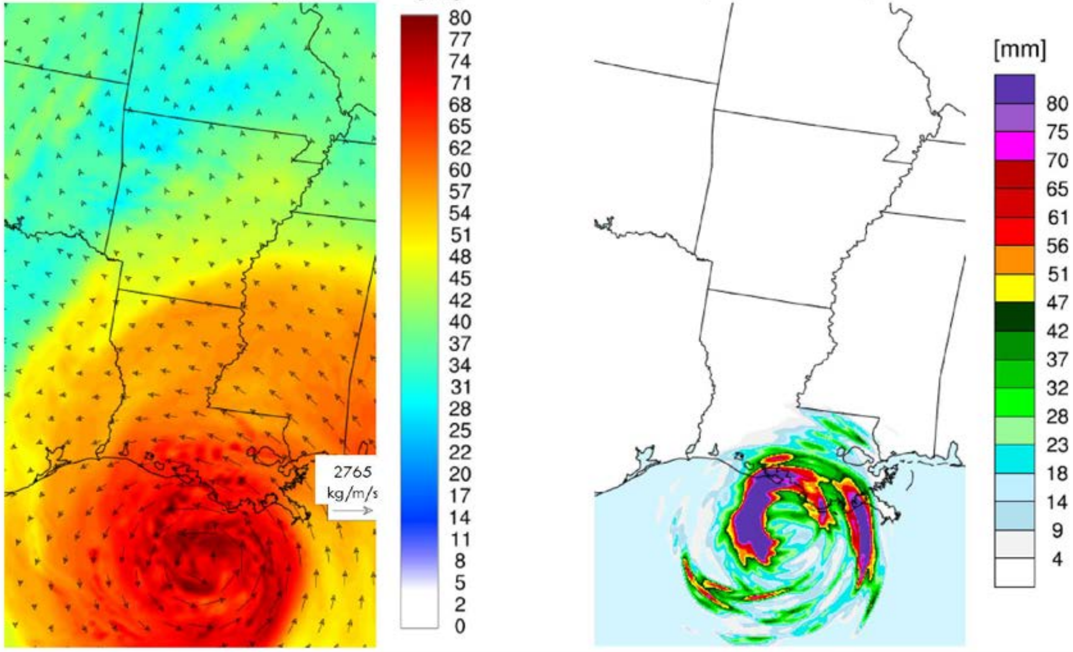
Accumulated precipitation from 09/01 06h to 09/01 12h

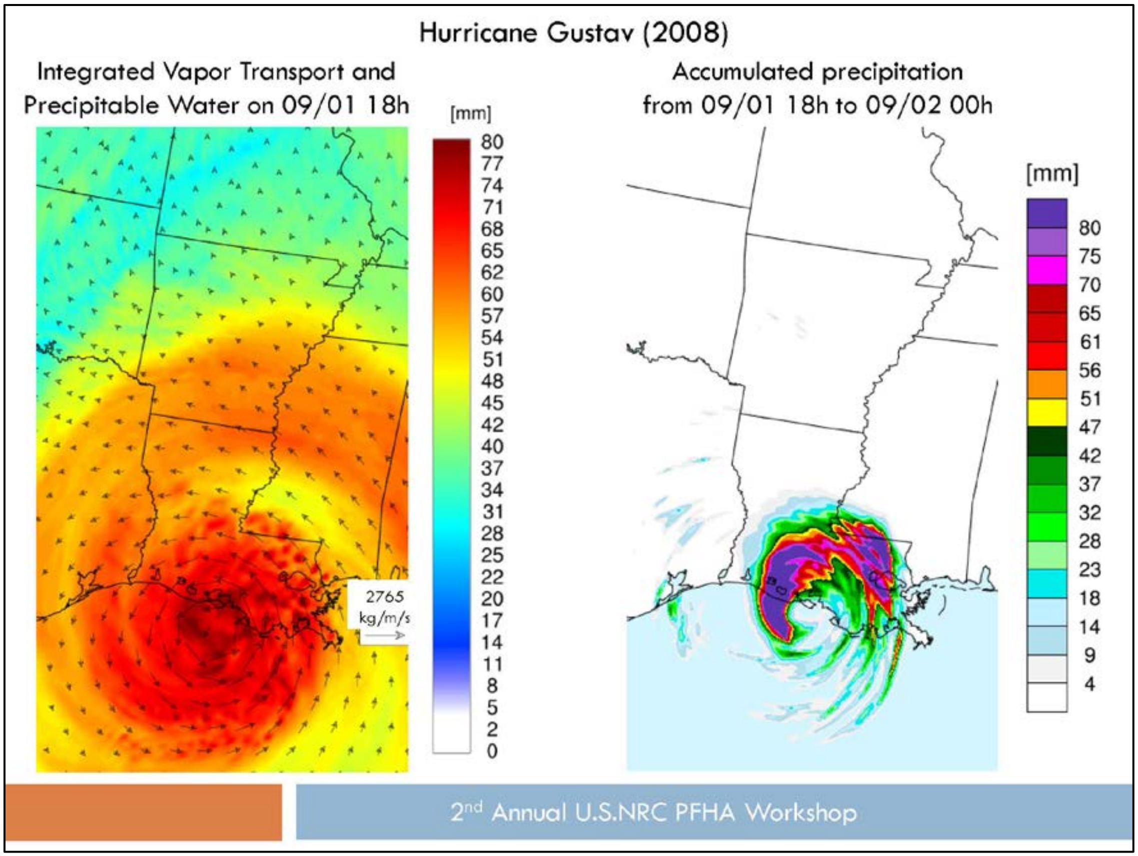


Hurricane Gustav (2008)

Integrated Vapor Transport and Precipitable Water on 09/01 12h

Accumulated precipitation from 09/01 12h to 09/01 18h

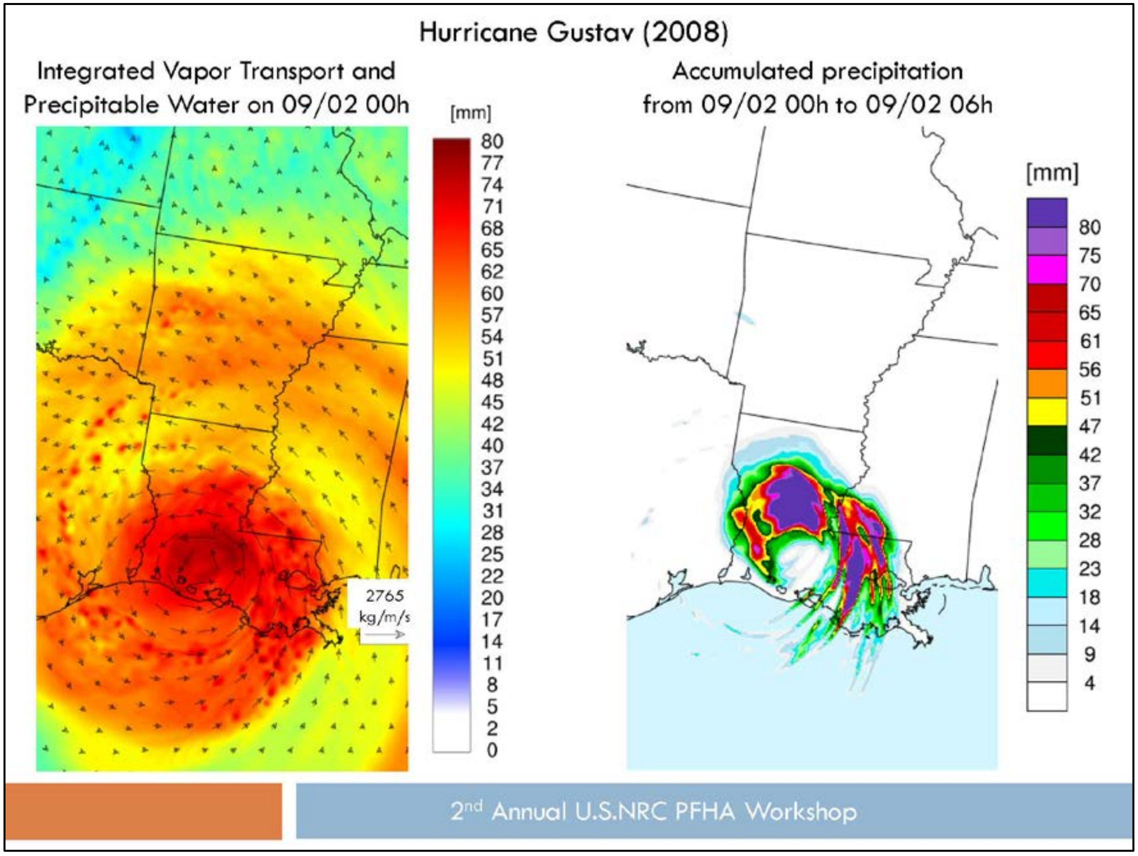




Hurricane Gustav (2008)

Integrated Vapor Transport and Precipitable Water on 09/01 18h

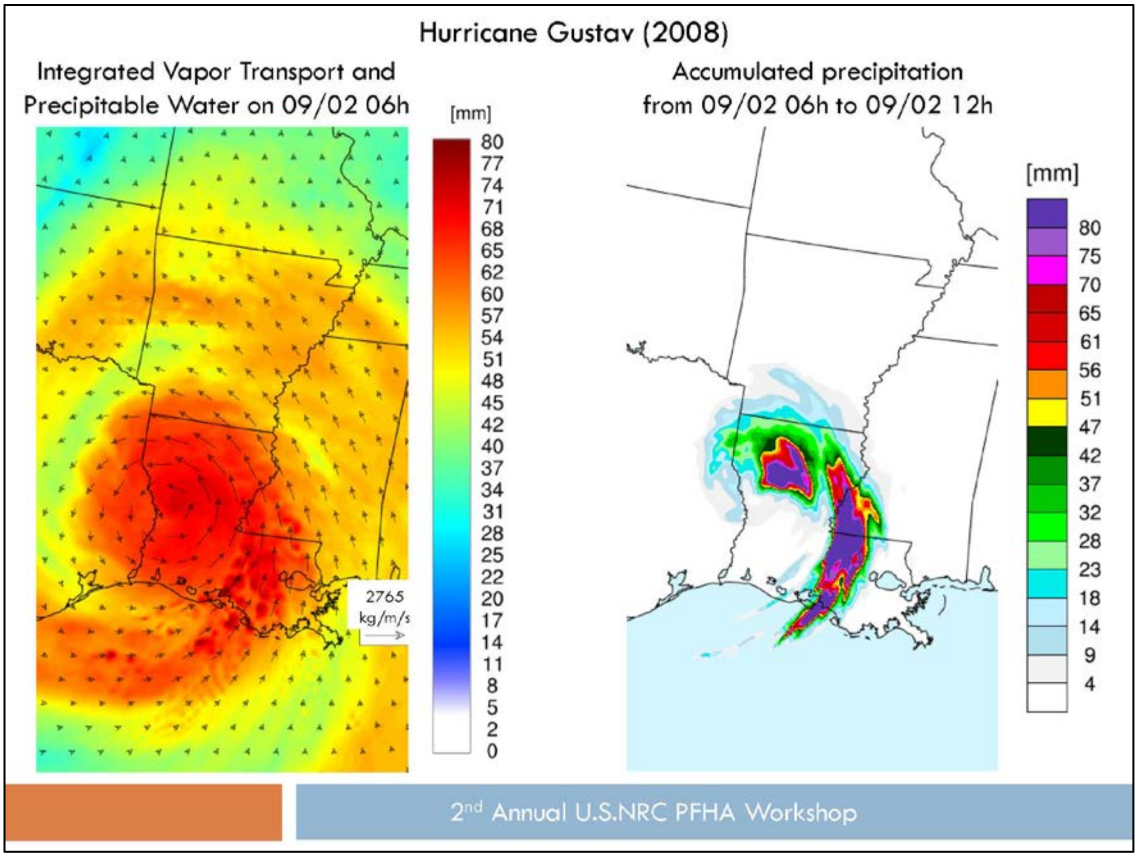
Accumulated precipitation from 09/01 18h to 09/02 00h



Hurricane Gustav (2008)

Integrated Vapor Transport and Precipitable Water on 09/02 00h

Accumulated precipitation from 09/02 00h to 09/02 06h



Hurricane Gustav (2008)

Integrated Vapor Transport and Precipitable Water on 09/02 06h

Accumulated precipitation from 09/02 06h to 09/02 12h

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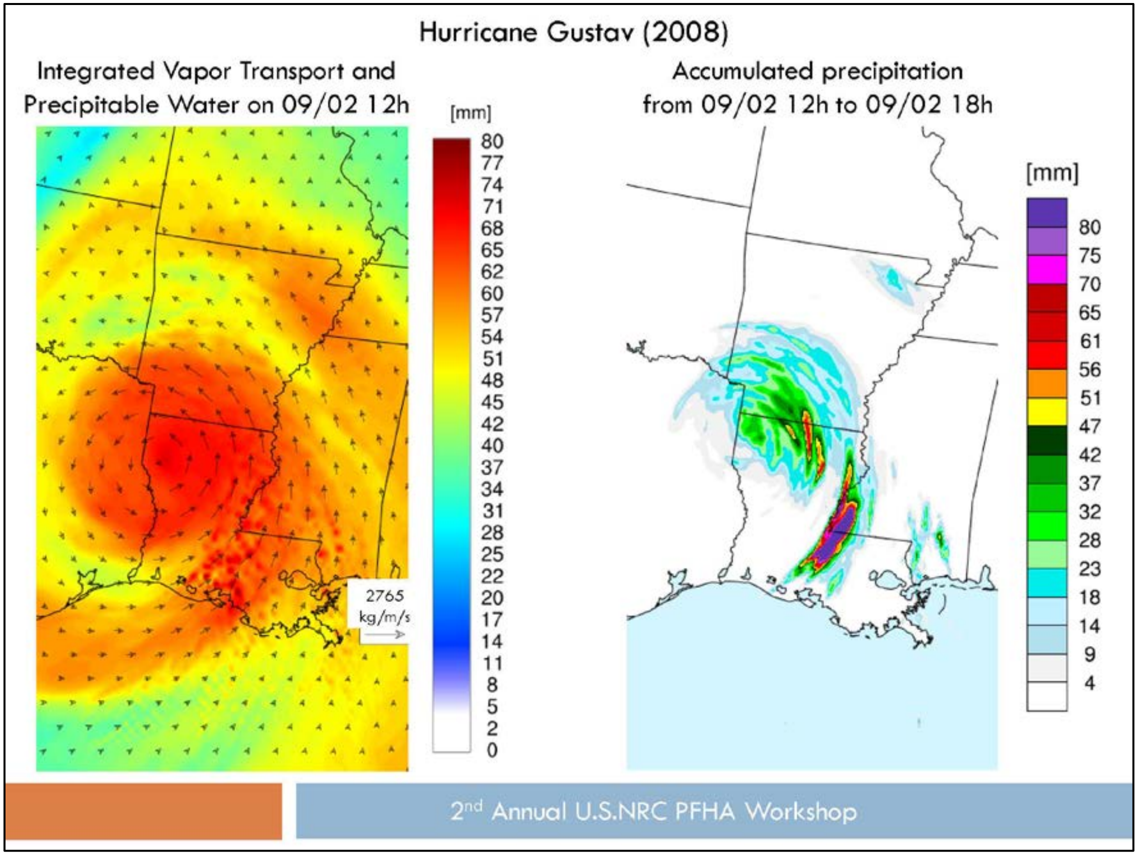

Hurricane Gustav (2008)

Integrated Vapor Transport and Precipitable Water on 09/02 12h

Accumulated precipitation from 09/02 12h to 09/02 18h

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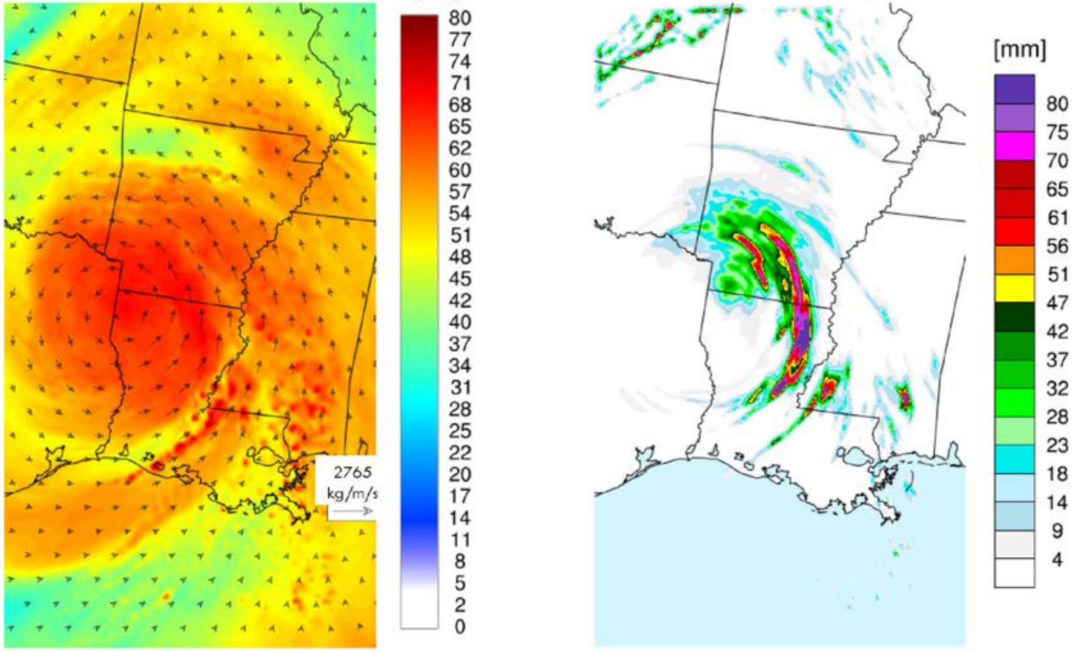
Hurricane Gustav (2008)

Integrated Vapor Transport and Precipitable Water on 09/02 18h

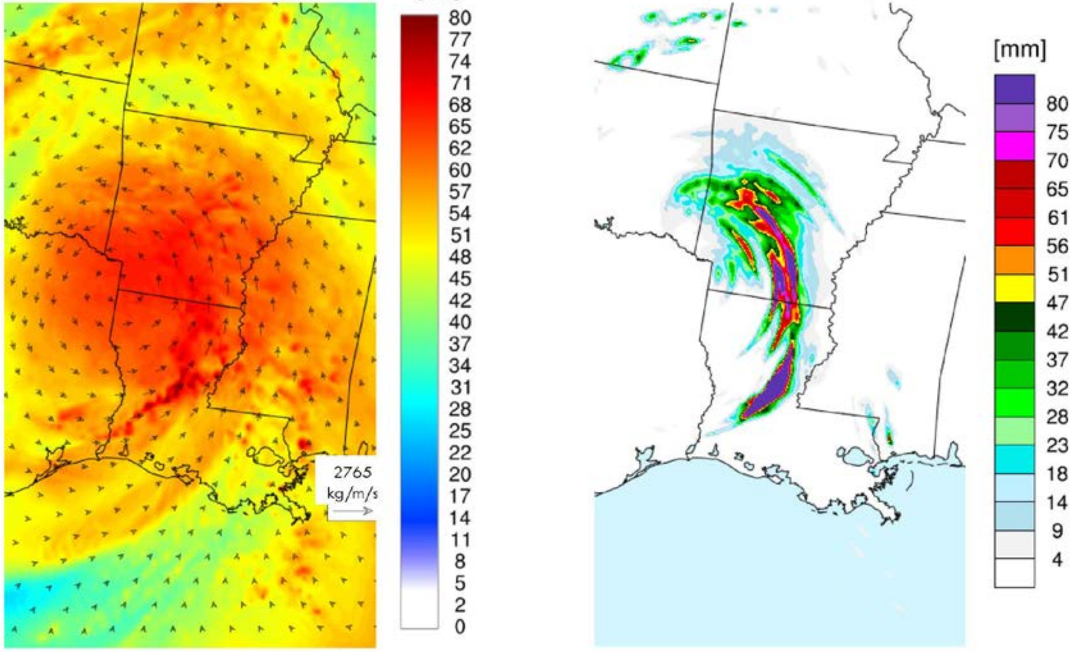
Accumulated precipitation from 09/02 18h to 09/03 00h

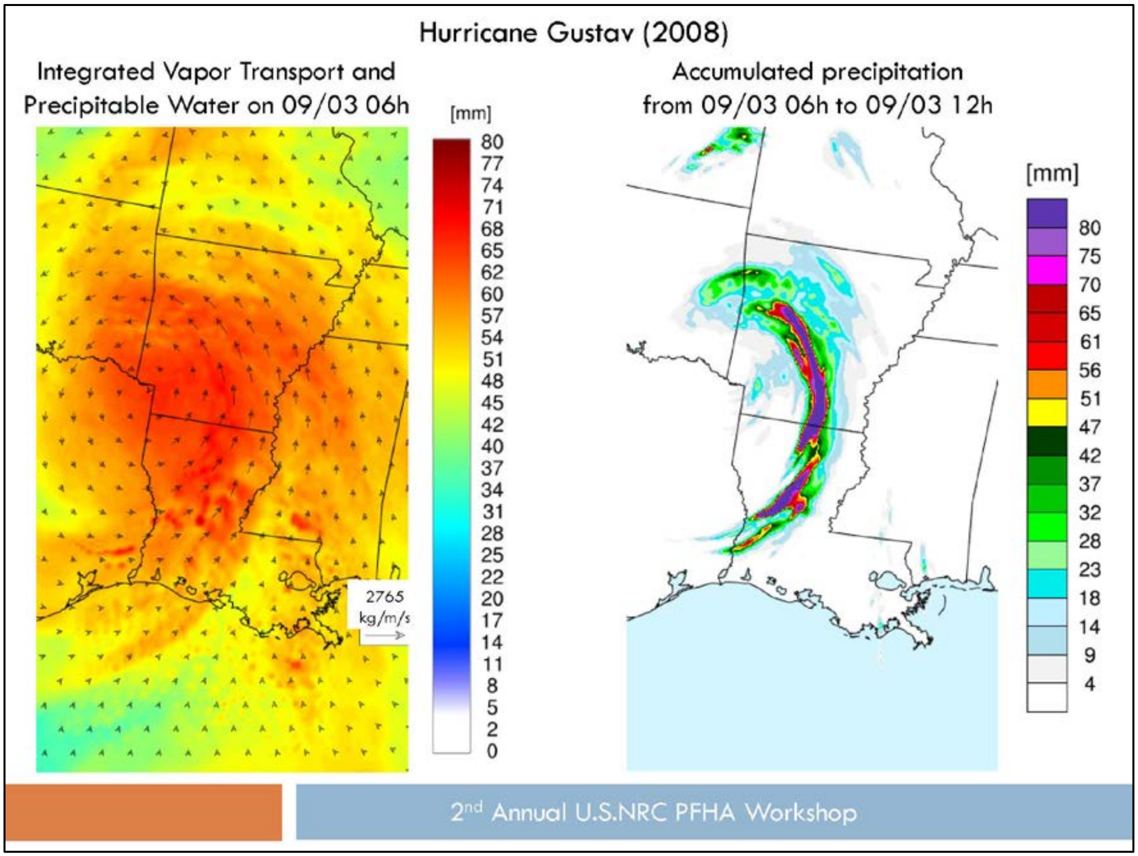


Hurricane Gustav (2008)

Integrated Vapor Transport and Precipitable Water on 09/03 00h

Accumulated precipitation from 09/03 00h to 09/03 06h



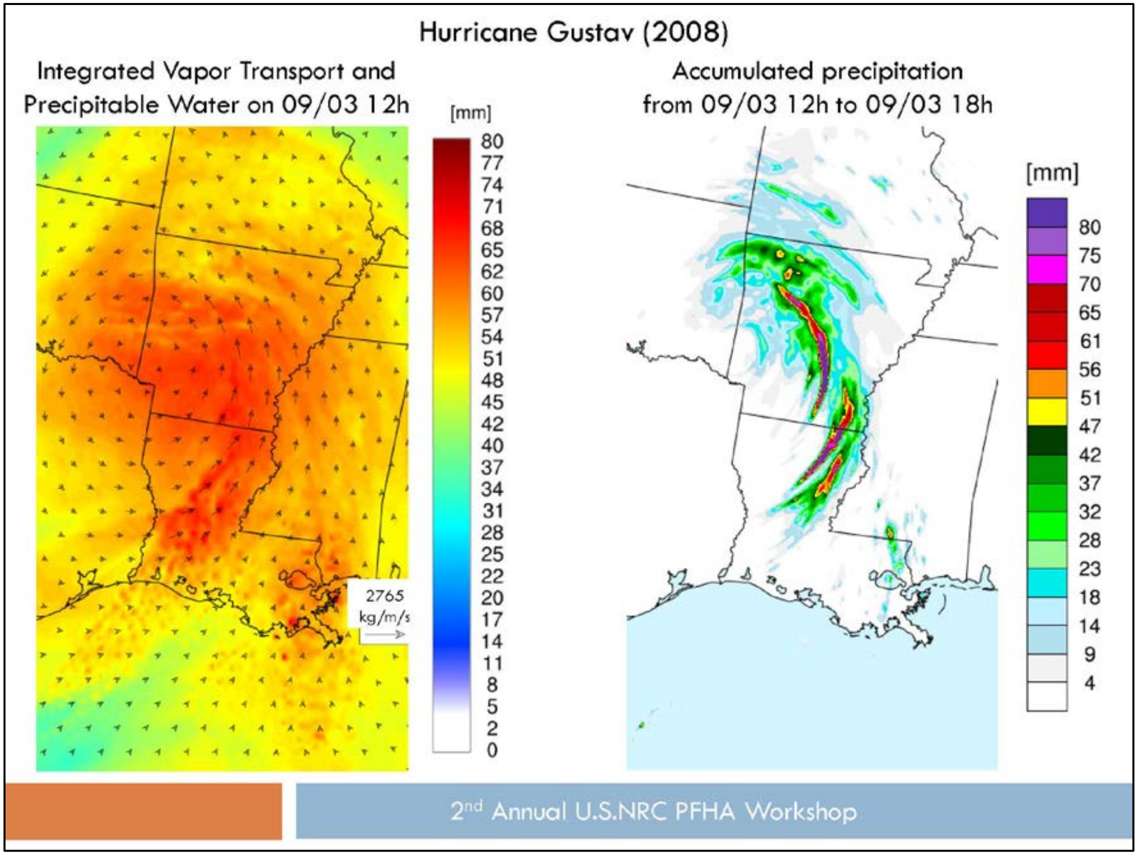


Hurricane Gustav (2008)

Integrated Vapor Transport and Precipitable Water on 09/03 06h

Accumulated precipitation from 09/03 06h to 09/03 12h

2nd Annual U.S.NRC PFHA Workshop

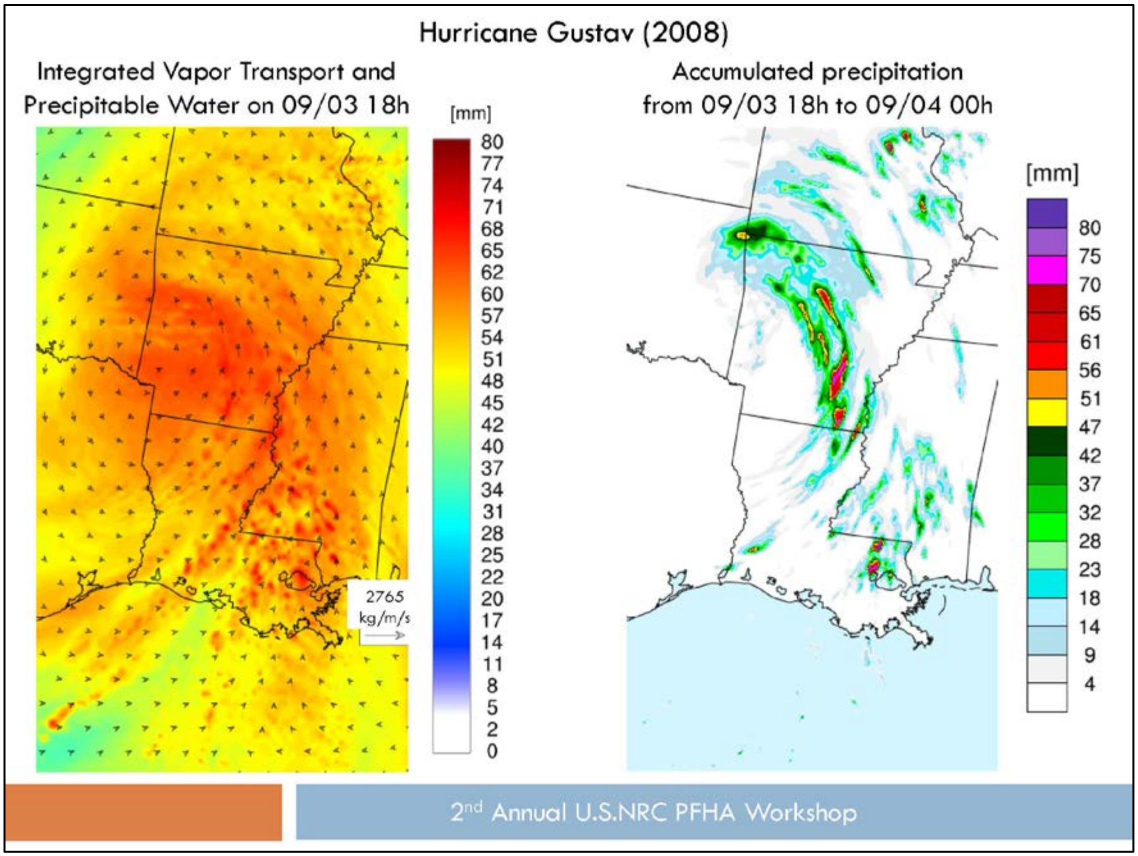


Hurricane Gustav (2008)

Integrated Vapor Transport and Precipitable Water on 09/03 12h

Accumulated precipitation from 09/03 12h to 09/03 18h

2nd Annual U.S.NRC PFHA Workshop

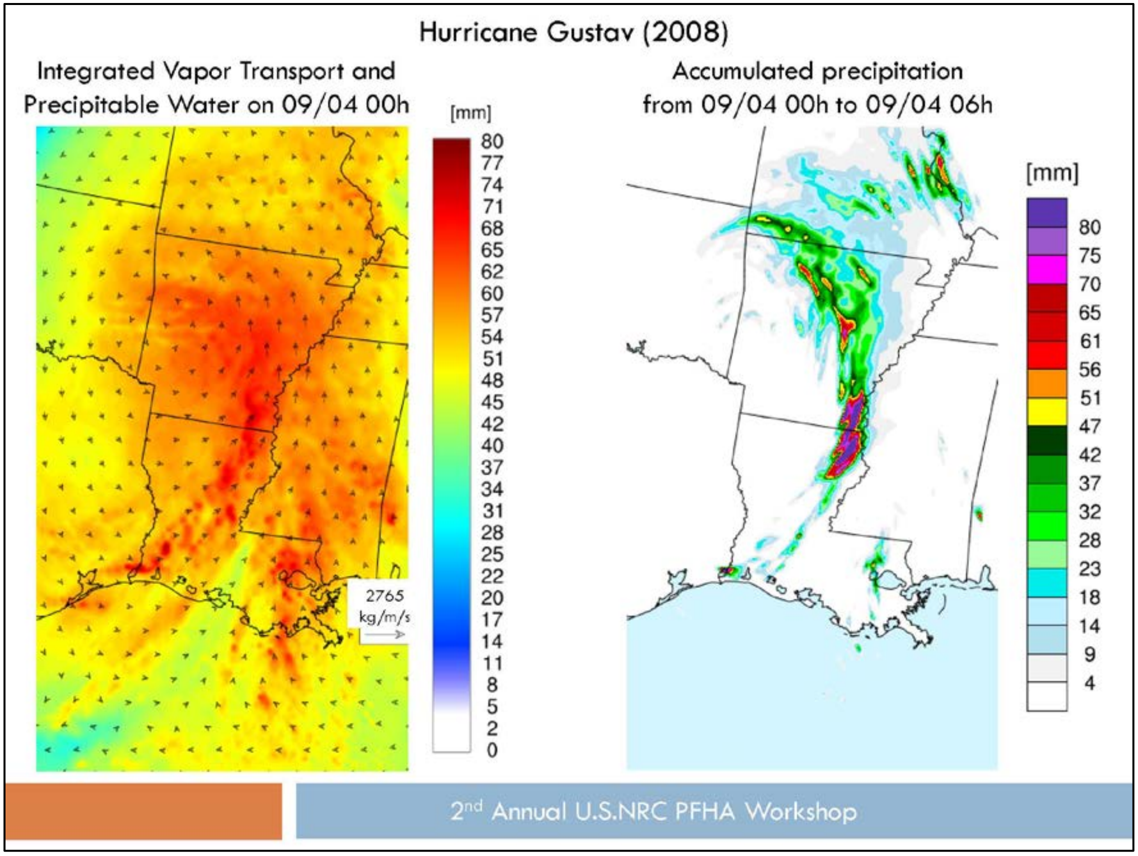


Hurricane Gustav (2008)

Integrated Vapor Transport and Precipitable Water on 09/03 18h

Accumulated precipitation from 09/03 18h to 09/04 00h

2nd Annual U.S.NRC PFHA Workshop



Hurricane Gustav (2008)

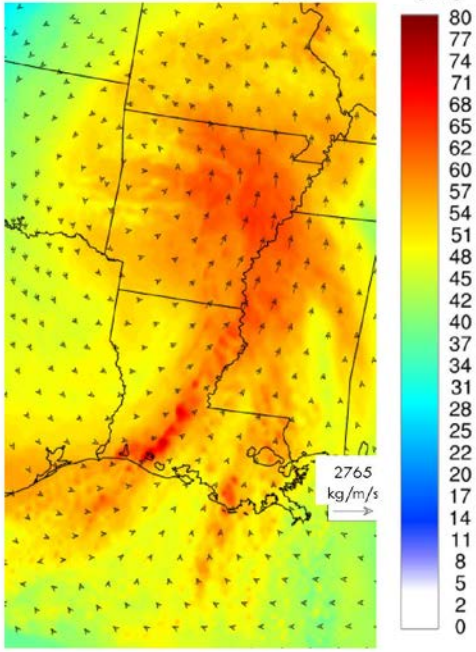
Integrated Vapor Transport and Precipitable Water on 09/04 00h

Accumulated precipitation from 09/04 00h to 09/04 06h

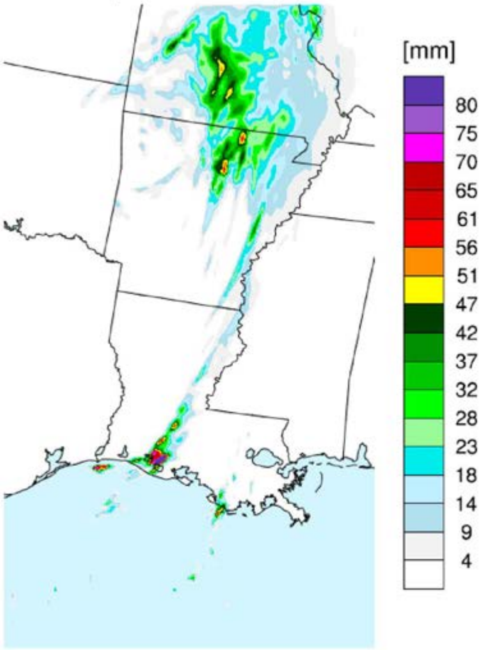
2nd Annual U.S.NRC PFHA Workshop

Hurricane Gustav (2008)

Integrated Vapor Transport and Precipitable Water on 09/04 06h

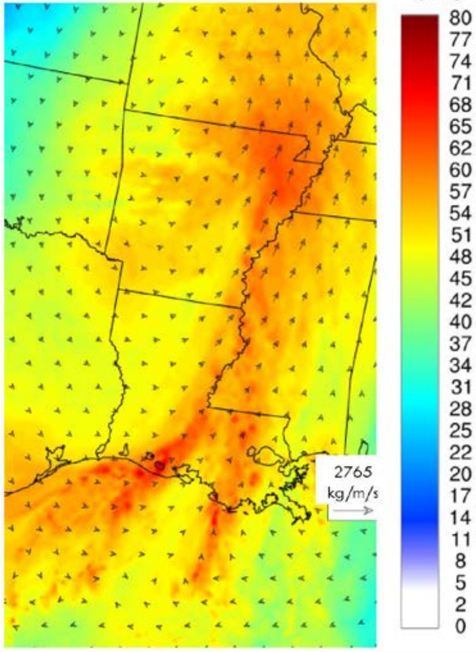


Accumulated precipitation from 09/04 06h to 09/04 12h

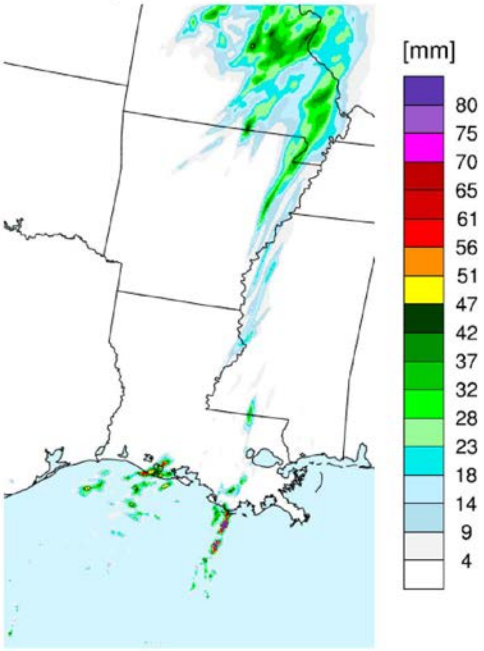


Hurricane Gustav (2008)

Integrated Vapor Transport and Precipitable Water on 09/04 12h



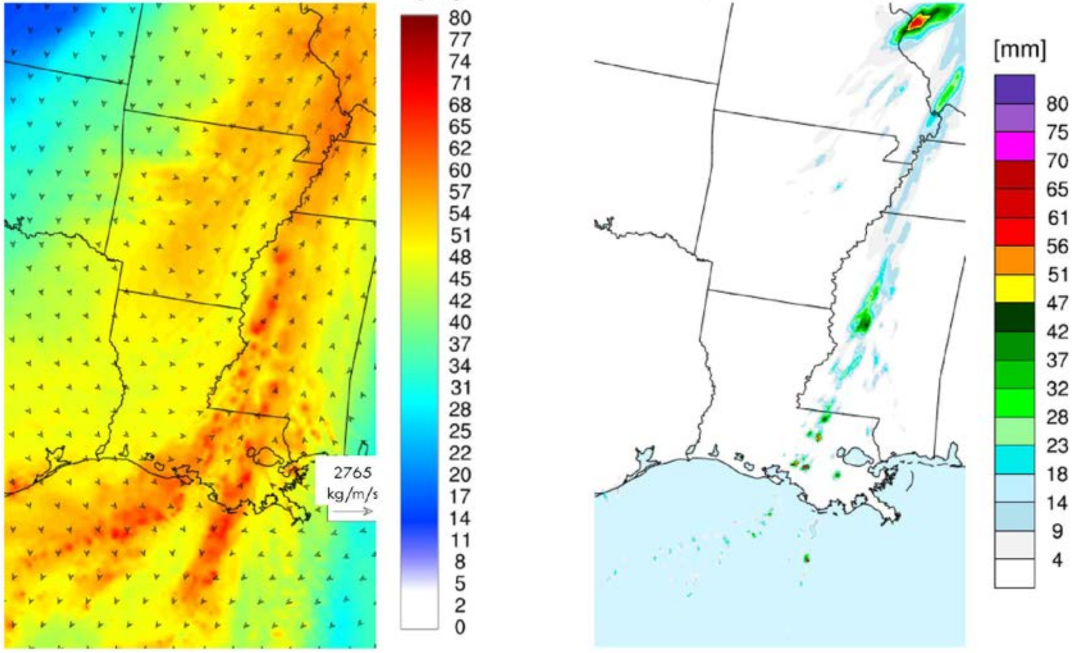
Accumulated precipitation from 09/04 12h to 09/04 18h



Hurricane Gustav (2008)

Integrated Vapor Transport and Precipitable Water on 09/04 18h

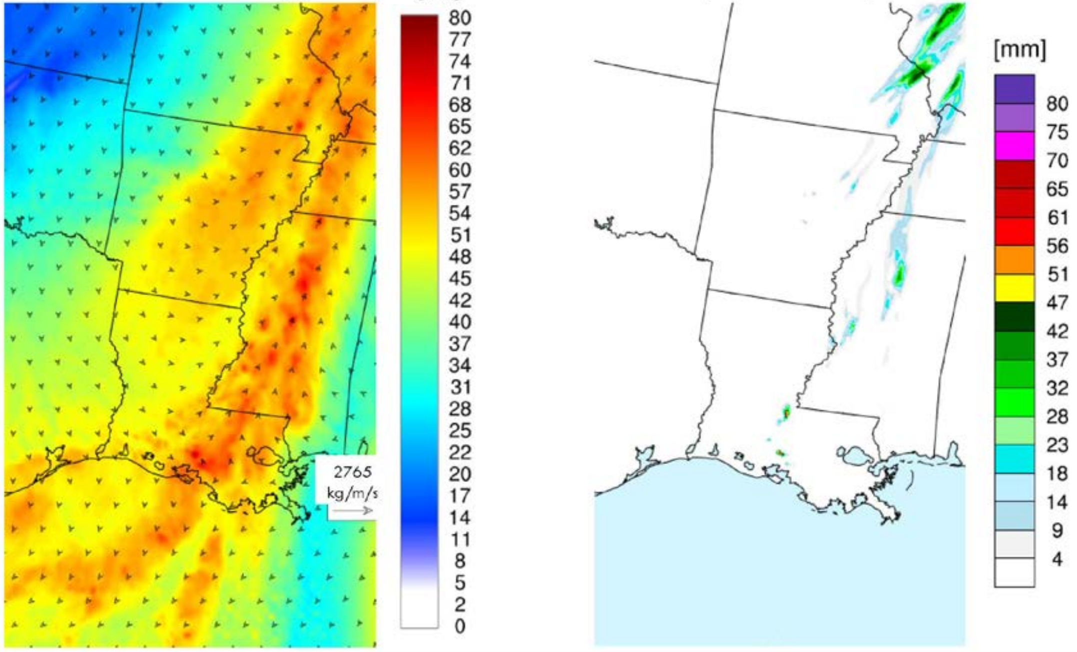
Accumulated precipitation from 09/04 18h to 09/05 00h



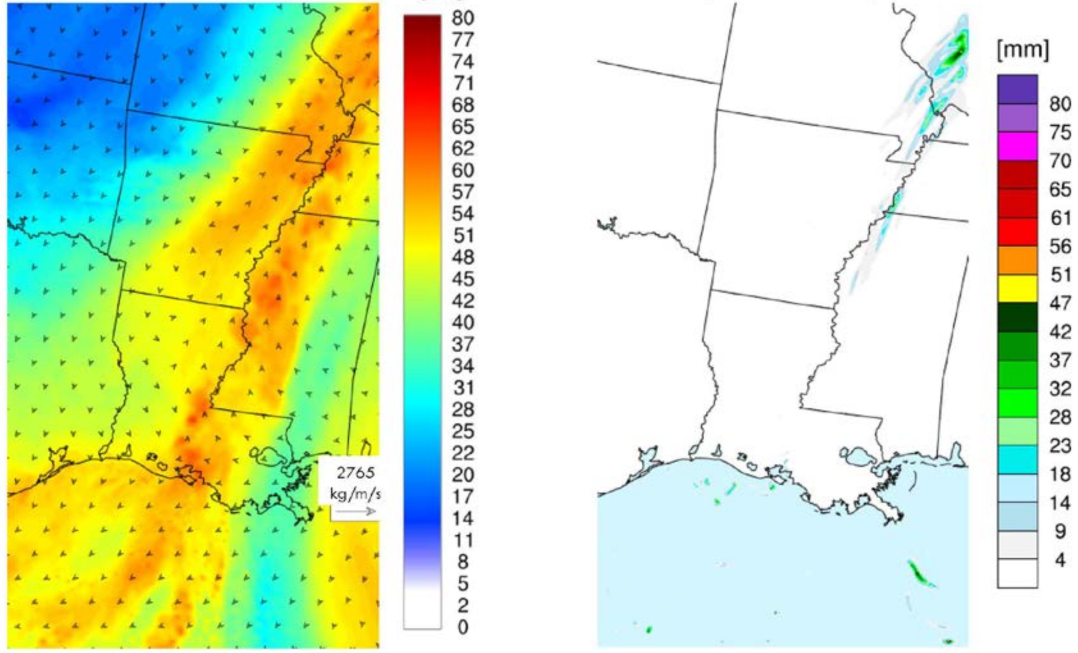
Hurricane Gustav (2008)

Integrated Vapor Transport and Precipitable Water on 09/05 00h

Accumulated precipitation from 09/05 00h to 09/05 06h



Hurricane Gustav (2008)



Integrated Vapor Transport and Precipitable Water on 09/05 06h

Accumulated precipitation from 09/05 06h to 09/05 12h

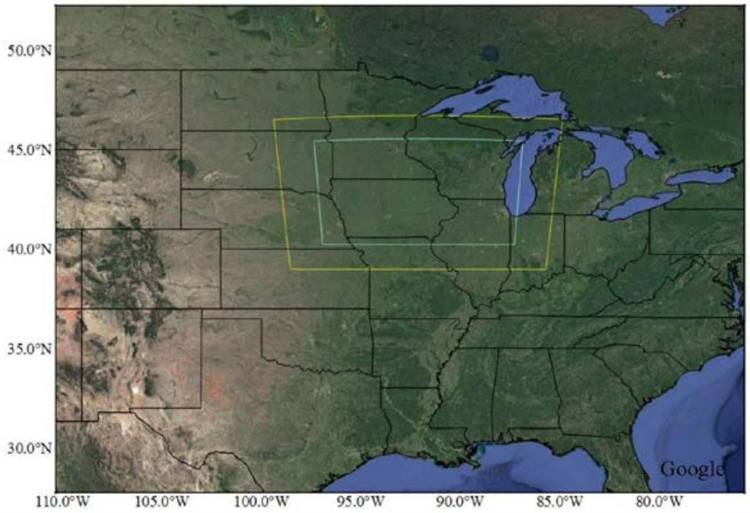
---

1. Simulations of the intense Tropical Cyclones

2. Simulations of the intense Mesoscale Convective Systems

WRF Domains for MCSs

- Two nested domains
  - Domain 1: 15 km (76 x 58)
  - Domain 2: 5 km (166 x 118)
  - 40 vertical levels



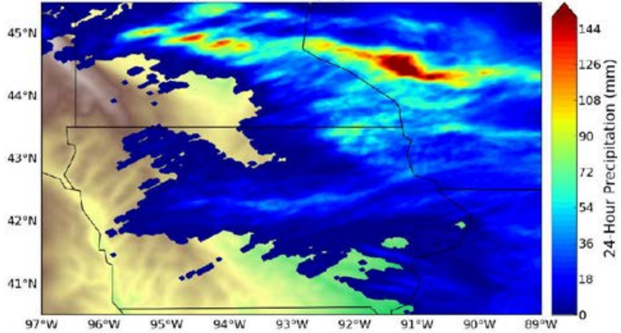
Simulated Severe MCS events

- August 18, 2005
- September 25, 2005
- August 8, 2009
- July 23, 2010
- September 23, 2010
- July 28, 2011
- June 22, 2013

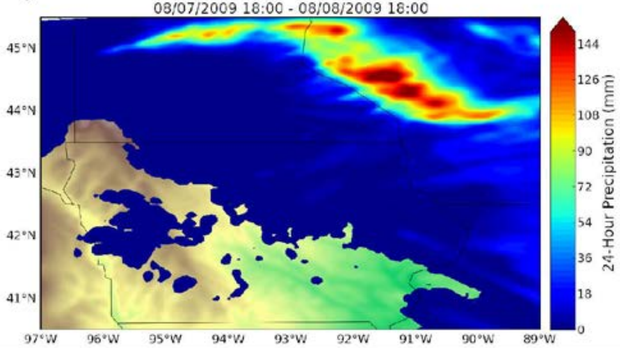
2009 August 8 MCS event

18:00 on August 7, 2009
- 18:00 on August 8, 2009

a) StageIV

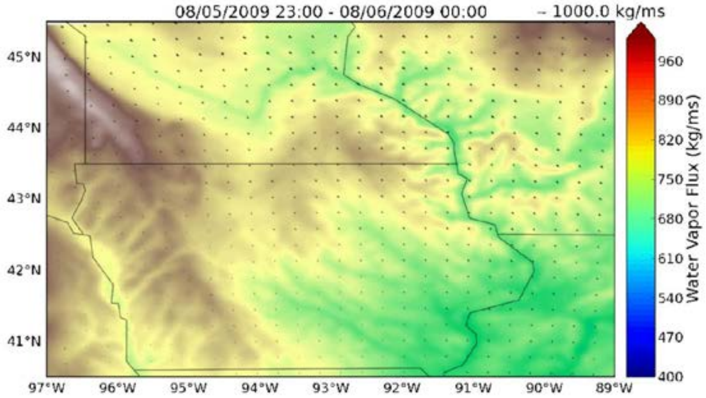


b) WRF simulated

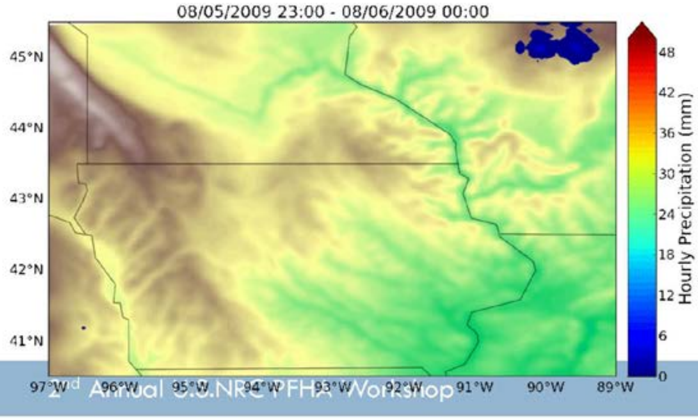


2009 August 8 MCS event

a) Water Vapor Flux



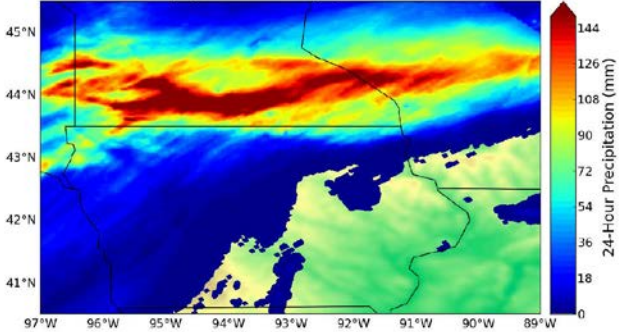
b) Hourly Precipitation



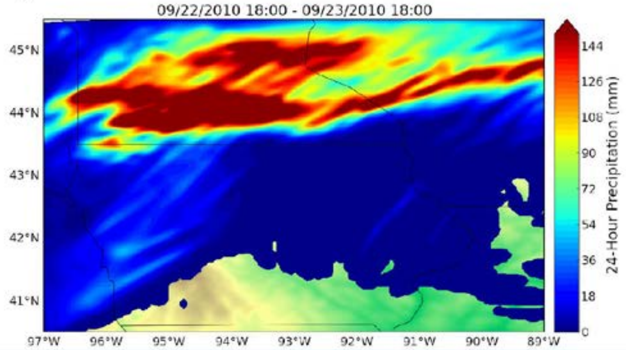
2010 September 23 MCS event

18:00 on September 22, 2010
- 18:00 on September 23 , 2010

a) StageIV

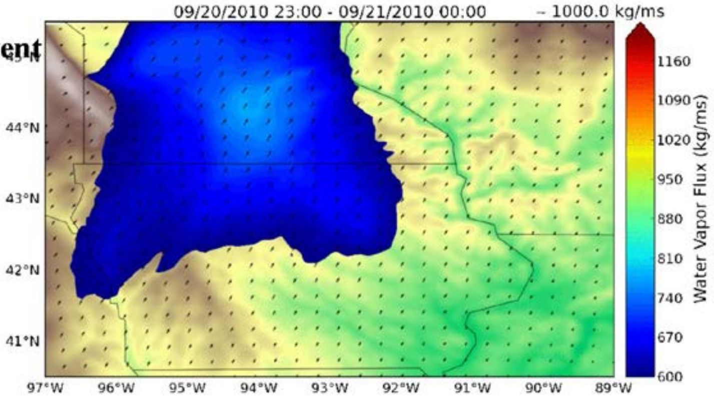


b) WRF simulated

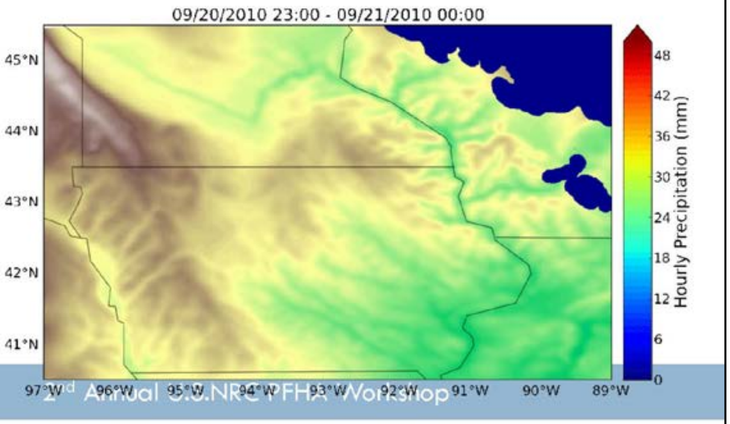


2010 September 23 MCS event

a) Water Vapor Flux



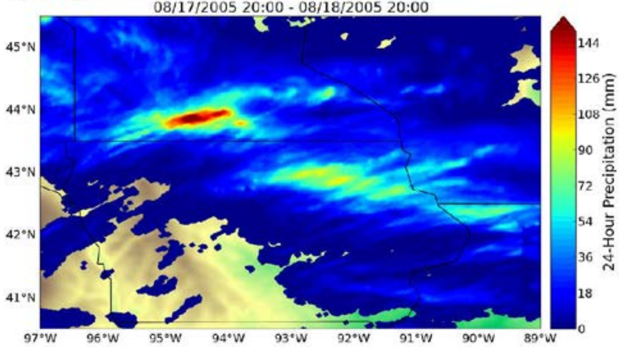
b) Hourly Precipitation



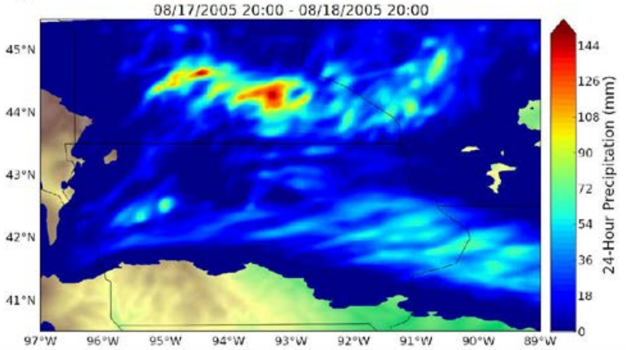
2005 August 18 MCS event

20:00 on August 18, 2005
- 20:00 on August 18, 2005

a) StageIV



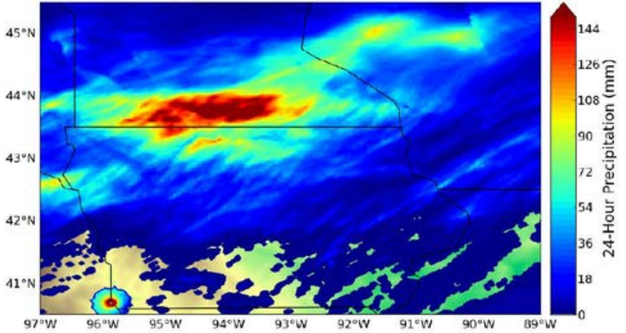
b) WRF simulated



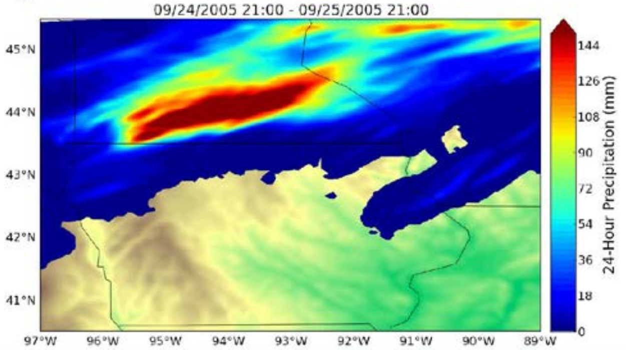
2005 September 25 MCS event

21:00 on September 24, 2005
- 21:00 on September 25, 2005

a) StageIV



b) WRF simulated

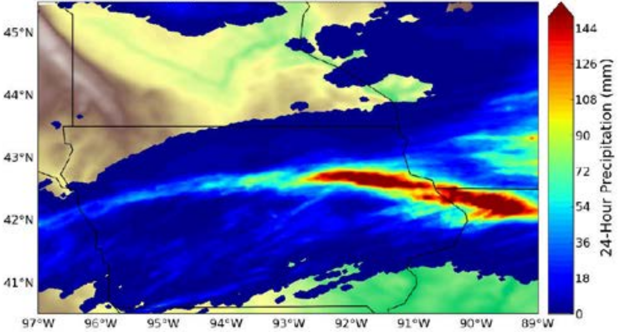


2010 July 23 MCS event

18:00 on July 22, 2010
- 18:00 on July 23, 2010

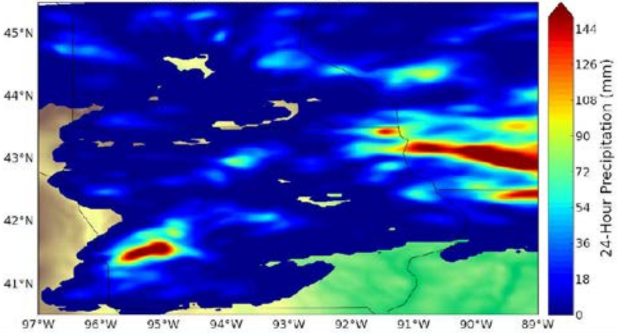
a) StageIV

07/22/2010 18:00 - 07/23/2010 18:00



b) WRF simulated

07/22/2010 18:00 - 07/23/2010 18:00

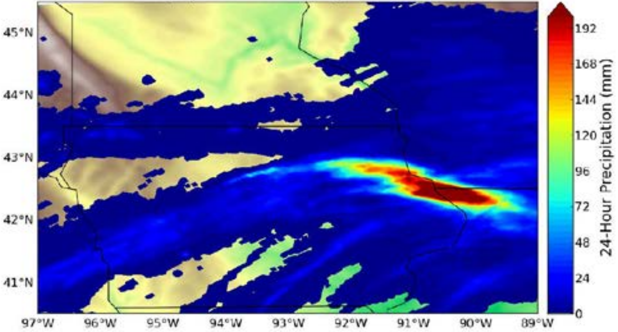


2011 July 28 MCS event

15:00 on July 27 , 20011
- 15:00 on July 28 , 2011

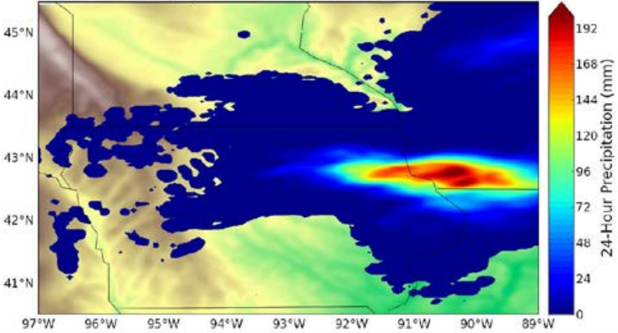
a) StageIV

07/27/2011 15:00 - 07/28/2011 15:00



b) WRF simulated

07/27/2011 15:00 - 07/28/2011 15:00

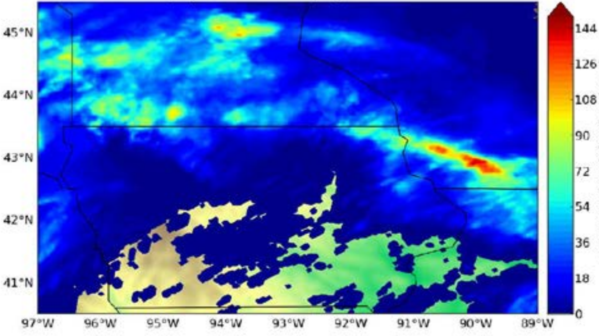


2013 June 22 MCS event

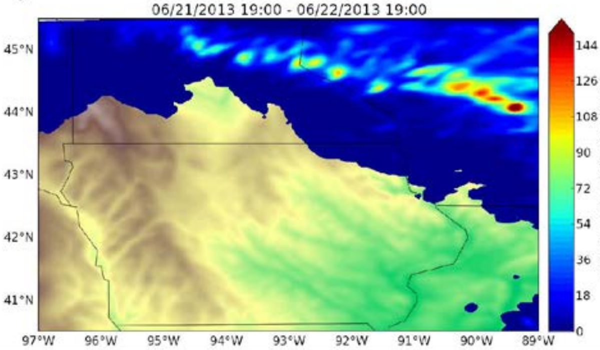
19:00 on June 22, 2013

- 19:00 on June 22, 2013

a) StageIV



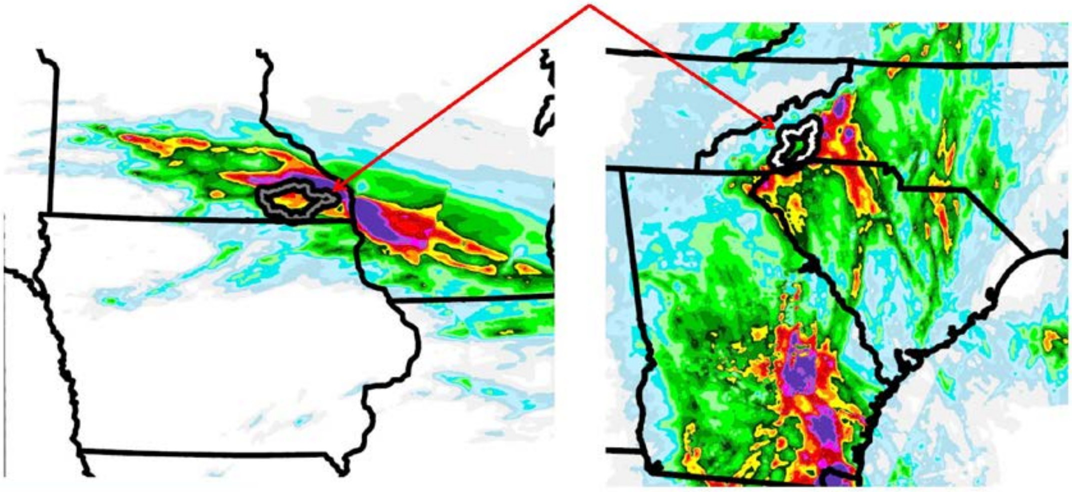
b) WRF simulated

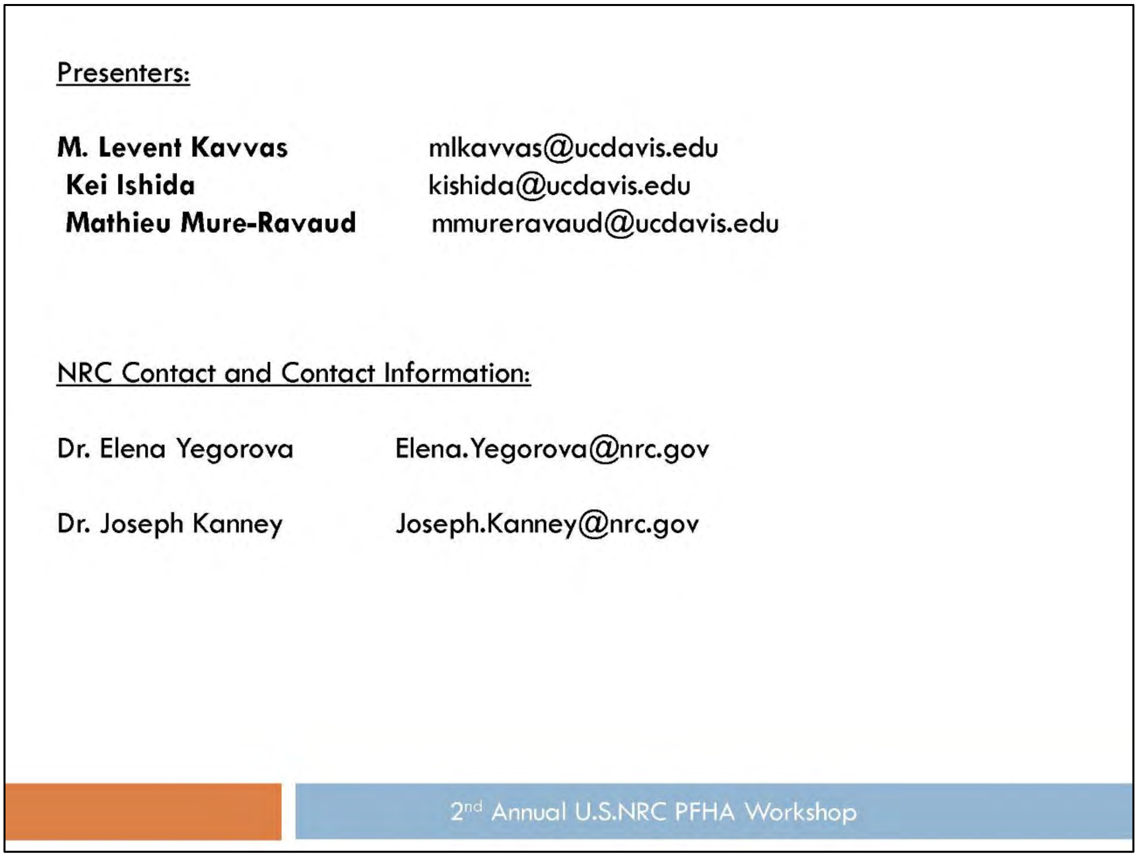


What comes next

- Evaluating the model's performances for each storm system

- Perform a storm transposition exercise for one MCS event and for one Hurricane event using the following 2 target areas:





<u>Presenters:</u>

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Kei Ishida	kishida@ucdavis.edu
Mathieu Mure-Ravaud	mmureravaud@ucdavis.edu

<u>NRC Contact and Contact Information:</u>

Dr. Elena Yegorova	Elena.Yegorova@nrc.gov
Dr. Joseph Kanney	Joseph.Kanney@nrc.gov

2.3.3.2.3 Questions and Answers

Question:

The models seem to reproduce the storms well. When the storm is moved to a different location, what assumptions do you make in order to conclude that the initial and boundary conditions that occurred in the Midwest could happen in the Southeast? How do we know when we have transposed a storm to a region that is not realistic, that we have done something that is not meteorologically possible? Are there limits on where we can transpose storms and in what situations?

Response:

The modeling is not creating new artificial initial or boundary conditions. We performed a similar exercise for atmospheric rivers, in California and in the West. This modeling involved a shift in the boundary conditions in the zonal direction, with respect to the meridional direction, or with respect to the latitudinal direction, and as such there must be realism. However, in this case, we are using historically observed conditions and shifting them either in the south-north direction or in the east-west direction. These storms are historical cases that have set initial and boundary conditions in the CFSR reanalysis data.

Follow-up Question:

Could those initial and boundary conditions occur in a different location?

Response:

Yes; before starting a transposition exercise, analysts need to justify how much shifting is realistic. The new work is investigating synoptic conditions and will help analysts decide what level of shifting is realistic. In this case, we are simply shifting historically observed boundary conditions and not creating any. The storms' initial conditions are just moved.

Question:

Have you considered the Goddard database on intense storms?

Response:

No, we did not.

Comment:

The Goddard database provides satellite data with a much lower resolution of storms as Stage IV reanalysis data.

Response:

The reanalysis data set is good for assessing the performance of these models.

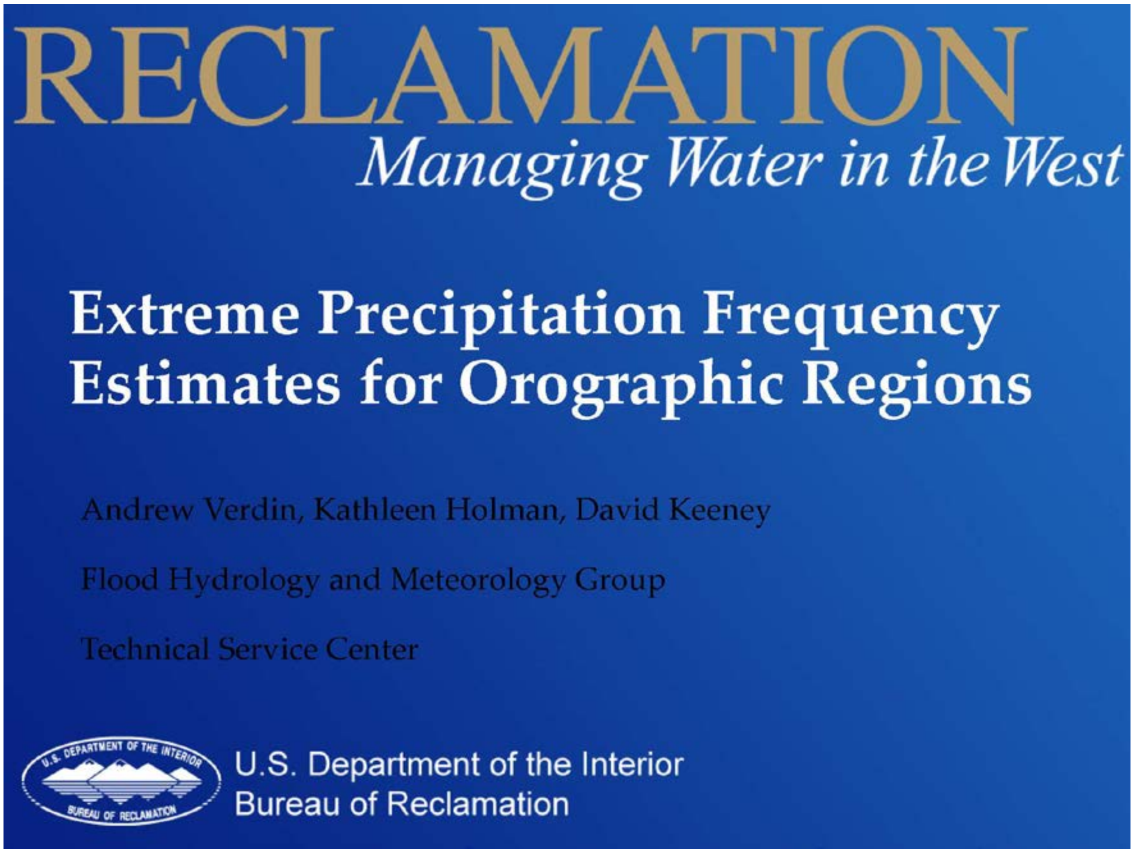
2.3.3.3 Extreme Precipitation Frequency Estimates for Orographic Regions, Andrew Verdin*, Kathleen Holman, and David Keeney, Flood Hydrology and Meteorology Group, Technical Services Center, U.S. Bureau of Reclamation (Session 2A-3; ADAMS Accession No. ML17054C506)

2.3.3.3.1 Abstract

This presentation gave an update to the research project "Phase II: Research to Develop Guidance on Extreme Precipitation Frequency Estimates for the Tennessee Valley." The focus of this presentation was the use of sophisticated statistical techniques for identifying homogeneous regions within greater orographic domains and the subsequent fitting of extreme value distributions for point-scale return-level estimates of precipitation within each homogeneous region. Identification of homogeneous regions is essential for regional frequency analysis. Regional analyses are based on the assumption that data from stations within each homogeneous region come from the same theoretical distribution, which is a common method of extending environmental datasets. Parameter estimation is sensitive to a number of influential factors, the period of record being one of the most important. It is essential, then, to strengthen the parameter estimates by substituting "space for time." The presentation discussed the Self-Organizing Maps (SOM) algorithm, a widely used method of identifying homogeneous regions, and the application of the SOM algorithm to the Tennessee River Valley. Results from the SOM algorithm are consistent with subjective methods of regionalization. For each homogeneous region, the study applied two distinct methods of regional frequency analysis for estimating the extreme value distribution parameters of the regional growth curve: L-moments and Bayesian . The regional growth curve for each homogeneous region is produced using scaled annual maximum precipitation data. Subsequently, a point-scale return level is estimated by scaling the

regional growth curve by the at-site mean of the location of interest. However, it may be of interest to estimate precipitation magnitudes at locations where no historical observations exist. To this end, gridded reanalysis may be used as input to regional frequency analysis. Specifically, the Newman et al. (2015)[2] dataset offers an ensemble of gridded daily precipitation for 33 years. The ensemble contains 100 members, each of which is an equally plausible precipitation total for the grid cell of interest. Similar to the identification of homogeneous regions, the study assumed that all ensemble members come from the same theoretical distribution, which extends the period of record by two orders of magnitude. The ensemble members may be collapsed into a single dataset, and the extreme value distribution parameters are estimated independently at each grid cell. The presentation discussed differences in the inherent assumptions and resulting differences in the two methods. The presentation ended with an illustration of the two methods' abilities in quantifying small exceedance probability precipitation events with associated uncertainty .

2.3.3.3.2 Presentation



RECLAMATION

Managing Water in the West

Extreme Precipitation Frequency Estimates for Orographic Regions

Andrew Verdin, Kathleen Holman, David Keeney

Flood Hydrology and Meteorology Group

Technical Service Center

U.S. Department of the Interior
Bureau of Reclamation

---

[2] Newman, A. J., Clark, M. P., Craig, J., Nijssen, B., Wood, A., Gutmann, E., Mizukami, N., Brekke, L. & Arnold, J. R. (2015). Gridded ensemble precipitation and temperature estimates for the contiguous United States. Journal of Hydrometeorology, 16(6), 2481-2500.

NRC Research Overview

Previous Research (Phase 1):

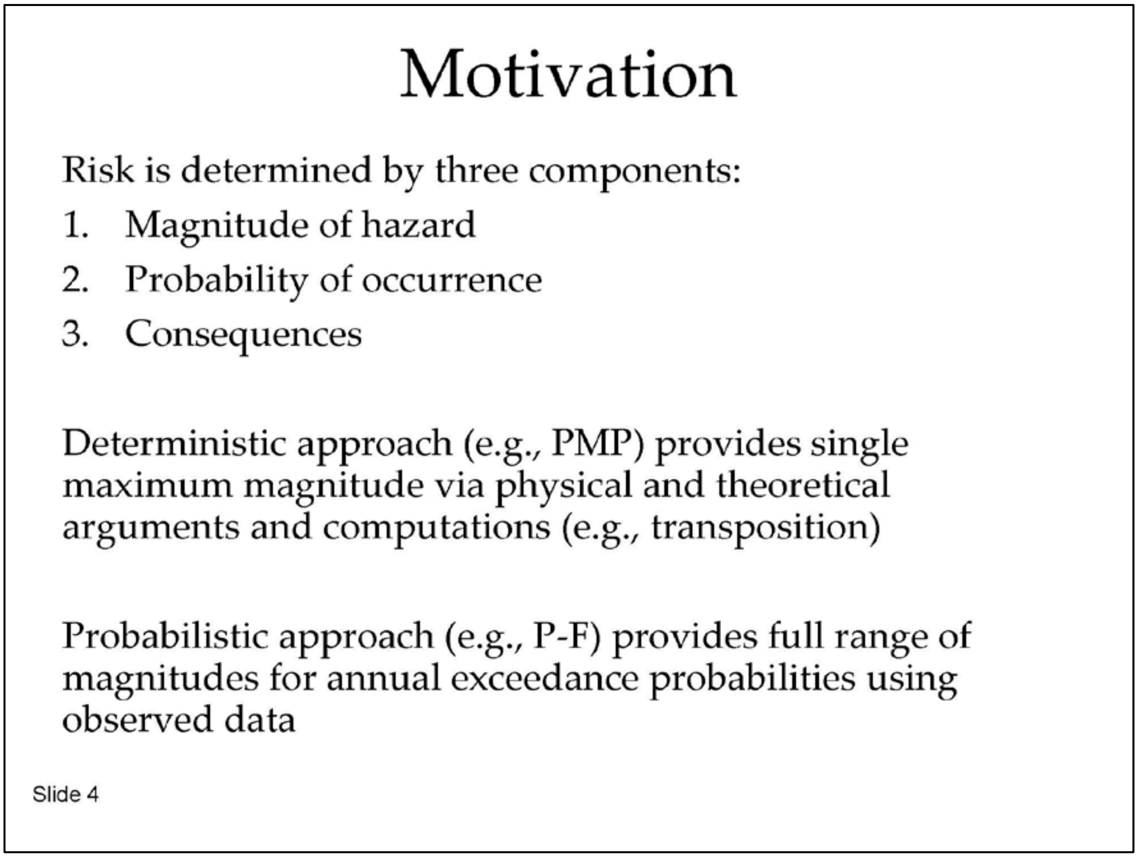
Research to Develop Guidance on Probable Maximum Precipitation Estimates for the Eastern United States

Current Research (Phase 2):

Research to Develop Guidance on Extreme Precipitation Frequency Estimates for the Tennessee River Valley

Outline

1. Motivation
2. Precipitation-Frequency
3. Regional P-F analysis
4. Case study in Tennessee River Valley
    A. L-moments
    B. Bayesian
5. Summary



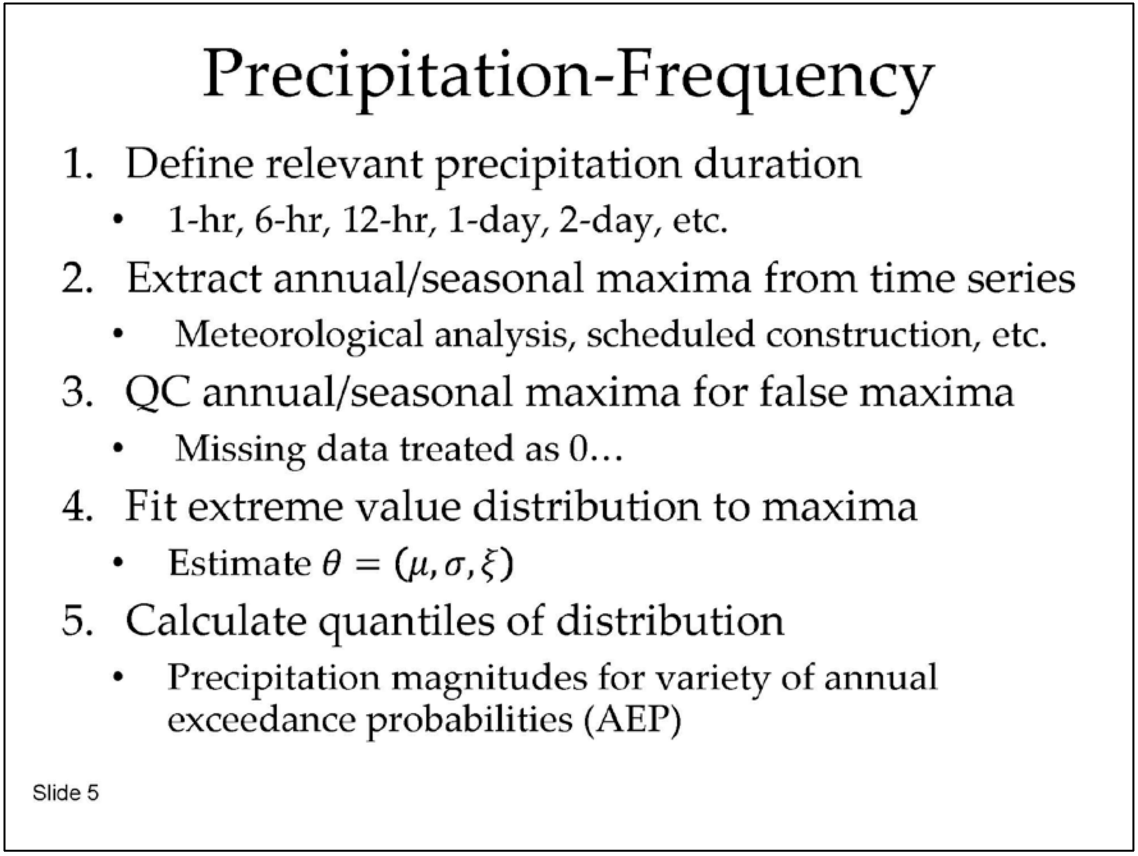
Motivation

Risk is determined by three components:

1. Magnitude of hazard
2. Probability of occurrence
3. Consequences

Deterministic approach (e.g., PMP) provides single maximum magnitude via physical and theoretical arguments and computations (e.g., transposition)

Probabilistic approach (e.g., P-F) provides full range of magnitudes for annual exceedance probabilities using observed data



Precipitation-Frequency

1. Define relevant precipitation duration
   - 1-hr, 6-hr, 12-hr, 1-day, 2-day, etc.
2. Extract annual/seasonal maxima from time series
   - Meteorological analysis, scheduled construction, etc.
3. QC annual/seasonal maxima for false maxima
   - Missing data treated as 0…
4. Fit extreme value distribution to maxima
   - Estimate $\theta = (\mu, \sigma, \xi)$
5. Calculate quantiles of distribution
   - Precipitation magnitudes for variety of annual exceedance probabilities (AEP)

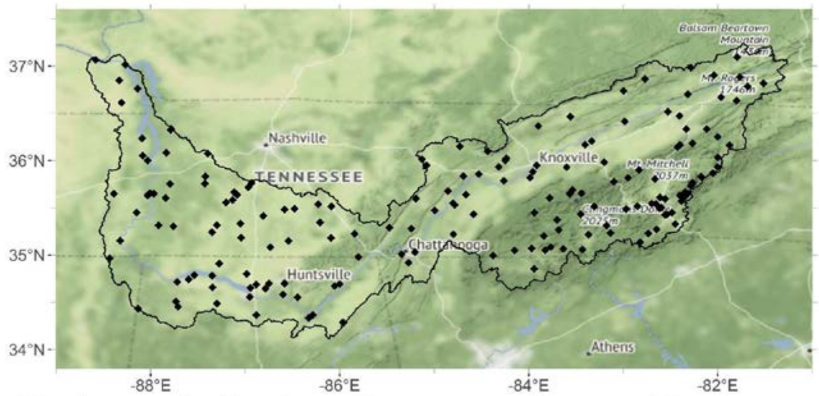
Regional Frequency Analyses

1. Assume observations within homogeneous region (HR) described by single distribution
   - Collect all annual/seasonal maxima within HR
2. Scale the annual/seasonal maxima by the at-site mean of the maxima
   - Mean of maxima at each site = 1
   - Shape describes all sites, magnitudes may differ
3. Compute precipitation-frequency relationship as before, produce regional growth curve (RGC is *dimensionless*)
   - Scale by site-specific mean for point estimates

Case Study

Study Region

Tennessee River Valley watershed



Good example of region with pronounced orographics

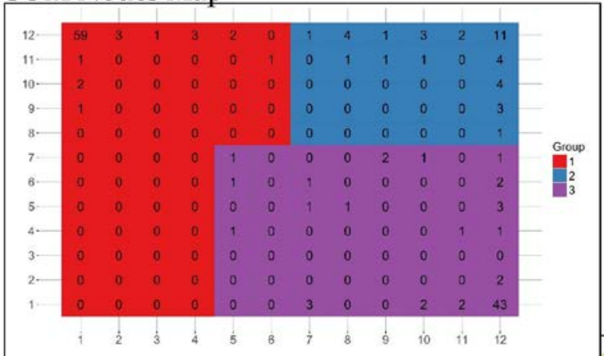
GHCN-Daily gauges with 85% data availability for 10+ years period of record (POR)

Homogeneous Regions

- Methods to define HR (Hosking and Wallis 1997)
  - Subjective methods
    - Geographical location
    - Seasonal timing of peak events
    - Mean annual precipitation (MAP)
    - Similar forcing mechanisms (synoptics)
  - Objective methods
    - ***Self-Organizing Maps (SOM)***
    - Hierarchical clustering analysis (HCA)
    - Heterogeneity measures

Self-Organizing Map

SOM Nodes Map



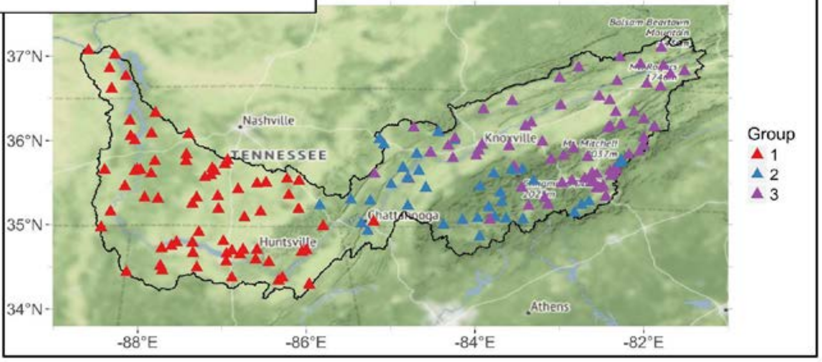
	1	2	3	4	5	6	7	8	9	10	11	12
12	59	3	1	3	2	0	1	4	1	3	2	11
11	1	0	0	0	0	1	0	1	1	1	0	4
10	2	0	0	0	0	0	0	0	0	0	0	4
9	1	0	0	0	0	0	0	0	0	0	0	3
8	0	0	0	0	0	0	0	0	0	0	0	1
7	0	0	0	0	1	0	0	0	2	1	0	1
6	0	0	0	0	1	0	1	0	0	0	0	2
5	0	0	0	0	0	0	1	1	0	0	0	3
4	0	0	0	0	1	0	0	0	0	0	1	1
3	0	0	0	0	0	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0	0	0	0	0	2
1	0	0	0	0	0	0	3	0	0	2	2	43

Apply SOM algorithm to :

- Latitude
- Longitude
- *Elevation*
- *Avg annual precipitation*
- *Avg monthly precipitation*

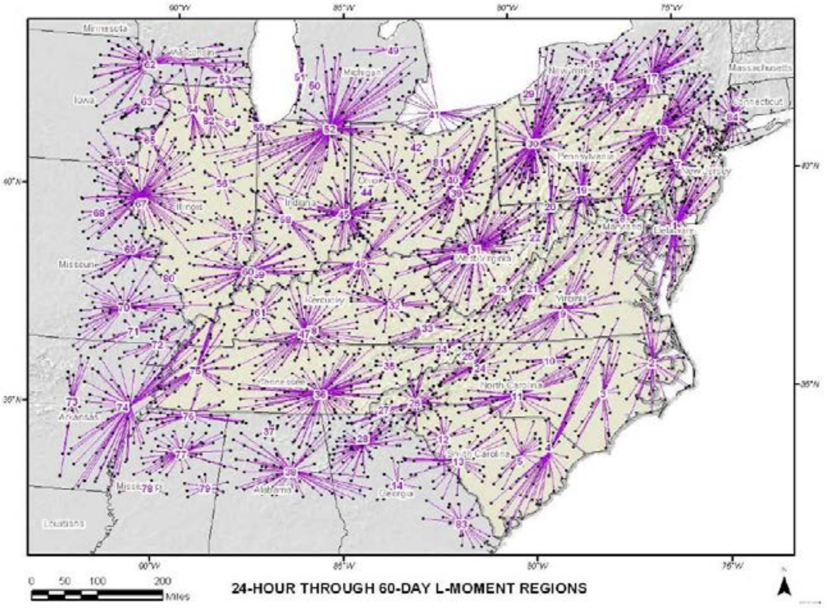
Each gauge maps to SOM node

Group neighboring nodes



SOM reference:
Kohonen (1990)

NOAA Atlas 14 HR

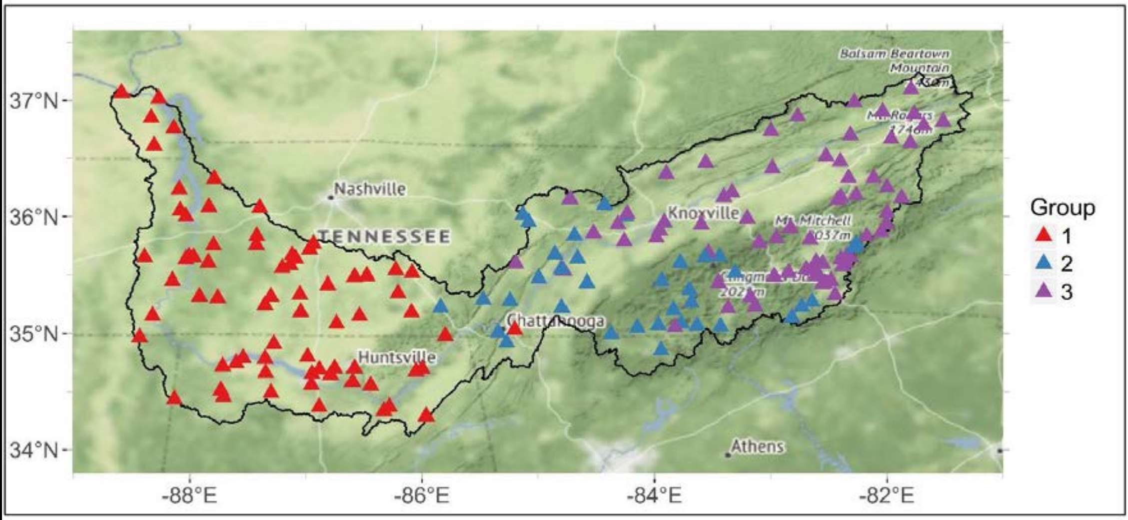


L-Moments

L-Moments

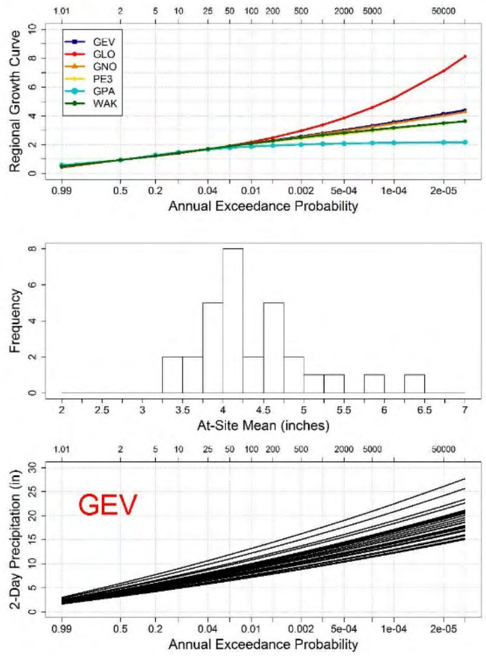
1. Identify weather stations (sites) within HR
    - Screened, quality-controlled maxima
2. Compute L-statistics for each site
    - L-mean, L-scale, L-skewness, L-kurtosis
3. Test for heterogeneity
    - Discordancy measures (e.g., $D_i \leq 3$)
4. Calculate regional L-statistics (weighted by POR)
5. Identify a suitable distribution
    - GEV, GPD, GNO, GLO, PE3, Wakeby
6. Calculate regional growth curve
    - Scale growth curve (point, basin, region)

SOM Homogeneous Regions

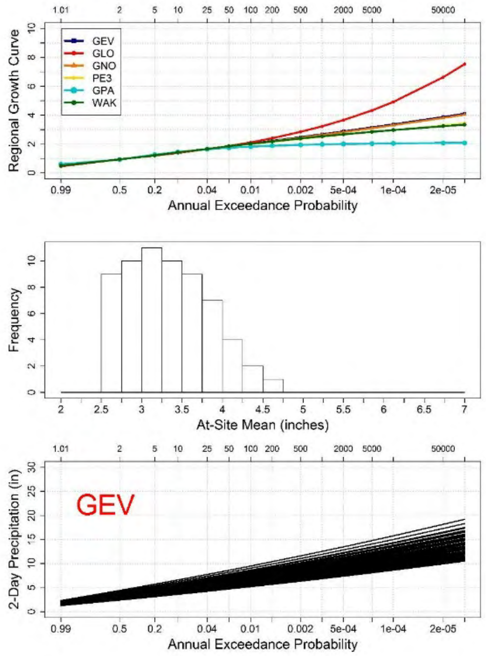


Slide 14

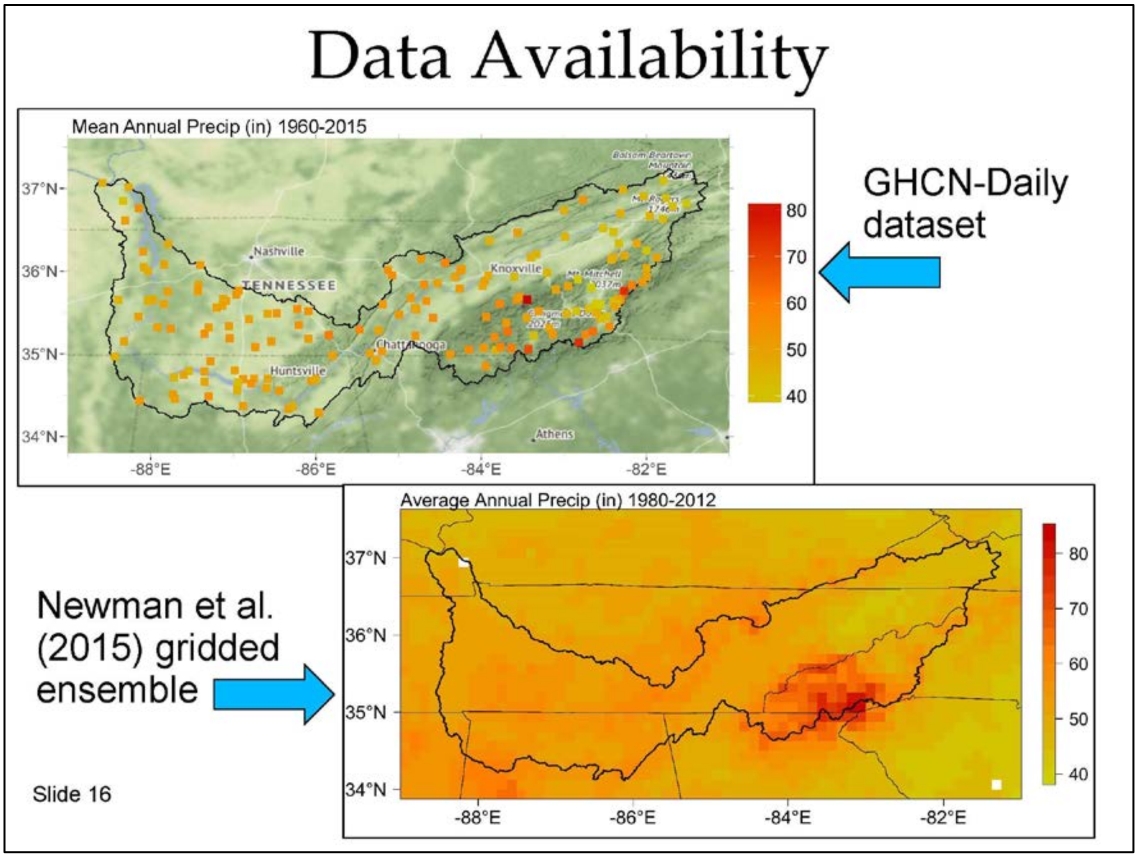
Two-Day Precipitation, Group 2



Two-Day Precipitation, Group 3



Slide 15



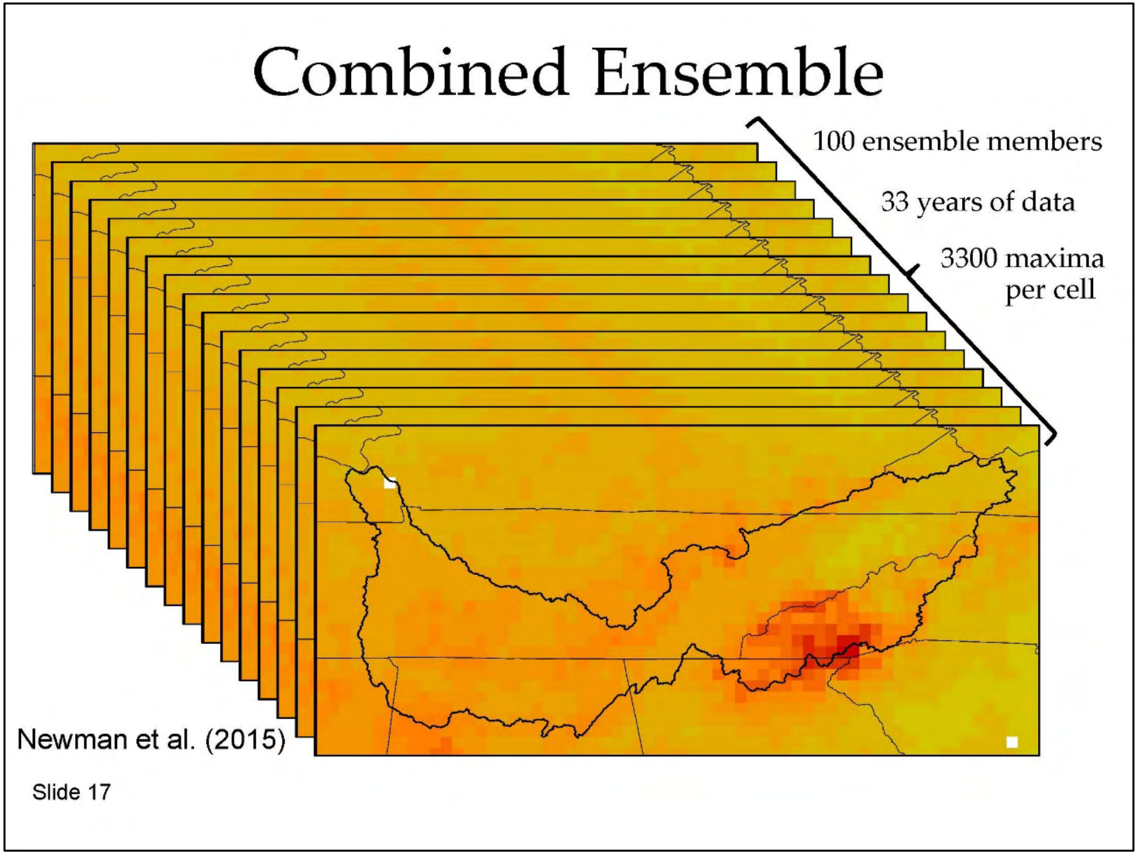
Data Availability

Mean Annual Precip (in) 1960-2015

GHCN-Daily dataset

Average Annual Precip (in) 1980-2012

Newman et al. (2015) gridded ensemble



Combined Ensemble

100 ensemble members

33 years of data

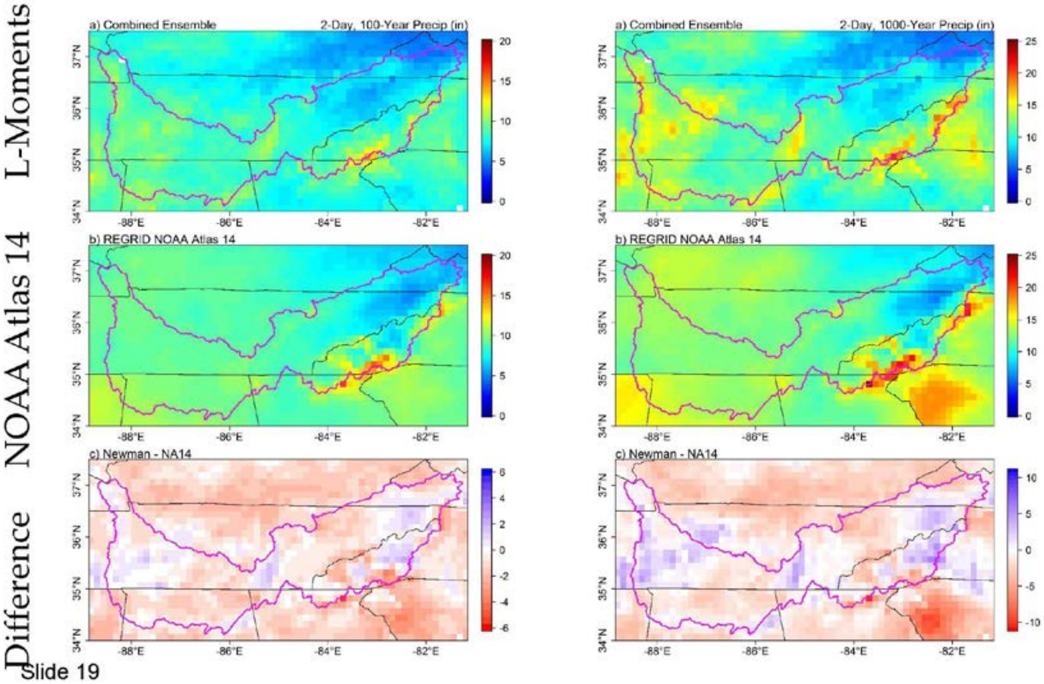
3300 maxima per cell

Newman et al. (2015)

Gridded Frequency Maps

1. Assume ensemble members described by single theoretical distribution
   - Extend POR by two orders of magnitude (100 ensemble members)
2. Calculate L-Moments distribution parameters at each grid cell
   - Distinct P-F relationship at each grid cell
   - Spatial correlation is not specifically accounted for
3. Similar to RGC, calculate quantiles of P-F for specific return periods
   - e.g., 10-, 50-, 100-, 500-, 1000-years

Gridded L-moments



Bayesian

Bayesian

Bayes' rule:

$$p(\theta|\boldsymbol{Y}) = \frac{p(\boldsymbol{Y}|\theta)p(\theta)}{p(\boldsymbol{Y})} \propto p(\boldsymbol{Y}|\theta)p(\theta)$$

e.g., $\boldsymbol{Y} = (y_1, y_2, \dots, y_n); \theta = (\mu, \sigma, \xi)$

Define *prior distributions* for model parameters

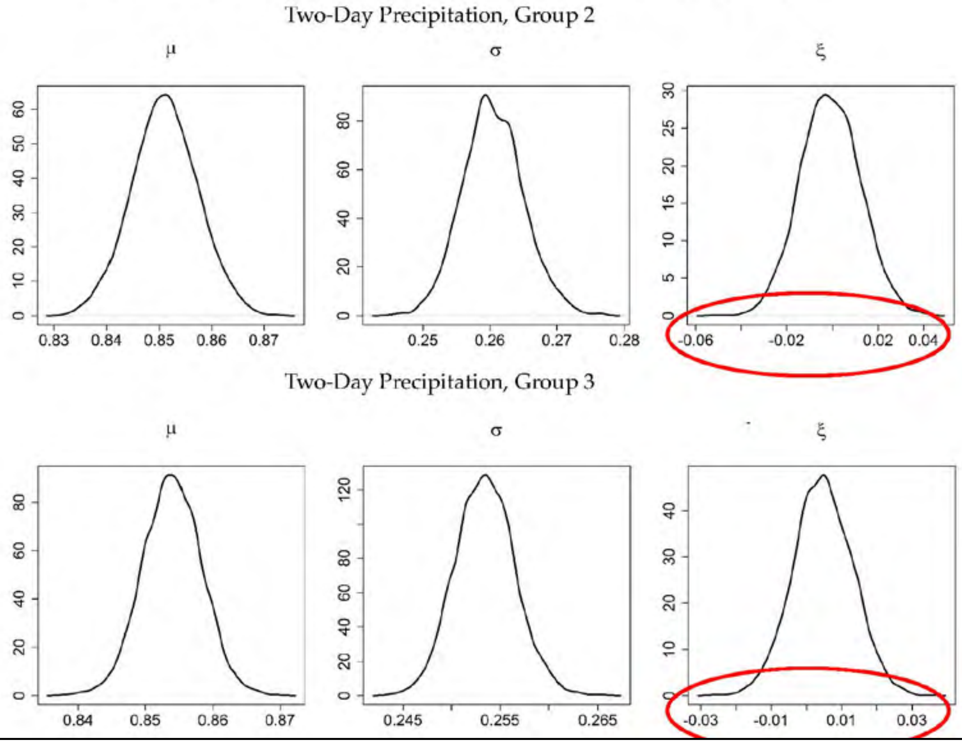
Monte Carlo sampling, acceptance criteria, develops *posterior distributions* of θ

Regional Bayesian

1. Scale annual maxima by at-site mean
2. Scaled maxima within HR described by single distribution
    - Generalized Extreme Value (GEV) distribution
3. Monte Carlo sampling routine initialized with Maximum Likelihood Estimates of $\hat{\theta} = (\hat{\mu}, \hat{\sigma}, \hat{\xi})$
    - 100,000 iterations with 50,000 discarded as "burn-in"
4. Posterior distributions of $\theta = (\mu, \sigma, \xi)$
    - Quantification of uncertainty in return levels

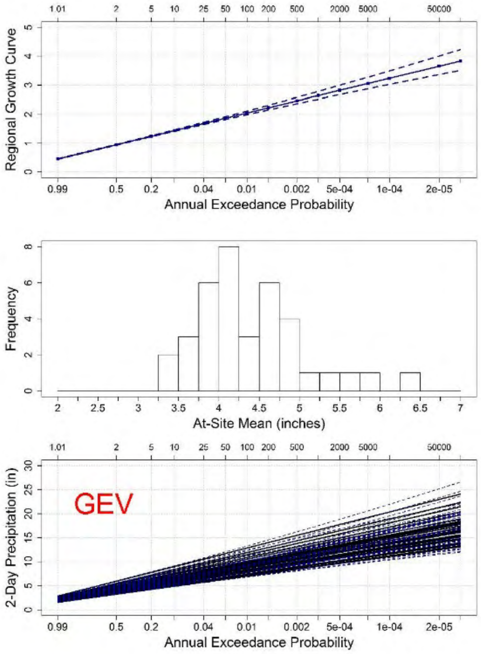
Slide 22

Posterior Distributions

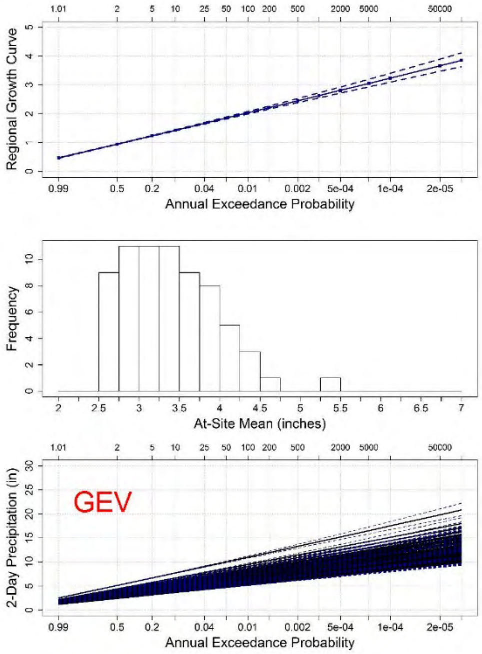


Slide 23

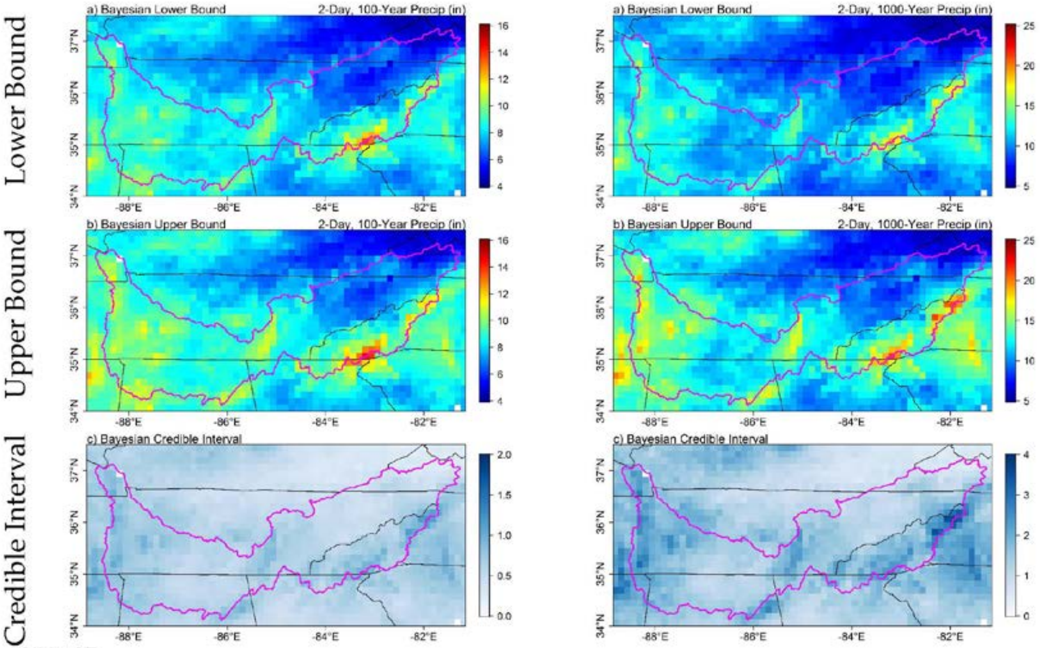
Two-Day Precipitation, Group 2



Two-Day Precipitation, Group 3



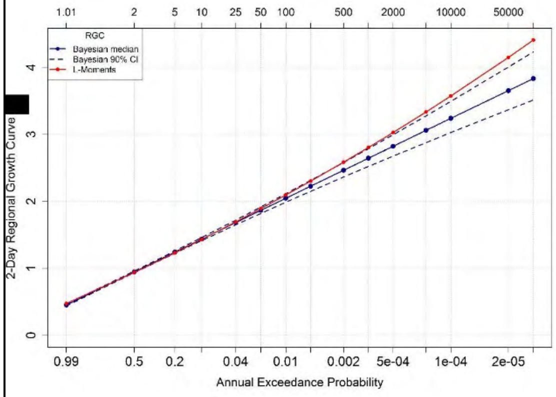
Gridded Bayesian – Uncertainty



L-Moments vs. Bayesian

Regional Growth Curves

Two-Day Precipitation, Group 2



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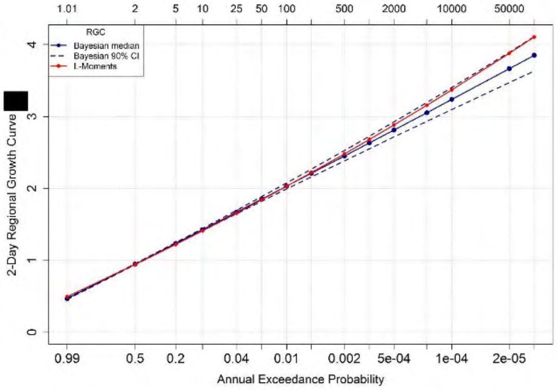
Two-Day Precipitation, Group 3



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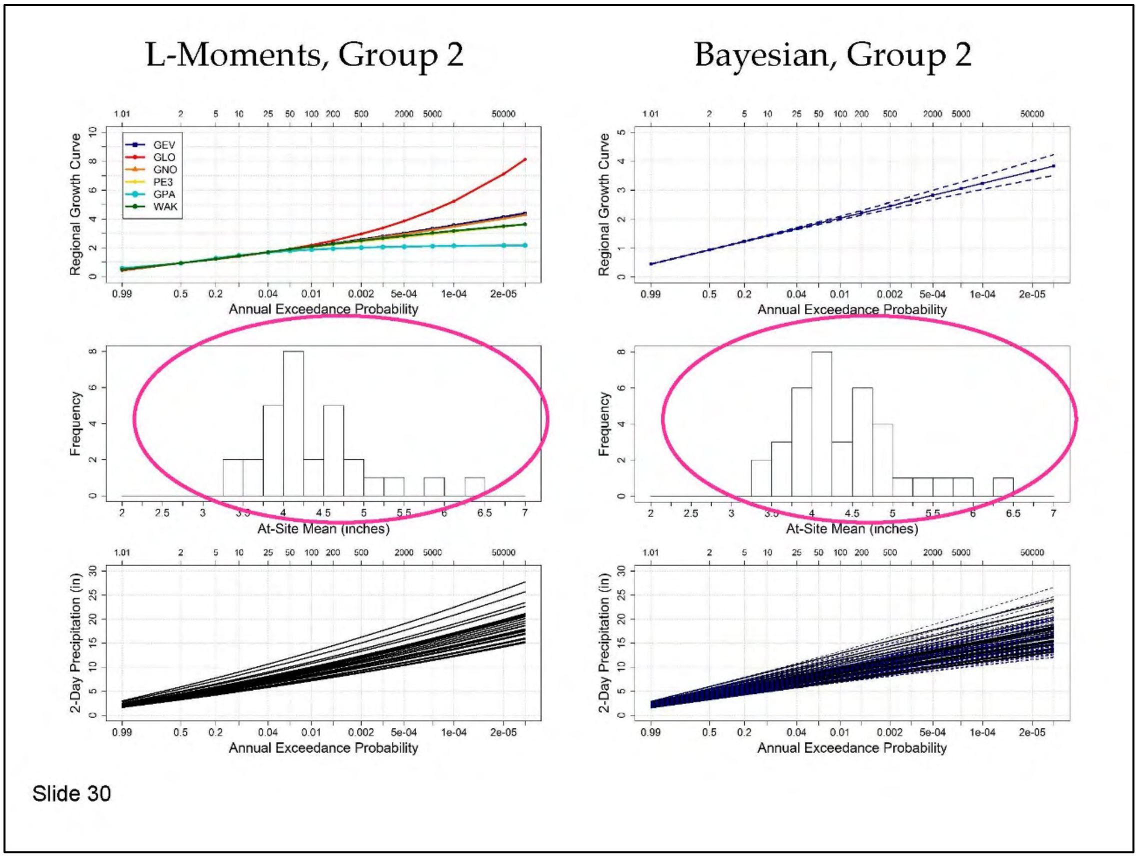
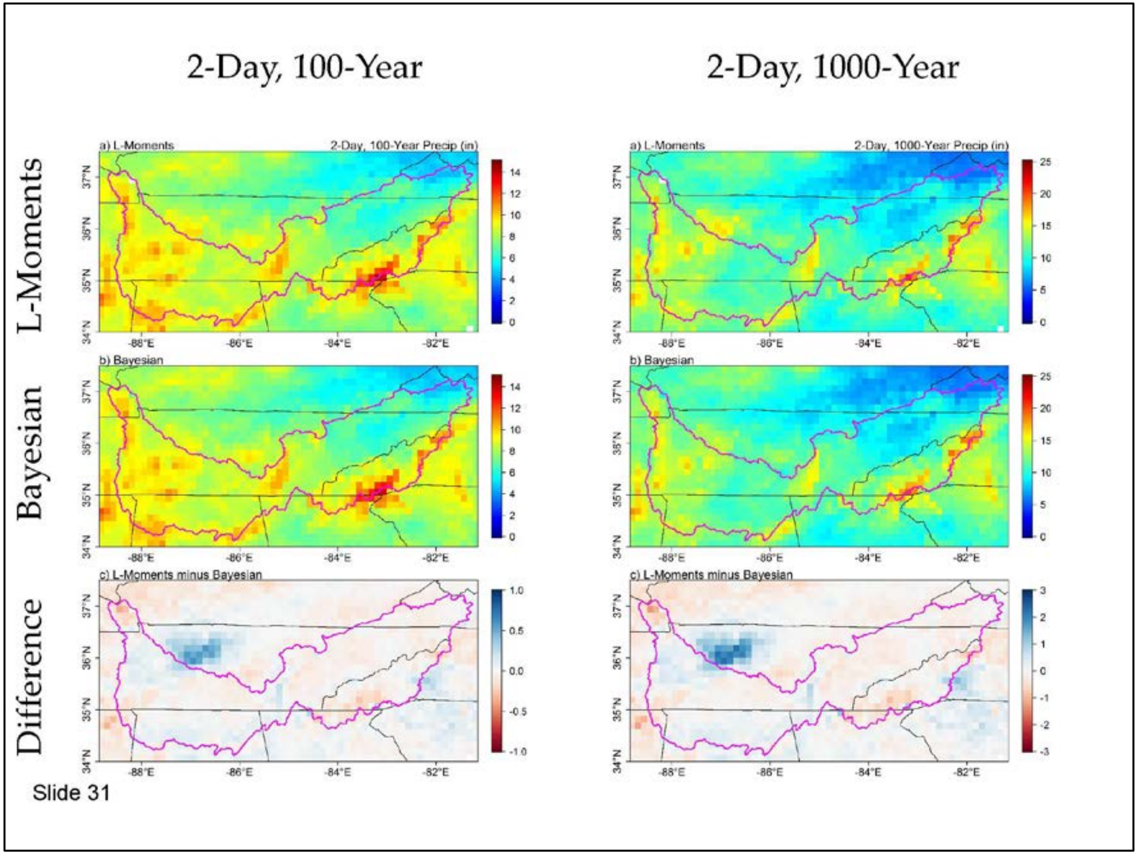


L-Moments, Group 2

Bayesian, Group 2

Slide 30



2-Day, 100-Year

2-Day, 1000-Year

Slide 31

Summary

Regional P-F analysis is a useful framework for quantifying risk of extreme precipitation on local scale

Self-Organizing Maps algorithm addresses orographic effects, defines HRs

Regional growth curve describes maxima at any point within HR

Bayesian addresses parametric uncertainty, computationally expensive

L-Moments is an efficient method for frequency analysis; robust regional estimates of extreme value distribution parameters

Gridded products useful for P-F estimates at unmonitored locations

Many sources of gridded products (e.g., radar, satellite, numerical models)

Questions?

Reclamation contacts

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NRC contact

Joseph Kanney:	joseph.kanney@nrc.gov	+1.301.415.1920

2.3.3.3.3 Questions and Answers

Comment:

The methods that were used in National Oceanic and Atmospheric Administration (NOAA) Atlas, "Precipitation-Frequency Atlas of the United States," Volume 2, issued 2004 and revised 2006, were changed, in large part because of regionalization. Regionalization is an approach that combines a lot of stations together in a way that is actually very subjective, and the results vary significantly depending on how many clusters are chosen and the parameters chosen for the kinds of clusters. In addition, when defining clusters that have many stations, the data end up being smoothed because you are averaging too much, especially when the method is combined with the L-moments approach. The resulting estimates hardly represent the local estimates that are needed in engineering design, which is the primary purpose for producing precipitation frequency estimates. Because of this, NOAA has changed these results and will also change the first volumes of the series if funds are available. It is surprising that the L-moments ended up being higher than in the Bayesian approach, because they tend to be very low for extreme frequencies. This is why NOAA is moving away from their use and toward a maximum likelihood approach. A climate change analysis that is based on annual maxima series cannot take into account changes in frequencies of extreme events. For this reason, we should not do further analysis on the annual maximum series, methods used in the first few volumes of NOAA Atlas 14 and proposed to use here but that were developed in the 1990s. Instead, we need to move toward a more advanced methodology. To best apply NOAA Atlas 14, use the methodology in more recent volumes.

2.3.3.4 Local Intense Precipitation Frequency Studies, John Weglian, EPRI (Session 2A-4; ADAMS Accession No. ML17054C507)

2.3.3.4.1 Abstract

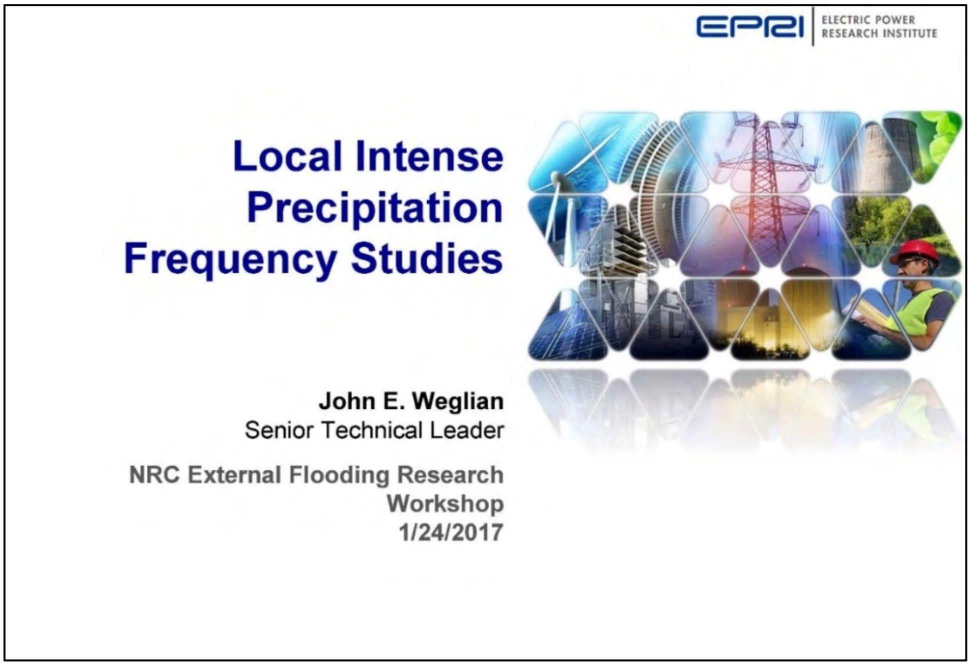
To ensure that NPPs are adequately protected against extreme rainfall, plant design has traditionally relied on deterministic requirements to define the extent of flooding that might need to be accommodated. For purposes of PRA, a more comprehensive understanding of the relationship between the frequency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

To explore the state of the technology and data available to support a more comprehensive probabilistic evaluation, EPRI undertook an evaluation of the precipitation-frequency relationship for two sites in the United States, one an inland site and the other an Atlantic Ocean coastal site. The study was primarily based on regional precipitation-frequency relationships that embody NWS data from a large number of precipitation measurement stations in the vicinity of the plant sites. The study was published as "Local Precipitation -Frequency Studies: Development of 1-Hour/1-Square Mile Precipitation—Frequency Relationships for Two Example Nuclear Power Plant Sites," EPRI ID 3002004400, dated October 2, 2014 (http://www.epri.com/abstracts/Pages/ProductAbstract.aspx?ProductId=000000003002004400).

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

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

2.3.3.4.2 Presentation



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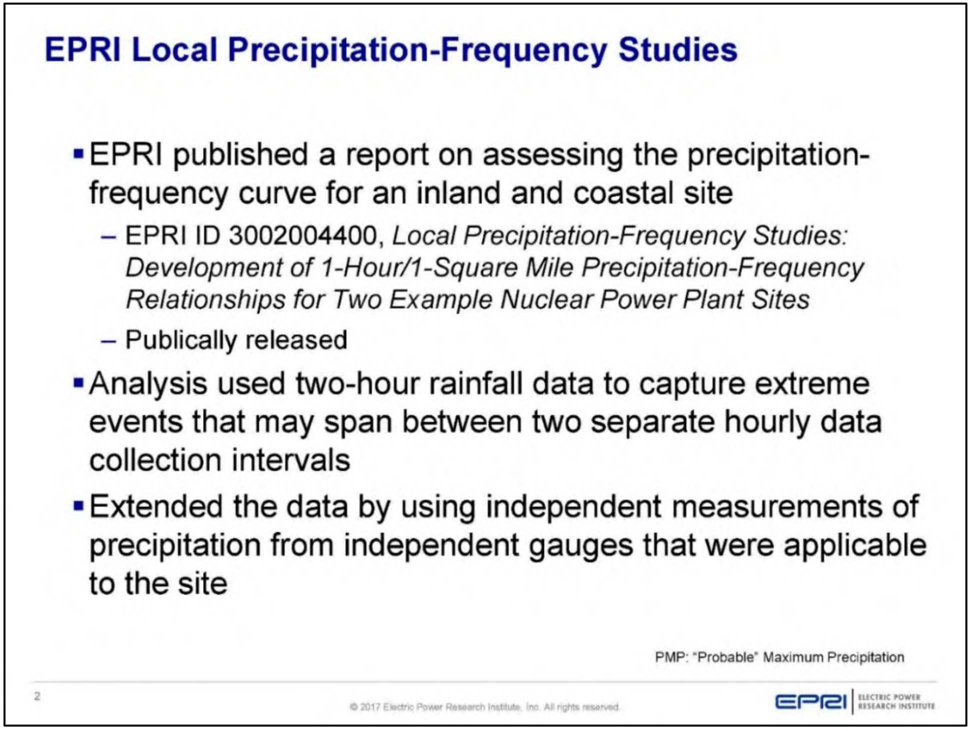
Local Intense Precipitation Frequency Studies

John E. Weglian
Senior Technical Leader

NRC External Flooding Research Workshop
1/24/2017



EPRI Local Precipitation-Frequency Studies

- EPRI published a report on assessing the precipitation-frequency curve for an inland and coastal site
  - EPRI ID 3002004400, *Local Precipitation-Frequency Studies: Development of 1-Hour/1-Square Mile Precipitation-Frequency Relationships for Two Example Nuclear Power Plant Sites*
  - Publically released
- Analysis used two-hour rainfall data to capture extreme events that may span between two separate hourly data collection intervals
- Extended the data by using independent measurements of precipitation from independent gauges that were applicable to the site

PMP: "Probable" Maximum Precipitation

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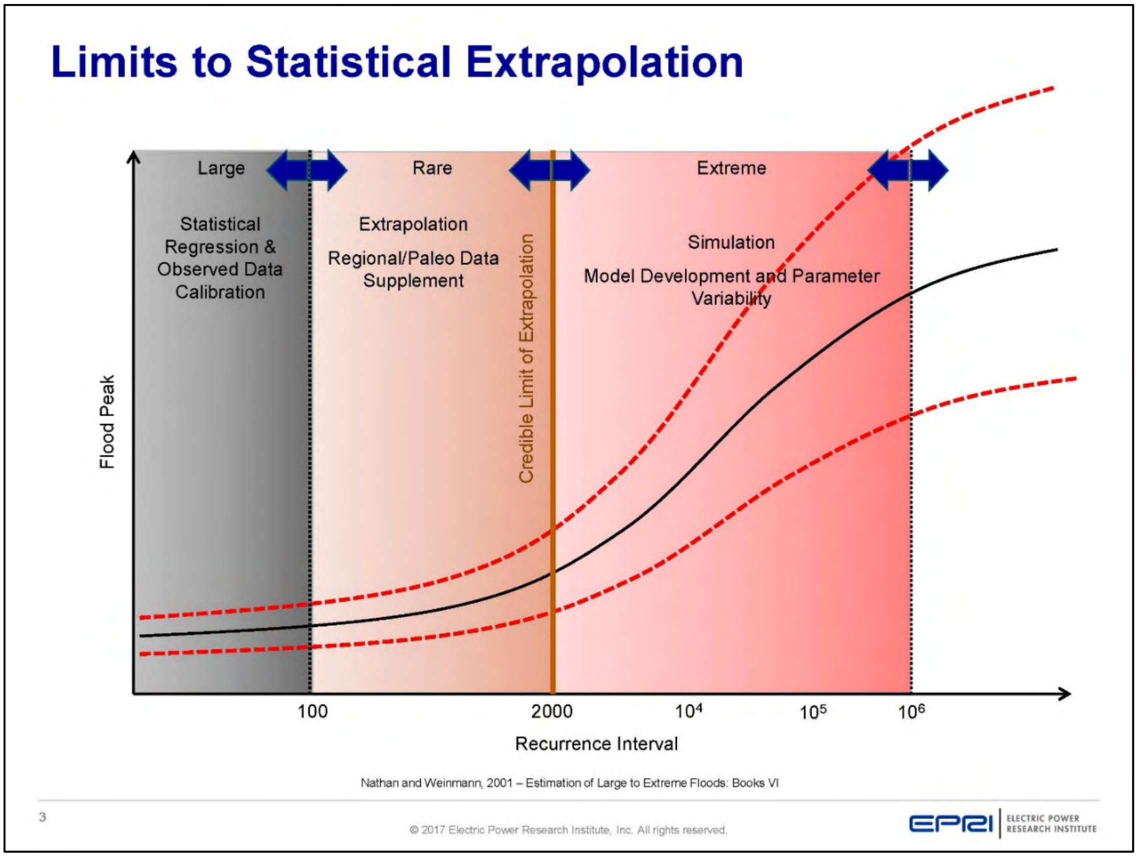
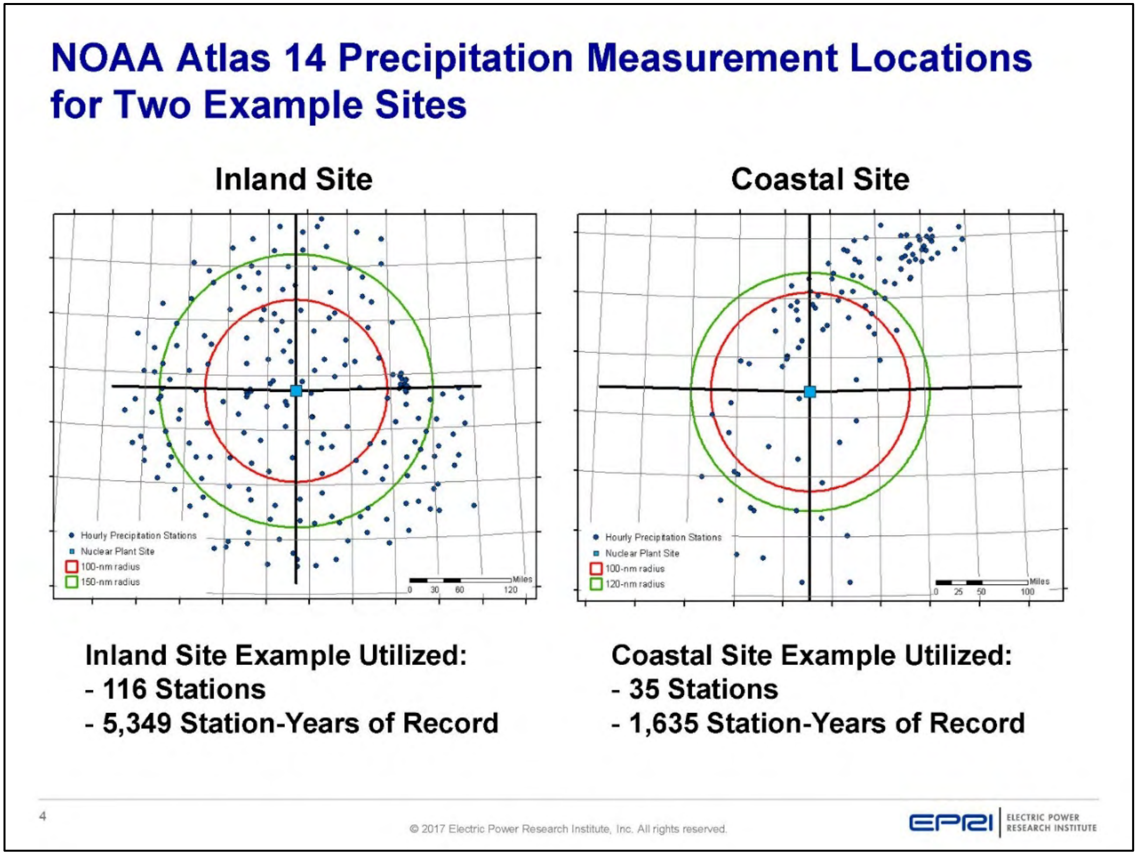


Limits to Statistical Extrapolation

Nathan and Weinmann, 2001 – Estimation of Large to Extreme Floods: Books VI



NOAA Atlas 14 Precipitation Measurement Locations for Two Example Sites

Inland Site

Coastal Site

Inland Site Example Utilized:
- 116 Stations
- 5,349 Station-Years of Record

Coastal Site Example Utilized:
- 35 Stations
- 1,635 Station-Years of Record

Seasonality

- Seasonality data can be used for modeling rainfall runoff
- Provides an estimate of soil-moisture conditions
- Probability of a storm where precipitation annual maxima exceeds the 20-year recurrence interval (inland site) or 10-year recurrence interval (coastal site) threshold is plotted vs the numerical date (e.g., July 20 = 7.65)
- The data is well described with a near-normal distribution both sites

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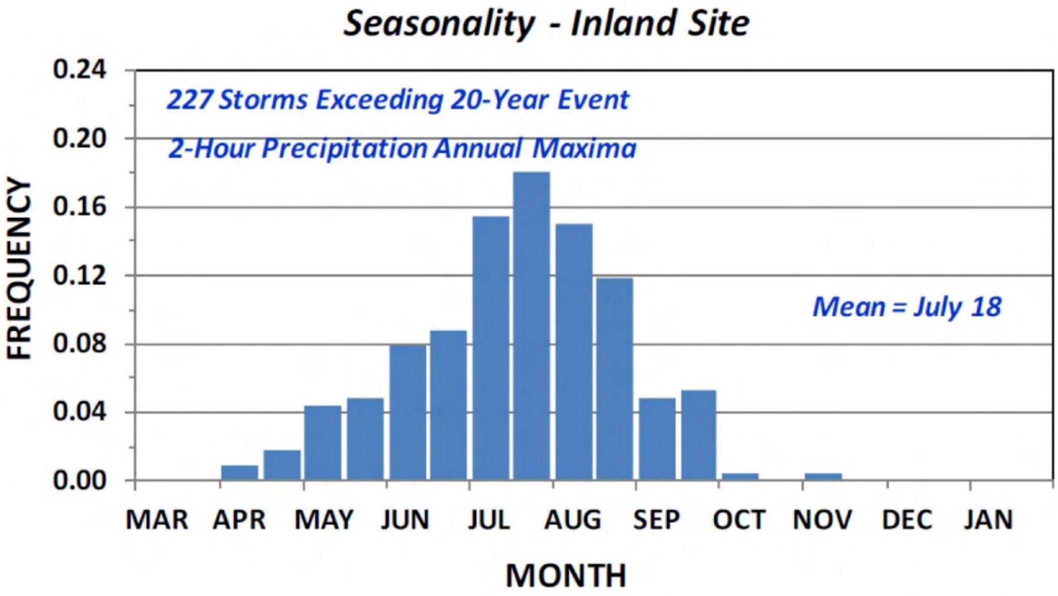
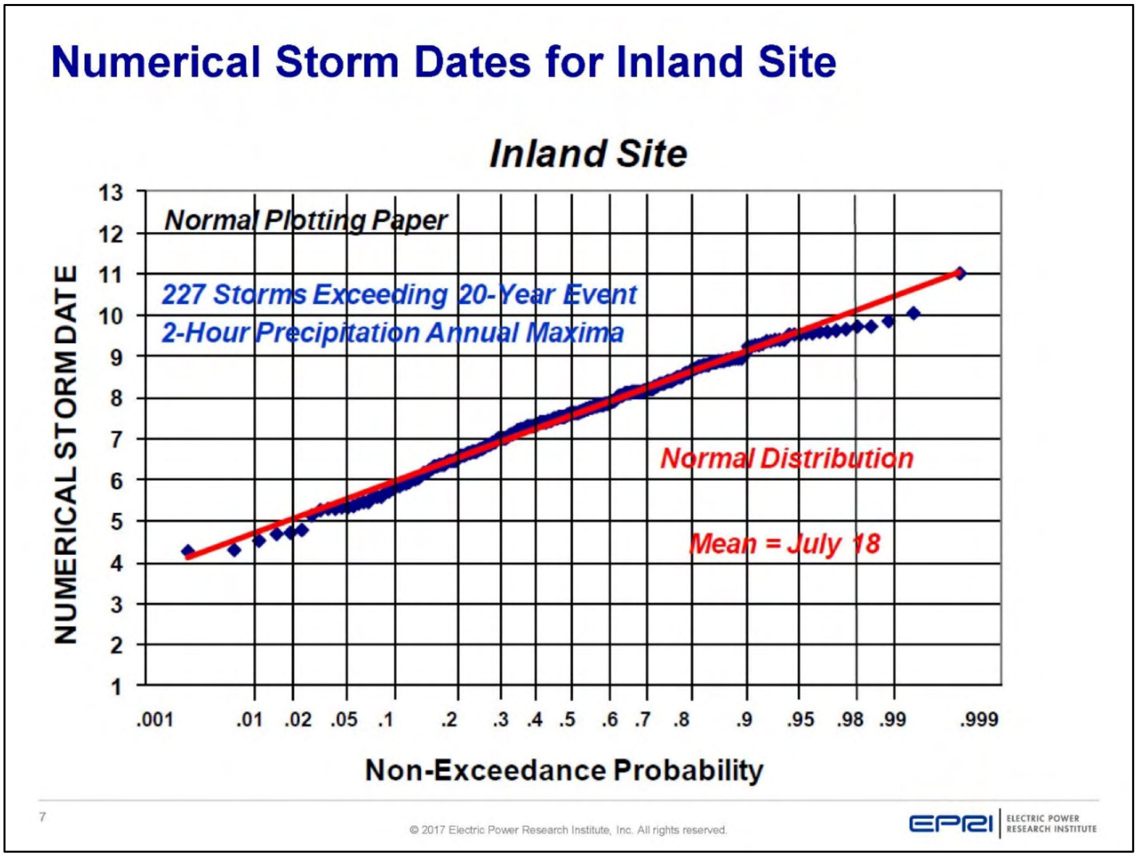
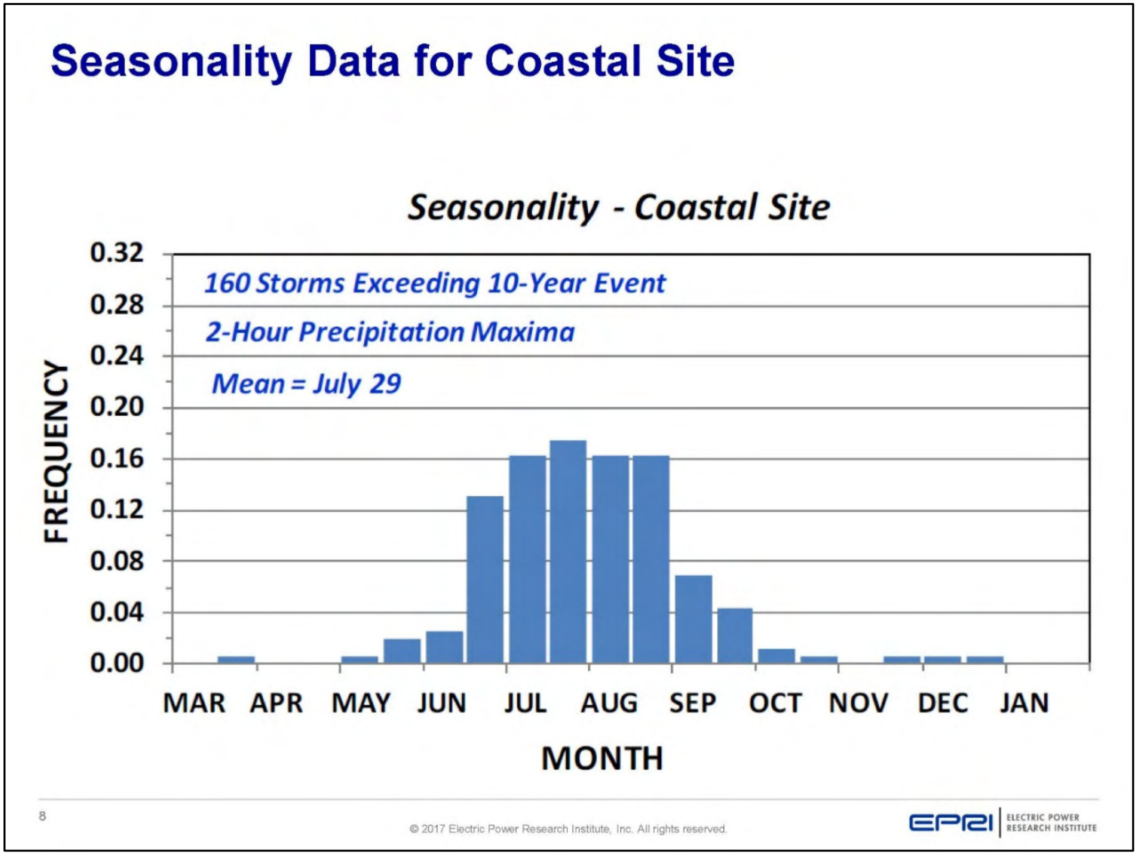
Seasonality Data for Inland Site



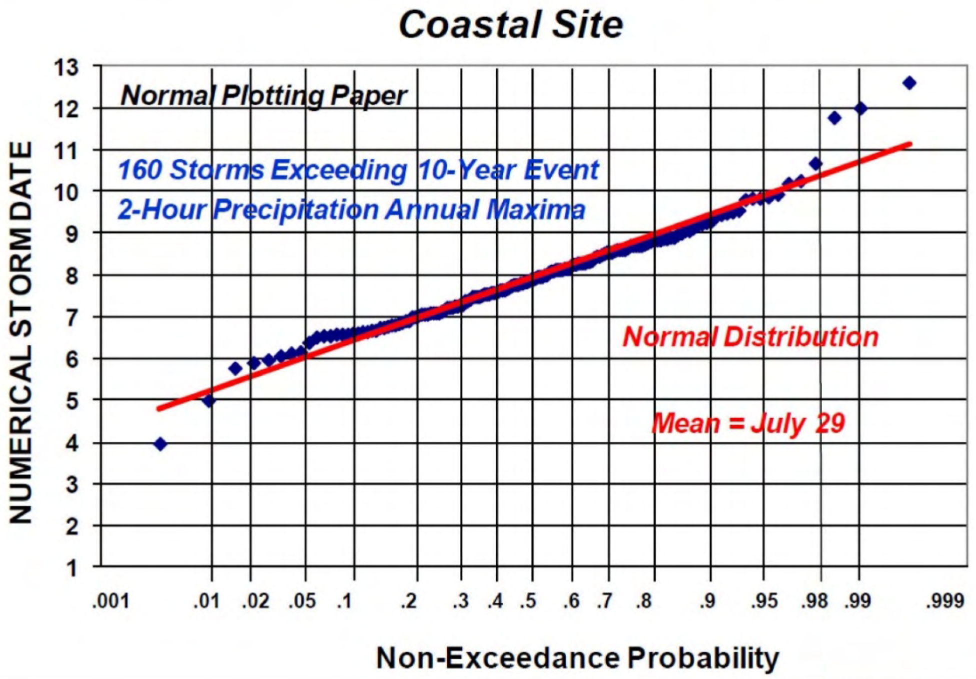


Numerical Storm Dates for Inland Site



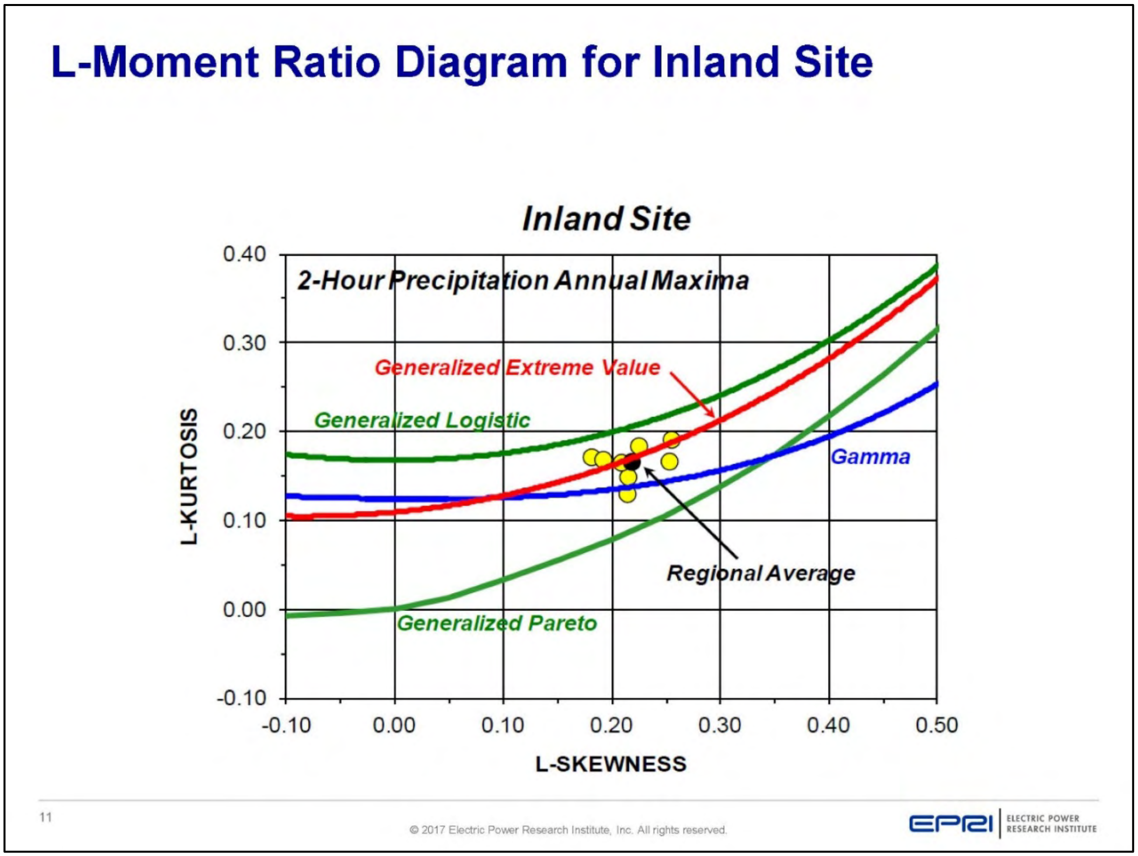
Seasonality Data for Coastal Site

Numerical Storm Dates for Coastal Site



Regional Probability Distributions

- Regional L-moments were computed for annual maxima data
- L-moment ratio diagrams were created with L-skewness and L-kurtosis pairs
- General Extreme Value (GEV) distribution was identified as a suitable three-parameter probability distribution
- The four-parameter Kappa distribution was selected to describe the annual maxima data
  - Very flexible and capable of emulating GEV distribution
  - Allows for possibility of emulating other distributions in an uncertainty analysis



L-Moment Ratio Diagram for Inland Site

11

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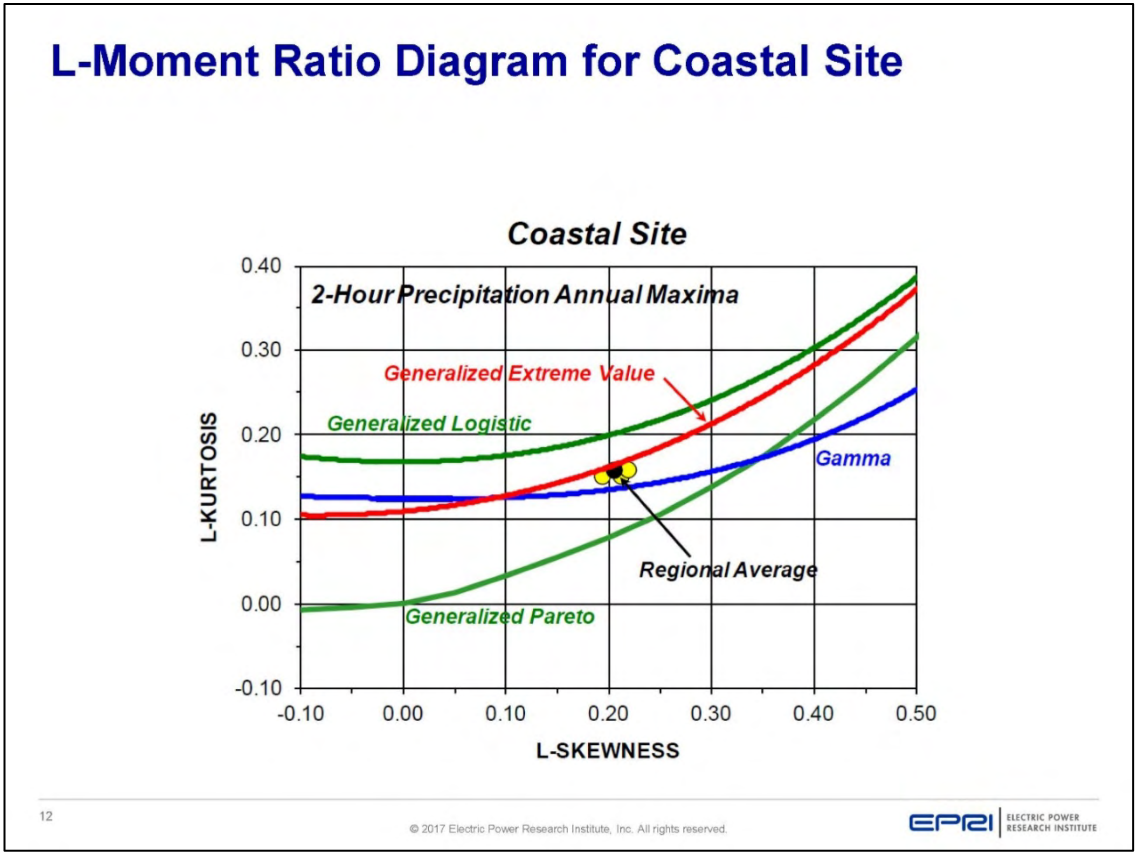

L-Moment Ratio Diagram for Coastal Site

12

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Equivalent Independent Record Length (ERIL)

- Applicable rain gauges in the vicinity of the site can be used if they measure independent storm events
- If the storms of interest have large areal coverage (relative to the gauge density), the ERIL will be small
  - Significant correlation between gauges would reduce the independent measurements
- If the storms of interest have small areal coverage, the ERIL will be large
- LIP analyses show that the storms of interest are small relative to the density of gauge stations

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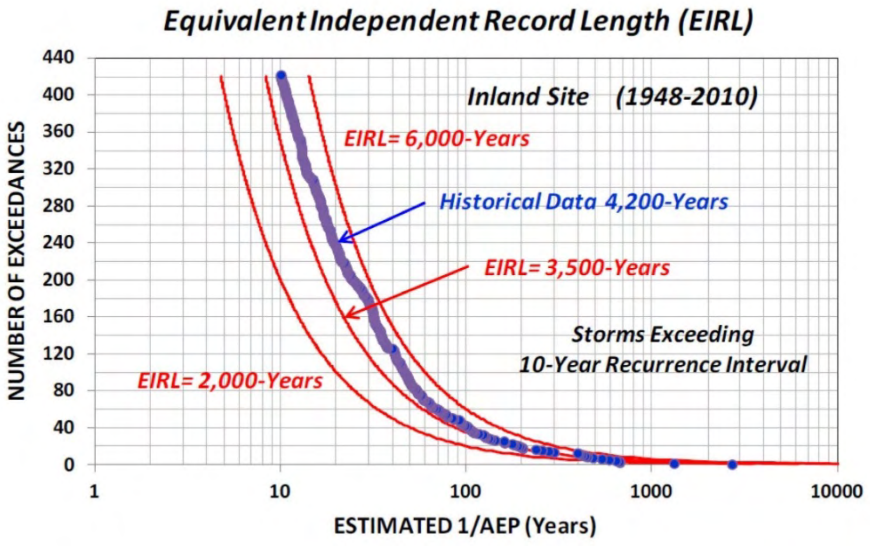
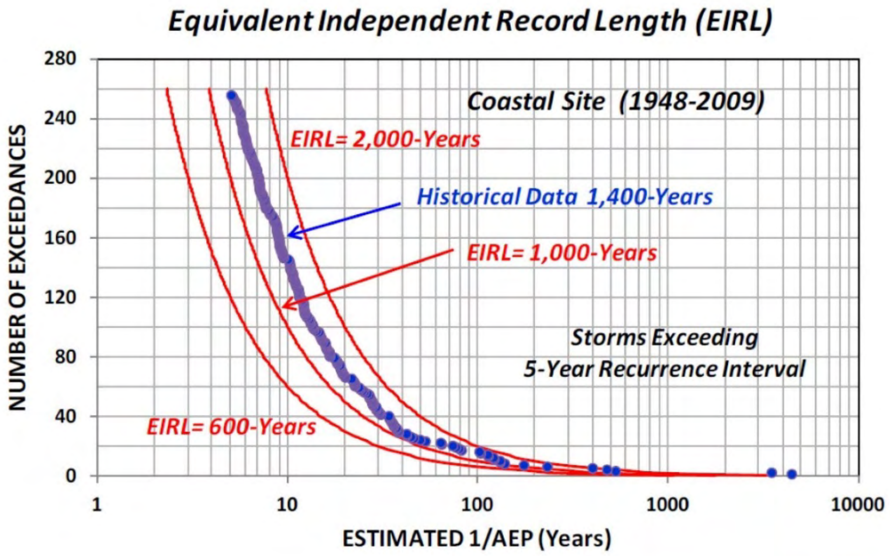
EIRL for Inland Site

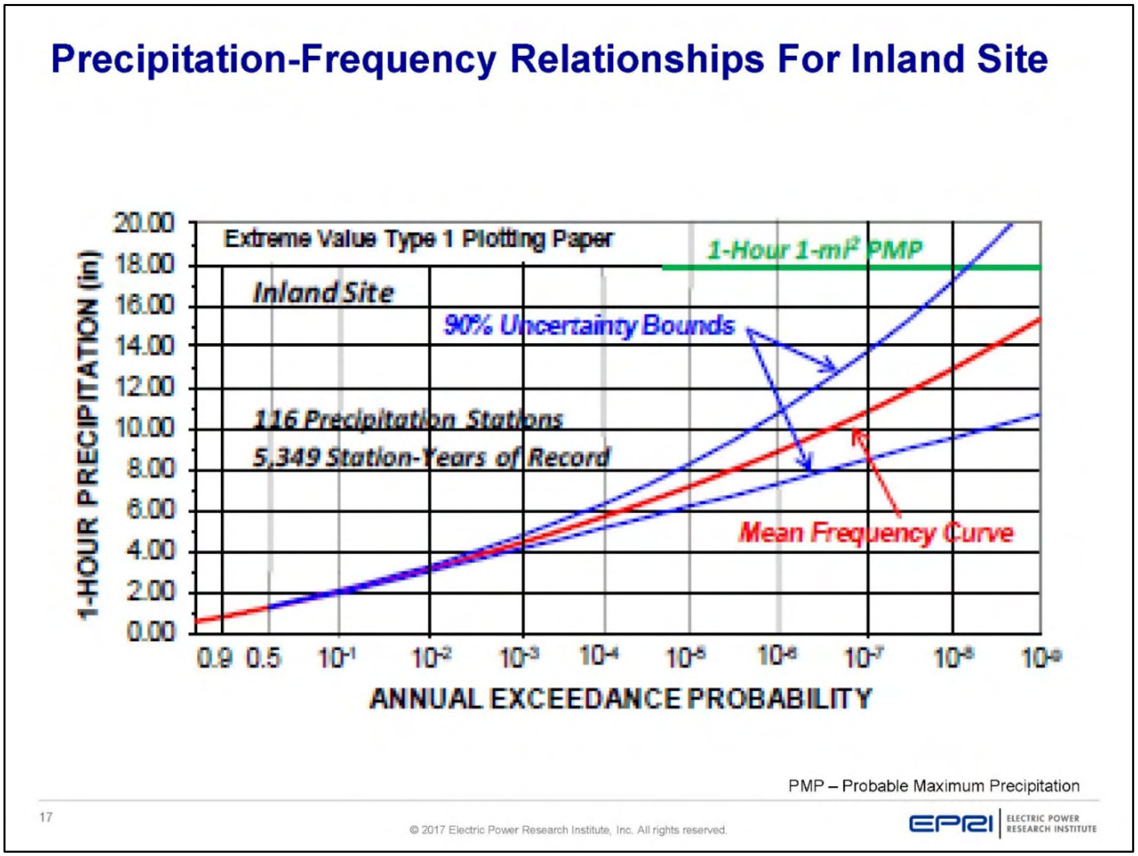


EIRL for Coastal Site



Assessment of Uncertainty

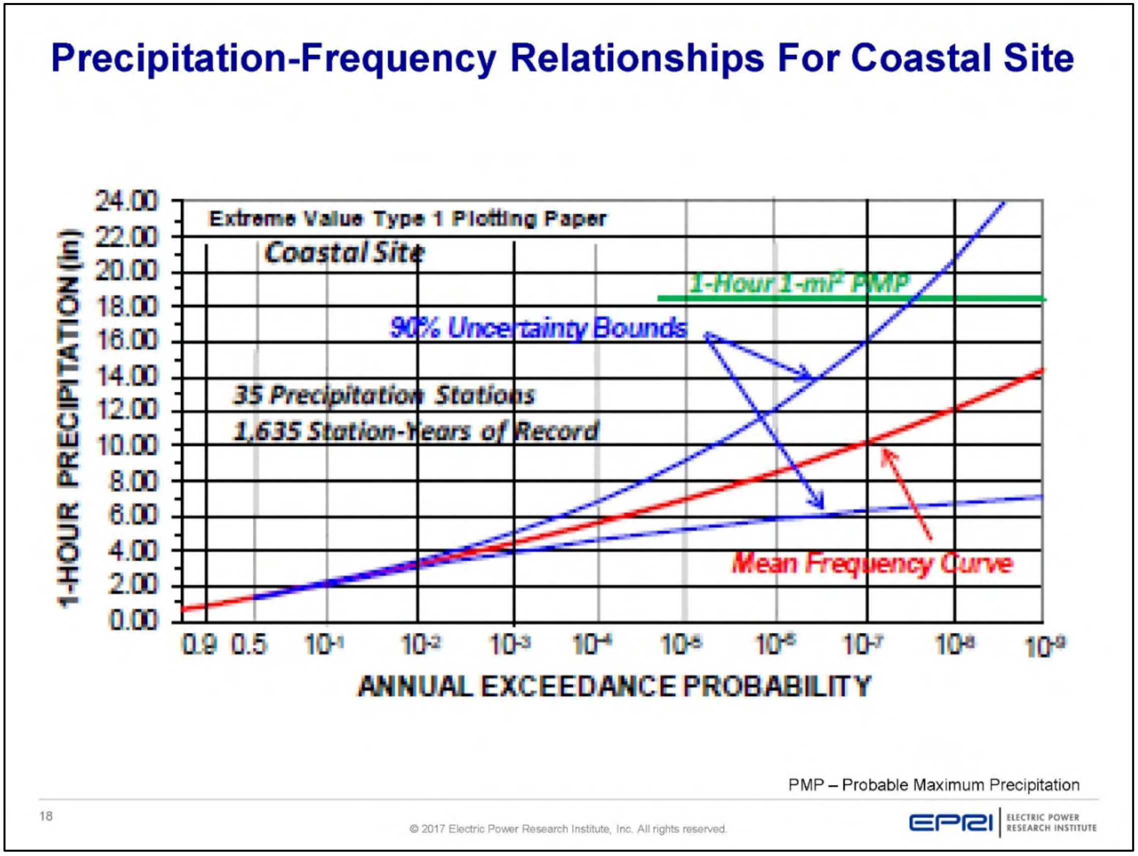
- Uncertainty was modeled considering the regional probability distribution to be a 3-parameter distribution represented by a form of the 4-parameter Kappa distribution with a fixed value of the 2nd shape parameter (h)
- In the uncertainty analysis, the parameter h was allowed to vary around the regional h value
- This method preserves the correlation between L-kurtosis and L-skewness and provides for variability in the shape parameter, h
- Latin-hypercube sampling used to select 1000 sample sets



Precipitation-Frequency Relationships For Inland Site

PMP – Probable Maximum Precipitation

EPRI | ELECTRIC POWER RESEARCH INSTITUTE



Precipitation-Frequency Relationships For Coastal Site

PMP – Probable Maximum Precipitation

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Local Precipitation Summary Statistics

Description	Inland Site	Coastal Site
PMP for the Site	17.9 “	18.4”
World Meteorological Organization Record Short Duration (1-Hour or Less) Rainfalls	12.0” – 15.8”	
Study Area 1-Hour Maximum Rainfall	3.5”	4.0”
Study Area 2-Hour Maximum Rainfall	5.5”	6.5”
PMP AEP Estimated by Extending Mean Precipitation-Frequency Relationship	$<10^{-9}$	$<10^{-9}$
10^{-6} AEP Precipitation Using Mean Precipitation-Frequency Relationship	8.9”	8.5”

AEP – Annual Exceedance Probability

Together…Shaping the Future of Electricity

John E. Weglian
Senior Technical Leader
jweglian@epri.com
704-595-2763

2.3.3.4.3 Questions and Answers

Comment:

Because of the dependence in the data, when nearby stations are used, you are basically creating a sample from the same store. As a result, when using the regional approach, the actual record is much shorter than perceived. It is not the sum of the station years from all the stations in the region. That sometimes leads to overconfidence when estimating precipitation frequency at extreme frequencies. This was a mistake; the first few volumes of NOAA Atlas 14 did not account for the spatial correlation and independence of observations at nearby stations, and therefore the confidence intervals in those volumes were very narrow. This approach gives the appearance of high levels of confidence in our estimates even for a return period of 1,000 years. One slide of the presentation showed a 1,000- or 2,000-year rare event, not even an extreme. I may be one of a few people who feels that we should not extrapolate to those return periods. One slide in a presentation for tomorrow will address this issue. There is lots of disagreement over this issue and feel that some type of approach must be taken, as some designs need those numbers. Although we are assuming a distribution, such as generalized extreme value (GEV) distribution, in many cases there are many other distributions that pass the statistical test. We use L-moments to calculate distribution parameters but there are other ways to fit distribution parameters. Because of this, when all these uncertainties are put together at the 1,000- and 2,000-year return periods, the range of estimates is so wide, practically between zero and infinity. We should be very careful when selecting those numbers and using them, especially in a deterministic mode as it is currently done in engineering design.

Response:

I agree that it is extremely dangerous to extrapolate to very long levels. For example, from my aerospace background, in the failure of the space shuttle Columbia, when analysts saw on the camera that foam had hit the leading edge of a wing on takeoff, they took the existing foam data and extrapolated three orders of magnitude to conclude that it was not an issue. That extrapolation was inaccurate and in fact there was a very serious issue. It is extremely difficult to rely on extrapolation to those extreme levels. Because of this, our industry relies both on deterministic, with a PMP approach, and risk-based approaches to help inform decisions. A PRA practitioner who wishes to assess vulnerabilities at a site to a level commensurate with other hazards faced there needs to have an estimate that can be used down to low frequencies (e.g., 10^{-6}), but also needs to keep in mind at the same time the wide range of uncertainty associated with such an estimate. The PRA can be used to show vulnerabilities to try to make the plant safer, but it cannot indicate that a plant is safe to a certain level and nothing can go wrong.

Comment:

The assignment of frequencies to deterministic stylized events is of concern (e.g., the frequency of exceedance of the PMP for a stylized 1-hour event), even understanding the deterministic concept and the assignment of assumptions. Ponding elevation on the ground is an important example. The value for this can come from a 1-hour event, 6-hour events, or any other durations, as well as different temporal distributions and other characteristics. As a result, we report this one number on this stylized event, and we underestimate the frequency of, for example, experiencing inconsequential flooding. There is not a one-to-one mapping between the concepts. Analysts should be cautious when using a frequency of one duration of precipitation from one type of event when the relevant consideration is the frequency of exceeding ponding elevations on the ground as a result from many different types of events.

Response:

This is a good point. The PRAs in other areas show something similar. For example, the risk of core damage from a large-break loss-of-coolant accident (LOCA) is extremely small because the probability of a large-break LOCA is extremely small. The probability of a small-break LOCA leading to core damage is usually significantly higher just because the event happens more often. Similarly, a lesser but longer duration flood may result in more water intrusion into a plant. Even if the flood does not result in a higher water level in the plant, it may still have some impact because it occurs more often and thus may challenge the plant enough to be more risk significant than the isolated worst-case scenario.

2.3.4 Day 2: Session 2B - Leveraging Available Flood Information I

This session covered research to develop the means by which the staff can leverage available frequency information on flooding hazards.

2.3.4.1 Development of Flood Hazard Information Digest for Operating NPP Sites,

Curtis Smith*, Ph.D. and Kellie Kvarfordt, Idaho National Laboratory (Session 2B-1; ADAMS Accession No. ML17054C508)

2.3.4.1.1 Abstract

The objective of this project is for Idaho National Laboratory (INL) to develop and demonstrate a database architecture for a flood hazard information digest to facilitate gathering, organizing, and presenting a variety of flood hazard data sources. Additionally, INL is assisting in the population of the digest.

The goal of the project is to provide information and tools to support external flooding-related activities, particularly the risk-informed aspects of the Significance Determination Process (SDP). Under the SDP, the use of probabilistic flood hazard information and insights is an important input in the determination for follow-up inspection actions and resource allocation, and for risk-informing licensing actions. However, the NRC staff has had to improvise and only use probabilistic flooding hazard estimates on an ad hoc basis, in a limited manner, with acknowledged limitations with respect to the technical defensibility of the resulting estimates.

A particular challenge in developing probabilistic flooding hazard estimates within the SDP is that the required flood hazard information is not readily accessible. It is challenging for the NRC staff to assemble and analyze the information within the time available for the SDP. Thus, there is a need to better organize flooding information at operating reactor sites and improve its accessibility for the NRC staff performing SDP analyses. The Flood Hazard Information Digest application has been developed to address these needs.

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

- flood hazard information, including flood protection and mitigation strategies, available from sources that include NUREGs, final safety analysis reports, individual plant examination for external events submittals, and SDP analyses
- recommendations of the Fukushima Near-Term Task Force (ML111861807)

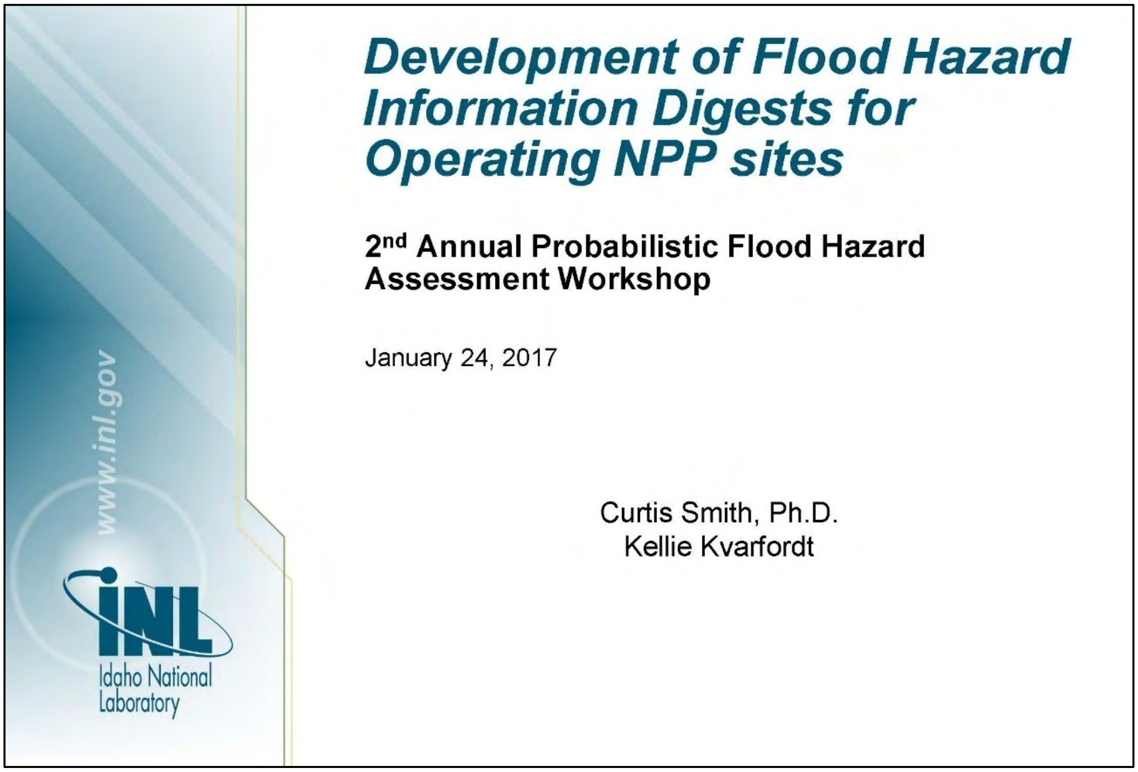
    - Recommendation 2.1: Flood hazard reevaluation submittals
    - Recommendation 2.3: Walkdown submittals
- available precipitation frequency information from the NOAA Atlas 14 database
- available flood frequency information from U.S. Geological Survey (USGS) databases
- available information for hurricane landfall and intensity along U.S. coastal areas

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

The Flood Hazard Information Digest has been implemented as a cloud-based Web application. The digest utilizes INL's Safety Portal, a system that helps integrate and manage a comprehensive collection of many different kinds of content, including Web pages, Web applications, models, and documents, where users may store, use, share, modify, or otherwise contribute to projects. The emphasis of the Safety Portal is to serve as a resource to promote collaboration between producers and users of information. The flood digest shares available services such as user account management, file sharing, and a publications/permissions/ subscriptions model.

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

2.3.4.1.2 Presentation



Development of Flood Hazard Information Digests for Operating NPP sites

2nd Annual Probabilistic Flood Hazard Assessment Workshop

January 24, 2017

Curtis Smith, Ph.D.
Kellie Kvarfordt

Project Overview

- Organize flooding information and build database of currently available site-specific flood hazard information to
  - Support development of a risk-informed analytical approach for flood hazards
  - Help Senior Reactor Analysts (SRAs) develop simple flooding models and reasonable hazard curves that fit into SAPHIRE modeling world

…in order to
  - Develop regulatory tools and guidance for NRC staff with regard to probabilistic flood hazard assessment (PFHA) for nuclear facilities
  - Support risk-informed reactor oversight activities such as evaluating the risk-significance of inspection findings

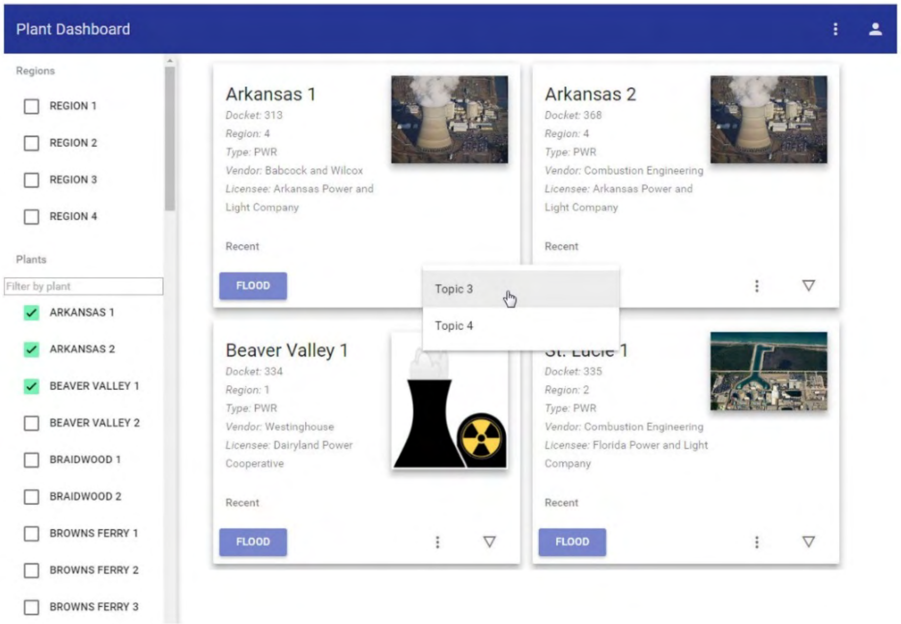
Status

- Completed
  - Flooding Hazard Information Needs Workshop
  - Reviewed existing NRC databases
  - Designed and implemented beta of flood hazard information database
  - Produced Draft User Guide
  - Beta testing/demonstrations over the summer
    - Received many good comments
    - Lots of different viewpoints
- Remaining
  - Final Users Guide
  - PFHA Summary Report
  - Database population

Flood Digest Web Application

*Registration and approval required

Plant Dashboard



☐ REGION 1
☐ REGION 2
☐ REGION 3
☐ REGION 4

☑ ARKANSAS 1
☑ ARKANSAS 2
☑ BEAVER VALLEY 1
☐ BEAVER VALLEY 2
☐ BRAIDWOOD 1
☐ BRAIDWOOD 2
☐ BROWNS FERRY 1
☐ BROWNS FERRY 2
☐ BROWNS FERRY 3

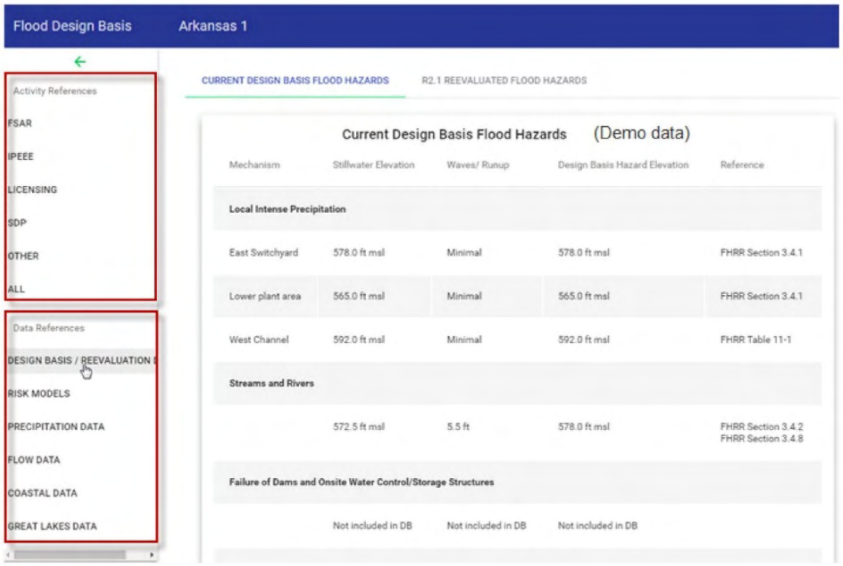
Arkansas 1
Docket: 313
Region: 4
Type: PWR
Vendor: Babcock and Wilcox
Licensee: Arkansas Power and Light Company
Recent

Arkansas 2
Docket: 368
Region: 4
Type: PWR
Vendor: Combustion Engineering
Licensee: Arkansas Power and Light Company
Recent

Beaver Valley 1
Docket: 334
Region: 1
Type: PWR
Vendor: Westinghouse
Licensee: Dairyland Power Cooperative
Recent

St. Lucie 1
Docket: 335
Region: 2
Type: PWR
Vendor: Combustion Engineering
Licensee: Florida Power and Light Company
Recent

Drill-down to Flood Activities and Data References



Flood Design Basis   Arkansas 1

Activity References
- FSAR
- IPEEE
- LICENSING
- SDP
- OTHER
- ALL

Data References
- DESIGN BASIS / REEVALUATION
- RISK MODELS
- PRECIPITATION DATA
- FLOW DATA
- COASTAL DATA
- GREAT LAKES DATA

CURRENT DESIGN BASIS FLOOD HAZARDS   R2.1 REEVALUATED FLOOD HAZARDS

Current Design Basis Flood Hazards   (Demo data)

Mechanism	Stillwater Elevation	Waves/ Runup	Design Basis Hazard Elevation	Reference
Local Intense Precipitation				
East Switchyard	578.0 ft msl	Minimal	578.0 ft msl	FHRR Section 3.4.1
Lower plant area	565.0 ft msl	Minimal	565.0 ft msl	FHRR Section 3.4.1
West Channel	592.0 ft msl	Minimal	592.0 ft msl	FHRR Table 11-1
Streams and Rivers				
	572.5 ft msl	5.5 ft	578.0 ft msl	FHRR Section 3.4.2 FHRR Section 3.4.8
Failure of Dams and Onsite Water Control/Storage Structures				
	Not included in DB	Not included in DB	Not included in DB	

Key Data Sources

- Mitigating Strategies Flood Hazard Information (MSFHI)
  - Current Design Basis
  - R2.1 Reevaluated Flood Hazards
- US Geological Survey (USGS)
  - Flow Data
- National Oceanic Atmospheric Administration (NOAA)
  - Precipitation Data
  - Coastal Datums, Sea Level Trends, and Extreme Water Levels
  - Great Lakes Data Inventory
  - Hurricane Historical Data

Key Document Sources

- Final Safety Analysis Reports (FSARs)
- Individual Plant Examination for External Events (IPEEE) submittals
- Significance Determination Process (SDP) Analyses
- Fukushima Near Term Task Force (NTTF)
  - 2.1 Flood Hazard Reevaluation submittals
  - 2.3 Walk-down submittals
- NUREG Publications

Summary

- Flood Hazard Information Digest utilizes the Safety Portal as a resource emphasizing collaborative focus between producers and users of information
- The Flood Hazard Information Digest further organizes and presents a variety of relevant, plant specific information
- Major data sources have been identified and interfaces established using sample data
- Database population efforts will be main activity for this project during FY17
- Application was designed in such a way as to facilitate additional external event hazards if needed

Contacts

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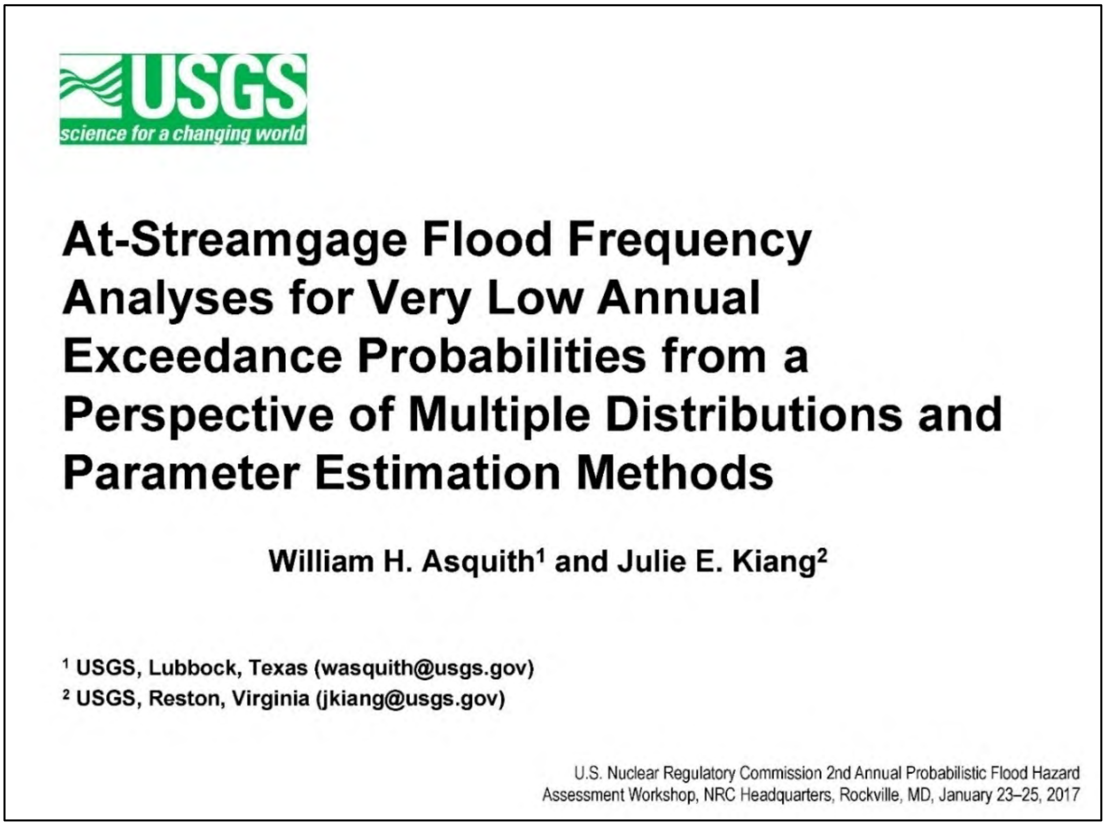
2.3.4.2 At-Streamgage Flood Frequency Analyses for Very Low Annual Exceedance Probabilities from a Perspective of Multiple Distributions and Parameter Estimation Methods, William H. Asquith^, Ph.D., P.G., U.S. Geological Survey, Lubbock, TX; and Julie Kiang, Ph.D., U.S. Geological Survey, Reston, VA (Session 2B-2; ADAMS Accession No. ML17054C509)

2.3.4.2.1 Abstract

USGS , in cooperation with the NRC, is investigating statistical methods for flood hazard analyses. One task is to provide guidance on very low annual exceedance probability (AEP) estimation and the quantification of corresponding uncertainties using streamgage-specific data. The term “very low AEP” implies exceptionally rare events, defined as those having AEPs less than about 0.001 (or 10^{-3} in scientific notation). Such low AEPs are of great interest for flood frequency analyses for critical infrastructure such as NPPs. Flood frequency analyses at streamgages are most commonly based on annual instantaneous peak streamflow data and a probability distribution fit to these data. The fitted distribution provides a means to extrapolate to small AEPs . Within the United States, the Pearson type III probability distribution, when fit to the base-10 logarithms of streamflow, is widely used, but other distribution choices exist. The USGS - PeakFQ software implementing well-known guidelines of USGS**Error! Bookmark not defined.**, Bulletin 17B “Guidelines for Determining Flood Flow Frequency,” issued 1982 (method of moments), and pending updates (Bulletin 17C , the expected moments algorithm using the Pearson type III) was specially adapted for an “Extended Output” user option to provide estimates at selected AEPs from 10^{-3} to 10^{-6}. Parameter estimation methods, in addition to the product moments and expected moments algorithm, include L-moments, maximum likelihood, and maximum product of spacings (maximum spacing estimation). This project comprehensively studies multiple distributions and parameter estimation methods for two USGS streamgages (01400500 Raritan River at Manville, NJ, and 01638500 Potomac River at Point of Rocks, MD). This task involved the four techniques of parameter estimation and up to nine probability distributions, including the generalized extreme value, generalized log-normal, generalized Pareto, and Weibull. Uncertainties in streamflow estimates related to AEP are depicted and quantified as two primary forms: quantile (aleatoric (random sampling) uncertainty)and distribution-choice (epistemic (model) uncertainty). Sampling uncertainties of a given distribution are relatively straightforward to compute from analytical or Monte Carlo-based approaches. Distribution-choice uncertainty stems from choices of potentially applicable probability distributions for which divergence among the choices increases as AEP decreases. Conventional goodness-of-fit statistics, such as Cramér-von Mises, and L-moment ratio diagrams are demonstrated to hone distribution choice. The results in a generalized sense show that distribution choice uncertainty is larger than sampling uncertainty for very low AEP values. Future work includes consideration of nonstandard flood data at streamgage locations, regional information, and nonstationarity in flood frequency analyses.

2.3.4.2.2 Presentation

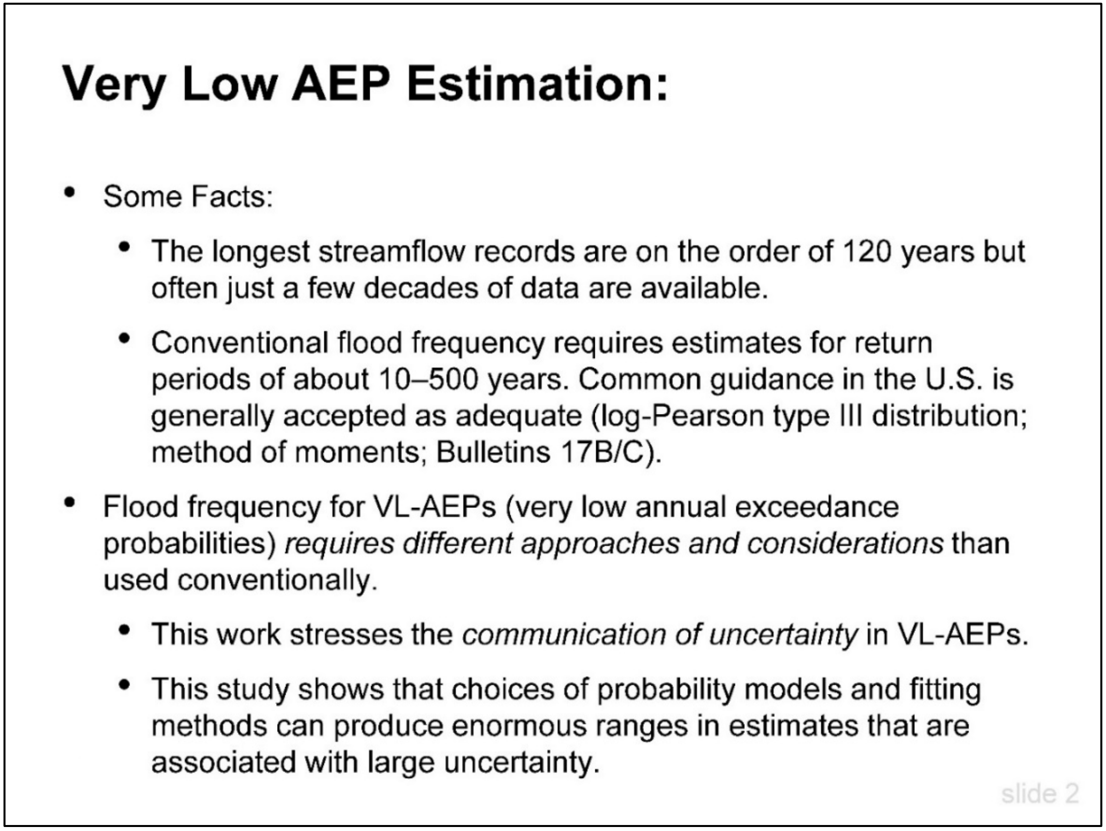


At-Streamgage Flood Frequency Analyses for Very Low Annual Exceedance Probabilities from a Perspective of Multiple Distributions and Parameter Estimation Methods

William H. Asquith[1] and Julie E. Kiang[2]

[1] **USGS, Lubbock, Texas (wasquith@usgs.gov)**
[2] **USGS, Reston, Virginia (jkiang@usgs.gov)**

U.S. Nuclear Regulatory Commission 2nd Annual Probabilistic Flood Hazard
Assessment Workshop, NRC Headquarters, Rockville, MD, January 23–25, 2017



Very Low AEP Estimation:

- Some Facts:
  - The longest streamflow records are on the order of 120 years but often just a few decades of data are available.
  - Conventional flood frequency requires estimates for return periods of about 10–500 years. Common guidance in the U.S. is generally accepted as adequate (log-Pearson type III distribution; method of moments; Bulletins 17B/C).
- Flood frequency for VL-AEPs (very low annual exceedance probabilities) *requires different approaches and considerations* than used conventionally.
  - This work stresses the *communication of uncertainty* in VL-AEPs.
  - This study shows that choices of probability models and fitting methods can produce enormous ranges in estimates that are associated with large uncertainty.

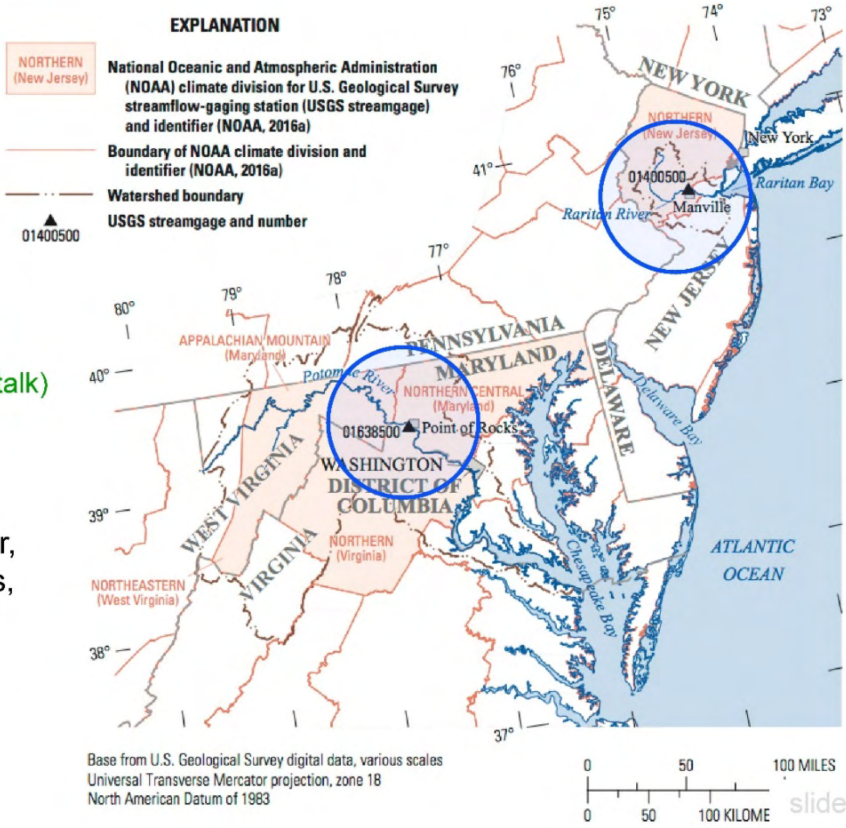
Overall Project Details

- **U.S. Geological Survey in cooperation with U.S. Nuclear Regulatory Commission (2015–2017)**
- **Magnitude and frequency of instantaneous peak streamflow**
  - **Task 1 (This talk and pending USGS Scientific Investigations Report [SIR])**
  - Tasks 2 and 3 (nonstandard flood information, nonstationarity, another USGS SIR)
  - Task 4 (USGS-led training seminar)
- **Task 1 concerns estimation at very low AEPs (VL-AEPs) and uncertainty (error) quantification.**
- DATA: annual peaks at two USGS long-term streamgages.
- **AEP: annual exceedance probability and VL-AEP < 0.001 or >1,000 year equivalent recurrence intervals [“AEP” preferred].**
- We also say “distal tail estimation” when VL-AEP are sought.

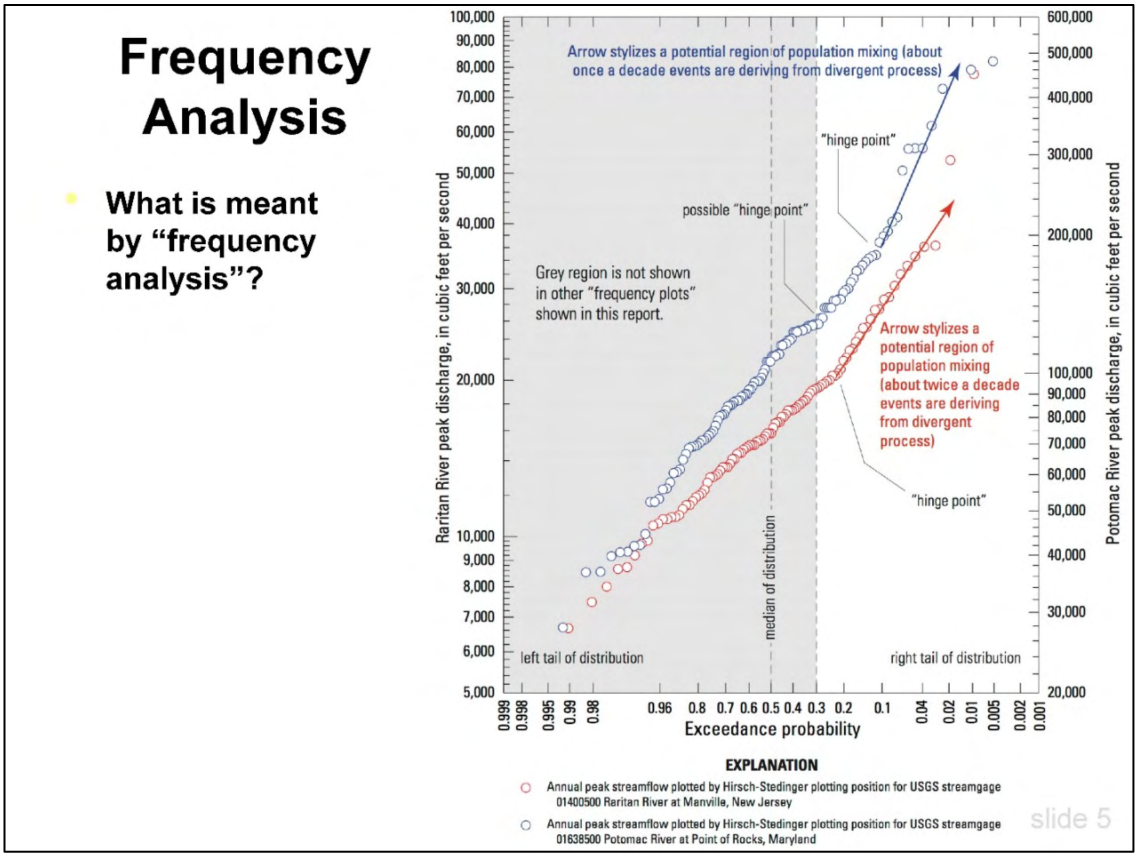
Raritan River,
Manville, NJ
≈1904–2014
(highlighted in talk)

and

Potomac River,
Point of Rocks,
MD
≈1895–2015

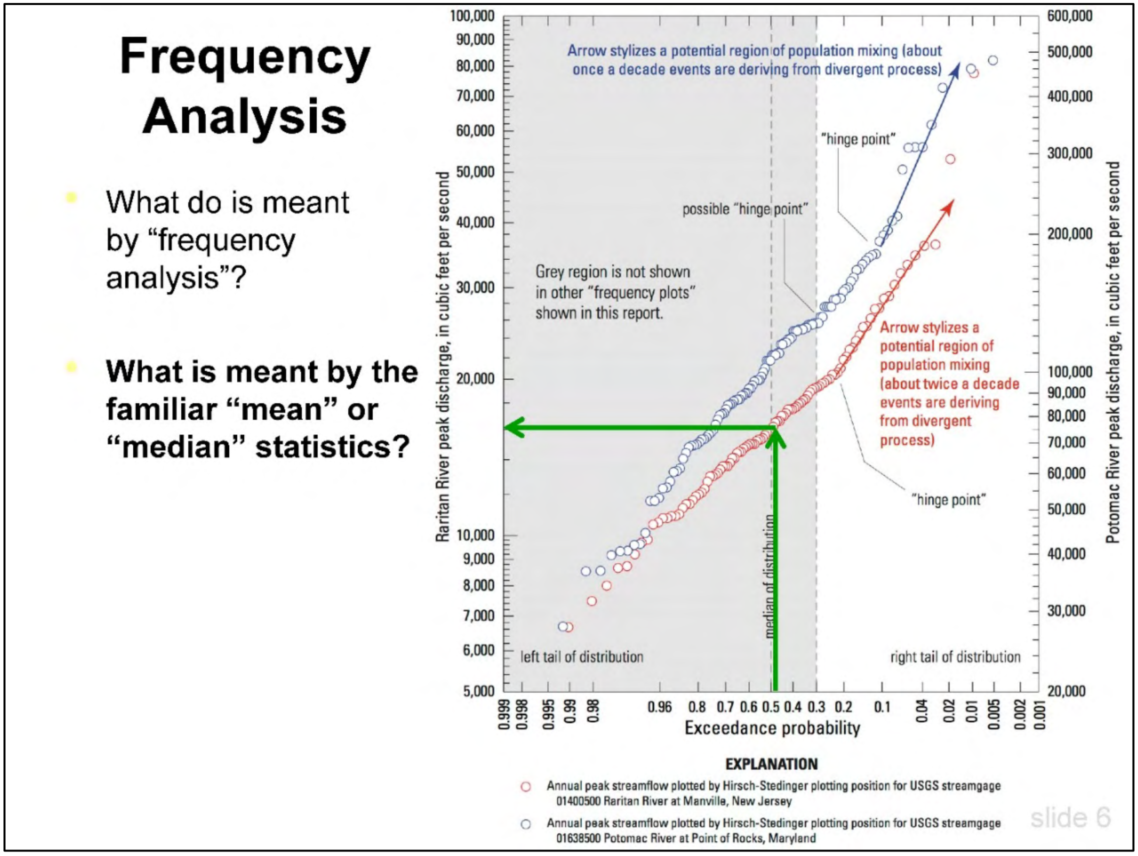


Base from U.S. Geological Survey digital data, various scales
Universal Transverse Mercator projection, zone 18
North American Datum of 1983



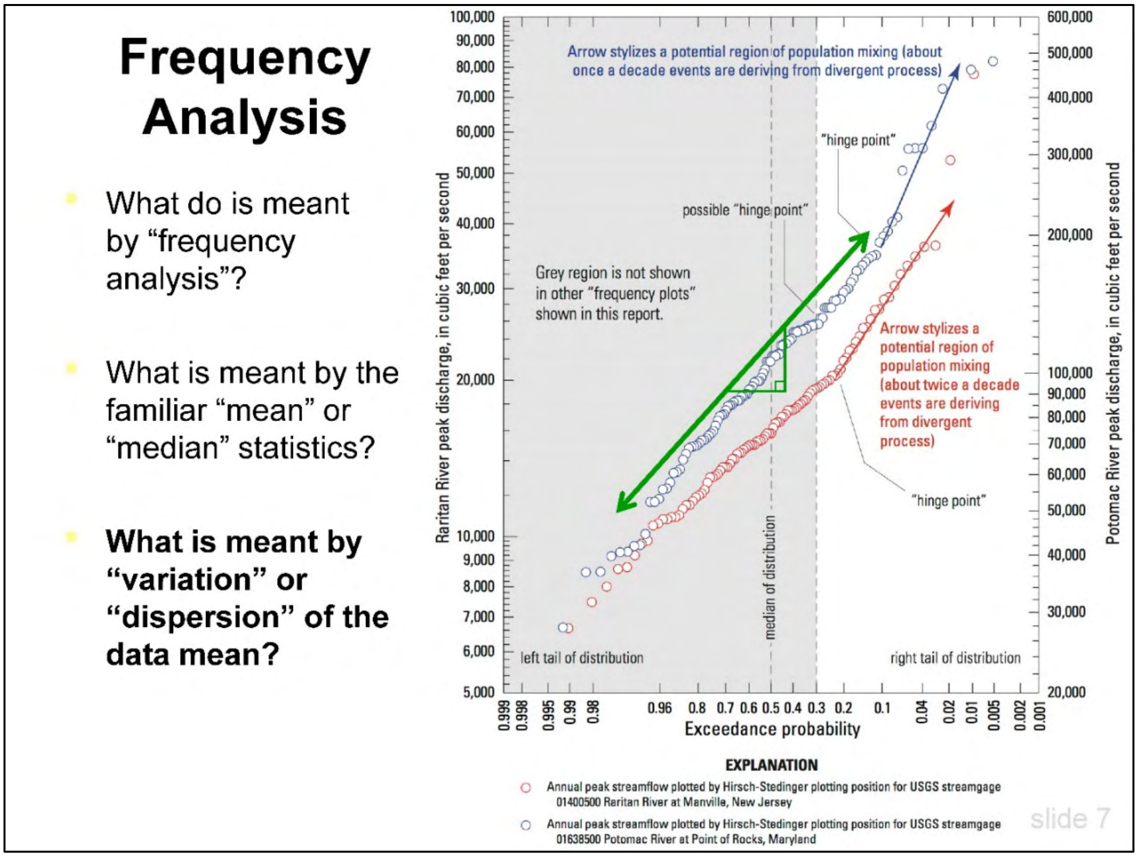
Frequency Analysis

- **What is meant by “frequency analysis”?**



Frequency Analysis

- What do is meant by “frequency analysis”?
- **What is meant by the familiar “mean” or “median” statistics?**



Frequency Analysis

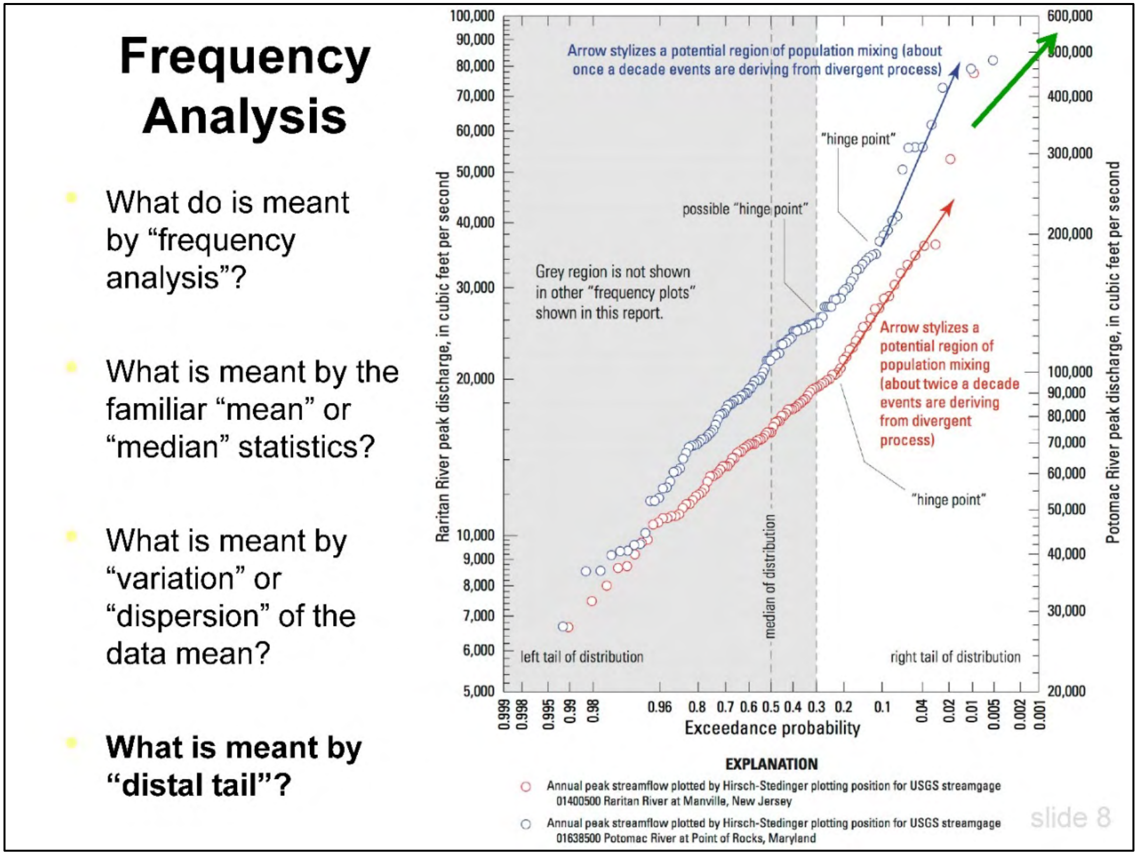
- What do is meant by “frequency analysis”?
- What is meant by the familiar “mean” or “median” statistics?
- **What is meant by “variation” or “dispersion” of the data mean?**

EXPLANATION

○ Annual peak streamflow plotted by Hirsch-Stedinger plotting position for USGS streamgage 01400500 Raritan River at Manville, New Jersey

○ Annual peak streamflow plotted by Hirsch-Stedinger plotting position for USGS streamgage 01638500 Potomac River at Point of Rocks, Maryland

slide 7



Frequency Analysis

- What do is meant by “frequency analysis”?
- What is meant by the familiar “mean” or “median” statistics?
- What is meant by “variation” or “dispersion” of the data mean?
- **What is meant by “distal tail”?**

EXPLANATION

○ Annual peak streamflow plotted by Hirsch-Stedinger plotting position for USGS streamgage 01400500 Raritan River at Manville, New Jersey

○ Annual peak streamflow plotted by Hirsch-Stedinger plotting position for USGS streamgage 01638500 Potomac River at Point of Rocks, Maryland

slide 8

Task 1 Details — Uncertainty

- **At-streamgage analysis (single site data)**
  - **Exclusion of covariates (conditional probability) influencing distal tails (*quantile dependency* [e.g. Tropical Cyclones as possible trigger for highest magnitude peaks])**
- **Quantification of uncertainty into two forms:**
  - ***Sampling uncertainty* (aleatoric, random chance [stochastic])**
    - This is a <u>sampling error</u> related to variances-covariances of either sample moments or parameters. This uncertainty can be reduced by including more data.

Task 1 Details — Uncertainty

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    - This is a <u>sampling error</u> related to variances-covariances of either sample moments or parameters. This uncertainty can be reduced by including more data.
  - ***Distribution choice uncertainty* (epistemic, model error)**
    - True probability model unknown, semi-quantitative, dependent on choices. This uncertainty can possibly be reduced by regional study of distribution tails and goodness-of-fit.

Both uncertainties increase as AEP decreases, and both are relatively large for very low AEP estimation.

Task 1 Details — Distributions

- **Logarithmic transformation of annual peaks used, and the adjective "log-" (e.g. log-Pearson type III) implied in talk.**
- **Nine probability distributions:**
  - Generalized Extreme Value (GEV, three parameter)
  - Generalized Logistic (GLO, three parameter)
  - Generalized ("skew") Normal (GNO, three parameter; log-Normal3)
  - Generalized Pareto (GPA, three parameter)
  - Pearson type III (PE3, three parameter; a standard choice in U.S.)
  - Weibull (WEI, three parameter; reversed GEV)
  - Kappa (KAP, four parameters; common in regional L-moments)
  - Asymmetric Exponential Power (AEP4, four parameters)
  - Wakeby (five parameters)

Task 1 Details — Parameter Estimation

- **Four methods of parameter estimation are used:**
  - Expected Moments Algorithm (EMA, product moments) though restricted to PE3 (Pearson type III). "Bulletin 17C" publication pending from USGS.
    - Special "Extended Output" option added to USGS-PeakFQ software for <0.001 AEP estimation and on out to AEP = 10^{-6}.

$$M_r = \mathrm{E}[(X-\mu)^r] = \int_{-\infty}^{\infty} (x-\mu)^r f(x)\,\mathrm{d}x$$

  - L-moments (LMR): linear combinations of the *quantile function*

$$\lambda_r = \frac{1}{r}\sum_{k=0}^{r-1}(-1)^k \binom{r-1}{k} \frac{n!}{(j-1)!(n-j)!} \int_0^1 x(F) \times F^{j-1} \times (1-F)^{n-j}\,\mathrm{d}F,$$

  - Maximum Likelihood (MLE): maximization of sum of logarithmic densities via *probability density function*

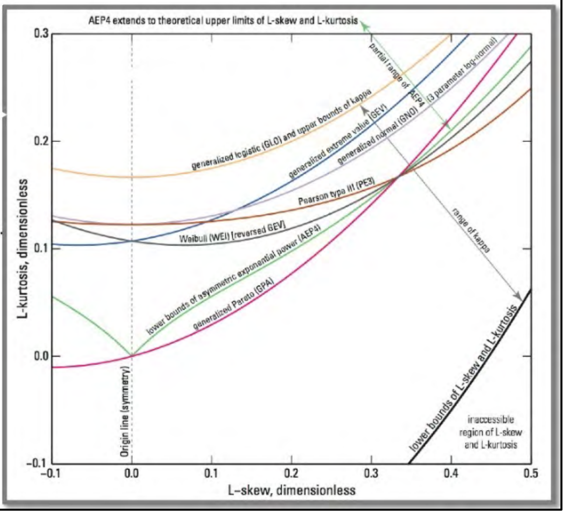
$$\log(L_n) = \sum_{i=1}^{n} \log(f(x_i;\theta)),$$

  - Maximum Product of Spacings (MPS): maximization of sum of U-statistic increments of the *cumulative distribution function*

$$M_n(\theta) = \sum_{i=1}^{n+1} \log\left[U_i(\theta) - U_{i-1}(\theta)\right] \text{ for } U_i(\theta) = F(x_{i:n};\theta)$$

Task 1 Details — Goodness-of-Fit

- **Goodness-of-Fit measures considered for the distributions:**
  - **Akaike Information Criterion (AIC)**
  - **Cramér–von Mises**
  - **Moran's M**
  - **Kolmogorov–Smirnov**
- **L-moment ratio diagram**
  - Delta L-kurtosis — The difference between L-kurtosis of a fitted distribution and the sample L-kurtosis.
  - Three-parameter distributions have their own unique L-kurtosis once fit to the mean, variation, and L-skew.

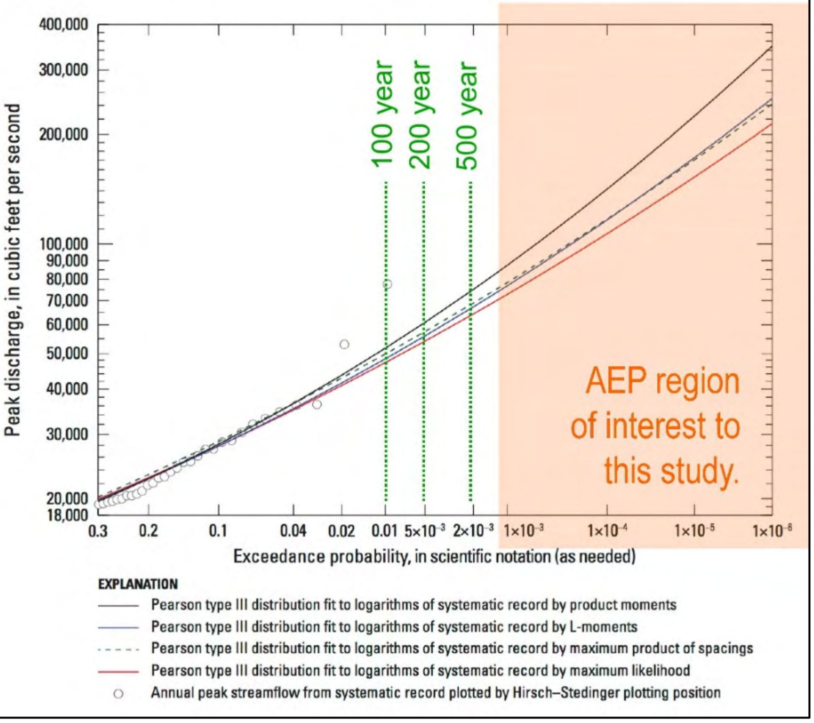


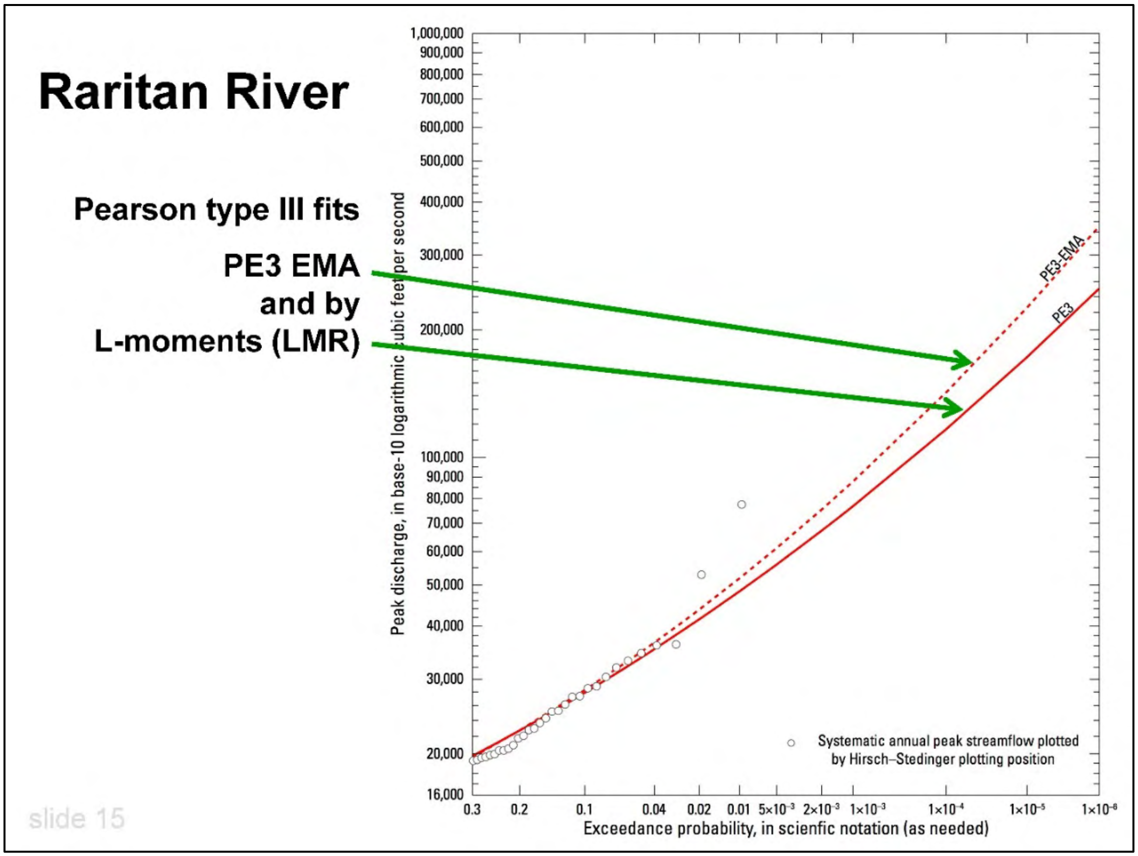
Task 1 Results — Raritan River, Manville, NJ

Four PE3 fit by EMA, LMR, MLE, and MPS:

The four methods estimate similarly for AEPs of interest to transportation design and flood plain management (AEP < 0.002).

We do not quantify this concept as another type of uncertainty, but we acknowledge it.

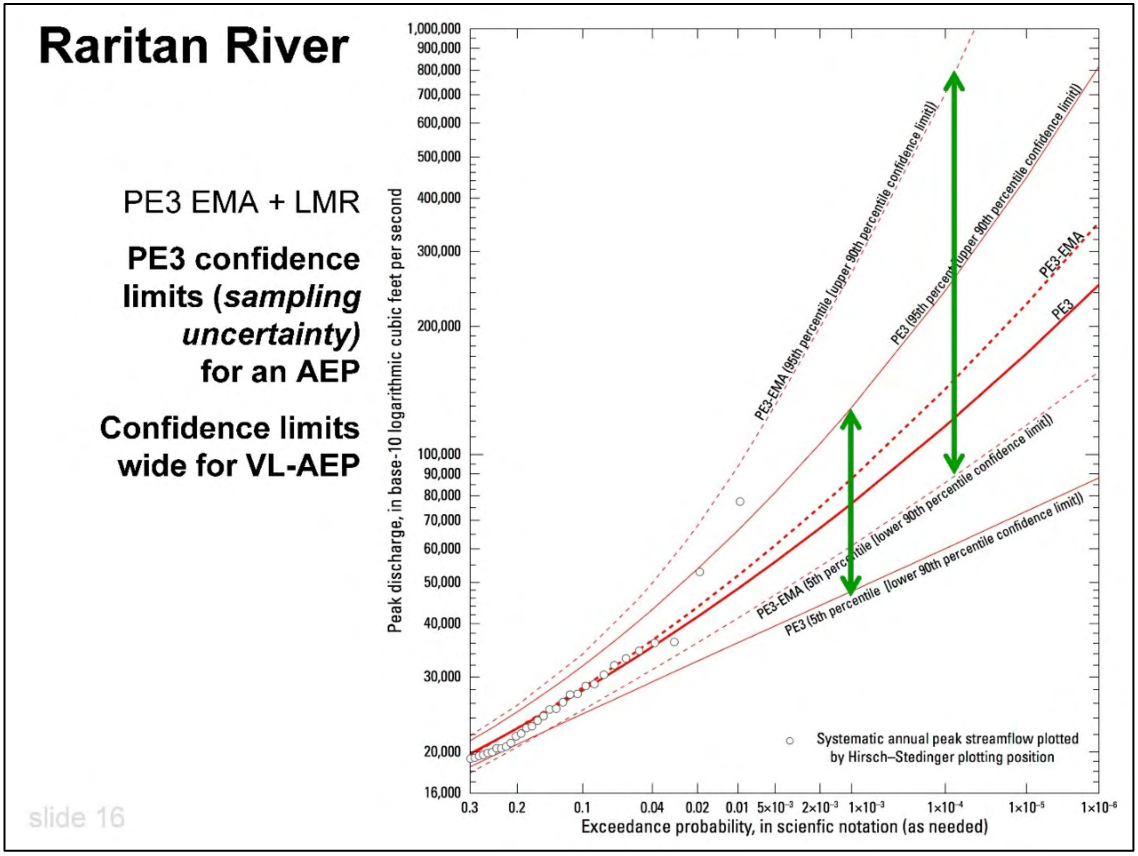




Raritan River

Pearson type III fits

PE3 EMA and by L-moments (LMR)

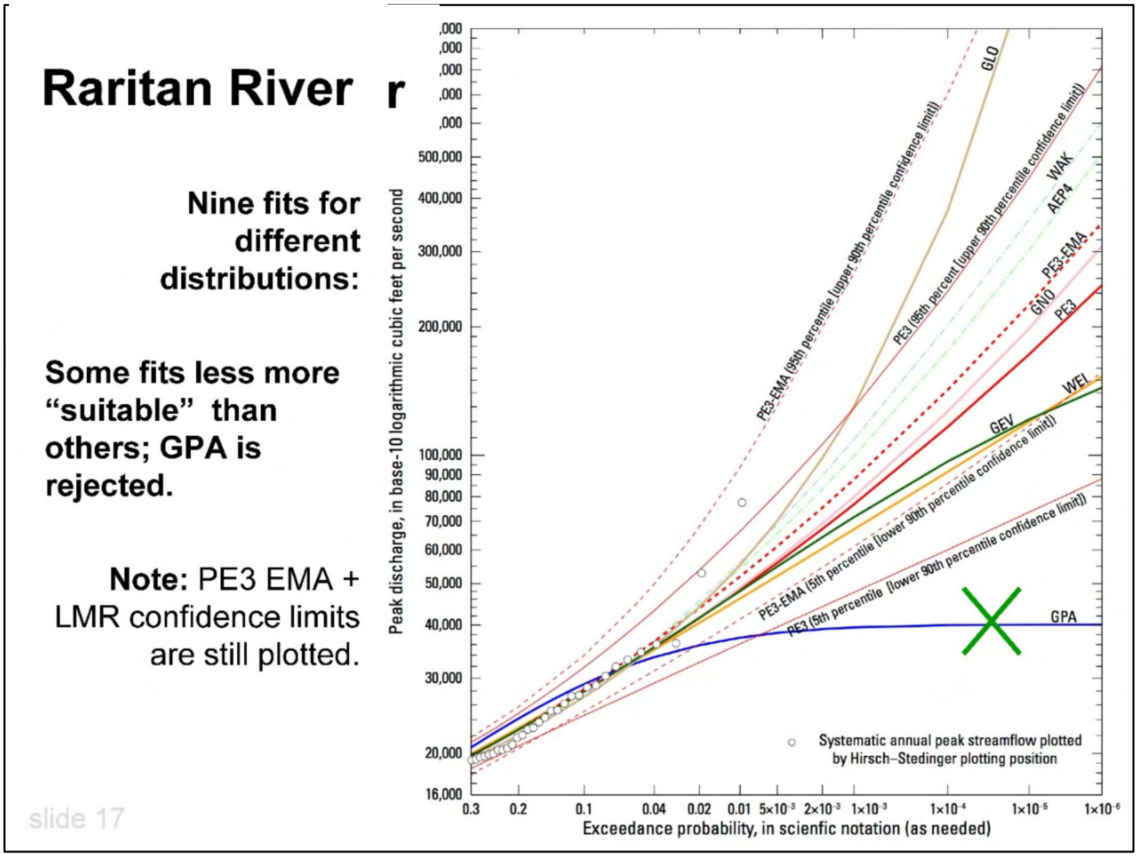


Raritan River

PE3 EMA + LMR

PE3 confidence limits (*sampling uncertainty)* for an AEP

Confidence limits wide for VL-AEP

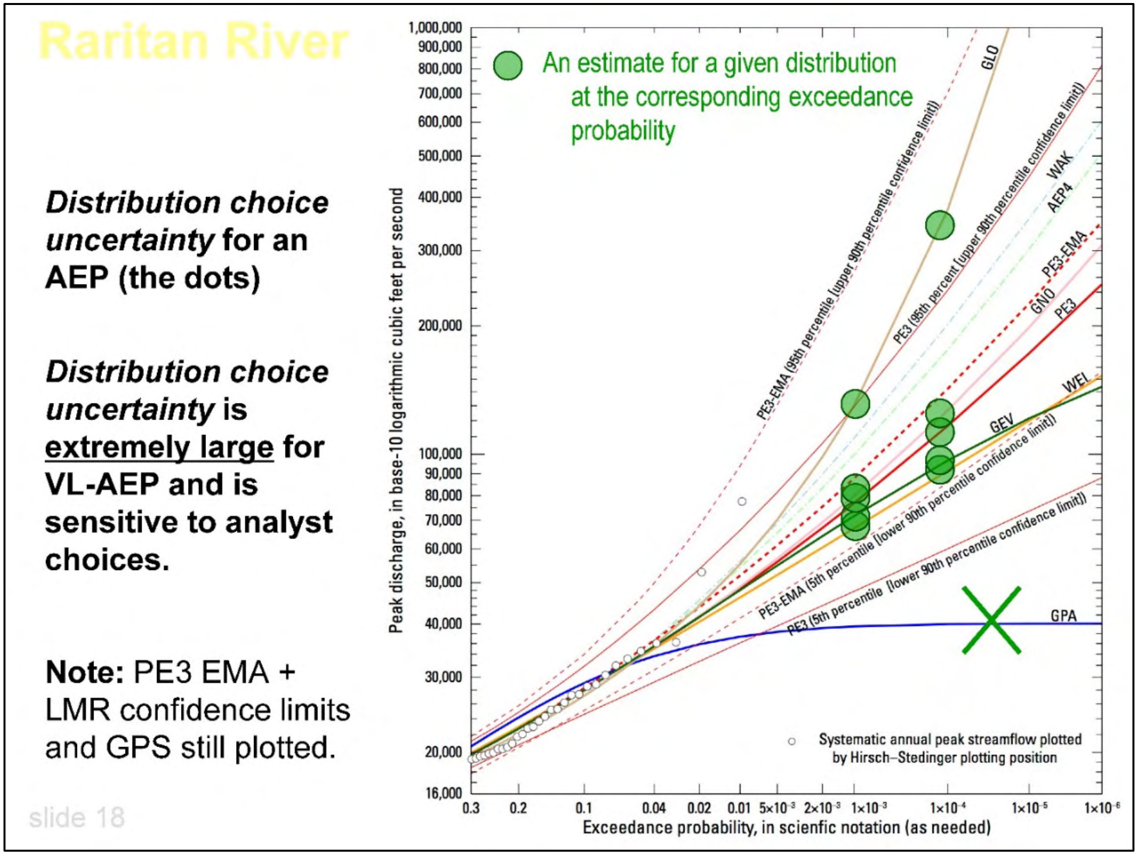


Raritan River r

Nine fits for different distributions:

Some fits less more "suitable" than others; GPA is rejected.

Note: PE3 EMA + LMR confidence limits are still plotted.

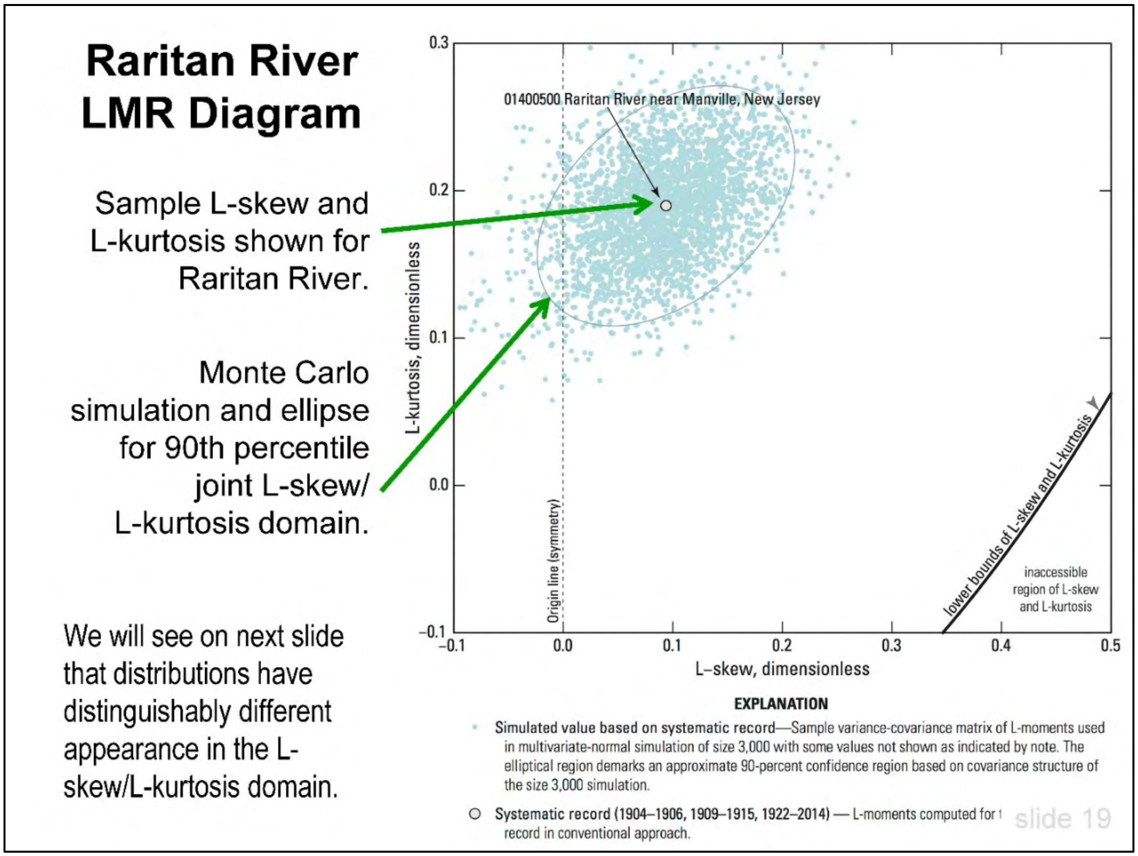


Raritan River

***Distribution choice uncertainty* for an AEP (the dots)**

***Distribution choice uncertainty* is <u>extremely large</u> for VL-AEP and is sensitive to analyst choices.**

Note: PE3 EMA + LMR confidence limits and GPS still plotted.



Raritan River LMR Diagram

Sample L-skew and L-kurtosis shown for Raritan River.

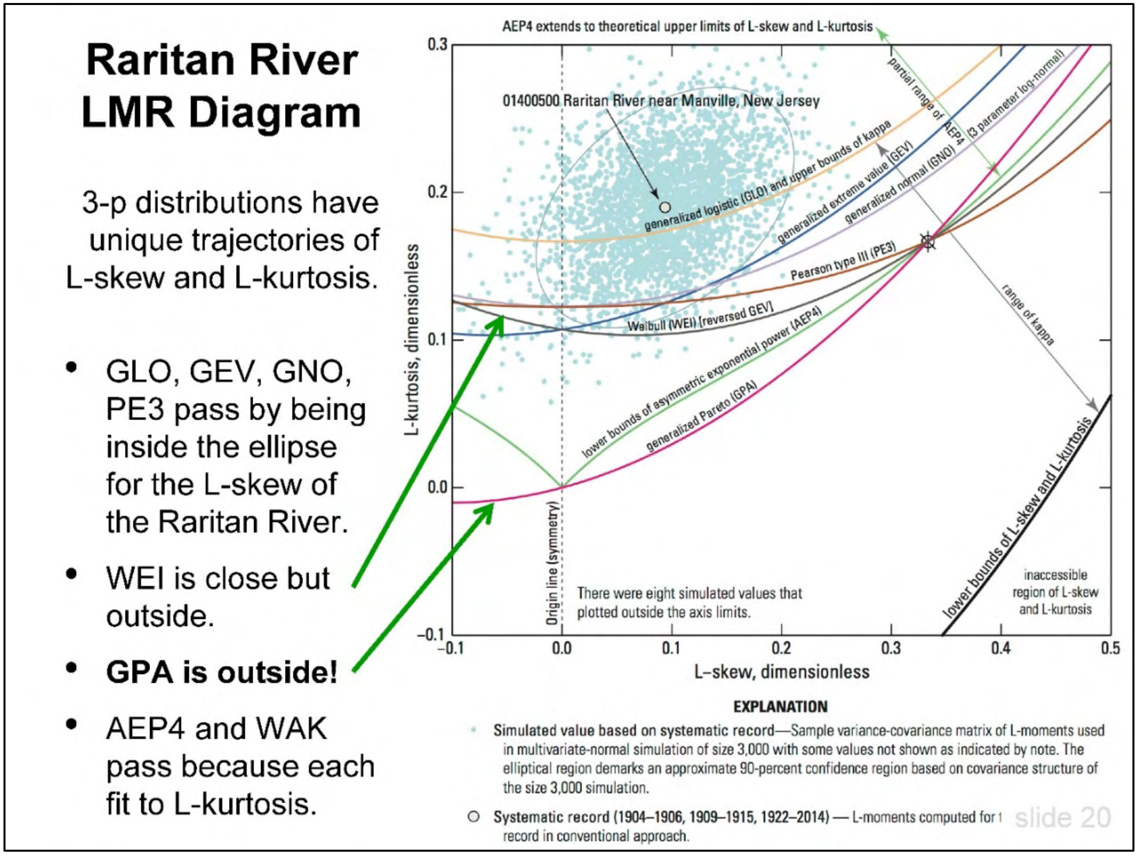
Monte Carlo simulation and ellipse for 90th percentile joint L-skew/ L-kurtosis domain.

We will see on next slide that distributions have distinguishably different appearance in the L-skew/L-kurtosis domain.

EXPLANATION

- **Simulated value based on systematic record**—Sample variance-covariance matrix of L-moments used in multivariate-normal simulation of size 3,000 with some values not shown as indicated by note. The elliptical region demarks an approximate 90-percent confidence region based on covariance structure of the size 3,000 simulation.

○ **Systematic record (1904–1906, 1909–1915, 1922–2014)** — L-moments computed for t record in conventional approach.



Raritan River LMR Diagram

3-p distributions have unique trajectories of L-skew and L-kurtosis.

- GLO, GEV, GNO, PE3 pass by being inside the ellipse for the L-skew of the Raritan River.
- WEI is close but outside.
- **GPA is outside!**
- AEP4 and WAK pass because each fit to L-kurtosis.

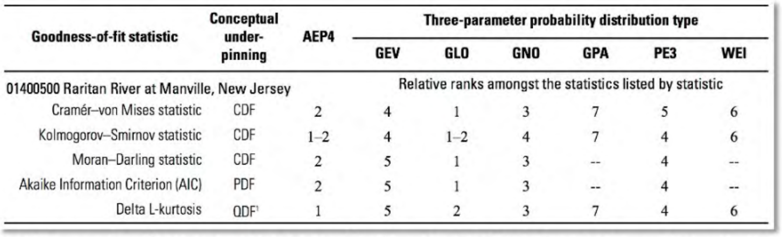
EXPLANATION

- **Simulated value based on systematic record**—Sample variance-covariance matrix of L-moments used in multivariate-normal simulation of size 3,000 with some values not shown as indicated by note. The elliptical region demarks an approximate 90-percent confidence region based on covariance structure of the size 3,000 simulation.

○ **Systematic record (1904–1906, 1909–1915, 1922–2014)** — L-moments computed for t record in conventional approach.

Raritan River — Goodness-of-Fit (GoF)

- **GoF is immensely challenging with no optimality for VL-AEPs.**
  - **Sample sizes involved nearly assure zero observations of the phenomena that the analyst is trying to predict.**



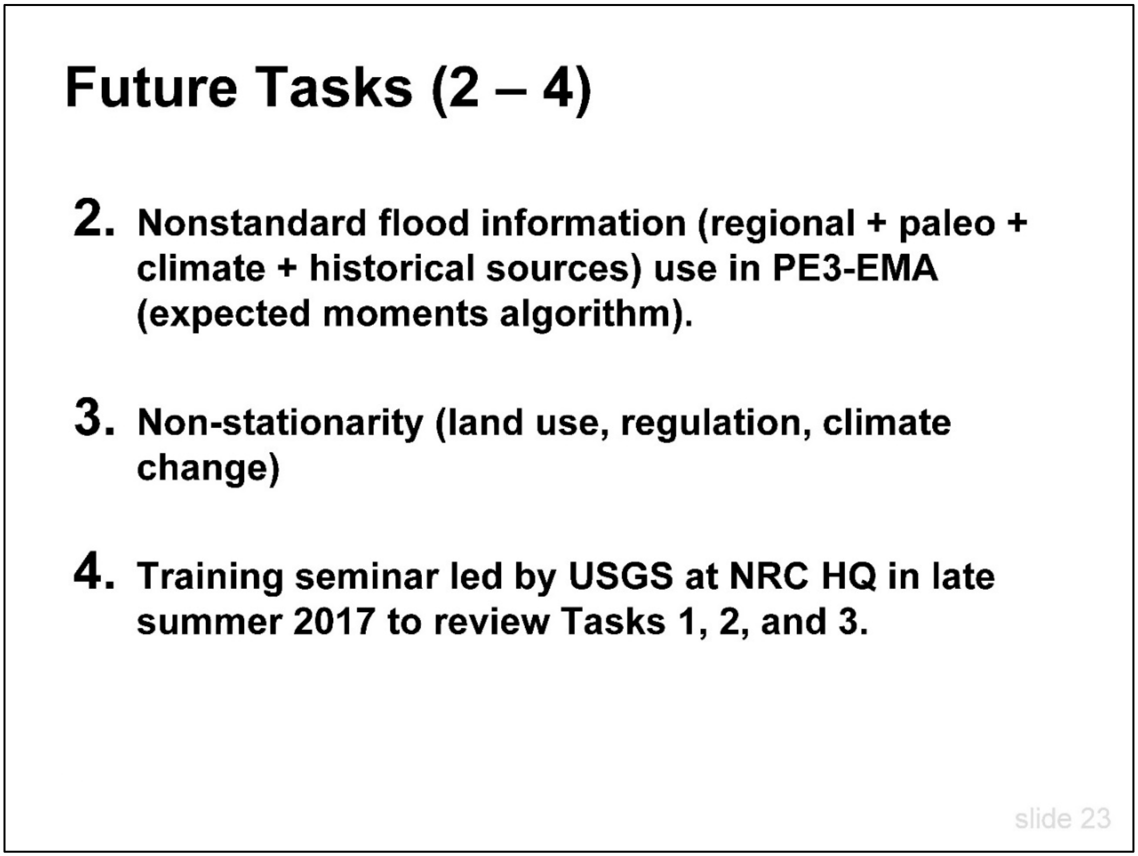
Goodness-of-fit statistic	Conceptual under-pinning	AEP4	Three-parameter probability distribution type					
			GEV	GLO	GNO	GPA	PE3	WEI
01400500 Raritan River at Manville, New Jersey			Relative ranks amongst the statistics listed by statistic					
Cramér–von Mises statistic	CDF	2	4	1	3	7	5	6
Kolmogorov–Smirnov statistic	CDF	1–2	4	1–2	4	7	4	6
Moran–Darling statistic	CDF	2	5	1	3	--	4	--
Akaike Information Criterion (AIC)	PDF	2	5	1	3	--	4	--
Delta L-kurtosis	QDF[1]	1	5	2	3	7	4	6

- **Ranks for the six 3-parameter dists. + AEP4 (asym. exp. power).**
  - **Most 3-parm+ distributions pass GoF hypothesis tests.**
  - **Delta L-kurtosis pushes the fit question to the next highest shape parameter. (Reason AEP4 ranks over GLO.)**

These metrics do not answer the fundamental question:
Is a given fit inclusive of distribution form *good enough*?

Raritan River — Results in Plain Speech

- **The study is designed:**
  - To explore VL-AEP estimation from a perspective of multiple distributions and parameter fitting methods,
  - To quantify two uncertainties *(***distribution choice [σ_s]** and **sampling uncertainty [σ_{dc}]** as standard deviations in $\log_{10}$), and
  - Not to recommend prescriptive streamflows for either the Raritan River or Potomac River.
- **Plain Speech Example of a VL-AEP Estimate:**
  - Of six three-parameter distributions, the GLO has best ‘fit.’ (*However, this statement implies little in terms of most suitable or good enough for VL-AEP.*)
  - “The 10^{-4} AEP estimate based on the GLO distribution is 373,600 ft^3/s (90-percent conf. interval 103,600 to 2,793,000 ft^3/s) based on $\sigma_s = 0.442 \log_{10}$ with $\sigma_{dc} = 0.250 \log_{10}$.”

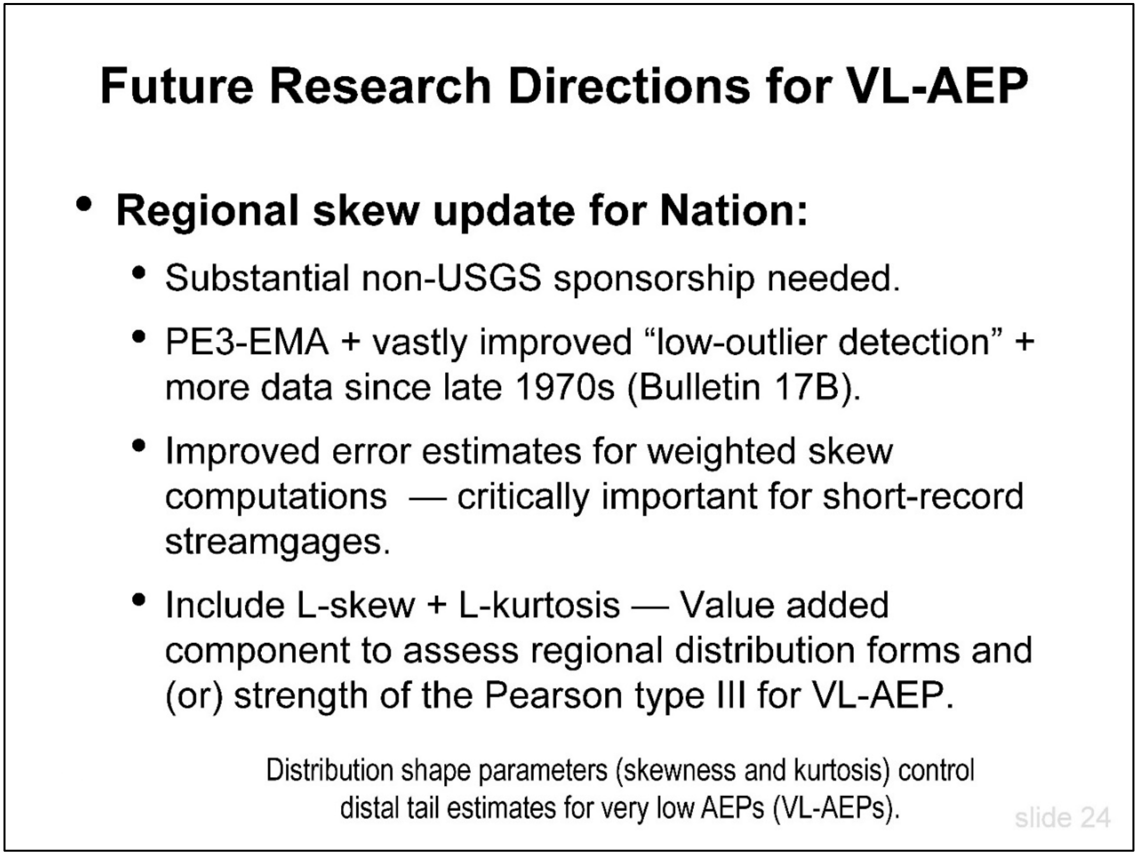


Future Tasks (2 – 4)

2. **Nonstandard flood information (regional + paleo + climate + historical sources) use in PE3-EMA (expected moments algorithm).**

3. **Non-stationarity (land use, regulation, climate change)**

4. **Training seminar led by USGS at NRC HQ in late summer 2017 to review Tasks 1, 2, and 3.**



Future Research Directions for VL-AEP

- **Regional skew update for Nation:**
  - Substantial non-USGS sponsorship needed.
  - PE3-EMA + vastly improved “low-outlier detection” + more data since late 1970s (Bulletin 17B).
  - Improved error estimates for weighted skew computations — critically important for short-record streamgages.
  - Include L-skew + L-kurtosis — Value added component to assess regional distribution forms and (or) strength of the Pearson type III for VL-AEP.

Distribution shape parameters (skewness and kurtosis) control distal tail estimates for very low AEPs (VL-AEPs).

Future Research Directions for VL-AEP

- **EMA extension to other three-parameter dists.**
  - Generalized Extreme Value (GEV) and thus Weibull
  - Generalized “Skew” Normal and thus log-Normal3
- **Unification of theory for historical data (censoring) for L-moments.** (We barely explore L-moment left-censoring by indicator variable within this USGS/NRC project.)
- **Method of MPS[1] needs further review.**
- **Further look into four-parameter distributions**
  - Kappa + Asymmetric Exponential Power distributions as a “joint family” canvasing the L-skew / L-kurtosis domain.

---

[1] Maximum product of spacings or “maximum spacing estimation.”

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2.3.4.2.3 Questions and Answers

Question:

Have you considered other examples in the United States besides the Northeast, such as the Pecos River?

Response:

This study is limited to the Potomac and Raritan Rivers. For this project, the criteria required a very long record period and a fair amount of skew in the data, free from regulation; therefore, it was limited to this area. The continuing work in this project will review data from a host of additional gauges across the United States, from west to east.

Comment:

One of the future tasks in the project appears to be to consider nonstationarity by urban effects or climate change. The experience with NOAA Atlas 14 leads to some suggestions. First, when discussing nonstationarity, you should distinguish between a change in frequency or in magnitude, or whether there is a change in both of them. If there is a change in magnitude only, approaches based on annual maxima series could be applicable. However, if there is a change in the frequency of extreme events, either streamflow or precipitation, you should change the series used in the analysis. That is, you should go from annual maxima series to partial duration or peaks over threshold, because extremes are more common in recent periods than they were before. Applying this suggestion does pose some issues. Methods currently being used for streamflow and precipitation, in USGS Bulletin 17B and NOAA Atlas 14, are based either on conventional moments or L-moments and cannot be adjusted easily to include nonstationarity. However, the maximum likelihood approach can be adjusted. L-moments were suggested for frequency in 1990s when sample sizes were relatively small, and relations showed that they were more reliable than maximum likelihood. However, with 20 more years of data available for the analysis of extreme events, there may no longer be a reason to use L-moments. Recent studies show that we should abandon L-moments in the analysis of extreme events and instead move to maximum likelihood. There are a number of other conflicts like this. For example, Federal agencies have agreed to use the term “AEP.” If we change from annual maximum series (AMS) to partial duration series (PDS), we will need to go back to using the terms “return period” or “recurrence interval,” because AEP does not go with the partial duration series. In general, care must be taken with terminology because we use different terms to define the same thing. For example, the term “extreme event” means different things to different professions and different people. An event for some is something that has a beginning and an end. We perform frequency analysis, which is very important for precipitation. We are not analyzing events, but rather the amounts per duration, which can be from a single event or multiple events. It is therefore necessary to distinguish between the two [events and partial duration series], because there are a lot of differences in methodologies that are used to analyze these two different things.

Response from NRC Project Manager:

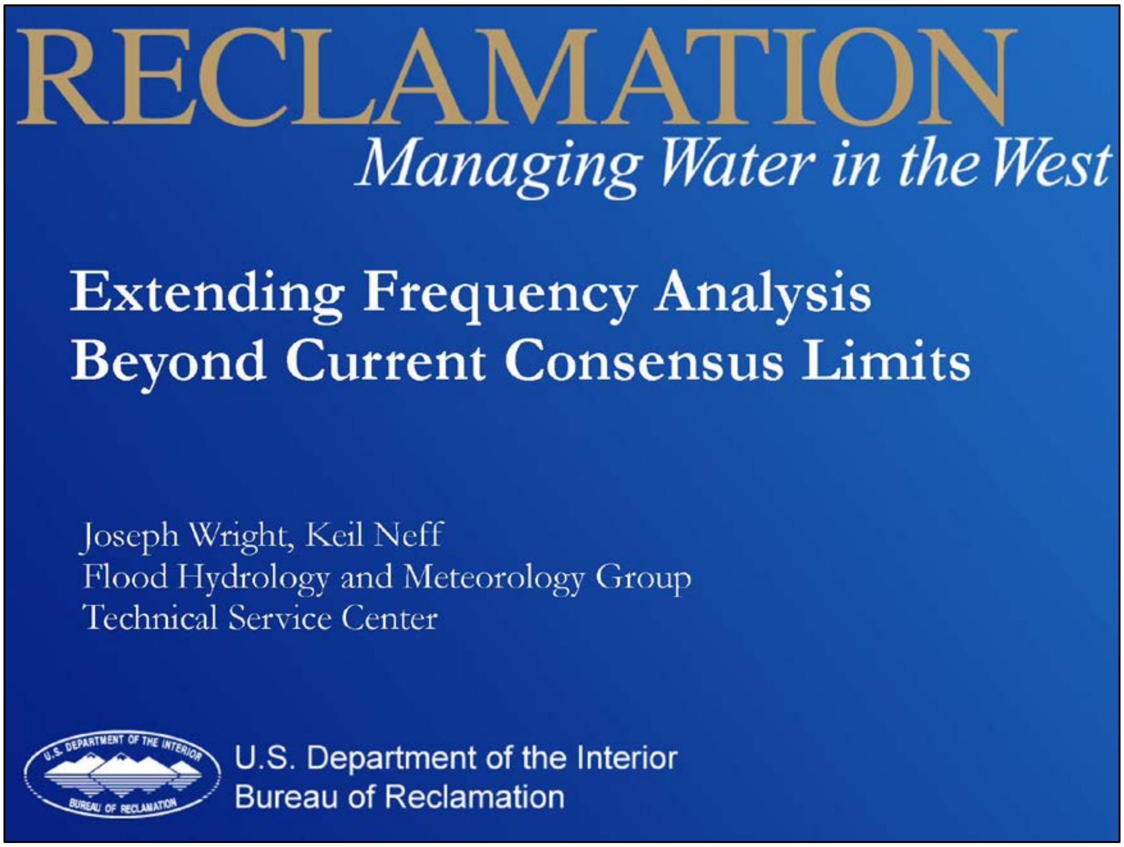
Another example of the difference is considering the frequency of a particular volume for a dam on a reservoir. The number of events contributing to that volume is not important, but rather the frequency of getting a particular volume.

2.3.4.3 Extending Frequency Analysis beyond Current Consensus Limits, Keil Neff, Ph.D., P.E., and Joseph Wright, P.E., U.S. Bureau of Reclamation ,Technical Service Center, Flood Hydrology and Mete orology (Session 2B-3; ADAMS Accession No. ML17054C510)

2.3.4.3.1 Abstract

Traditionally, deterministic methods have been used to determine inflow design floods based on a particular loading event to meet regulatory criteria. For infrastructure with high hazard potential, including nuclear facilities and many large dams, the probable maximum flood (PMF) has often been used as the inflow design flood. Risk-informed decision-making is currently used by the U.S. Bureau of Reclamation (USBR), USACE, and other agencies to assess the safety of dams, recommend safety improvements, and prioritize expenditures. This involves developing estimates of hydrologic hazards to perform PRAs . Hydrologic hazard curves provide magnitudes and probabilities for the entire ranges of peak flow, flood volume, and water surface elevations. There are multiple methods available to estimate magnitudes and probabilities of extreme flood events; these methods can be generally classified as streamflow-based statistical analyses or rainfall-based with statistical analyses of the modeled runoff. Method selection is based on the level of detail necessary and site-specific consideration, including data availability, hydrologic complexity, and required level of confidence. This presentation focused on describing recommended methods and approaches for extending frequency analysis methods beyond current consensus limits (AEPs greater than $1:10^5$) for both rainfall and riverine flooding applications.

2.3.4.3.2 Presentation



RECLAMATION

Managing Water in the West

Extending Frequency Analysis
Beyond Current Consensus Limits

Joseph Wright, Keil Neff
Flood Hydrology and Meteorology Group
Technical Service Center

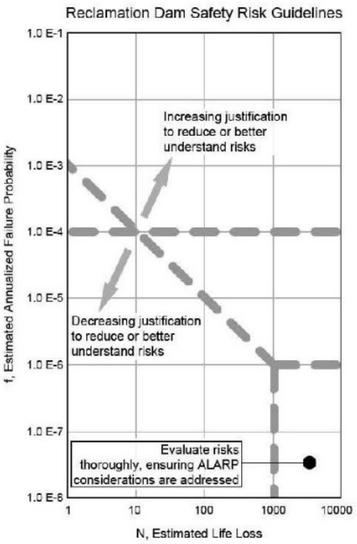
U.S. Department of the Interior
Bureau of Reclamation

Hydrologic Loads and Risk Analysis

Annual Probability of Failure (f)

$$f = \begin{bmatrix}\text{Probability} \\ \text{of a Load}\end{bmatrix} \times \begin{bmatrix}\text{Probability of an} \\ \text{Adverse Response} \\ \text{from Given Load}\end{bmatrix}$$

Hydrologic Load Estimate



Hydrologic Hazard Curve Definition

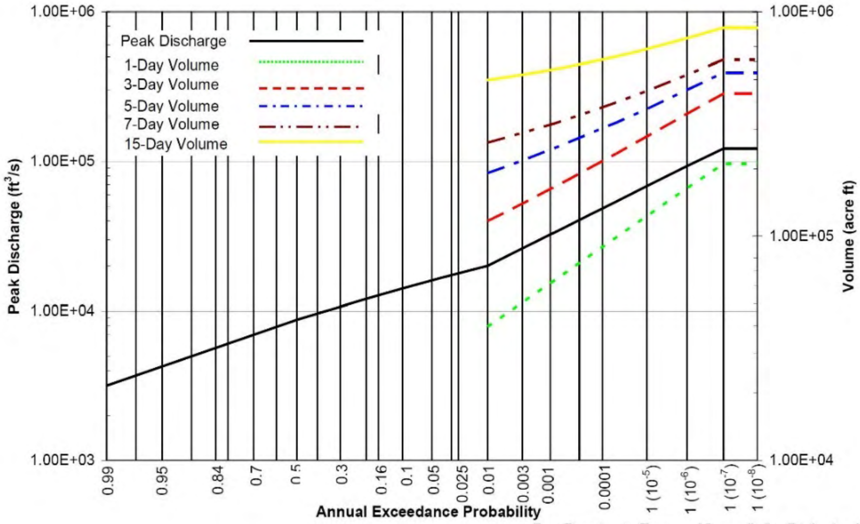
A Hydrologic Hazard Curve is defined as a graph of peak flow and/or volume (for specified duration) versus Annual Exceedance Probability (AEP) ***(< 1 in 10,000 for Reclamation).***

Hydrologic Hazard Curves may also depict Maximum Reservoir Elevation versus AEP.

AEP estimates are made for peak flows, runoff volumes and reservoir elevations to cover the range of values needed for risk-based dam safety decision making at specific facility.

Evaluate specific Potential Failure Modes (overtopping, gates, spillway chute, etc.).

Hydrologic Hazard Curve



Best Practices in Dam and Levee Safety Risk Analysis

Hydrologic Hazard Guidelines

Guidelines Report provides details on the HHA methods and overall framework.

Reclamation technical reports for specific facilities describe advances in data and methods.

RECLAMATION
Managing Water in the West

Guidelines for Evaluating
Hydrologic Hazards

U.S. Department of the Interior
Bureau of Reclamation

June 2006

https://www.usbr.gov/ssle/damsafety/TechDev/DSOTechDev/DSO-04-08.pdf

Some Key Hydrologic Hazard Analysis (HHA) Concepts

Hierarchy and Risk Process – Agency Specific

Probability Estimates and Full Distributions needed, with Uncertainty

PMF and Single (Point) Deterministic Flood Estimate No Longer Adequate – more information required

Hydrologic Hazard Curves are the Load Input to Risk

- Peak Flow and Volume Frequency Curves
- 1/1,000 AEP to 1/10,000 AEP (typical for failure probability)
- less than 1/10,000 AEP extrapolation!

Hydrographs; Maximum Reservoir Levels

HHA Methods vary; depend on study level

Multiple HHA Methods Used and Combined

Hydrologic Hazard Curve Principles

Data - focus on past (paleoflood) and present (recent) data

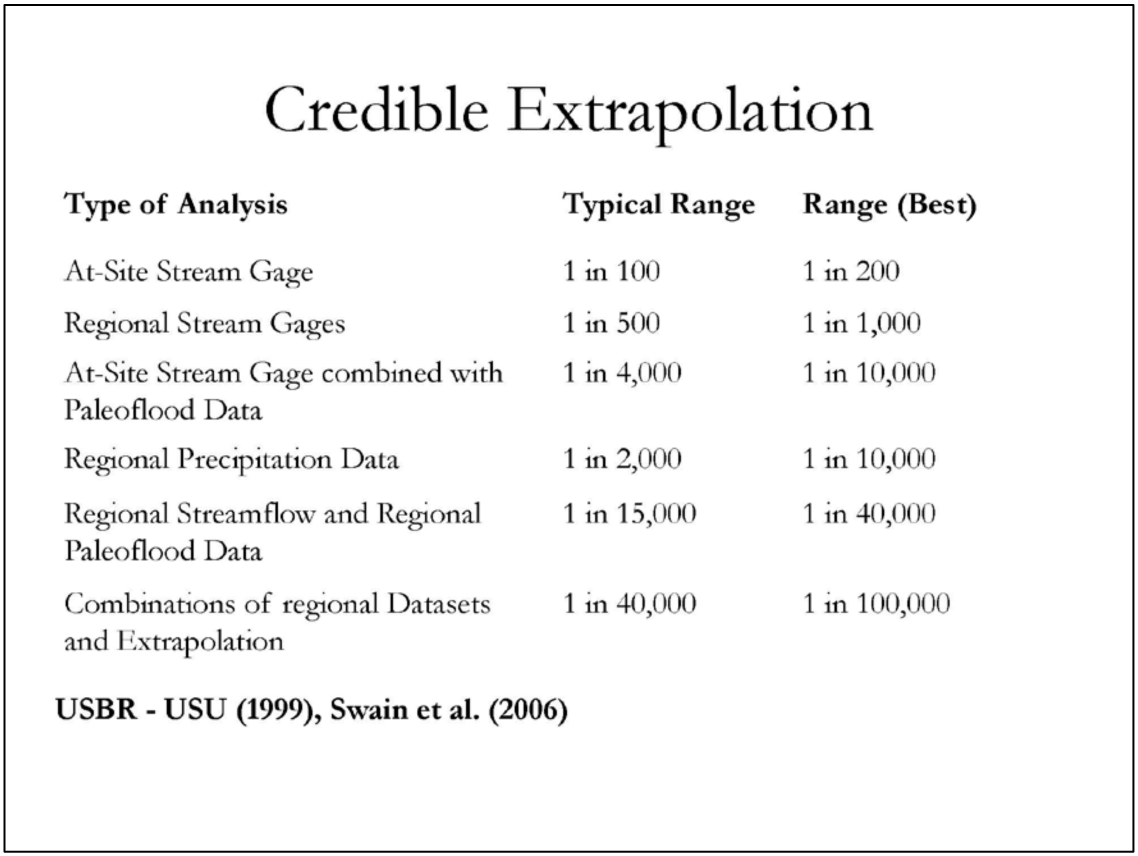
Flood Hazards Estimated using Interdisciplinary Teams

Flood Models, Relationships and Tools developed in-house by Reclamation and collaborators

Uncertainty of Estimates is Quantified

Fundamental challenge - We have short records of past floods but we want to characterize future floods with long return periods

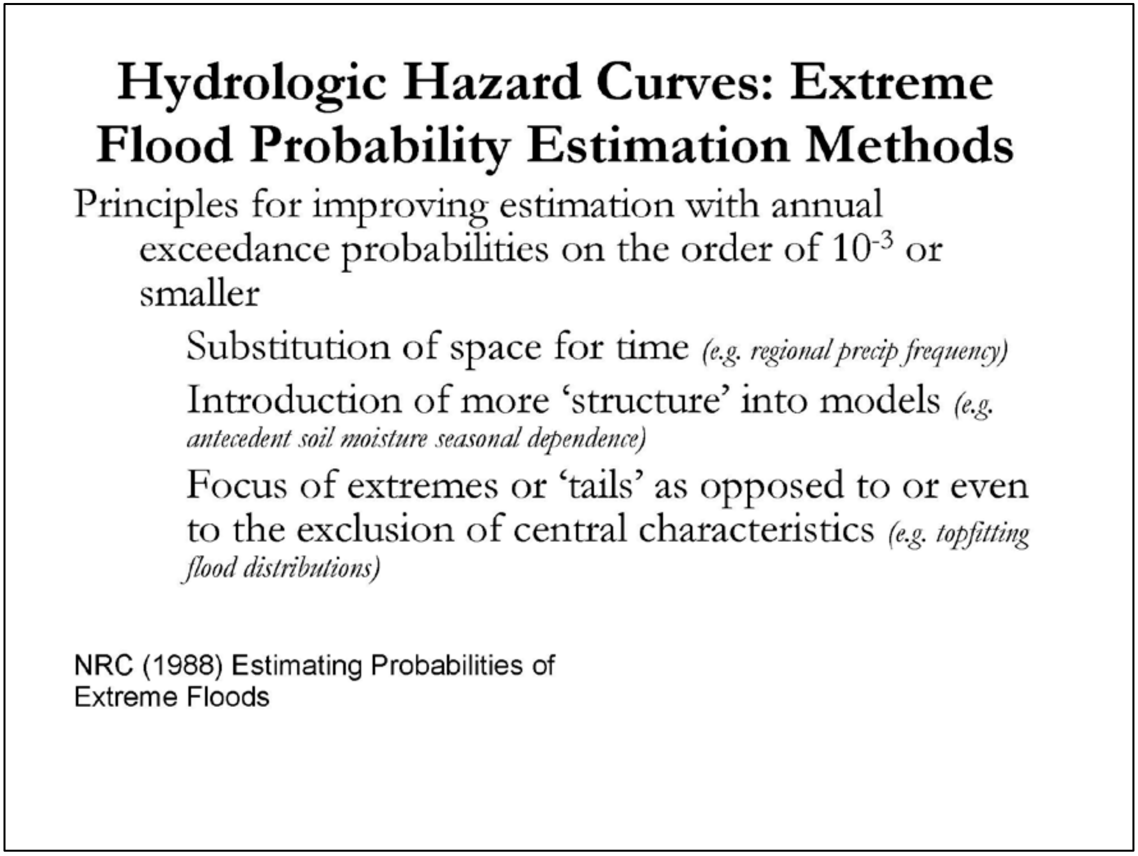
Because estimation of Hydrologic Hazard Curves involves substantial extrapolations, use of multiple methods and independent data sets provides more reliable results



Credible Extrapolation

Type of Analysis	Typical Range	Range (Best)
At-Site Stream Gage	1 in 100	1 in 200
Regional Stream Gages	1 in 500	1 in 1,000
At-Site Stream Gage combined with Paleoflood Data	1 in 4,000	1 in 10,000
Regional Precipitation Data	1 in 2,000	1 in 10,000
Regional Streamflow and Regional Paleoflood Data	1 in 15,000	1 in 40,000
Combinations of regional Datasets and Extrapolation	1 in 40,000	1 in 100,000

USBR - USU (1999), Swain et al. (2006)



Hydrologic Hazard Curves: Extreme Flood Probability Estimation Methods

Principles for improving estimation with annual exceedance probabilities on the order of 10^{-3} or smaller

- Substitution of space for time *(e.g. regional precip frequency)*
- Introduction of more 'structure' into models *(e.g. antecedent soil moisture seasonal dependence)*
- Focus of extremes or 'tails' as opposed to or even to the exclusion of central characteristics *(e.g. topfitting flood distributions)*

NRC (1988) Estimating Probabilities of Extreme Floods

Hydrologic Hazard Methods

Method	Data Inputs	Assumptions
Graphical Flood Frequency	peak flow, reconnaissance paleofloods, PMF hydrograph	logNormal flood frequency; PMF hydrograph represents volume
EMA	peak flow, detailed paleofloods	LP3 flood frequency distribution with moments
FLDFRQ3	peak flow, detailed paleofloods	various flood frequency distributions with likelihood
Hydrograph Scaling	hydrographs and volumes	hydrographs represent extreme flood response; requires FFA for scaling
GRADEX	rainfall gages/regional statistics; streamflow volumes	flood frequency same shape as rainfall frequency with exponential tail; saturated basin
Australian Rainfall-Runoff	PMP design storm; rainfall frequency; watershed parameters	Exceedance Probability of PMP; average watershed parameter values; runoff frequency same as rainfall frequency
NWS SAC-SMA	Precipitation frequency, 6-hr P,T, soil parameters, snow parameters, hourly and 6-hr streamflow (calibration)	existing RFC calibration acceptable; runoff frequency approximated by rainfall frequency; calibrated parameters apply to extremes
SEFM	rainfall gages/detailed regional rainfall frequency, watershed parameters, snowpack, reservoir data	main inputs defined by distributions; unit hydrograph; rainfall frequency using GEV/lmoments
Distributed R-R Model	regional extreme storm DAD data, watershed parameters, snowpack	diffusive wave runoff; stochastic storm transposition rainfall frequency

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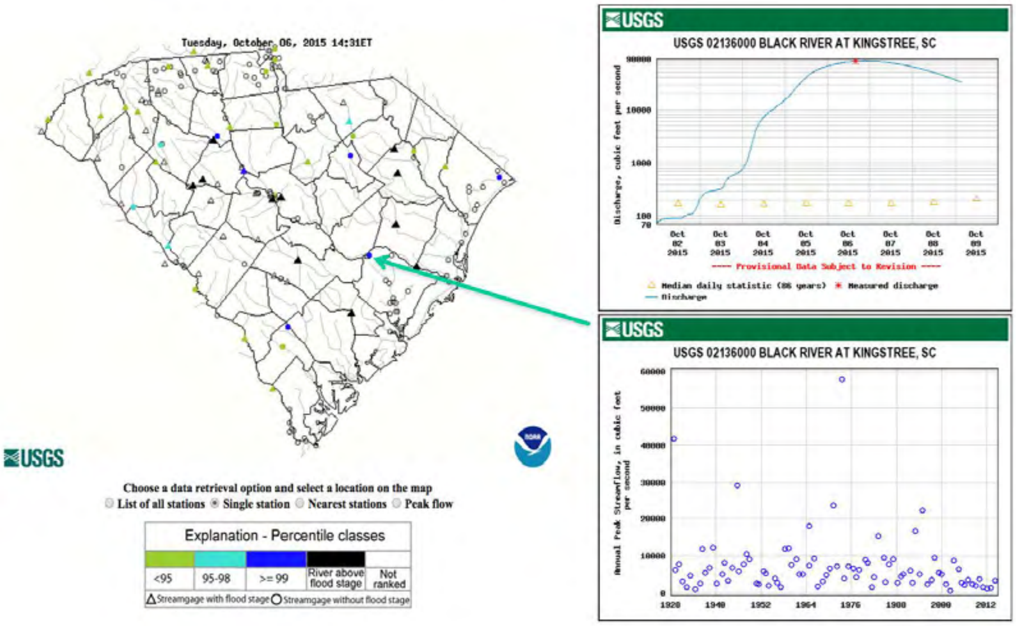
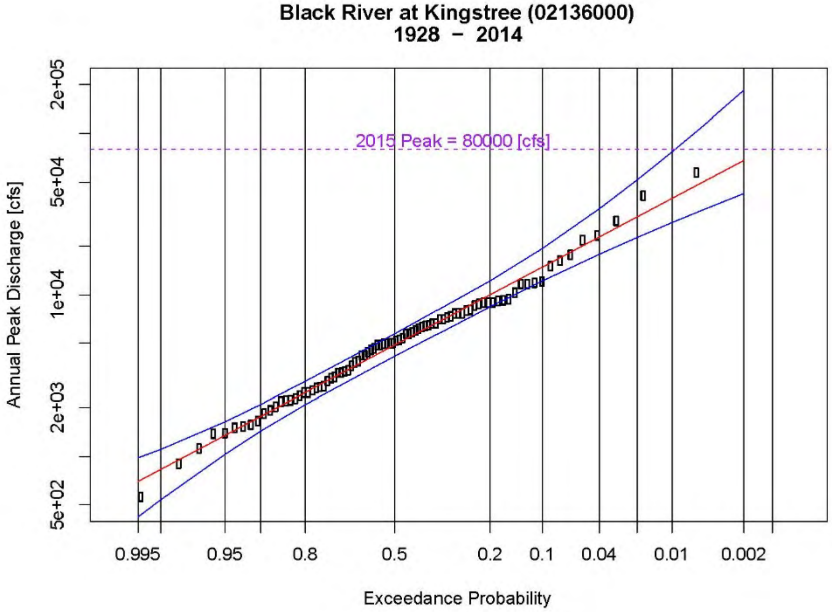
Statistical Approach
Black River at Kingstree (SC)





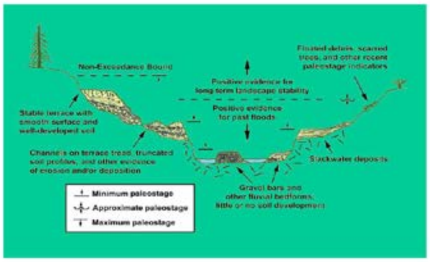
Black River at Kingstree (02136000)
1928 − 2014

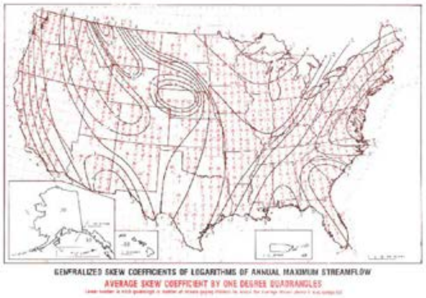
Improving the Precision of Statistical Flood Frequency Estimates

Additional at-site data:
- Gage
- Historical
- Paleo

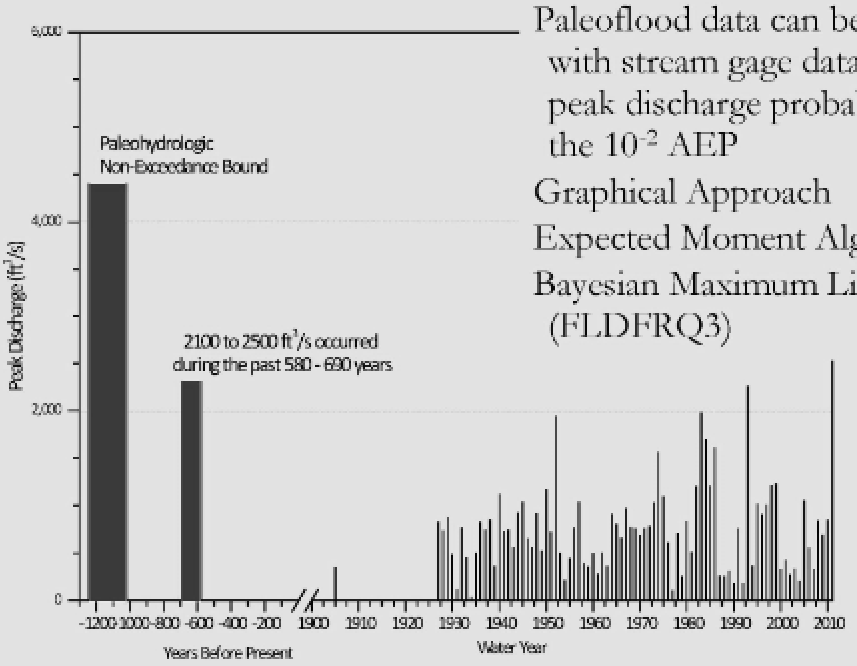
Regional Information

Models
- Statistical
- Process-oriented





Incorporating Paleoflood Data

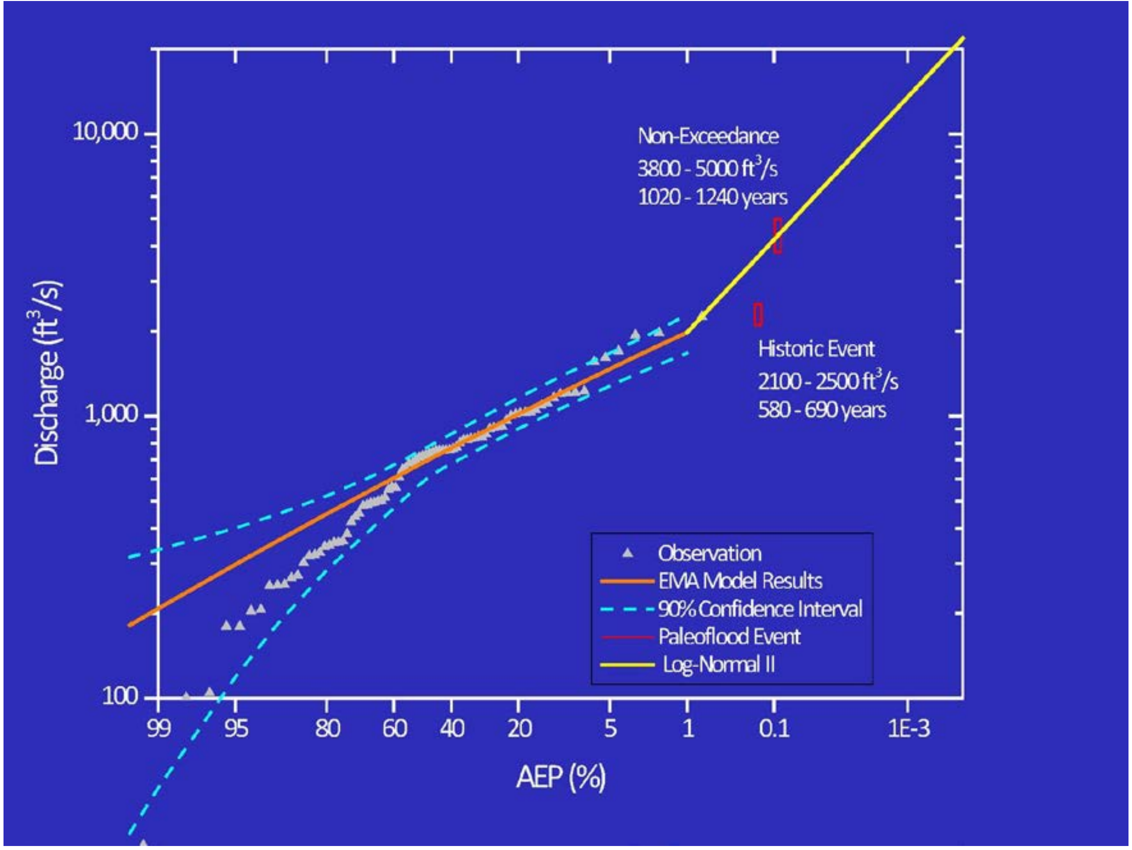


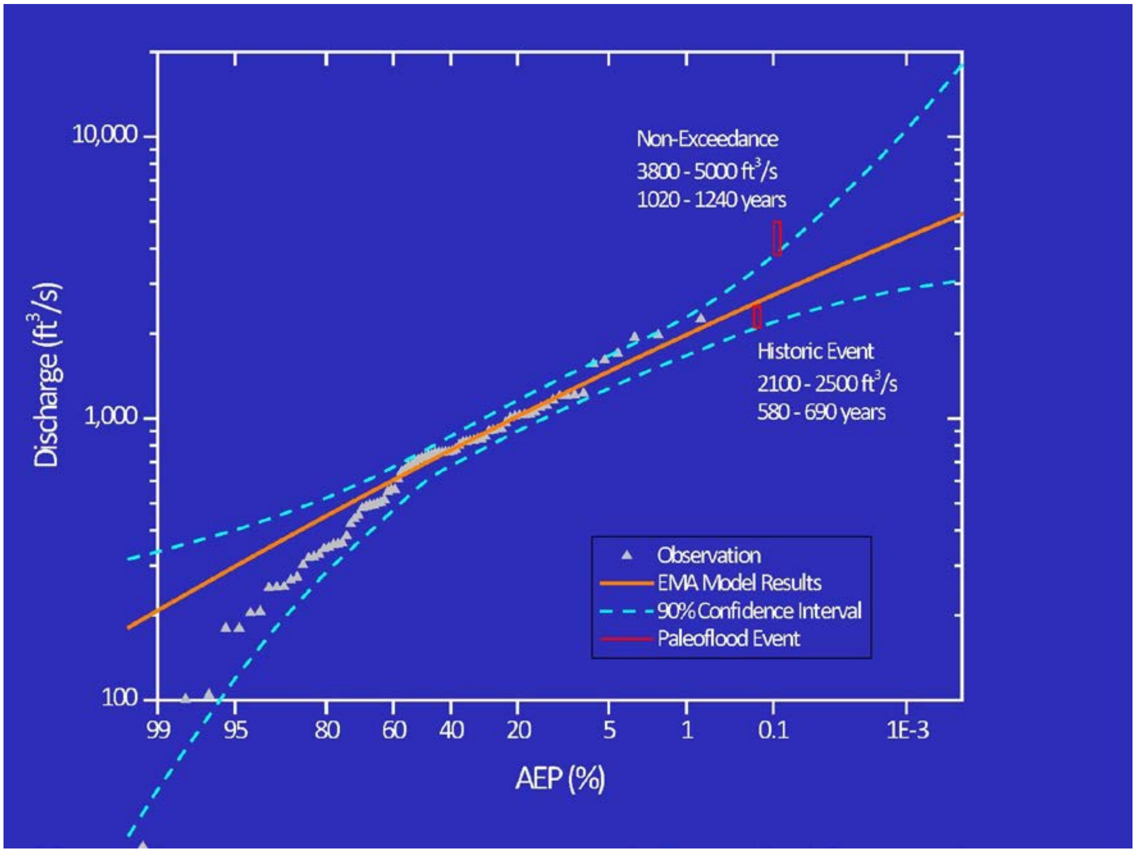
Paleoflood data can be combined with stream gage data to extrapolate peak discharge probabilities beyond the 10^{-2} AEP

Graphical Approach

Expected Moment Algorithm (EMA)

Bayesian Maximum Likelihood (FLDFRQ3)





Rainfall-Runoff Modeling

USBR uses multiple methods. Typically a combination of a physical based model with a statistical component that analyzes historic (and prehistoric) streamflow

USBR often considers a rainfall-runoff model to represent the extreme flood potential in a watershed that is typically controlled by snowmelt flooding

Rainfall-Runoff Models

Lumped (1-Dimensional)
- HEC-HMS (HEC-1)
- SAC-SMA
- SWMM

Quasi-Distributed
- Hydrologic Runoff Unit (HRU) Approach

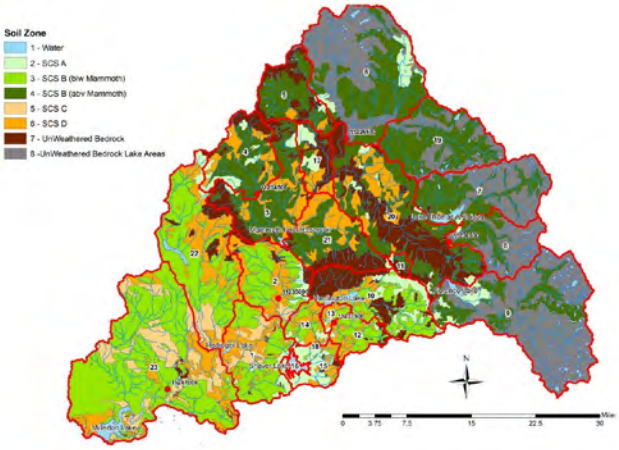
Distributed (2D)
- Variable Infiltration Capacity (gridded)
- WRF-Hydro
- TREX

Rainfall-Runoff Modeling

Precipitation Frequency
- Regionalized precipitation (L-moments)
- Australian Rainfall-Runoff
- NOAA Atlas 14

Temporal
- Derived from observed data
- Design templates (SCS Type II, USBR 2/3, etc.)
- Modeled (WRF)

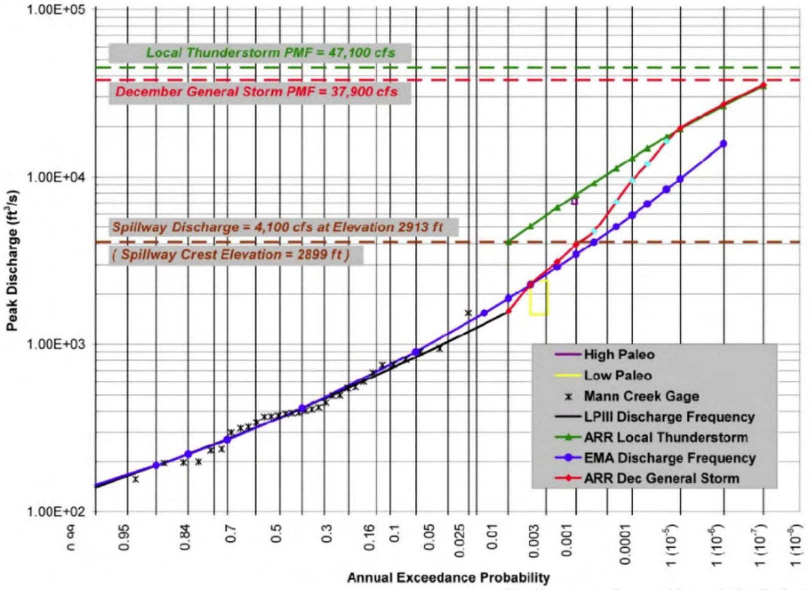
Spatial
- Derived from observed data (at-site, transposition)
- Design templates (HMRs)



Australian Rainfall-Runoff Method

- Use ARR rainfall/PMP probability concepts
- Customize ARR concepts on spatial/temporal patterns, runoff models, loss rates and sensitivity by Reclamation
- Estimate rainfall distribution to 1/100 (NOAA 2) or 1/1000 (NOAA 14, state studies)
- Assume rainfall distribution from this AEP to PMP using ARR shape factors.
- Assign AEP to point PMP from drainage area
- Develop rainfall point to area relationship, temporal pattern, and spatial pattern
- Use runoff model (e.g. unit hydrograph) with AEP neutral parameters for losses, lag time, antecedent floods, initial reservoir level

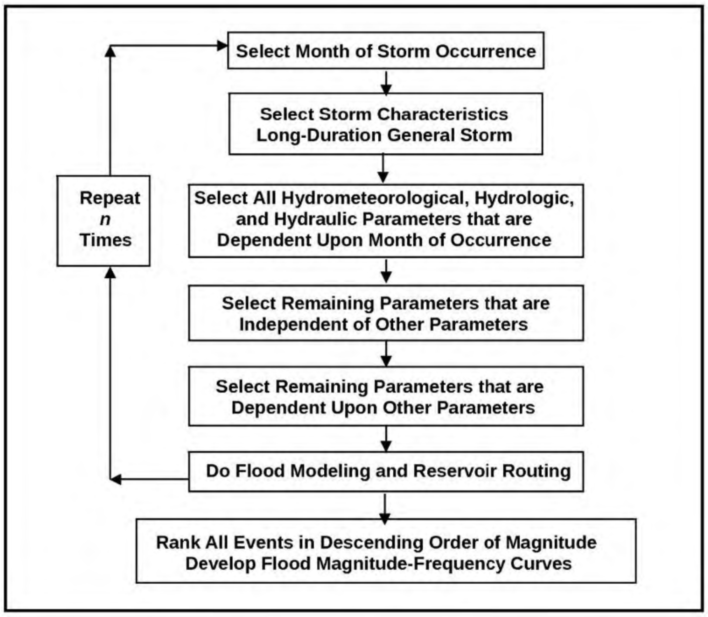
Australian Rainfall-Runoff



Best Practices in Dam and Levee Safety Risk Analysis

Stochastic Event-Based Rainfall-Runoff Model (SEFM) Key Elements

- Regional Rainfall Frequency using L-Moments
- Hydrometeorological parameters treated as random variables (snowpack , infiltration, …)
- Utilize Storm Patterns and Sequence of Storms
- Runoff Computed using HRU Approach with Unit Hydrograph
- Perform Monte Carlo Simulations - Frequency Analysis on output; examine combinations that cause largest floods



Select Month of Storm Occurrence

Select Storm Characteristics
Long-Duration General Storm

Select All Hydrometeorological, Hydrologic, and Hydraulic Parameters that are Dependent Upon Month of Occurrence

Select Remaining Parameters that are Independent of Other Parameters

Select Remaining Parameters that are Dependent Upon Other Parameters

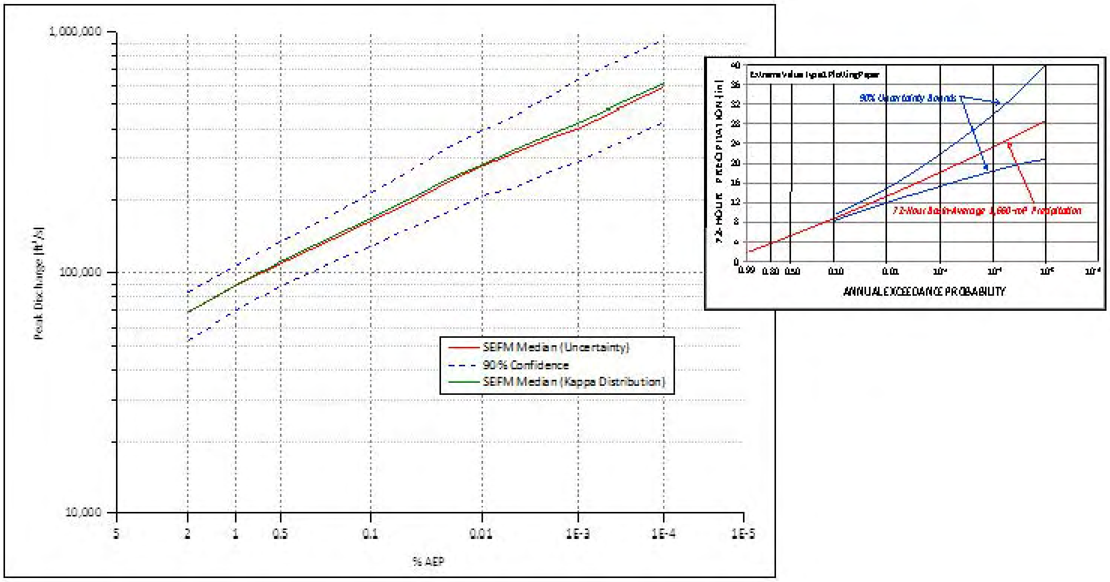
Do Flood Modeling and Reservoir Routing

Rank All Events in Descending Order of Magnitude
Develop Flood Magnitude-Frequency Curves

Repeat *n* Times

MGS Engineering Consultants, Inc.

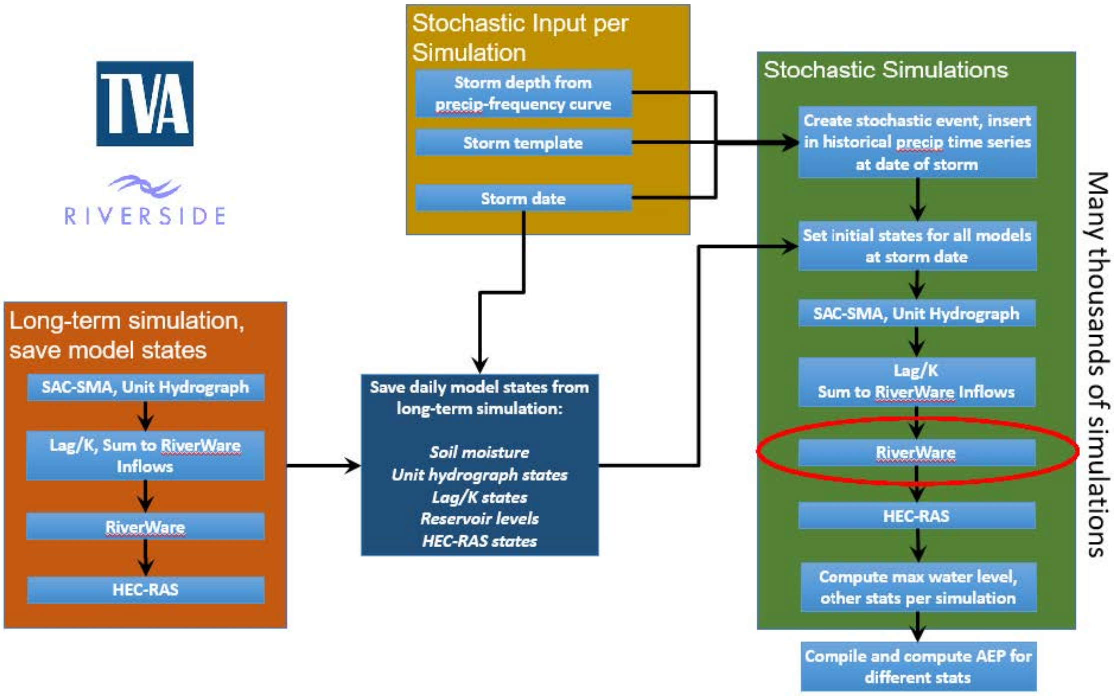
Hydrologic Hazard Reservoir Frequency Curve with Uncertainty (SEFM)



Stochastic Flood Simulation Approach

TVA

RIVERSIDE



Stochastic Input per Simulation
- Storm depth from precip-frequency curve
- Storm template
- Storm date

Long-term simulation, save model states
- SAC-SMA, Unit Hydrograph
- Lag/K, Sum to RiverWare Inflows
- RiverWare
- HEC-RAS

Save daily model states from long-term simulation:

Soil moisture
Unit hydrograph states
Lag/K states
Reservoir levels
HEC-RAS states

Stochastic Simulations
- Create stochastic event, insert in historical precip time series at date of storm
- Set initial states for all models at storm date
- SAC-SMA, Unit Hydrograph
- Lag/K Sum to RiverWare Inflows
- RiverWare
- HEC-RAS
- Compute max water level, other stats per simulation

Compile and compute AEP for different stats

Many thousands of simulations

Multiple Methods and Weighting

- For detailed Issue Evaluation (IE), Corrective Action Studies (CAS) and design studies, Reclamation uses multiple methods.
- Methods typically include:
  - Peak-flow frequency using EMA or FLDFRQ3 with detailed paleoflood data
  - SEFM or equivalent stochastic rainfall-runoff model
- Results are combined and weighted by a team of hydrologists
- Weights are subjective and case-specific
- Typical goal is to ensure rainfall-runoff model is consistent with field observations, causal information, streamflow and paleoflood data

g4-13

NRC Research

Current Research

This project will develop a technical basis document to provide guidance for extending frequency analysis methods beyond current consensus limits for both rainfall and riverine flooding applications.

The focus will be on describing alternative methods and approaches for integration of the characterizations from multiple approaches to estimate rainfall and floods with AEPs $1X10^{-5}$ *to* $1X10^{-6}$.

Uncertainty characterization and quantification will also be a focus of this project.

U.S. Bureau of Reclamation
Technical Service Center
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2.3.4.3.3 Questions and Answers

Question:

Are any other similar projects underway, and what did you learn from their application?

Response:

Another current project uses a SEFM [Stochastic Event Flood Model] to estimate frequencies, which gives a much better understanding of the process that is involved, both for infrequent events and more frequent events.

Question:

The presentation mentioned that a team of hydrologists came to a consensus decision. Do you have any more details about that?

Response:

USBR has an internal review process and works in a team approach for more complicated studies.

2.3.5 Day 2: Session 2C - Leveraging Available Flood Information II

This session presented research to develop the means by which the staff can leverage available frequency information on flooding hazards.

2.3.5.1 Collection of Paleoflood Evidence, John Weglian, EPRI (Session 2C-1; ADAMS Accession No. ML17054C511)

2.3.5.1.1 Abstract

In a PRA, it is important to estimate the frequency of initiating events (events that can cause or demand an immediate trip of the reactor). The estimation of this frequency is challenging for rare events and particularly so for external hazards like external flooding, for which the historical record is limited to about 100 to 200 years. An external flooding PRA would use a flood hazard frequency curve that plots at much rarer return periods.

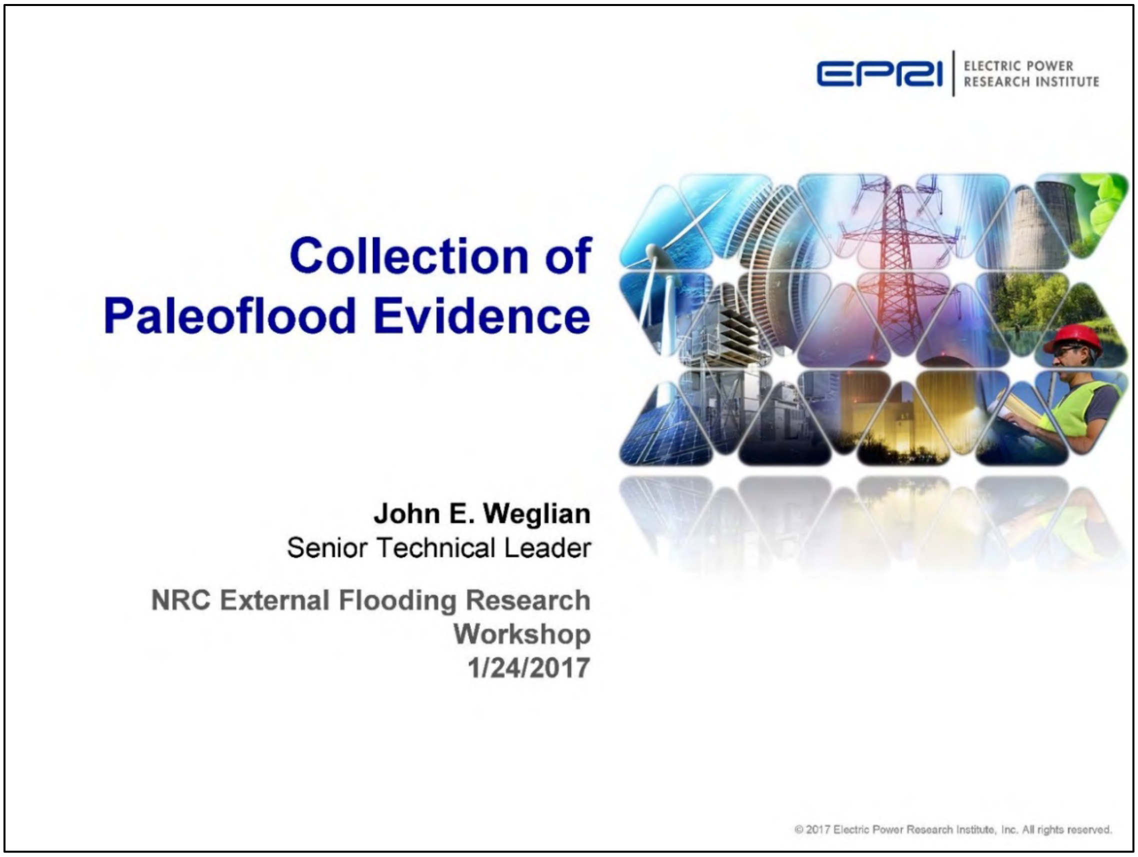
Various techniques are available to extend the data at a particular site, including the use of storm transposition and numerical generation of synthetic storms, but these are still based on data collected in the recent past. The investigation of paleoflood evidence (evidence of flooding that occurred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

In major flooding events, debris and sediment can be suspended and transported long distances in the fast-moving water. When the water enters a low-flow region, some of the suspended material will sink and become deposits on the surrounding floor. If these deposits are preserved in the environment, they can be used to estimate the time of the event and the flood discharge.

Paleoflood evidence can be found in terrace or overbank deposits when the water exceeds the riverbank and leaves the deposits on the surrounding land. These deposits may be good for estimating the frequency of flooding events that exceed that particular height, but they may not be good at estimating the flood stage for any particular event. Paleoflood evidence may also be deposited in caves or canyon walls, which could provide a good estimate for the flood stage, but the topography may be more prone to have one flooding event wash away the evidence of previous flooding events.

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

2.3.5.1.2 Presentation

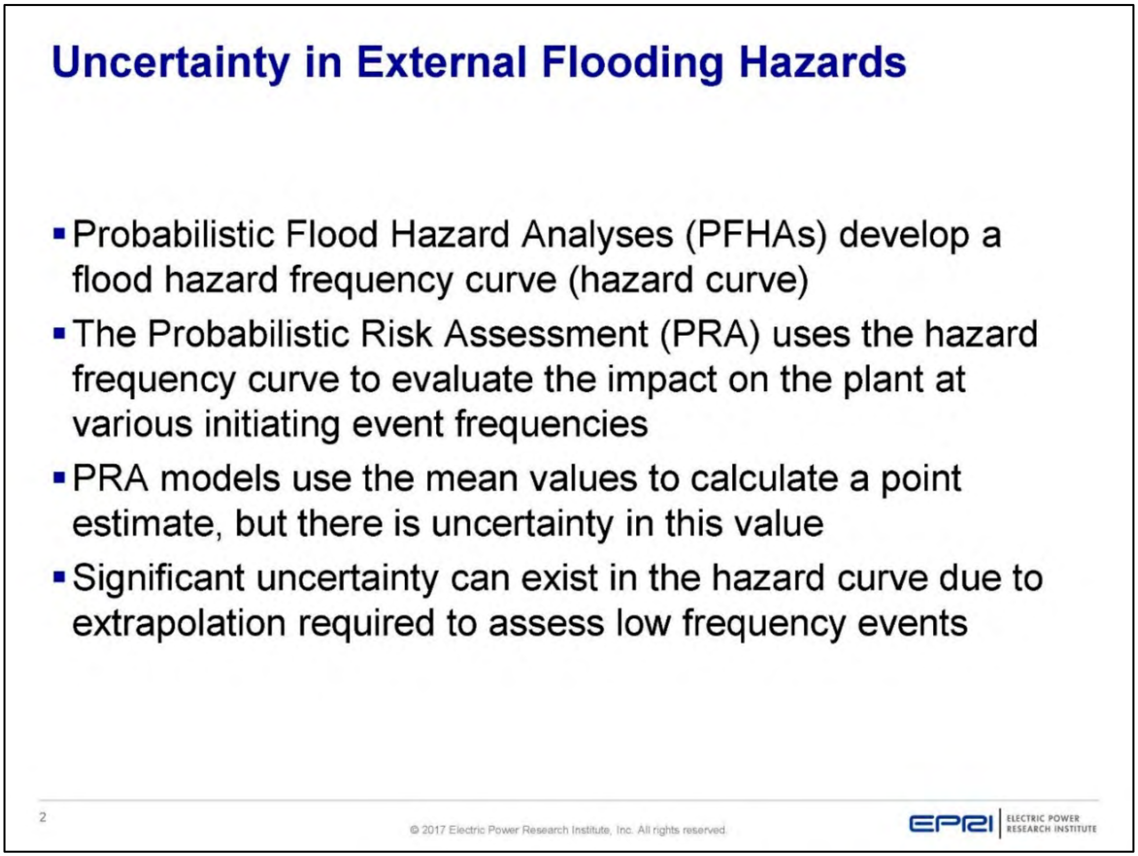


ELECTRIC POWER RESEARCH INSTITUTE

Collection of Paleoflood Evidence

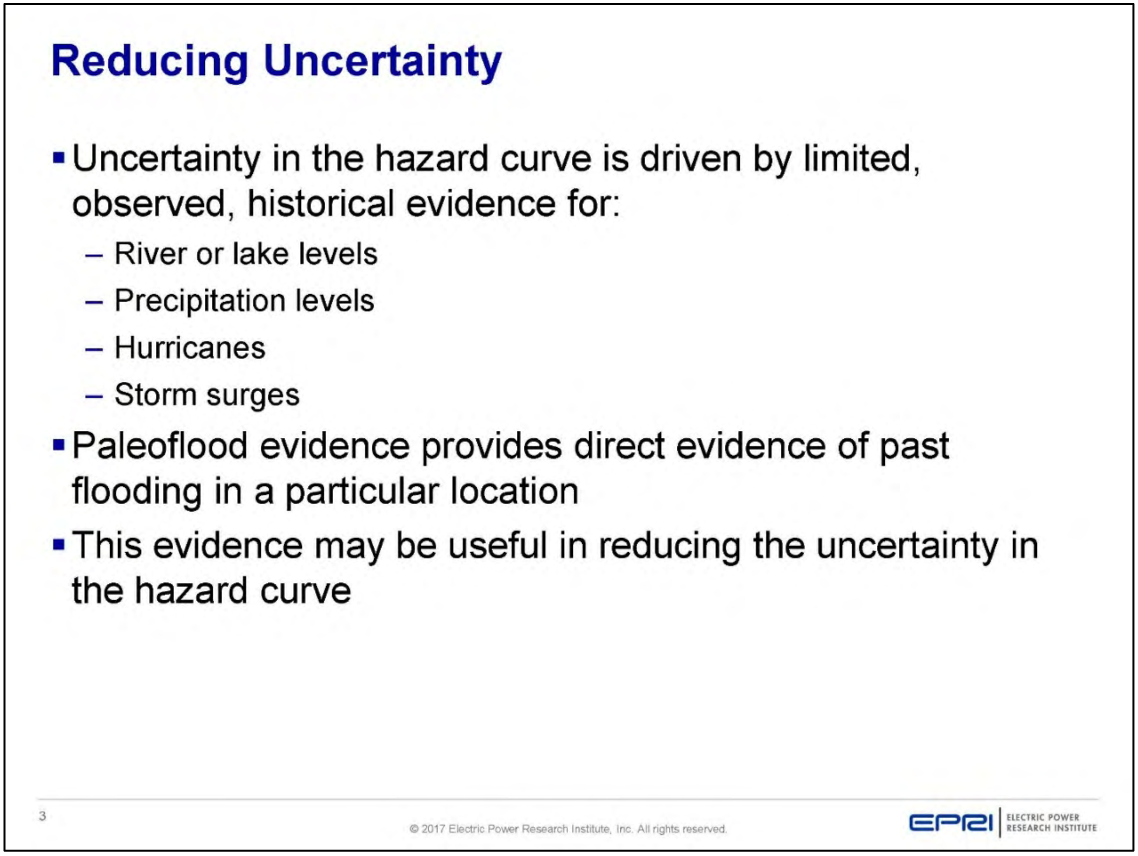
John E. Weglian
Senior Technical Leader

NRC External Flooding Research Workshop
1/24/2017



Uncertainty in External Flooding Hazards

- Probabilistic Flood Hazard Analyses (PFHAs) develop a flood hazard frequency curve (hazard curve)
- The Probabilistic Risk Assessment (PRA) uses the hazard frequency curve to evaluate the impact on the plant at various initiating event frequencies
- PRA models use the mean values to calculate a point estimate, but there is uncertainty in this value
- Significant uncertainty can exist in the hazard curve due to extrapolation required to assess low frequency events

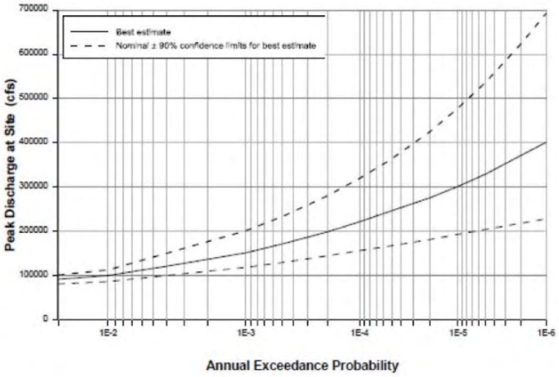


Reducing Uncertainty

- Uncertainty in the hazard curve is driven by limited, observed, historical evidence for:
  - River or lake levels
  - Precipitation levels
  - Hurricanes
  - Storm surges
- Paleoflood evidence provides direct evidence of past flooding in a particular location
- This evidence may be useful in reducing the uncertainty in the hazard curve

Incorporation of Paleoflood Data into Probabilistic Models

- Large uncertainties exist at very rare AEPs
- Information about flooding events in the 10^{-2} to 10^{-4} AEP range will help:
  - Anchor the mean
  - Reduce the uncertainty



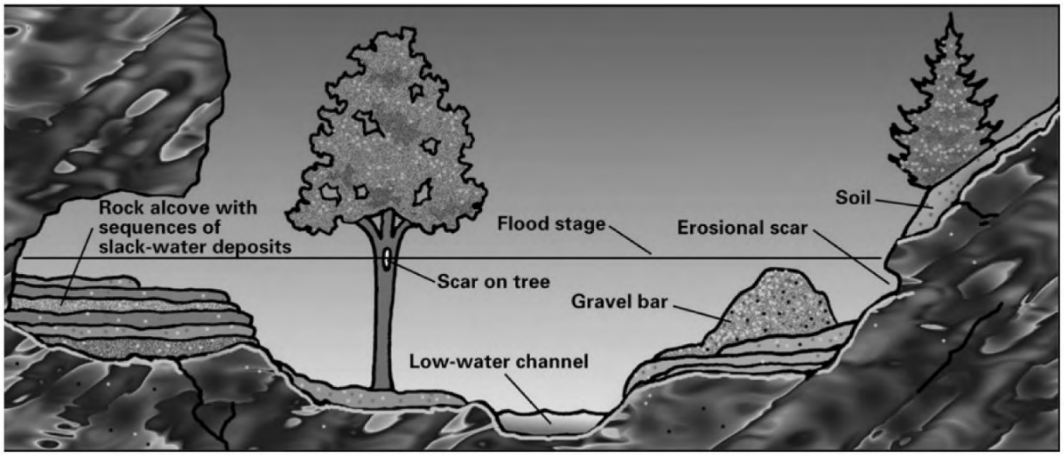
Paleoflood Evidence

- Evidence can provide:
  - Frequency of occurrence of extreme flooding events
  - Estimate of flood stage (i.e., water level) during flooding events
- Multiple sources of data may be needed for a more complete picture of the extreme flooding history

Sources of Paleoflood Evidence

- Flooding typically involves fast-moving water that can entrain a significant amount of solid material in the water
- At low-flow areas, this material can no longer be entrained and drops to the ground creating slack-water deposits
  - Terrace or overbank deposits
  - Cave deposits
  - Canyon wall deposits
- Trees can display impact scars from fast-moving debris
- Tree rings may provide evidence of inundation

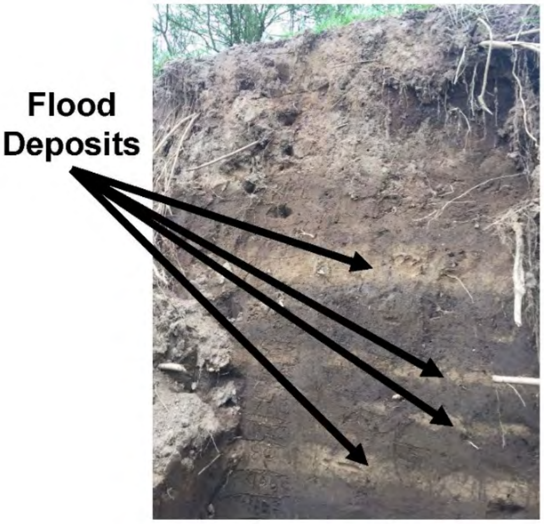
Paleoflood Evidence



Picture curtesy of Army Corps of Engineers

Terrace Deposits

- Terrace deposits can provide a good estimate for the frequency of floods that exceed the river banks
- Provides a lower bound on the flood stage
- Deposits may be mixed with soil by bioturbation (mixing by the effect of plant roots)



Cave Deposits

- Caves may provide a low-flow region that captures flood deposits without as much bioturbation
- Caves may contain archeological artifacts or other issues that complicate investigations
  - The cave in this picture is known to have human remains
  - White nose fungus concerns requires the protective suits
- Caves may provide better estimate of flood stage than terrace deposits

Dendrochronology (Using Trees to Determine Age)

- Trees can be used to estimate the date of floods
  - Tree rings can show evidence of inundation
- Tree scars can provide an estimate of flood stage
- Limited by the lifespan of nearby trees

Tree ring bore to analyze tree rings

EPRI's Investigations of Paleoflood Evidence

- Multiple universities are working with EPRI in the Tennessee River basin to determine:
  - What flooding evidence is preserved in a humid environment?
  - Where can the best evidence be found?
  - How can this evidence be used to develop data to inform the hazard frequency curve?
- Preliminary results show that paleoflood evidence is preserved

Arid vs. Humid Climates

- Paleoflood evidence has been used in arid climates where the evidence is well preserved
- At the start of this investigation, it was not clear if the evidence would be preserved in humid climates
  - Would repeated rains wash away the evidence of past floods?
- Initial investigations indicate that evidence is preserved, but may be more challenging to extract
  - Bioturbation can make identification of small flood deposits more difficult

Incorporation of Incomplete Information

- The paleoflood information does not have to be perfect
  - The impossible quest for perfect information should not prevent us from looking at what the evidence shows
  - Partial information is better than no information
- Statistical analysis tools allow for the incorporation of incomplete data

EPRI's Investigations of Paleoflood Evidence

- Initial report on collecting paleoflood evidence is planned for 2017
- Follow-on report on incorporating paleoflood data into the hazard frequency curves is planned for 2018

Together…Shaping the Future of Electricity

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2.3.5.1.3 Questions and Answers

Question:

The presentation stated that partial information is better than looking for perfect information and as a result having no information. How do you understand the environmental setting at the time of the flood and whether there is collaborating evidence? That is, how can you tell if the information available is reliable and how should it be used in a flood assessment? This is particularly important with regard to frequency and the development of hazard curves.

Response:

The answer is very site specific. If a site appeared to be a meandering river that has changed flow paths you would consider results differently than at a site that is a canyon that has remained stable for 10,000 years. Therefore, the analyst has to consider the site environment and river basin and how they many have changed over time. Sensitivity studies provide on was to deal with this. For example, if you want to study how a river would change in depth or base height, you could consider depositional effects that lift up the riverbed and scouring effects that wear it down. However, if you are looking at paleoflood evidence, the river may have moved up or down a little bit but may have roughly maintained the same width… It takes a significant amount of water to make a difference in height at high elevations. However, in a sensitivity analysis, one can consider an area that is 10 feet deeper and determine whether that change has an impact on the results.

One concern is that though flooding may have occurred at some point in history, evidence of it cannot be found and so it would be missing from the data. However, this concern can be minimized by gathering information from multiple different locations. For example, data from the different universities that are working in different, yet nearby, locations could be combined. If there is evidence of floods around Knoxville, TN, that do not have corresponding evidence [from the sites studied by researchers working in the same area, but from] Alabama, that could indicate a problem and the need to gather data from many more places to have a good estimate of the flood history…

Question:

How is carbon dating applied to flooding studies for NPPs?

Response:

Radiocarbon dating can be used only over a certain period back in time and requires something in the flood deposit that has enough carbon to analyze. For example, a flood deposit may contain a twig, but to use radiocarbon dating the analyst would have to know whether that twig would have the same date as that flood, or whether that twig had been present for long time before the flood occurred and picked it up and carried it away. Another sampling technique called optically stimulated luminescence (OSL) looks at the effect of exposure to the sunlight of particular crystals. A sample that has been buried in the dark for a number of years, then collected and kept in the dark before analysis, would generate an output that can be correlated to much longer timeframes than radiocarbon samples. Other techniques may be able to date samples that are much older, but paleoflood evidence from a million years ago would not be applicable because a sample from that time would have been under the ocean. Paleoflood evidence is applicable for flooding events with AEPs of about 10^{-2} to 10^{-4} but becomes less credible beyond that.

Question:

The presence of freshwater clam shells and other evidence of reptiles and amphibians in these flood deposits can also provide some insight.

Response:

Depending on the finding, the finding could have been affected by humans because humans have been present during that time period. For example, some dirt next to a canyon wall was sunken. The geologists thought that it could have been the result of rainfall washing soil away. The archaeologist pointed out that looters digging for artifacts were a more likely cause. It takes a range of expertise to fully understand what the field evidence shows. You have to look in multiple places and see what all the evidence tells you to form a complete picture.

Question:

A researcher may find evidence in a particular location, but the site with the relevant frequency analysis is 10 miles downstream. What method would be used to try to bring that information together? Locations may have radically different responses in terms of the water surface elevation.

Response:

EPRI has partnered with the Tennessee Valley Authority (TVA), which has two different models. One includes all of the existing dams, but the other is a naturals model that assumes that none of the dams have been built. The naturals model can be run with a water level at a particular site, downstream or upstream, to determine water level at another site. The model has been calibrated with water flows. Models probably already exist for large rivers, but a hydraulic /hydrologic model could be built for the watershed of interest to determine the water height at the site of interest based on the water height at another location along the river. If the difference between the sites is significant, then the analysis would need to consider where the water came from in the first place. For example, if the cause was some kind of precipitation event that added water to the watershed, the water could have fallen in one part of the watershed and not the other. As these rivers filter into each other and combine, a flooding event may affect one part of the watershed and not another.

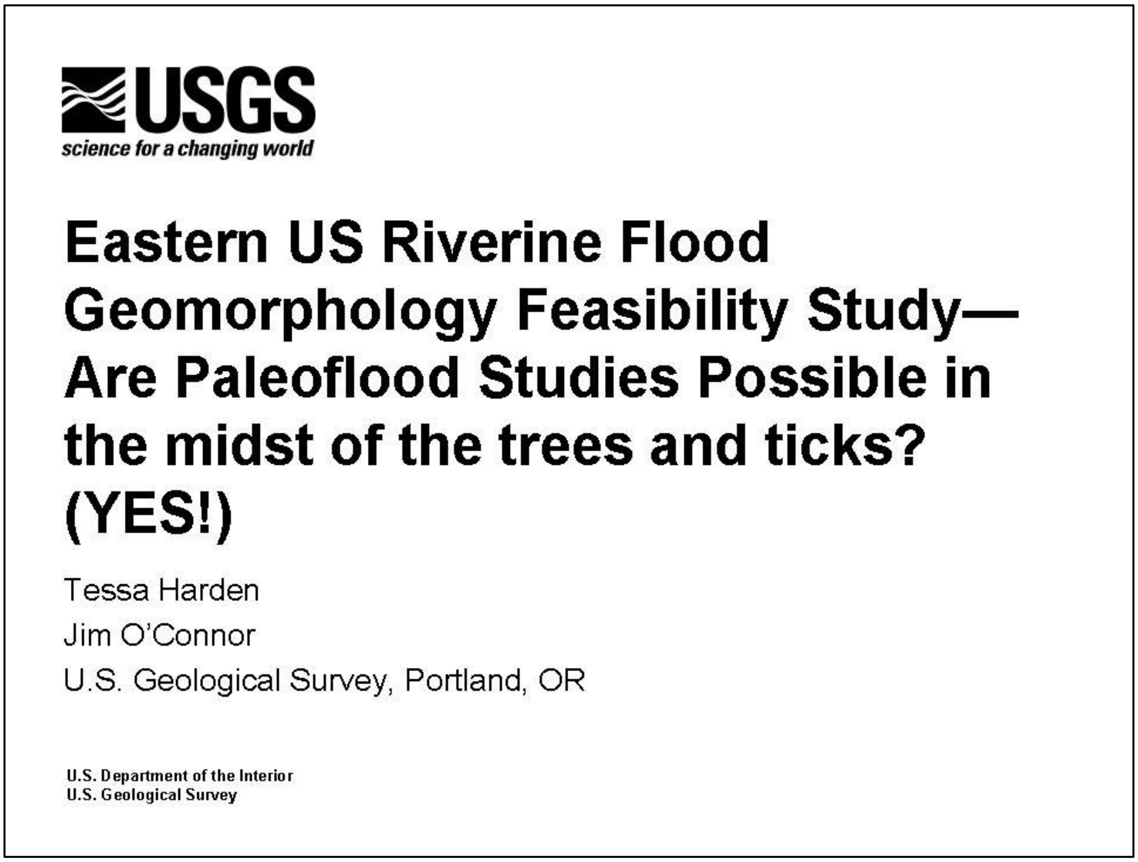
2.3.5.2 Paleofloods on the Tennessee River—Assessing the Feasibility of Employing Geologic Records of Past Floods for Improved Flood Frequency Analysis , or “Eastern US Riverine Flood Geomorphology Feasibility Study – Are Paleoflood Studies Possible in the midst of the tress and ticks?

Tessa Harden*, Ph.D., USGS, Oregon Water Science Center; and Jim O’Connor*, Ph.D., USGS, Geology, Minerals, Energy, and Geophysics Science Center, Portland, OR (Session 2C-2; ADAMS Accession No. ML17054C513)

2.3.5.2.1 Abstract

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

2.3.5.2.2 Presentation

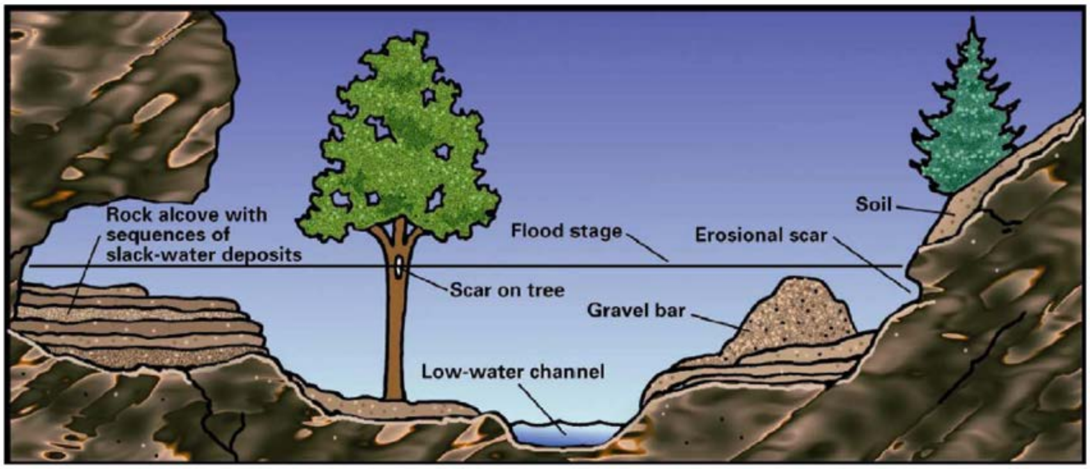


Eastern US Riverine Flood Geomorphology Feasibility Study—Are Paleoflood Studies Possible in the midst of the trees and ticks? (YES!)

Tessa Harden
Jim O’Connor
U.S. Geological Survey, Portland, OR

U.S. Department of the Interior
U.S. Geological Survey

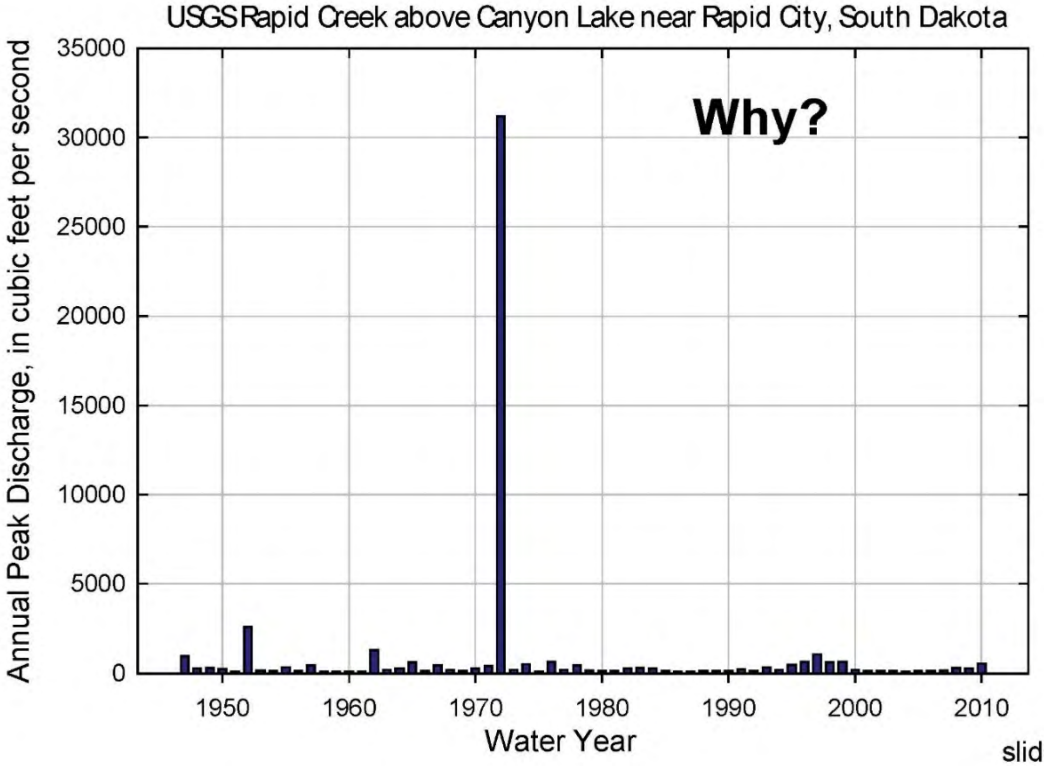
What is "Paleoflood" Hydrology



….using geologic evidence to understand flood history…

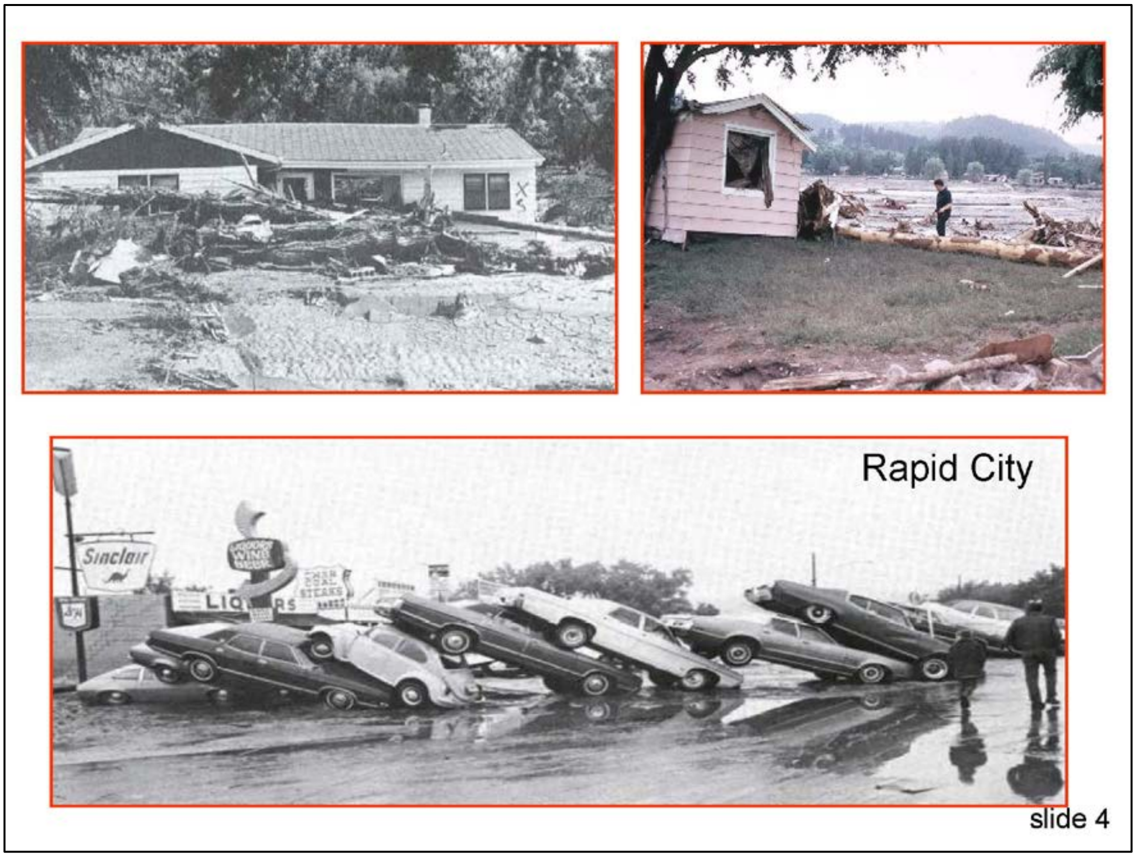
USGS

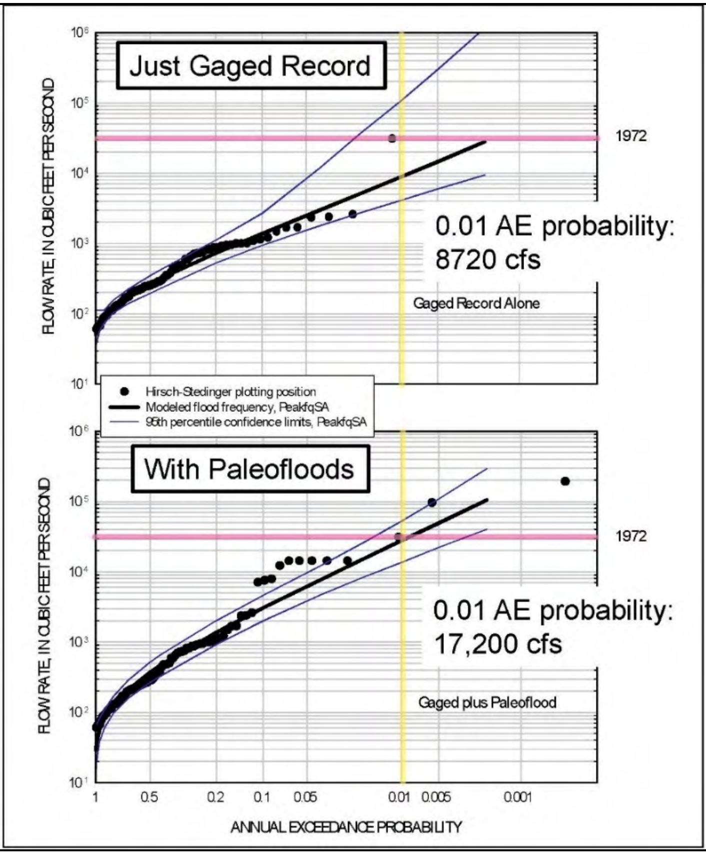
slide 2



Why?

slide 3


Sinclair
LIQUORS
Rapid City



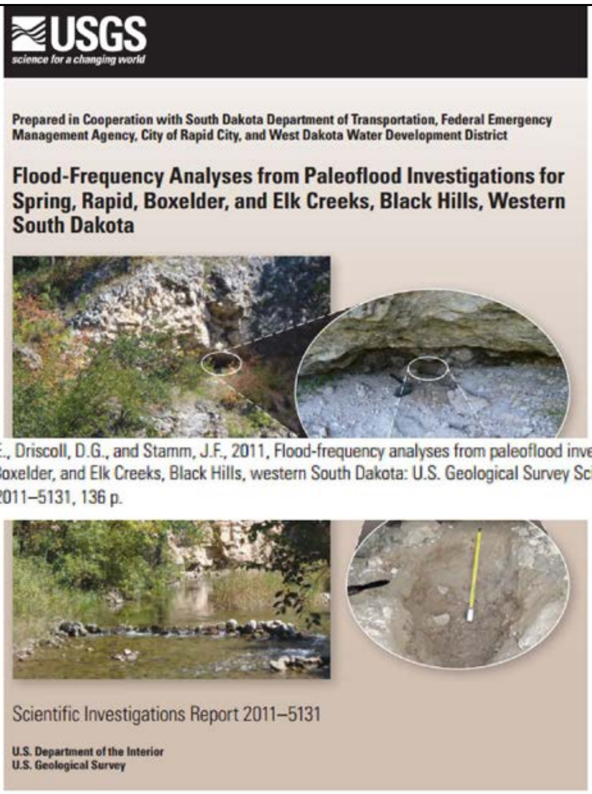
Just Gaged Record

0.01 AE probability:
8720 cfs

With Paleofloods

0.01 AE probability:
17,200 cfs

USGS



USGS
science for a changing world

Prepared in Cooperation with South Dakota Department of Transportation, Federal Emergency Management Agency, City of Rapid City, and West Dakota Water Development District

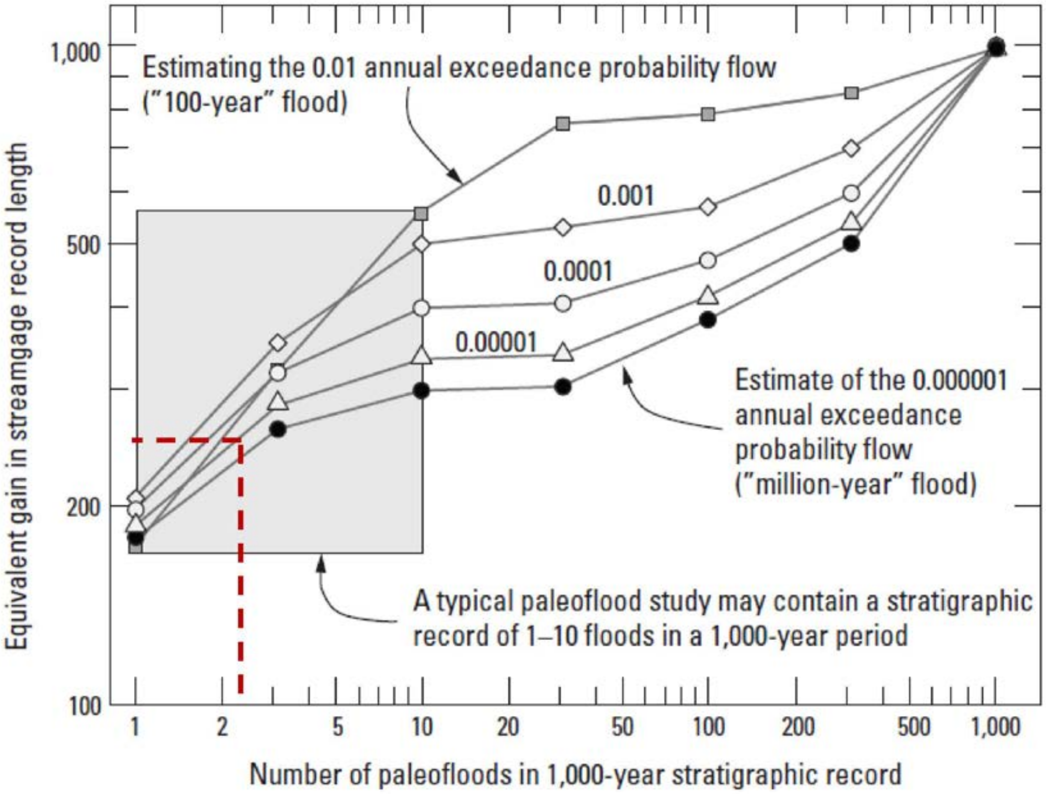
Flood-Frequency Analyses from Paleoflood Investigations for Spring, Rapid, Boxelder, and Elk Creeks, Black Hills, Western South Dakota

Scientific Investigations Report 2011–5131

U.S. Department of the Interior
U.S. Geological Survey

Harden, T.M., O'Connor, J.E., Driscoll, D.G., and Stamm, J.F., 2011, Flood-frequency analyses from paleoflood investigations for Spring, Rapid, Boxelder, and Elk Creeks, Black Hills, western South Dakota: U.S. Geological Survey Scientific Investigations Report 2011–5131, 136 p.

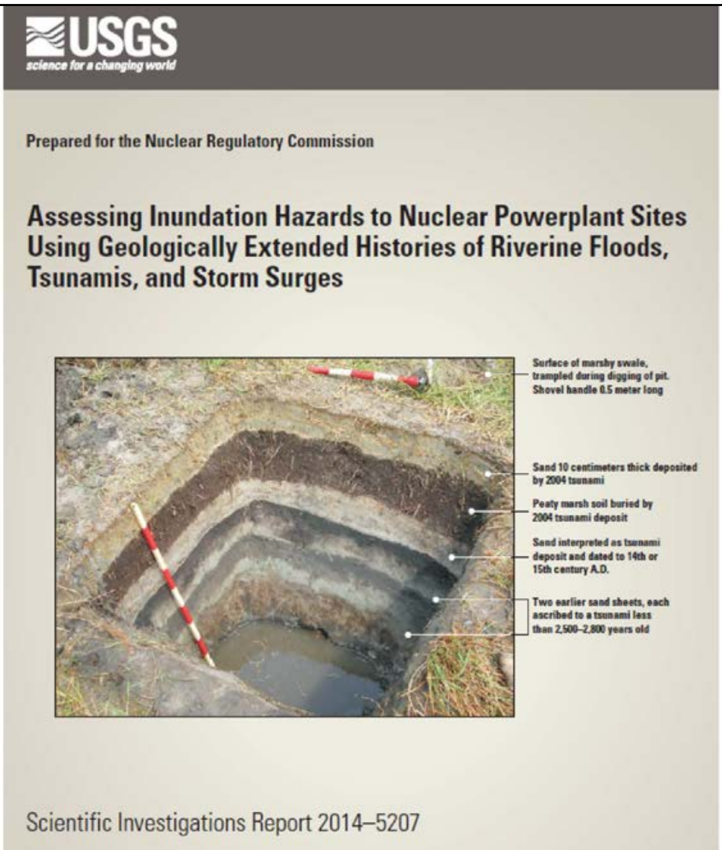
USGS



Estimating the 0.01 annual exceedance probability flow ("100-year" flood)

Estimate of the 0.000001 annual exceedance probability flow ("million-year" flood)

A typical paleoflood study may contain a stratigraphic record of 1–10 floods in a 1,000-year period



USGS
science for a changing world

Prepared for the Nuclear Regulatory Commission

Assessing Inundation Hazards to Nuclear Powerplant Sites Using Geologically Extended Histories of Riverine Floods, Tsunamis, and Storm Surges

Surface of marshy swale, trampled during digging of pit. Shovel handle 0.5 meter long

Sand 10 centimeters thick deposited by 2004 tsunami

Peaty marsh soil buried by 2004 tsunami deposit

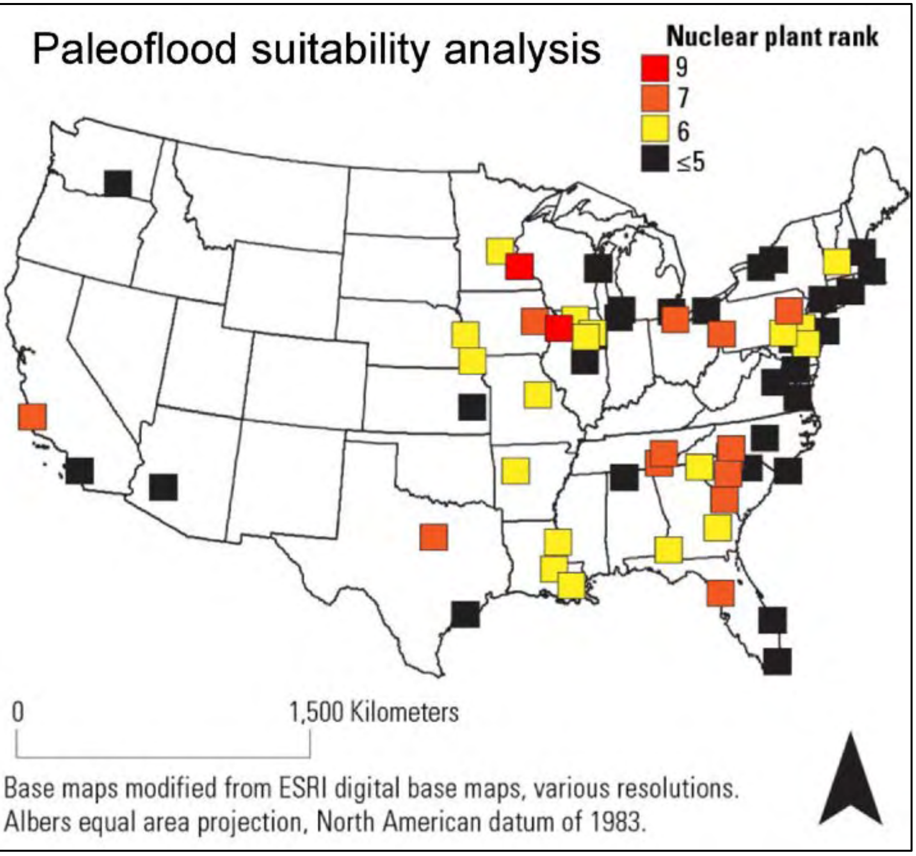
Sand interpreted as tsunami deposit and dated to 14th or 15th century A.D.

Two earlier sand sheets, each ascribed to a tsunami less than 2,500–2,800 years old

Scientific Investigations Report 2014–5207

USGS

Paleoflood suitability analysis



USGS

Base maps modified from ESRI digital base maps, various resolutions.
Albers equal area projection, North American datum of 1983.

Screening results:

- Several southeastern US sites are potentially suitable, including several rivers with multiple sites.

These include Susquehanna River, Pennsylvania; Tennessee River, Tennessee; and Catawba River, South Carolina.

O'Connor, J.E., Atwater, B.F., Cohn, T.A., Cronin, T.M., Keith, M.K., Smith, C.G., and Mason, R.R., 2014, Assessing inundation hazards to nuclear powerplant sites using geologically extended histories of riverine floods, tsunamis, and storm surges: U.S. Geological Survey Scientific Investigations Report 2014–5207, 66 p., *http://dx.doi.org/10.3133/sir20145207.*

USGS

Off to Chattanooga, March 20-26, 2016

Image from: http://caatn.org//

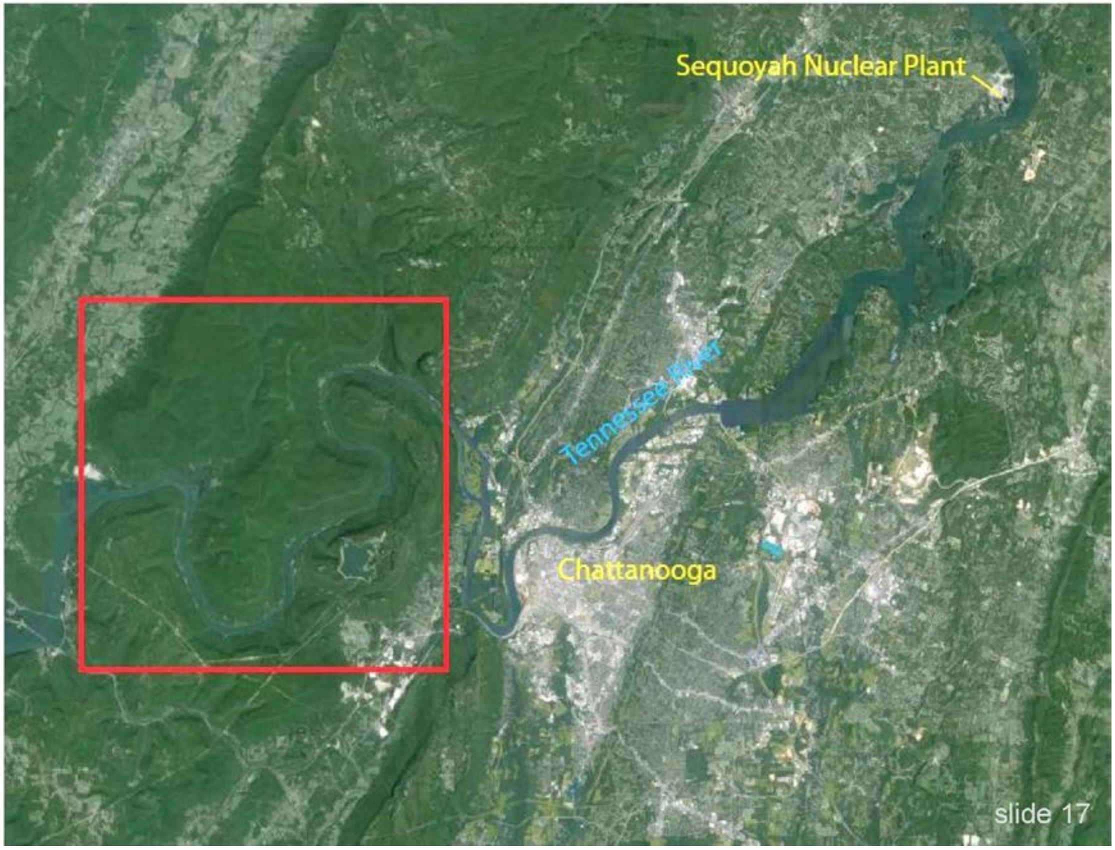
Objective (simple version):

- Is a paleoflood study feasible in the eastern United States?

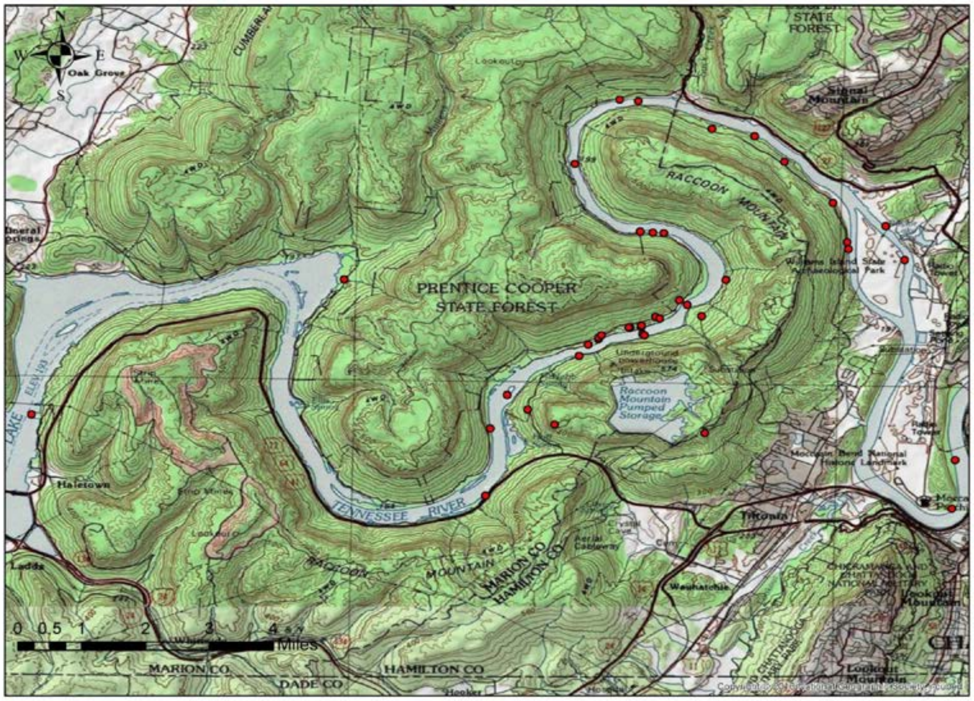
Approach:

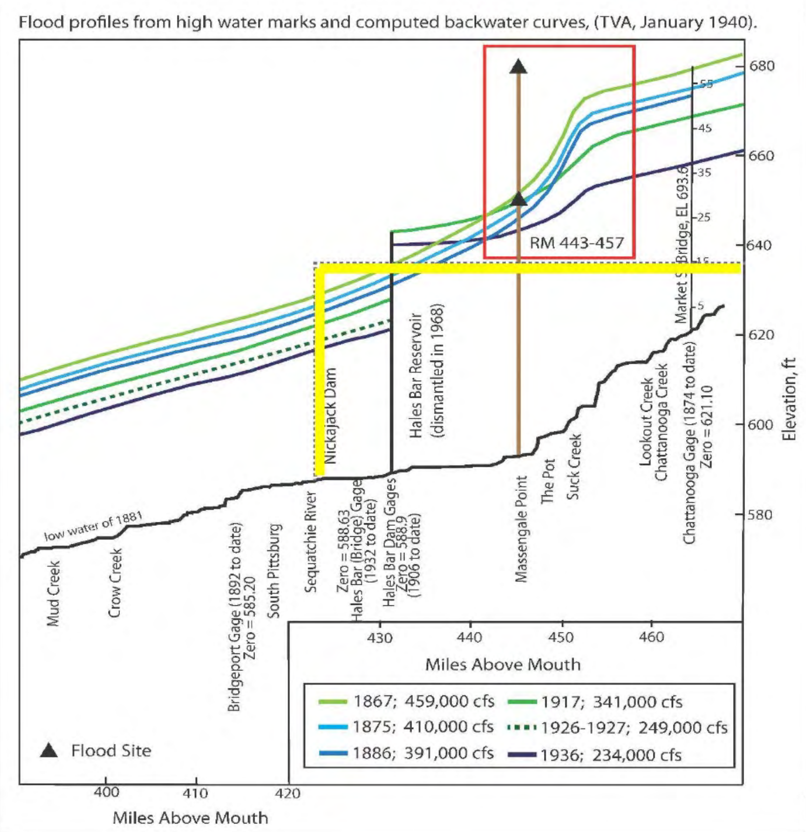
- Reconnaissance to identify potential sites
- Excavate and assess stratigraphy at a few key sites
- OSL and radiocarbon sample collection and analysis

USGS



Fieldwork, March 20-26, 2016:





Flood profiles from high water marks and computed backwater curves, (TVA, January 1940).

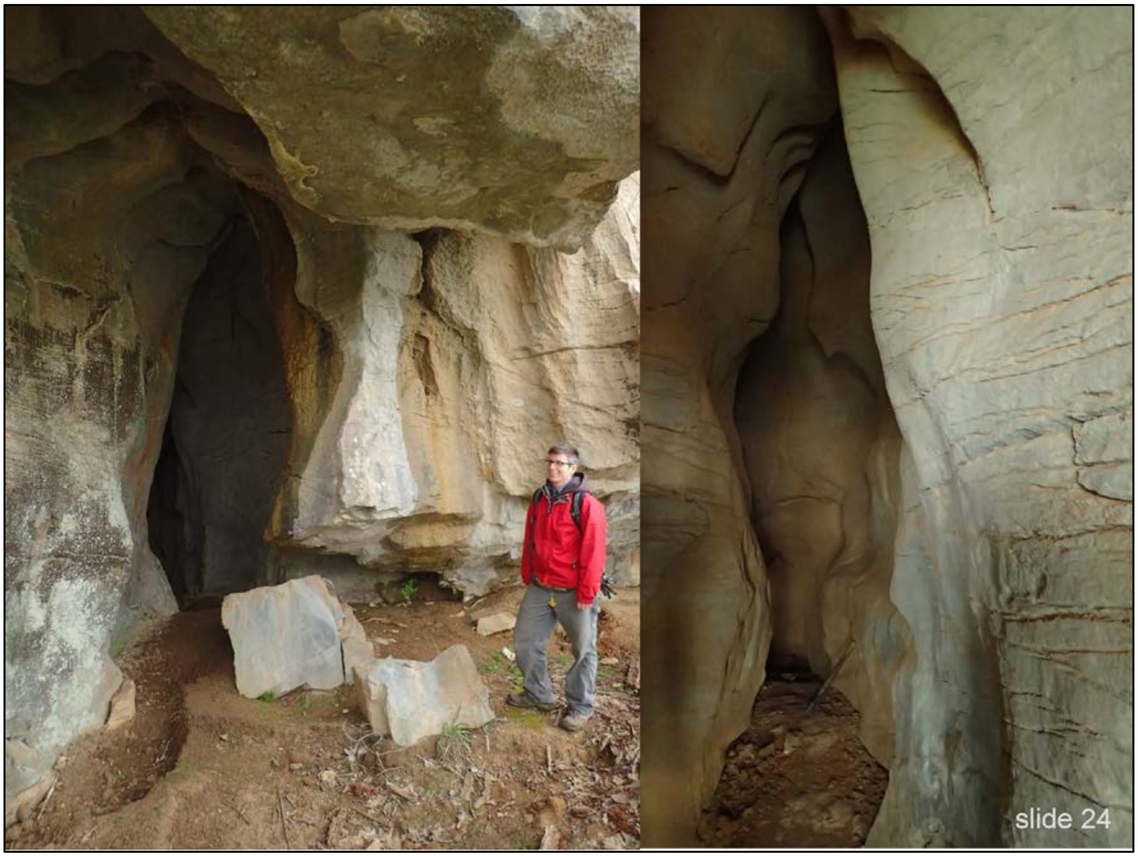
USGS

slide 20

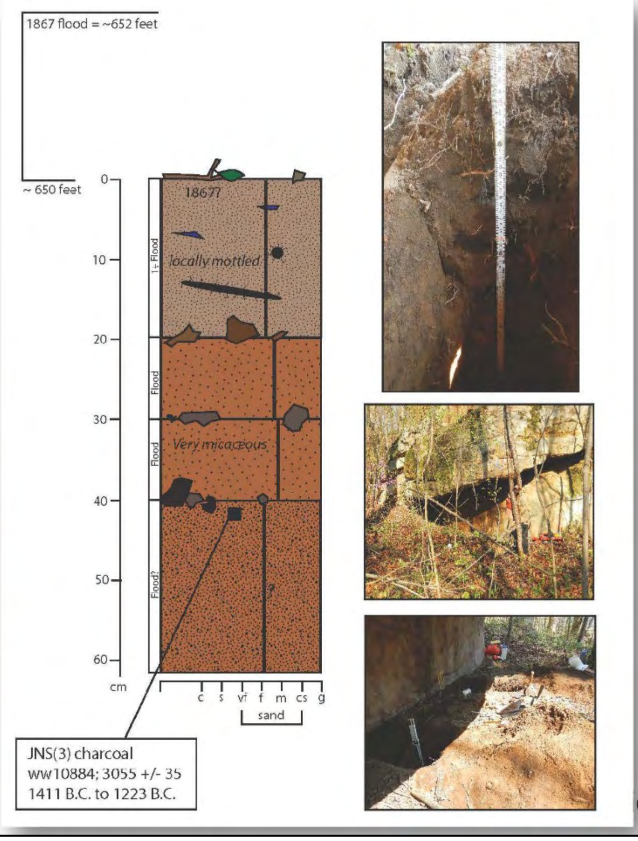
slide 21

slide 22

slide 23

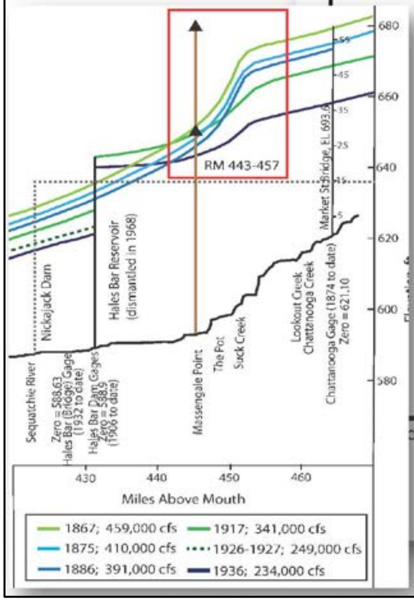


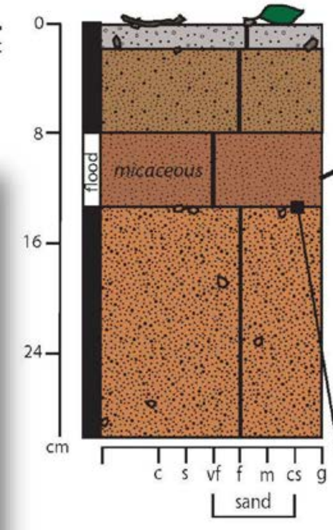
"Jeff-n-Steph" site located in the Gorge at a similar elevation as the 1867 high water marks. This sites contains at least 3+ flood deposits in the last ~3,000 years.

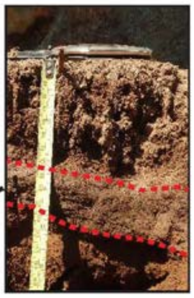


JNS(3) charcoal
ww10884; 3055 +/- 35
1411 B.C. to 1223 B.C.

"Red Flower" site in the Gorge. The elevation of this likely flood deposit is almost 30 feet higher than the 1867 flood stage.







Red(1) charred seed
ww10883; 180 +/- 30
A.D. 1652 to A.D. 1696,
A.D. 1726 to A.D. 1815

Tennessee River has all the ingredients:

- Sites
- Sediment
- Stratigraphy
- Potential for Chronology
- Bonus: Historical Information

Tasks for a Comprehensive Study (to begin in 2017)

- 1: Arrange for site access and permits
- 2: Thorough reconnaissance of potential sites (February, 2017)
- 3: Excavate and analyze the stratigraphy and chronology of the most promising sites
- 4: Determine likely flood magnitudes
- 5: Flood frequency analysis
- 6: Provide a USGS peer-reviewed report

Funding and contact information:

- National Screening, and the Tennessee River scoping (2016) and implementation (planned for 2017-2018) funded by Nuclear Regulatory Commission, Office of Nuclear Regulatory Research
- USGS Personnel: Tessa Harden tharden@usgs.gov); Jim O'Connor (oconnor@usgs.gov); and Harry Jenter (hjenter@usgs.gov)
- NRC Personnel: Mark Fuhrmann (mark.fuhrmann@nrc.gov); Meredith Carr (Meredith.Carr@nrc.gov); and Joseph Kanney (Joseph.Kanney@nrc.gov)

References:

- Harden, T.M., O'Connor, J.E., Driscoll, D.G., and Stamm, J.F., 2011, Flood-frequency analyses from paleoflood investigations for Spring, Rapid, Boxelder, and Elk Creeks, Black Hills, western South Dakota: U.S. Geological Survey Scientific Investigations Report 2011–5131, 136 p. http://pubs.usgs.gov/sir/2011/5131/
- Benito, G., and O'Connor, J.E., 2013, Quantitative paleoflood hydrology, in Shroder, J. (Editor in Chief), Wohl, E.E., ed., Treatise on Geomorphology, v. 9 (Fluvial Geomorphology), Academic Press, San Diego, California, p. 459-474.
- O'Connor, J.E., Atwater, B.F., Cohn, T.A., Cronin, T.M., Keith, M.K., Smith, C.G., and Mason, R.R., 2014, Assessing inundation hazards to nuclear powerplant sites using geologically extended histories of riverine floods, tsunamis, and storm surges: U.S. Geological Survey Scientific Investigations Report 2014–5207, 66 p. http://dx.doi.org/10.3133/sir20145207.

2.3.5.2.3 Questions and Answers

Question:

Among other things, the project looked at mica grains to help understand the energy of the flood and its deposit. Could you describe the energy regime and how you try to understand how big the flood is based upon the evidence of these so-called marker layers, as well as the scenario of the flood that might have deposited them? For example, could there have been ice jams or some earthquake that caused debris to create a dam that then caused the water levels to rise? What kinds of analysis have you done to think about the nature of the flood itself?

Response:

The first question relates to the method of extrapolation or taking the information of the deposit to determine how big the flood was. The approach is actually simple. The flood had to have a stage that was at least as high as a deposit. However, that is all that is known. For big floods or thick deposits, attempts are made to trace deposits up as high as possible in the existing records, but it is still not possible to know how much bigger the flood was above the deposit. One positive aspect of these new approaches is that they can accommodate that type of data (i.e., data that quantify the presence of a certain number of floods above a certain level in a given time period, but that do not indicate how much more above that level the floods were). However, that type of data is efficiently incorporated using these maximum likelihood techniques and the estimator approaches into the flood frequency analyses.

The second question relates to context issues. Historic information is valuable, in that if you find a deposit at the level of a known flood, it is certainly plausible that the found deposit was from an event similar to the known flood. However, if you find a deposit that is significantly higher or coarser, then you would need to consider what other types of mechanisms could generate higher stages. This is another advantage of these field studies in that they reveal considerations that are outside of those you were visualizing as the potential range of hazards affecting a site. For example, there could have been some sort of landslide in the Tennessee River Gorge that blocked the valley. Although that changes your flood frequency analysis, it is important to know for the plants upstream or downstream. As a result, these kinds of geological approaches are doubly valuable because they can tell you something about the problem of interest, but they might also tell you about problems that you should be interested in but did not know about.

Question:

Has Bulletin 17C been published yet?

Response:

Bulletin 17C is out for peer review, with plans to publish it by summer 2017[3].

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[3] Bulletin 17C was published March 29, 2018 as England, J.F., Jr., Cohn, T.A., Faber, B.A., Stedinger, J.R., Thomas, W.O., Jr., Veilleux, A.G., Kiang, J.E., and Mason, R.R., Jr., 2018, Guidelines for determining flood flow frequency—Bulletin 17C: U.S. Geological Survey Techniques and Methods, book 4, chap. B5, 148 p., https://pubs.usgs.gov/tm/04/b05/tm4b5.pdf

Question:

Have you used heavy mineral analysis? This could be an indicator for the movement based on the gravitational forces and the flood forces. It could also help in considering the particulate size distribution and determining how particles are distributed in the floods in different periods of time. Such information may indicate the dynamics for the flood forces taking place. The particulate size and shape of the particulate could be useful in determining the erosional forces that took place and thus the size of the flood. It may also be useful to conduct a heavy metal analysis for all of the sediments. It could be useful to separate the heavy minerals in the sediments of different layers and try to analyze them, including how they are distributed among the layers.

Response:

This study's stratigraphic approach is very simple, but there are many more complicated approaches that could be taken involving the techniques mentioned that would likely require expensive equipment. USBR does use the particle size, although it is not quantified in a rigorous way. Rather, it is used in a qualitative way in that, if one deposit is coarser or thicker than the other, it would hint that it was from a bigger flood. Although such an observation does not indicate flood size for certain, it inspires us to look higher. The minerology is also considered informally, mainly to be secure about the source of the sediment. For example, in the Tennessee River sites, one question is whether those deposits could have resulted from water coming down the hillslopes and somehow reaching underneath and into those caves. In that example, we know that could not have been the case because there is no source of mica in the rocks on the hill slopes. By contrast, the Tennessee River sediment is full of mica, which is easy to recognize in the sediments. Therefore, if mica is present, it indicates that this is Tennessee River sediment. This approach is simple, straightforward stratigraphy, although there are certainly ways to make it much more complicated and spend a lot more money doing it.

Question:

Did you observe any terrace deposits either in the Gorge or upstream that you could use to bracket the flood stages?

Response:

The Gorge itself does not contain much in the way of terrace deposits or alluvial deposits. At the upstream entrance to the Gorge, Williams Island has about a 10,000-year record of stratigraphy. We did study that; however, because that island was inundated by the 1867 flood and other historic floods, it does not reveal much about the full size of the floods. The stratigraphic record of thick and thin deposits could be correlated with the better record of high floods along the canyon margins. Further work at Williams Island will be done to determine whether that floodplain stratigraphy can be linked with what is seen up higher. The floodplain stratigraphy upstream could also be considered in terms of trying to evaluate flood history. In addition, although the valley was quite wide upstream, in some places the river banks up against bedrock, and that bedrock itself also contained higher flood deposits that could be evaluated. In addition to the Tennessee Gorge, other places on that river corridor are also worth investigating.

Question:

When the 1-in-500-year flood essentially turns out to be in the 60-year systematic data range, and research for the history of the flood reveals other floods, how can you be confident that you have not missed information in between the big floods, or on a lot of other smaller floods (but that are bigger than the regular-sized flood), affecting the statistical tails because you do not have the precisions that are available from observing floods (i.e., those 60 years of systematic data)?

Response:

One way to address this issue is by conducting a sensitivity test. For example, if the data are missing three floods in a particular timeframe between given sizes, how big a difference does it make to the results? It turns out that if the biggest flood in the last certain number of years can be determined, the other ones do not matter as much. This results in an interpretative conclusion, such as “We know that we have had at least one flood of 50,000 cubic feet per second in the last 1,000 years.” To help constrain the statistical tail, you would need to draw a conclusion about what has not happened. For example, if you can say that, because of the stratigraphy here, there was no flood this high in the last 10,000 years that helps constrain the flood frequency distribution. This type of information is also now much more efficiently employed in these newer flood frequency estimation techniques. In the end, you do need to have some confidence in some aspect of the record. This is one reason why both these studies are being done in parallel, to identify what happens when two different groups are doing the same work on the same river. Do the interpretive aspects work out to the same results in the end?

Comment:

In licensing, the approach is to base everything on procedures. The standard is presented, and peer reviews are conducted to determine whether the standard is met. The goal is to remove judgment from the process. In this discussion, there is concern with the extent that extrapolation can be done. These studies involve the professional judgment of expert geologists, statisticians, and others and provide good information to help improve decision-making. How does the NRC anticipate applying the information from these studies and this discussion into the nuclear power plant licensing process?

Response: NRC Hydrologist

The NRC will need to use multiple lines of evidence, multiple methods to increase our confidence in decision-making. This information is very good input to the risk-informed decision-making process, even though the answers may not be as crisp as we are used to obtaining in deterministic analysis.

2.3.6 Day 2: Session 2D - Reliability of Flood Protection and Plant Response I

This session considered the development of guidance for assessing the reliability of flood protection and plant response to flooding events.

2.3.6.1 EPRI Flood Protection Project Status, David Ziebell and John Weglian*, EPRI (Session 2D-1; ADAMS Accession No. ML17054C515)

2.3.6.1.1 Abstract

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

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

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

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

- design
- qualification
- maintenance
- design change process
- inspection
- periodic surveillance of flood protection features
- mitigating strategies for off-normal conditions
- training
- reevaluations of the adequacy of management methods
- integrated assessment
- documentation and reporting

2.3.6.1.2 Presentation

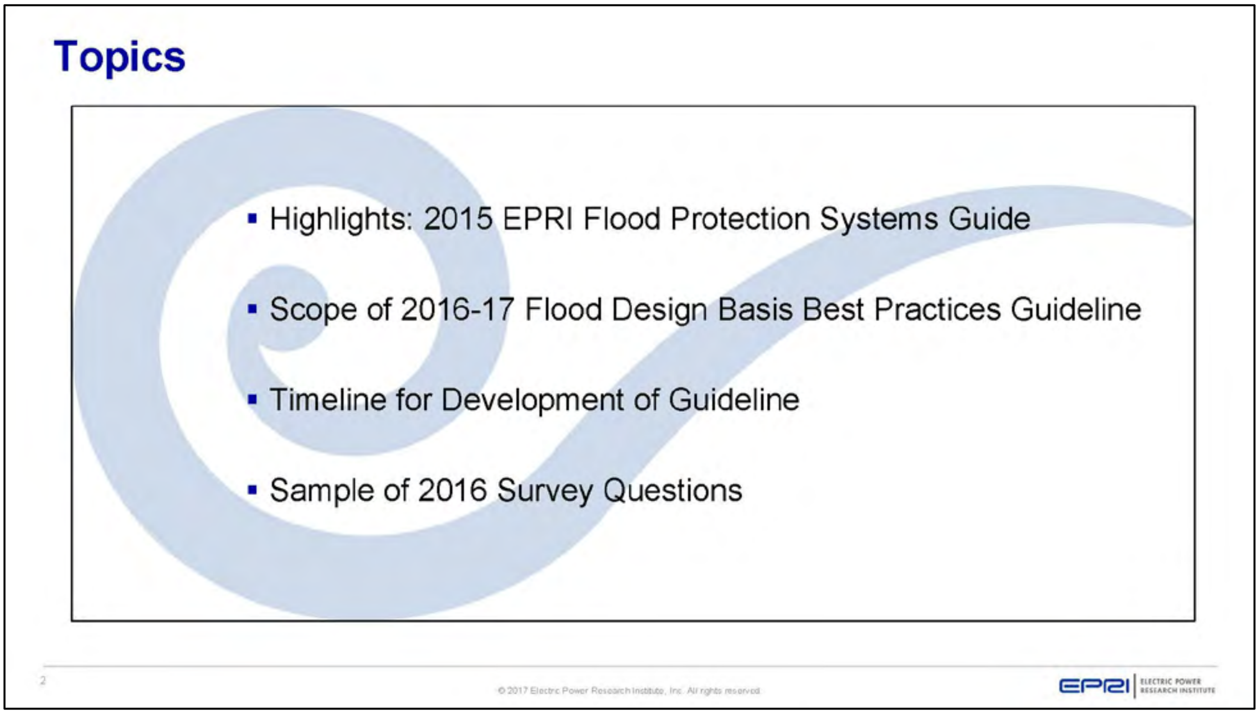
ELECTRIC POWER RESEARCH INSTITUTE

EPRI Flood Protection Project Status

David Ziebell
Senior Technical Leader

1/23/17

NRC External Flooding Research Workshop



Topics

- Highlights: 2015 EPRI Flood Protection Systems Guide
- Scope of 2016-17 Flood Design Basis Best Practices Guideline
- Timeline for Development of Guideline
- Sample of 2016 Survey Questions

Flood Protection Systems Guide – Available to Members

- 12 Utilities Involved in TAG
- Good Initial Industry Feedback
- Significant Product Downloads Since Publication 11/24/15

2015 TECHNICAL REPORT

Flood Protection Systems Guide

Product ID: **3002005423**

Flood Protection Systems Guide – 2015 Technical Report

- Immediate response to assist members by providing flood protection feature guidance.
- Focused on feature descriptions, design criteria, inspections, and available testing methods.

Flood Protection Systems Guide – Section Overview

- **Section 2**: Types of Flood Barriers Used in Nuclear Power Plant Applications
- **Section 3**: Current Testing Methods and Acceptance Criteria
- **Section 4**: Design Considerations Associated with Flood Protection Components
- **Section 5**: In-service Inspection, Testing, and Maintenance Recommendations
- **Section 6**: Industry Performance Analysis
- **Section 7**: Establishing and Managing Flood Bases Requirements

Flood Protection Systems Guide Overview

- **Section 2: Types of Flood Barriers**
- Sections of Guide Structured by Categories and Components Initially Defined in Section 2:
  - Passive Components
  - Active Components

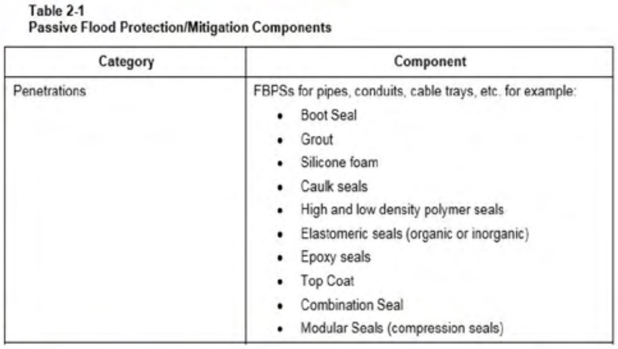


Table 2-1
Passive Flood Protection/Mitigation Components

Category	Component
Penetrations	FBPSs for pipes, conduits, cable trays, etc. for example: • Boot Seal • Grout • Silicone foam • Caulk seals • High and low density polymer seals • Elastomeric seals (organic or inorganic) • Epoxy seals • Top Coat • Combination Seal • Modular Seals (compression seals)

- **Flood Barrier Penetration Seal (FBPS) –** A material, combination of materials, or pre-manufactured device installed inside a penetration through a flood barrier to seal the opening and maintain the flood rating of the barrier. Typical penetrations include openings to accommodate the passage of pipe, tubes, conduits, cable trays, cables and ventilation ducts.

Flood Protection Systems Guide Overview

- **Section 3: Current Testing Methods and Acceptance Criteria**
  - Summary of Historic Penetration Seal Testing Methods
  - Primer for follow-on work related to test criteria development

Table 3-1
Summary of Historic Penetration Seal Testing Methods

Pressure Medium	Pressure Range	Hold Time(s)	Leakage Reported In	Max. Specimen Size Tested
Air	1/8"-40" WC	30-240 minutes	liters per minute (lpm) standard cubic feet per hour (SCFH)	48" x 48"
Air	0-30 psi	1-120 minutes	Units of leakage not reported	36" diameter
Steam	0-40 psi	1-30 minutes	Noted but not quantified	14" diameter
Water (Static)	½"-18" WC	½-20 hours	Noted but not quantified	30" x 30"
Water (Dynamic)	0-26 psi	1-10 days	Drops per unit of time Gallons per unit of time ml per unit of time liters per unit of time Noted but not quantified	4" diameter

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Flood Protection Systems Guide Overview

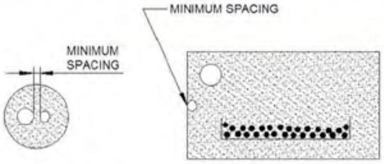


Figure 4–3
Examples of Minimum Spacing

- **Section 4: Design Considerations**
  - Focus on Flood Barrier Penetration Seals (FBPS)
    - Mechanical Penetrations
    - Electrical Penetrations
    - Ventilation Penetrations
    - Combination Penetrations

Table 4-1
Generic Design Considerations for all FBPSs

Design Consideration:	**Orientation**
Definition:	The position of the penetration seal with respect to the horizontal or vertical plane. Penetration seals installed in a wall are referred to as being vertically oriented, whereas penetration seals installed in a floor/ceiling are referred to as being horizontally oriented.
Importance:	For horizontally oriented FBPSs, the corresponding pressure associated with the flood event is added to the existing forces acting on the FBPS during normal operation (gravity, compartment pressures, etc.). The cumulative effect of all forces acting on the seal should be considered during FBPS design and qualification to guard against catastrophic failure of the FPBS during postulated flooding events. For vertically oriented FBPSs, material creep should be considered to ensure isolated leakage paths do not develop over time. Locations susceptible to leakage due to material creep include the interface between the top of the opening and FBPS materials, as well as, the interface between the underside of any rigid penetrating items and the adjacent FBPS materials.
Design Consideration:	**Barrier Type and Thickness**

Flood Protection Systems Guide Overview

- **Section 5: In-service Inspection, Testing, and Maintenance Recommendations**

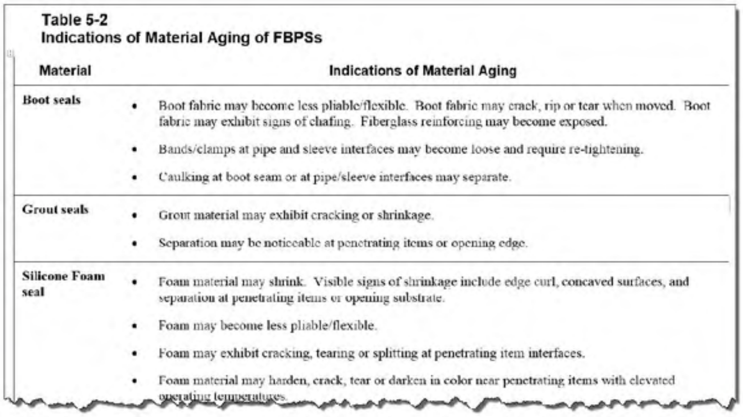
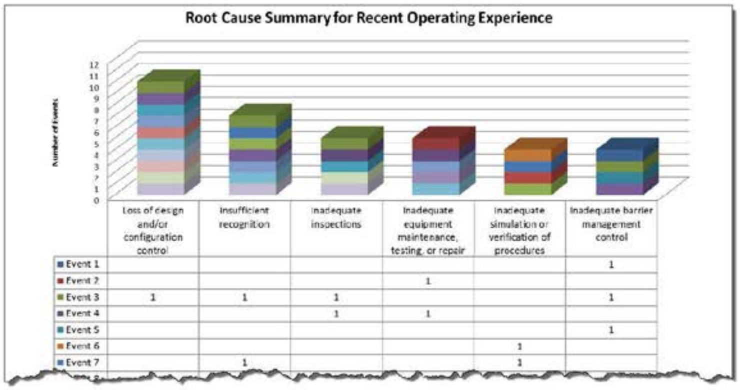


Table 5-2
Indications of Material Aging of FBPSs

Material	Indications of Material Aging
Boot seals	• Boot fabric may become less pliable/flexible. Boot fabric may crack, rip or tear when moved. Boot fabric may exhibit signs of chafing. Fiberglass reinforcing may become exposed. • Bands/clamps at pipe and sleeve interfaces may become loose and require re-tightening. • Caulking at boot seam or at pipe/sleeve interfaces may separate.
Grout seals	• Grout material may exhibit cracking or shrinkage. • Separation may be noticeable at penetrating items or opening edge.
Silicone Foam seal	• Foam material may shrink. Visible signs of shrinkage include edge curl, concaved surfaces, and separation at penetrating items or opening substrate. • Foam may become less pliable/flexible. • Foam may exhibit cracking, tearing or splitting at penetrating item interfaces. • Foam material may harden, crack, tear or darken in color near penetrating items with elevated operating temperatures.

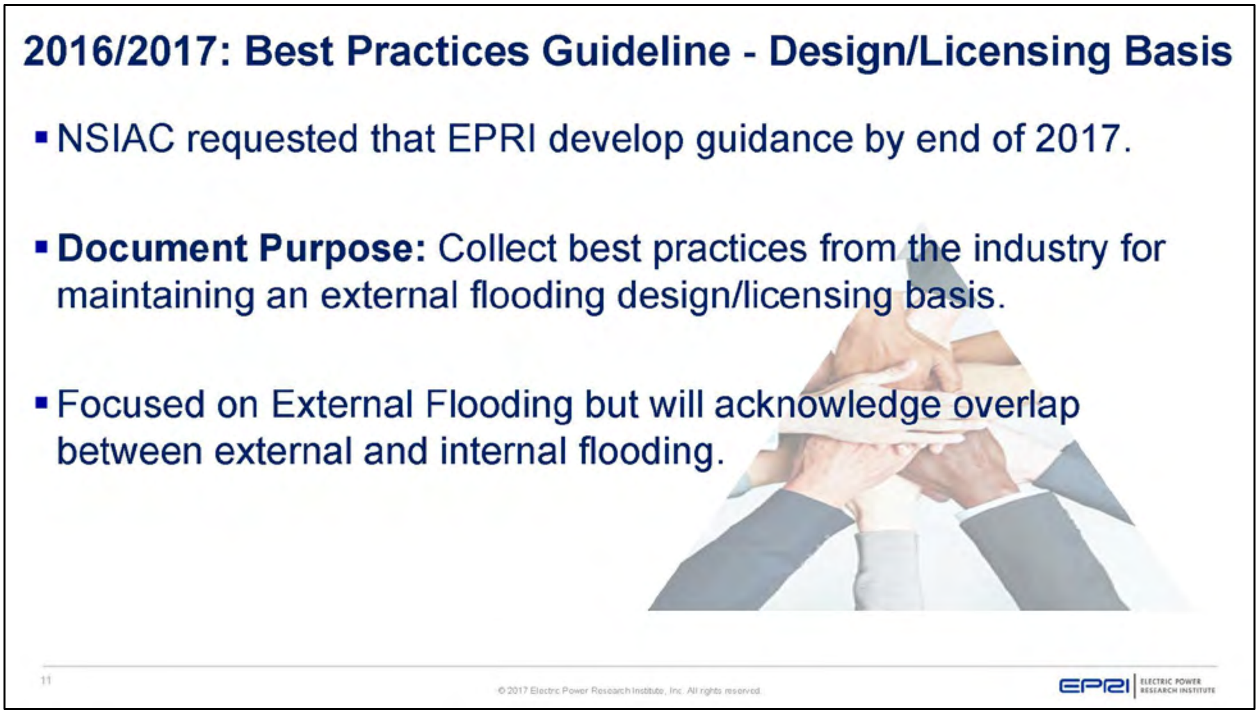
Flood Protection Systems Guide Overview



Root Cause Summary for Recent Operating Experience

	Loss of design and/or configuration control	Insufficient recognition	Inadequate inspections	Inadequate equipment maintenance, testing, or repair	Inadequate simulation or verification of procedures	Inadequate barrier management control
■ Event 1						1
■ Event 2				1		
■ Event 3	1	1	1			1
■ Event 4			1	1		
■ Event 5						1
■ Event 6					1	
■ Event 7		1			1	

- **Section 7: Establishing and Managing a Flood Bases**
  - Best practices from within TAG outlined
  - Primer for Design Basis Best Practices Guideline focused more on “programmatic” aspects



2016/2017: Best Practices Guideline - Design/Licensing Basis

- NSIAC requested that EPRI develop guidance by end of 2017.
- **Document Purpose:** Collect best practices from the industry for maintaining an external flooding design/licensing basis.
- Focused on External Flooding but will acknowledge overlap between external and internal flooding.

Design/Licensing Basis Best Practices Guideline - Outline

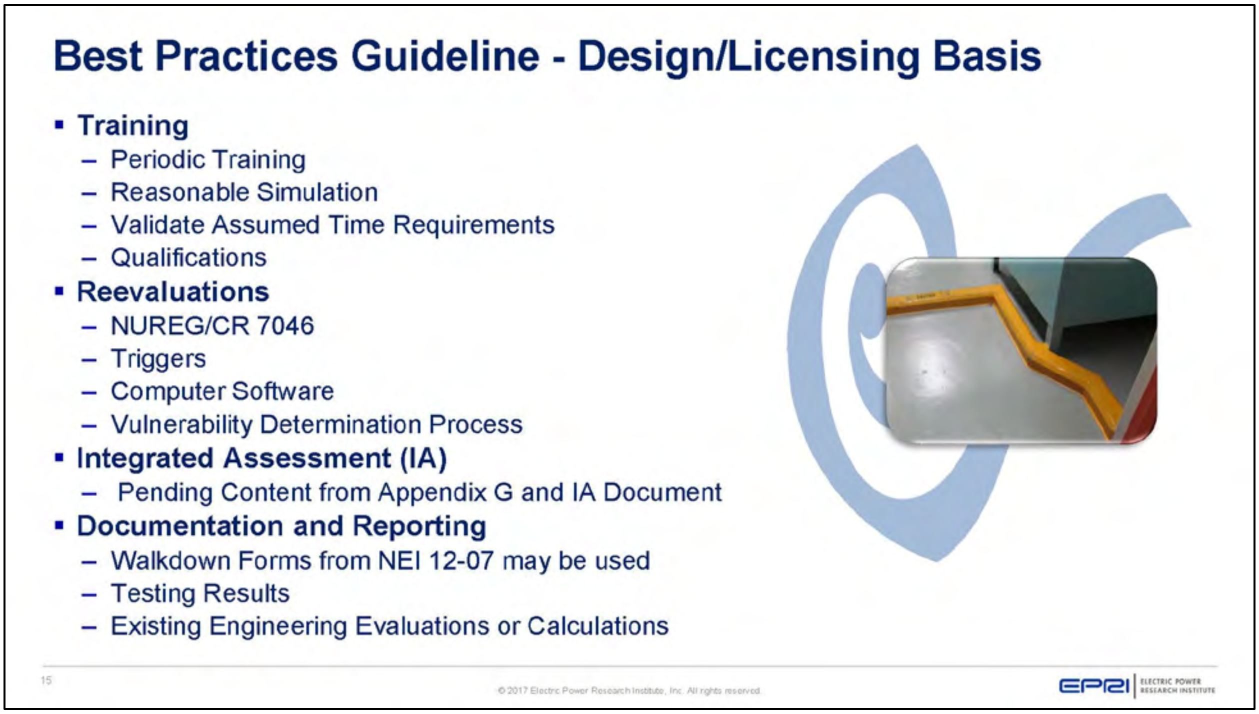
- Design (Method)
- Qualification (QA Requirements)
- Maintenance (Procedures)
- Modification (Design Change Process)
- Inspection (Flooding Design Basis Walk downs)
- Testing (Periodic Surveillance of Flood Protection Features)
- Mitigation (Mitigating Strategies)
- Training
- Reevaluations
- Integrated Assessment
- Documentation and Reporting

Best Practices Guideline – Section Outlines

- **Design (Method)**
  - Identification of features
  - Acceptable methods
  - Consolidated documents
  - PRA
- **Qualification (QA Requirements)**
  - Appendix B controls for back up
  - Augmented quality requirements or something else
  - Attributes
- **Maintenance (Procedures)**
  - Plant Configuration for Full Range of Operation
  - Work Management Procedures
  - Risk assessment during maintenance and aggregate risk
  - Maintenance Rule
  - PMs
  - Installation and Testing

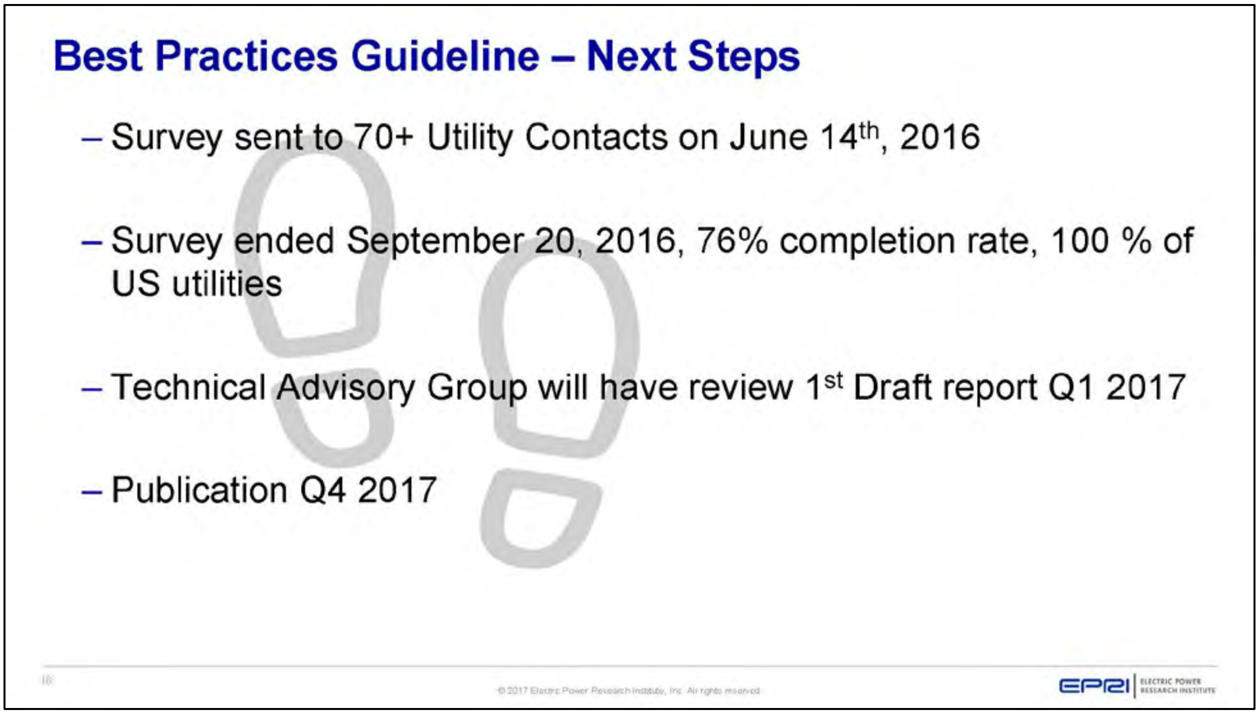
Best Practices Guideline - Design/Licensing Basis

- **Modification (Design Change Process)**
  - Requirements for Flooding Design Basis
  - New Seal Type Qualification for Design Basis
- **Inspection (Flooding Design Basis Walkdowns)**
  - Lessons Learned from NEI 12-07
  - Additional Requirements
  - Sampling of Flood Protection Features
- **Testing (Periodic Surveillance of Flood Protection Features)**
  - WCAP 17700-NP
  - Barrier Surveillance
  - Active / Passive / Temporary
- **Mitigation (Mitigating Strategies)**
  - Procedures in place and time requirements
  - Compliment FLEX Guidance without Duplication
  - Capture Lessons Learned from 50.54(f) Response



Best Practices Guideline - Design/Licensing Basis

- **Training**
  - Periodic Training
  - Reasonable Simulation
  - Validate Assumed Time Requirements
  - Qualifications
- **Reevaluations**
  - NUREG/CR 7046
  - Triggers
  - Computer Software
  - Vulnerability Determination Process
- **Integrated Assessment (IA)**
  - Pending Content from Appendix G and IA Document
- **Documentation and Reporting**
  - Walkdown Forms from NEI 12-07 may be used
  - Testing Results
  - Existing Engineering Evaluations or Calculations



Best Practices Guideline – Next Steps

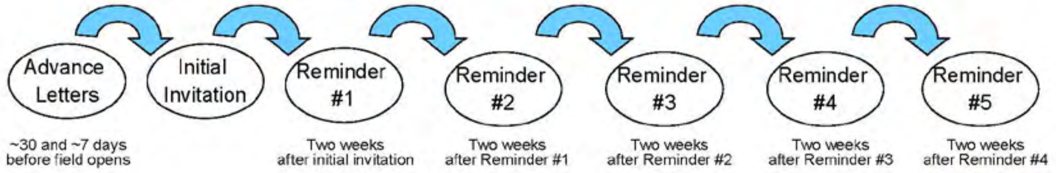
- Survey sent to 70+ Utility Contacts on June 14th, 2016
- Survey ended September 20, 2016, 76% completion rate, 100 % of US utilities
- Technical Advisory Group will have review 1st Draft report Q1 2017
- Publication Q4 2017

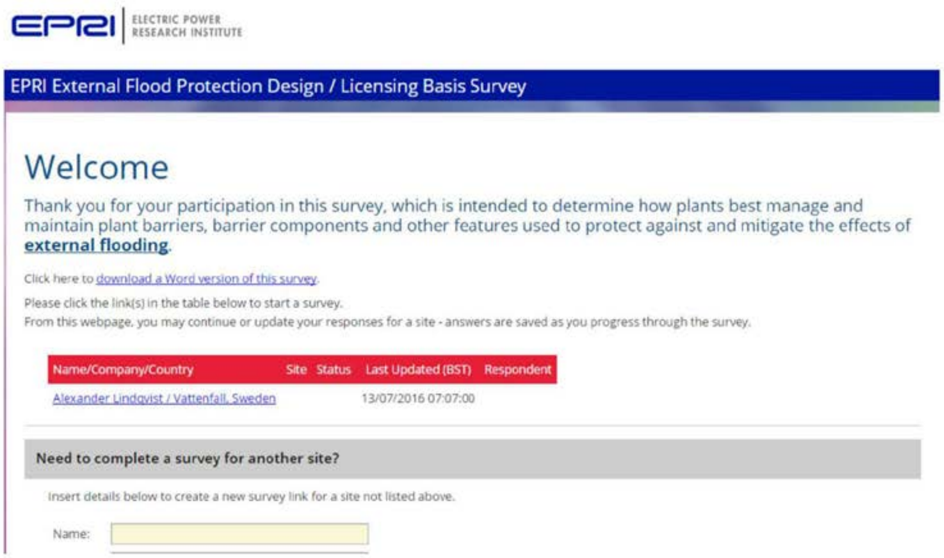
Detailed Web-Based Survey Developed

- Independent specialty firm conducted survey.
- Detailed Industry TAG Review of Questions:
  - *Only 1 opportunity to collect this information.*
  - Common titles for utility contacts:
    - Flood (External and/or Internal) Protection Program Managers
    - External Hazards Program Managers
    - Fukushima Task Force Managers
    - Civil Design Engineers
    - Fire Protection Program Managers

Data Collection Process for Survey

- Web-based methodology
  - Invitation and up to five reminders to non-respondents
  - Branded by EPRI and invitation "signed" by Ken Canavan (Director Plant Technology, EPRI)
  - Questionnaire format
    - Multi-page questionnaire
    - Skip patterns/auto fills programmed and transparent to respondent
    - View contains progress bar
    - Functionality to stop survey and resume (with previous responses saved) at a later time
    - Ability to upload documents





EPRI External Flood Protection Design / Licensing Basis Survey

Welcome

Thank you for your participation in this survey, which is intended to determine how plants best manage and maintain plant barriers, barrier components and other features used to protect against and mitigate the effects of **external flooding**.

Click here to download a Word version of this survey.

Please click the link(s) in the table below to start a survey.
From this webpage, you may continue or update your responses for a site - answers are saved as you progress through the survey.

Name/Company/Country	Site	Status	Last Updated (BST)	Respondent
Alexander Lindqvist / Vattenfall, Sweden			13/07/2016 07:07:00	

Need to complete a survey for another site?

Insert details below to create a new survey link for a site not listed above.

Name:

Examples of Survey Questions

- What is the maximum D/P your flood protection features are required to withstand?
- Do you have an External Flood Protection Program?
- Which departments are involved in management and support of these flood protection features?
- Are routine external periodic flood protection self-assessments being performed?
- What are configuration control methods being used for various features?
- What training / qualifications are required?

EPRI Point of Contact

Project Manager:
David Ziebell (dziebell@epri.com) – 404-316-9823

Supporting / Prior EPRI Participants:
Jeff Greene, Senior Technical Leader
Sam Harvey, Principal Technical Leader

Together…Shaping the Future of Electricity

Presenter:	**Technical Lead:**
John E. Weglian	**David Ziebell**
Senior Technical Leader	Senior Technical Leader
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704-595-2763	404-316-9823

2.3.6.1.3 Questions and Answers

Question:

You mention triggers and the advanced warning aspect of this effort. Because a warning affects the time available to potentially perform some actions, how was this aspect considered?

Response:

I will note that I do not have personal insight into this project and am just presenting it. External flooding is the only hazard that we consider that might provide time for a warning. The approach of a forest fire may also permit such a warning. Other hazards do not give that flexibility. Certain flooding events may allow between hours and days of forewarning that the event is coming, and temporary barriers such as sandbags could be included. Considerations would include how long it takes to put up those barriers, the training requirements, and best practices, both in actions and the triggers to use. Guidance provided should be clear-cut and unambiguous so that users will not get it wrong. Timing and training should be addressed to make sure that users implement those actions correctly.

Follow-up Question:

Many of these cases happened very recently because of the reassessment and the walkdowns. To what extent does this survey map or provide an image of a situation that is in flux? How much variability was evident between people who did have a well-established external flood program and those that did not, and between people who had well-established triggers and those that did not.

Response:

The goal is to find and report on the best practices of each particular aspect that are identified by industry respondents. The report will not consider the variability in the answers but provide the best practices and not the worst.

Comment:

With regard to external hazards, certain high-wind scenarios would also come with some sort of a warning time. In some cases, that will actually be correlated to the warning time for flooding. For example, in a hurricane, wind and storm surge are predicted. To a lesser extent, the convective environment that would be prone to hazards such as tornadic outbreaks might be known.

Response:

Utilities have high-wind procedures and actions that they would implement knowing that such a hazard was coming. This may include a tornado warning and additional steps, such as not sending people outside anymore.

Comment:

With regard to trigger points, some organizations have strived to identify actions that are easy to reverse and not too expensive and that can be based on the forecast. Actions that are hard to reverse and very big decisions should be based on rain on the ground. Quantitative precipitation forecasts (QPFs) can predict a large amount of rainfall but only a small amount falls, and organizations do not want to recommend difficult actions and be seen to "cry wolf."

Response:

Weather forecasters probably do not forecast the absolute extreme. For a rain forecast of 4 to 6 inches, the 90-percent probability may be 12 inches, but they are not forecasting 12 inches. They likely have particular wording to use when the model actually shows that 12 inches will fall. The approach also probably differs between an NWS forecast and one from the local news station.

Question:

Given that one of the future elements of the flood protection status will be the periodic surveillance of flood protection features, will flood risk significance be a criterion as to what, when, and how to inspect that flood protection feature? For example, because a plant may have 1,000 seals, external flooding would be a hazard. Would you consider all 1,000 of the seals or can only those seals that may lead to the greatest flood possibility be the focus, to best use limited resources? How will this periodic surveillance be accomplished?

Response:

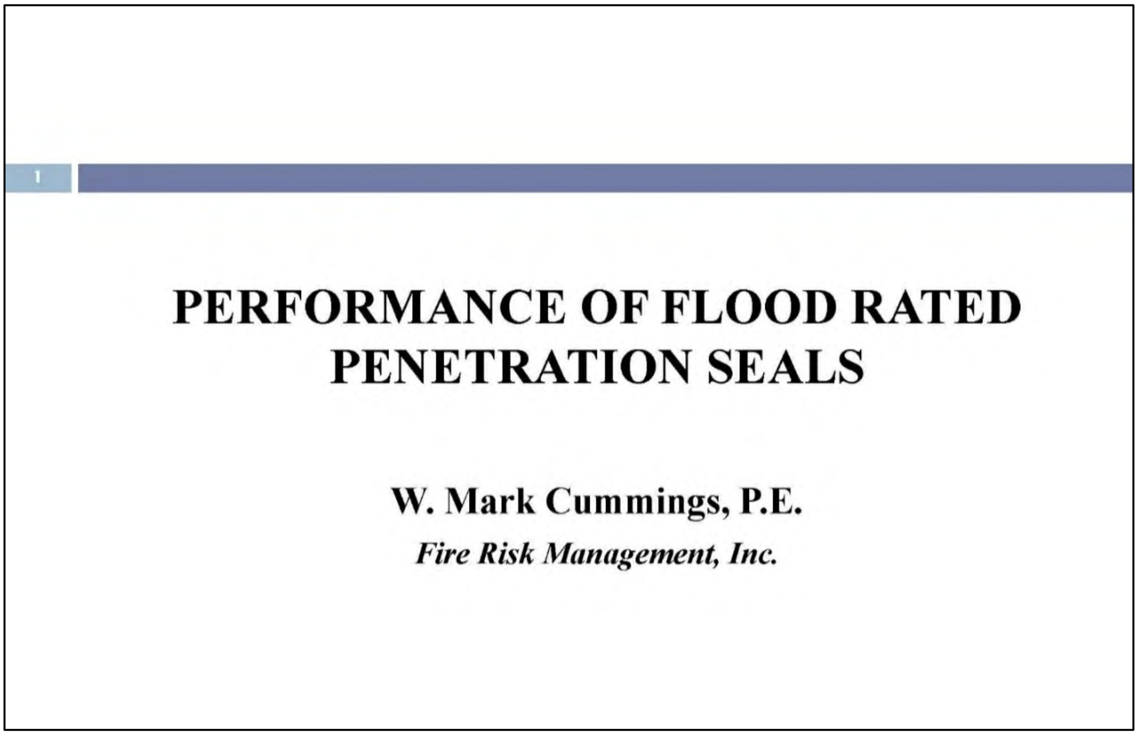
This activity will not incorporate risk-based methodologies to try to consider that aspect. Instead, it covers more of a deterministic side of the equation that looks for best practices in the industry and actions people take. If a reasonable approach to prioritization is made available, that would be communicated.

2.3.6.2 Performance of Flood-Rated Penetration Seals, William (Mark) Cummings*, P.E., Fire Risk Management, Inc. (Session 2D-2; ADAMS Accession No. ML17054C516)

2.3.6.2.1 Abstract

Overall risk analyses of NPPs include the need for protection against potential flooding events, both internal and external events. Typically, a primary method used to mitigate the effects of a flooding event is the implementation of flood-rated barriers that isolate areas of the plant from the intrusion or spread of flood waters. Any penetrations through flood-rated barriers to facilitate piping, cabling, or other components must be properly protected to maintain the flood resistance of the barrier. Numerous types and configurations of seal assemblies and materials are being used at NPPs to protect penetrations in flood-rated barriers. However, no standardized methods or testing protocols exist to evaluate, verify, or quantify the performance of these, or any newly installed, flood seal assemblies. The NRC has implemented a research program to develop a set of standard testing procedures that will be used to evaluate and quantify the performance of any penetration seal assembly that is, or will be, installed in flood-rated barriers. This presentation provided a status of that research project and outlined plans to perform flood testing on candidate seal assemblies. This testing will evaluate the ability of the procedures to adequately address and record the various performance parameters of individual seal assemblies/materials. The results of this research program may be used in the evaluation of a seal assembly/material and whether it is acceptable for protecting penetrations in flood-rated barriers.

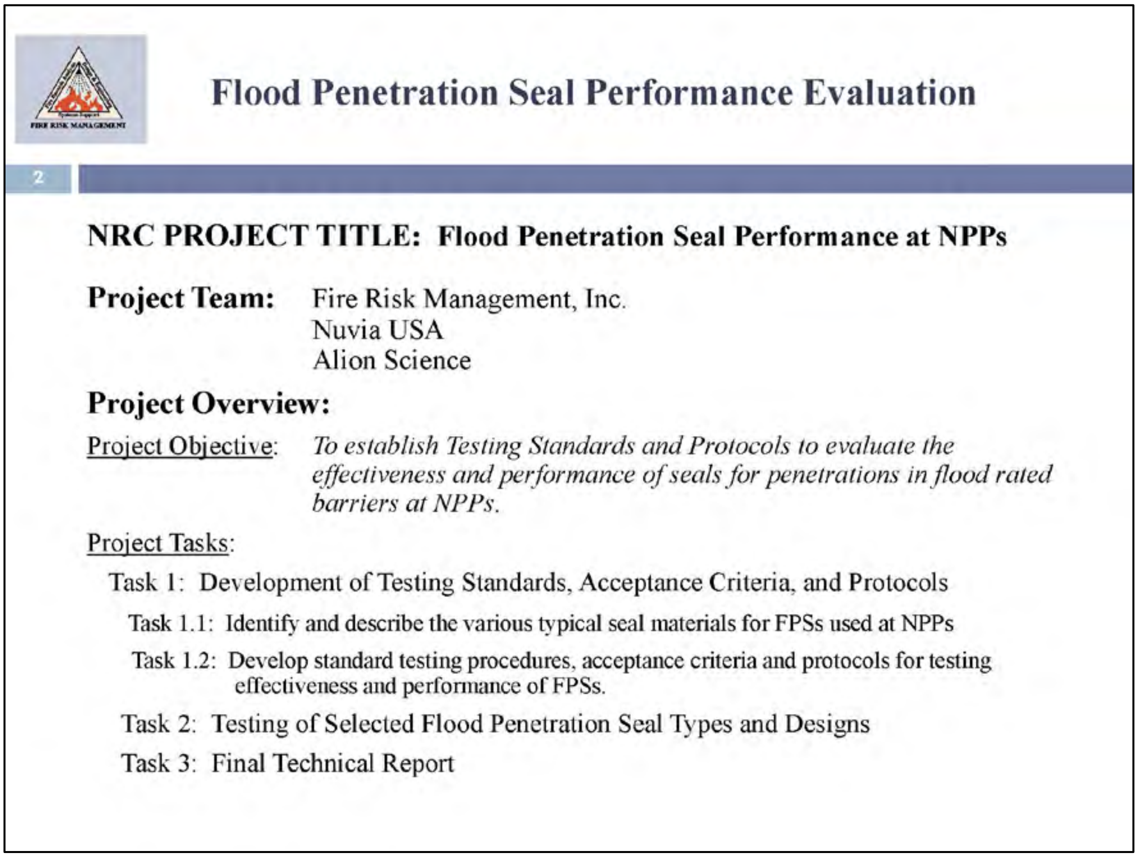
2.3.6.2.2 Presentation



PERFORMANCE OF FLOOD RATED PENETRATION SEALS

W. Mark Cummings, P.E.

Fire Risk Management, Inc.



Flood Penetration Seal Performance Evaluation

NRC PROJECT TITLE: Flood Penetration Seal Performance at NPPs

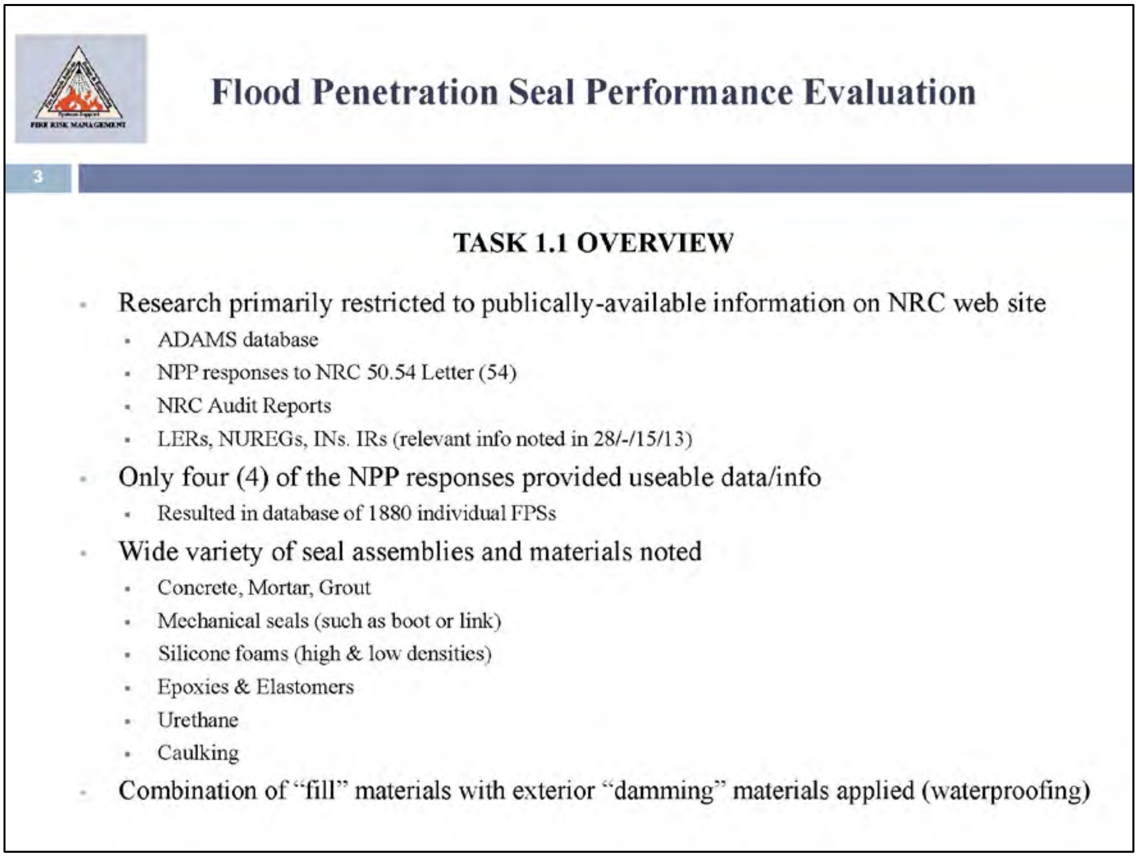
Project Team:	Fire Risk Management, Inc. Nuvia USA Alion Science

Project Overview:

Project Objective:	*To establish Testing Standards and Protocols to evaluate the effectiveness and performance of seals for penetrations in flood rated barriers at NPPs.*

Project Tasks:

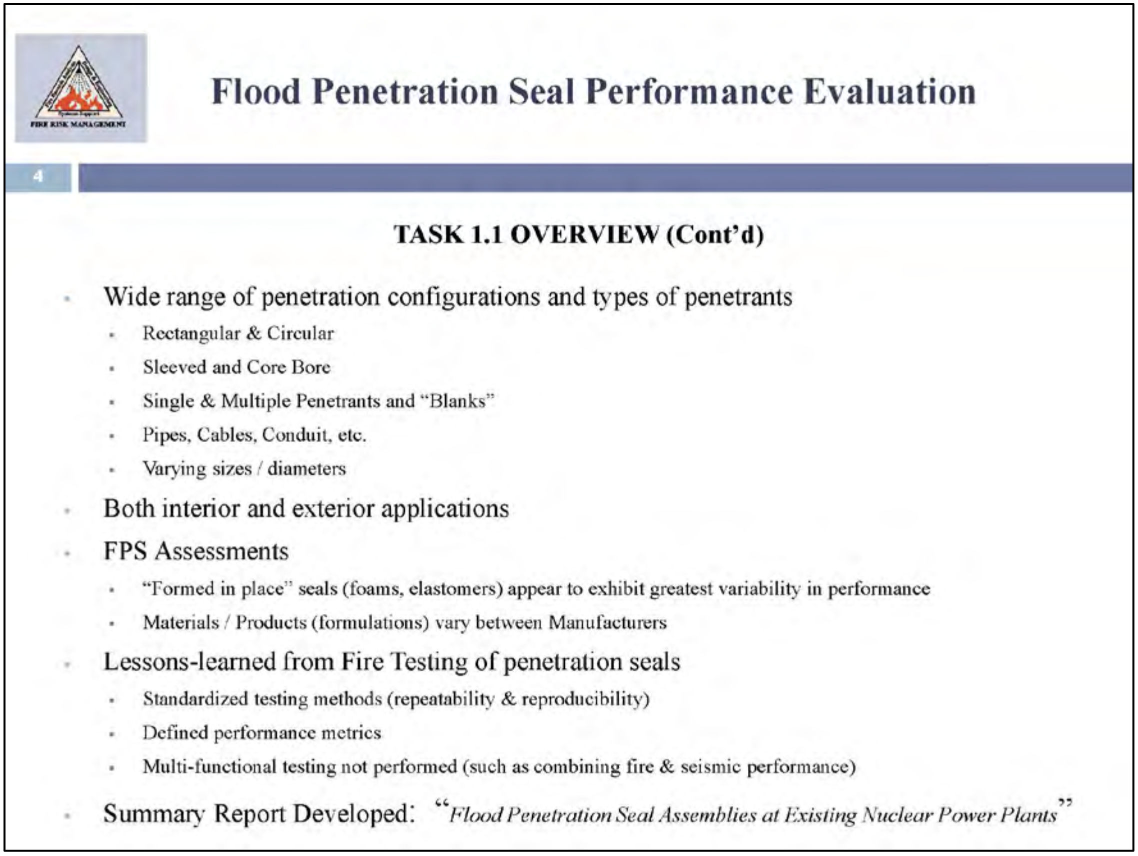
- Task 1: Development of Testing Standards, Acceptance Criteria, and Protocols
  - Task 1.1: Identify and describe the various typical seal materials for FPSs used at NPPs
  - Task 1.2: Develop standard testing procedures, acceptance criteria and protocols for testing effectiveness and performance of FPSs.
- Task 2: Testing of Selected Flood Penetration Seal Types and Designs
- Task 3: Final Technical Report



Flood Penetration Seal Performance Evaluation

TASK 1.1 OVERVIEW

- Research primarily restricted to publically-available information on NRC web site
  - ADAMS database
  - NPP responses to NRC 50.54 Letter (54)
  - NRC Audit Reports
  - LERs, NUREGs, INs. IRs (relevant info noted in 28/-/15/13)
- Only four (4) of the NPP responses provided useable data/info
  - Resulted in database of 1880 individual FPSs
- Wide variety of seal assemblies and materials noted
  - Concrete, Mortar, Grout
  - Mechanical seals (such as boot or link)
  - Silicone foams (high & low densities)
  - Epoxies & Elastomers
  - Urethane
  - Caulking
- Combination of "fill" materials with exterior "damming" materials applied (waterproofing)



Flood Penetration Seal Performance Evaluation

TASK 1.1 OVERVIEW (Cont'd)

- Wide range of penetration configurations and types of penetrants
  - Rectangular & Circular
  - Sleeved and Core Bore
  - Single & Multiple Penetrants and "Blanks"
  - Pipes, Cables, Conduit, etc.
  - Varying sizes / diameters
- Both interior and exterior applications
- FPS Assessments
  - "Formed in place" seals (foams, elastomers) appear to exhibit greatest variability in performance
  - Materials / Products (formulations) vary between Manufacturers
- Lessons-learned from Fire Testing of penetration seals
  - Standardized testing methods (repeatability & reproducibility)
  - Defined performance metrics
  - Multi-functional testing not performed (such as combining fire & seismic performance)
- Summary Report Developed: "*Flood Penetration Seal Assemblies at Existing Nuclear Power Plants*"

Flood Penetration Seal Performance Evaluation

TASK 1.2 OVERVIEW

- Review of NUVIA Flood Test Apparatus & Procedures
  - NUVIA is only entity currently testing FPSs; using standard procedures/protocols
- Review of UL 1479 – Fire Tests of Through-Penetration Firestops
  - Section 6A – Water Leakage Test (W rating)
  - UL has yet to qualify any penetration seal for water-resistance; no test apparatus constructed
- Review of FM Approval Standard for Flood Abatement Equipment
  - Does not address "penetrations" in flood barriers; primarily the barriers themselves, including dikes
  - Does provide some input regarding "impact" resistance
- Review of ASTM E814 – Standard Test Method for Fire Tests of Penetration Firestop Systems
  - Used as a primary "template" for formatting Flood Test Procedure
  - Industry familiarity with formatting

Flood Penetration Seal Performance Evaluation

TASK 1.2 OVERVIEW (Cont'd)

- Draft Procedure developed & delivered to NRC for review / comment
  - Includes "sample" test apparatus design (primarily for use with Task 2)
  - Procedure provides test "guidance" and standardized methodology
  - Minimal "hard" metrics for acceptance / failure
  - Minimum test pressures and/or duration may need specification

Flood Penetration Seal Performance Evaluation

TASK 2 OVERVIEW

- Development of Test Plan
  - Selection of candidate FPSs; types and numbers to be tested
  - Final design for Test Apparatus
  - Location for testing
- Test Objective(s)
  - Exercise & evaluate Flood Test Procedure ("test the test")
  - Research/Evaluation of specific FPS assemblies/materials noted as installed at NPPs
- Test Matrix
  - Include all types of seal assemblies & materials
  - Greater emphasis on "formed in place" seals
  - Some evaluation of existing (non-standard) seal configurations noted during Task 1 document research
- Scheduled Test Results/Report due mid-2018

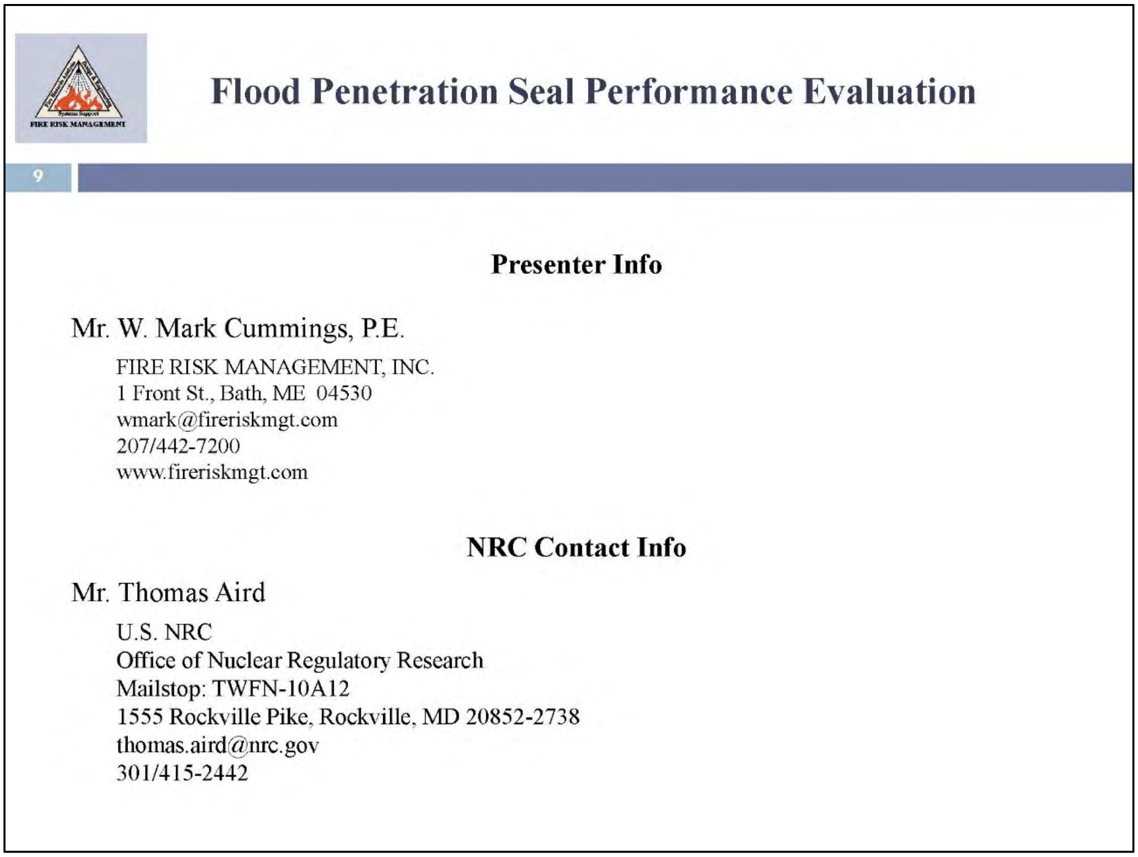
Flood Penetration Seal Performance Evaluation

TASK 3 OVERVIEW

- Development of Final Technical Report
  - Summation of Task 1 & 2 results
  - Suitable for NUREG
- Scheduled Project Completion; 3rd Qtr 2018

GOING FORWARD

- NUREG
  - Provide guidance to Industry for standardized process for evaluating/quantifying FPS performance
  - Support NRC oversight requirements
  - FPS pass/fail criteria will be function of Flood PRA requirements; NPP-specific
- Possible future development of commercial (industry) Test Standard



Flood Penetration Seal Performance Evaluation

Presenter Info

Mr. W. Mark Cummings, P.E.

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2.3.6.2.3 Questions and Answers

Question:

Companies such as Nuvia may test seals for NPPs, maybe in France or other parts of Europe. Have you considered whether there are protocols outside of the United States that can inform this work?

Response:

We are unaware of any other company in the world besides NUVIA that is making or testing actual flood seals. To consider seals associated with maritime uses, we looked at the standards available through Lloyds, the American Bureau of Shipping, and the military, well as non-U.S. entities, in terms of the authorities with jurisdiction. However, none of those organizations appear to be doing this work using a standard format.

Question:

This research appears to focus on new, manufactured seals produced by different manufacturers and testing them in a defined facility. How will this research translate to the plants? Will they have portable options to test seals? Will those be recommended in the study? How are you considering installed seals?

Response:

Ideally, many of the plants are using defined configurations, especially for the mechanical seals. Using the data provided by the plants on the exact nature of the seals, specific assemblies can be replicated in a test. The assembly may not be one that is currently marketed as a flood penetration or flood-rated seal assembly. This type of testing is planned for the second part of the study…

Follow-up Question:

The task will then be to provide recommendations on how to test the seals in place, and the pass criteria will be no more than a certain number of cubic centimeters of leakage.

Response:

The determination of the metrics is the question. The easiest approach, used in NUVIA's testing, is to state that the passing criterion is zero leakage. It will be more challenging to develop metrics that are performance based or risk informed (i.e., a little leakage may not lead to fail, if other mechanisms are in place to ensure that this leakage will not impact plant safety). For example, leakage of 0.6 liters per hour for one particular seal under 40 feet of head pressure may not pose a risk for plant A, but may for Plant B. Or 15 such seals replicated in a wall may pose a risk collectively. Therefore, we are trying to develop a protocol that gives a standardized way of looking at seals, testing those seals, and capturing whether there is leakage and if so what that leakage rate is. This information would return to the manufacturer to adjust designs for new seals. Existing plants would use the results as a basis to determine whether or not to replace a particular seal.

Question:

A previous presentation discussed the failure of some seals at the Blayais site in France. Did Électricité de France perform any failure mode analyses that could be taken into account in this study and the resulting recommendations? For example, you have spoken about hydraulic tests. What about thermal, chemical, biological, and longevity effects on the seals, or does that add too much complexity? Is the study only considering whether the seal will hold water regardless of the environment it will be put in?

Response:

The development and use of seals does need to take many other variables into account, such as chemical (i.e., material interactions). Many considerations are important to the adherence of a material, such as whether a penetration is sleeved or just core drilled. Manufacturers need to indicate what their material can or cannot do and then put restrictions on the use of the seals, such as that the penetration has to be sleeved or it has to be core drilled to get the proper adhesion properties to allow the seal to work.

A fire penetration seal for an application where seismic factors are a consideration, such as for a seismic rated wall or barrier, would have to be designed so that the penetrant is braced and moves as the wall moves. A significant amount of flex would not be expected in the penetration itself. The significance of such properties would need to be considered. The potential for an external seal to be exposed to impact damage during a flood would need to be considered. However, such analyses involving different variables can become very complicated, and the limits of the proposed protocol need to be established. From a thermal perspective, materials will experience some expansion, but a fire test would not consider this. For the study of seals and flooding, some questions will require interaction with manufacturers about the limitations of a given material. For example, can it support expansion and contraction? Does the material shrink? Are small gaps a problem? Over time, minor leakage around the seal may begin to occur—is this a separation of the material from the wall, whether it is a sleeve and concrete, or is it separation from the penetrant? Although such questions rely on the manufacturer as the one with knowledge of its chemical formulas, many of these data are proprietary and will not be available to researchers. Manufacturers should ideally perform the testing or installing, where appropriate, so that they cannot blame performance issues on incorrect testing or installation. A risk-informed approach needs to take such factors into consideration, as well as plant-specific sensitivity analysis (i.e., what makes a big difference for a particular plant?).

Question:

When modeling the degradation processes, is it possible to speed up the degradation? Is it possible to have a seal in the test apparatus that performs more like what is actually out there now, which could be very old?

Response:

This is less of a problem for mechanical seals, but boot seals can crack. In the field, a visual inspection would reveal a condition such as rust on a mechanical seal that would indicate that it would not perform as well. Other materials might show surface cracking. There are ways of age-accelerating such conditions, but these may or may not be appropriate or representative. For example, exposing a seal to higher heat or higher levels of ultraviolet light for short periods of time may make it age faster. The level of accuracy of these methods is not known in terms of replicating how a seal would perform after 20 years.

Follow-up Question:

Errors of installation, such as a failure to comply with the development length given in the manufacturer’s specifications, could occur. Do you plan to look at seals that are outside of the specifications for installation to determine how that does or does not affect their performance?

Response:

The human element is certainly a consideration. If the manufacturer’s specifications are not followed, a seal may not adhere or will pop out with a higher pressure. However, the assumption is that when an installation of a seal is signed off, that means that the seal was installed in accordance with the manufacturer’s requirements and the manufacturer or certified representative is liable for that assertion. If the seal fails, then an investigation would consider the reason for failure and whether it was a materials or an installation issue. In-service and other nondestructive testing cannot always tell whether installation was performed properly. Destructive testing is performed in some plants for some applications. If any were not installed properly, further investigation would be needed on others.

Comment:

Questions have arisen on aging and the fact that the performance or future performance of both new material/seals and existing seals needs to be considered, in both new and existing plants. In addition, once there is an accepted testing protocol, plants that are decommissioning will provide an opportunity to harvest and then test various types of seals that have been in service for various periods of time. This could provide an opportunity to apply the protocol and gather a lot of very significant data that could be put to use in plant PRAs.

Response:

The engineering of the seals is a factor. Evaluations are trying to extrapolate some of the test data to existing scenarios. For example, some seals use low-density forms. Testing has shown that in some cases, putting pressure around a low-density foam will cause it to shrink and can allow a greater flow of water around the seal. Evidence of that kind of performance may force the industry to investigate further and make some more broad-based decisions on the types of seals that may not be appropriate for use in a flood-rated barrier (as opposed to a fire-rated barrier).

It is a great suggestion to take advantage of opportunities to extract some seal materials from existing plants, because in some real-world applications, such as in a cable spreading room, accessing the penetrations is difficult, even for visual inspection.

Question:

Will the product provide guidance on selecting bounding tests for other seal assemblies that might have varying geometric properties (e.g., annular spaces, penetrant size/number)?

Response:

Such tests would need to be done on many different configurations to bound those materials and how they perform. For example, a 24-inch-diameter penetration has a 2-inch conduit running through it, which means that there is a lot of free surface area available to pressure. Such a configuration may react significantly differently when 10 conduits are running through that same penetration, with less free area to be subject to pressure. However, this configuration has more surface area, depending on the adhesive property of the materials, for the seal to adhere to that will keep the water from pushing through. Ultimately, this requires considering the types of materials that are used as the seal material and their individual properties to guide some of those bounding evaluations. If a material is tested with a fairly broad disparity between the configurations, it may be possible to extrapolate to determine how configurations in the middle of tested extremes will work as well. However, this will likely require a material assembly-type specific evaluation each time.

Question:

Are the tests under discussion laboratory testing or is situ testing or both?

Response:

At present, tests require an appropriate test apparatus, seals are not tested on a wall where they have been installed. This would not be feasible as a plant will not permit flooding of a compartment to test the seals there. Testing requires having a laboratory with the appropriate apparatus that can appropriately run the test using a standard methodology. The testing can involve changes to the protocol and a sensitivity analysis. For example, should the seal be hit immediately with a full range of pressure or should that pressure build up? There is a wide range of variables to address, depending on the flooding scenario.

Question:

There is a distinction between qualification and acceptance testing versus in-service testing. In-service testing may not be feasible for items such as flood seals. Are there examples of in-service testing for fire seals?

Response:

A fire seal would be examined visually using that manufacturer's recommendation for what it should look like when new. If some cracking is observed, look to the manufacturer's specifications. However, the only way to verify that a seal is still good is to perform destructive testing. To do this, a certain percentage of the seals would be removed and examined to determine whether the seal was still good. If those seals pass, there is a higher level of confidence in the installation of other seals with the same type of installation and installed during roughly the same time period.

Question:

Could an acoustic technique be used, either in the laboratory or in situ, in order to measure performance? Acoustic techniques are very effective in doing that. Long-term performance of the material and any kind of structural deformation could be examined. Even if it is not clear whether the material is degraded, you could see a lot about how the structure changes on an atomic scale.

Response:

This is outside my area of expertise. Acoustic testing may not be able to measure minor shrinkage that is not even visible to the naked eye. However, such testing may be able to provide information on some properties, such as the density and whether the material has any open areas or pores. Whether such testing is appropriate would likely depend on the specific material to be tested.

Question:

Some dams are solid concrete and might have 30 or 40 feet or more of head. Are you are assuming that the walls themselves are leak free?

Response:

This protocol is not meant to assess the actual wall leakage.

Follow-up Question:

If a plant has a concrete wall 2-feet thick, what would have more leakage, the wall or some kind of penetration?

Response:

Are you considering whether the concrete is water resistant or cracks over time? If there is a crack through all 2 feet of a wall, there are likely other issues from a structural standpoint.

Follow-up Question:

We have a seminar in about 2 weeks on the alkali-silica reaction. That may be a case that results in a lot of leakage through the concrete.

Response:

As part of their installation for a core drill, some manufacturers specify that a sealant needs to be applied to the concrete because there was some reaction between the material and the concrete that would not allow it to adhere properly.

2.3.7 Day 2: Daily Wrap-Up Question and Answer Period

Question:

Speakers were talking earlier about using fitting or uncertainty in frequency analysis and the apparently wide uncertainties in the AEP curve, especially for the very rare event. Is it necessary to examine so many different probability distributions that do not appear to vary among themselves within the uncertainty limits?

Response: Joseph Kanney, Hydrologist, NRC

This behavior is only evident once the analysis has been done and the different distributions evaluated. The point is to characterize and quantify the uncertainties. One way to do this is to run through the different factors that are contributing to the epistemic uncertainties. In the case of the flood frequency or precipitation frequency analysis, the different distributions are a key contributor to the uncertainties. It may turn out that, for some of the examples, the analysis shows that that there was not a lot of difference between certain distributions. The problem is that this is not known until the analysis is done.

2.3.8 Day 3: Session 3A - Reliability of Flood Protection and Plant Response II

This session considered the development of guidance for assessing the reliability of flood protection and plant response to flooding events.

2.3.8.1 *Effects of Environmental Factors on Manual Actions for Flood Protection and Mitigation at Nuclear Power Plants*, Rajiv Prasad*, Ph.D., Garill Coles^, and Angela Dalton^, Pacific Northwest National Laboratory; Kristi Branch and Alvah Bittner, Ph.D., CPE, Bittner and Associates; and Scott Taylor, Ph.D., Battelle Columbus (Session 3A-1; ADAMS Accession No. ML17054C517)

2.3.8.1.1 Abstract

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

The conceptual framework represents an FPM procedure as a set of manual actions, tasks and subtasks, generic actions (Gas), and performance demands (PDs). A manual action is a distinct group of interrelated tasks that are performed outside the main control room to achieve an operational goal. A task is one step of a manual action that has a distinct outcome or predetermined objective contributing to accomplishment of the manual action. A task generally requires both motor and cognitive abilities. Several subtasks may comprise a task. A GA is an individual component of a task or subtask that is sufficiently simple to evaluate the impact of ECs on human performance. Successful completion of a GA may require several PDs, which are human abilities including cognitive, motor, and communication. The PDs were developed from three sources: (1) NUREG/CR-5680 performance abilities, (2) O'Brien et al. (1992)[4] task taxonomy, and (3) cognitive functions from NUREG-2114, "Cognitive Basis for Human Reliability Analysis," issued January 2016. The proposed PDs include (1) detection and noticing, (2) understanding, (3) decision-making, (4) action, and (5) teamwork. The PD "action" is further subdivided into fine motor and coarse motor skills, and the PD "teamwork" is further subdivided into (1) reading and writing, (2) oral communication, and (3) crew interaction.

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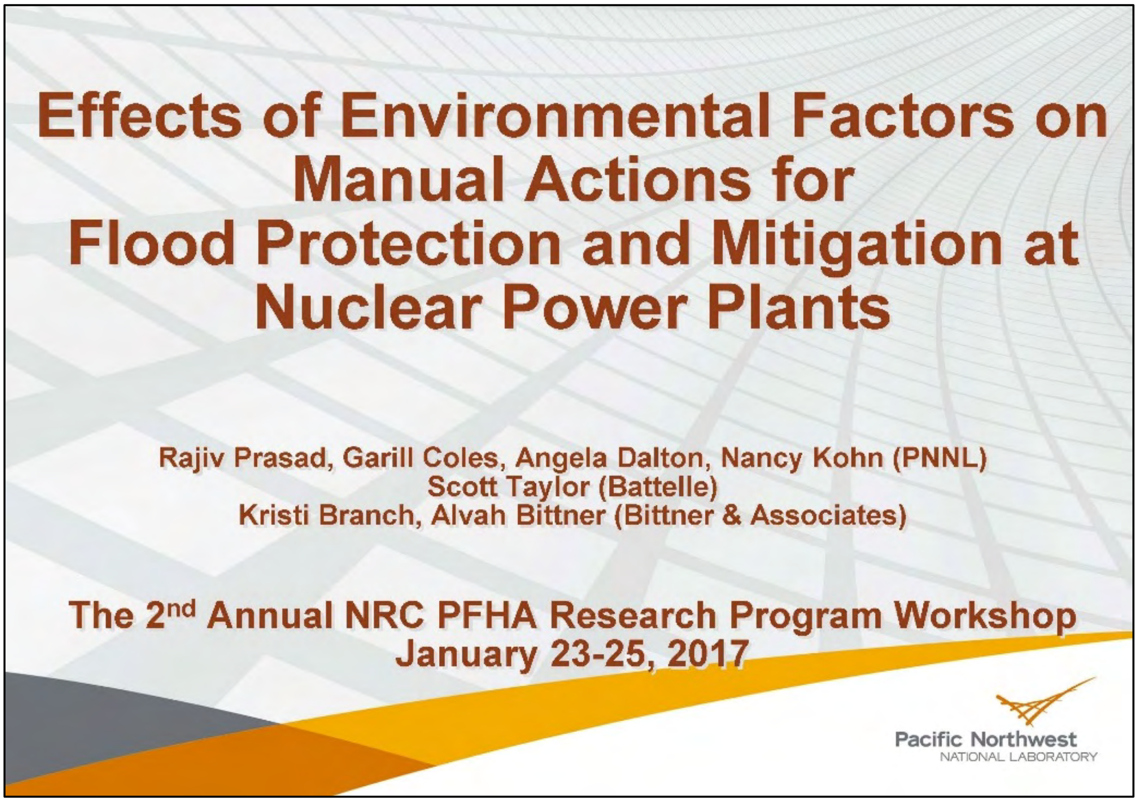
[4] O'Brien, L.H., Simon, R., and H. Swaminathan, "Development of the Personnel-Based System Evaluation Aid (PER-SEVAL) Performance Shaping Functions," United States Army Research Institute for the Behavioral and Social Sciences, 1992.

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

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

2.3.8.1.2 Presentation



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

Rajiv Prasad, Garill Coles, Angela Dalton, Nancy Kohn (PNNL)
Scott Taylor (Battelle)
Kristi Branch, Alvah Bittner (Bittner & Associates)

The 2nd Annual NRC PFHA Research Program Workshop
January 23-25, 2017

Scope and Objectives

◆ Project scope

- Review technical literature on effects of environmental conditions (ECs) on human performance
- An extension of NUREG/CR-5680, The Impact of Environmental Conditions on Human Performance, Volumes 1 and 2 (1994)
- Consider environmental conditions that could occur during a flood and the manual actions taken to prepare/respond

◆ Research objectives

- Develop a framework for assessing the impact of ECs on human performance of manual actions for flood protection and mitigation
- Develop a technical literature review on effects of ECs on human performance
- Develop a proof-of-concept method for EC impact assessment
- Identify approaches to using literature review results in the EC impact assessment method

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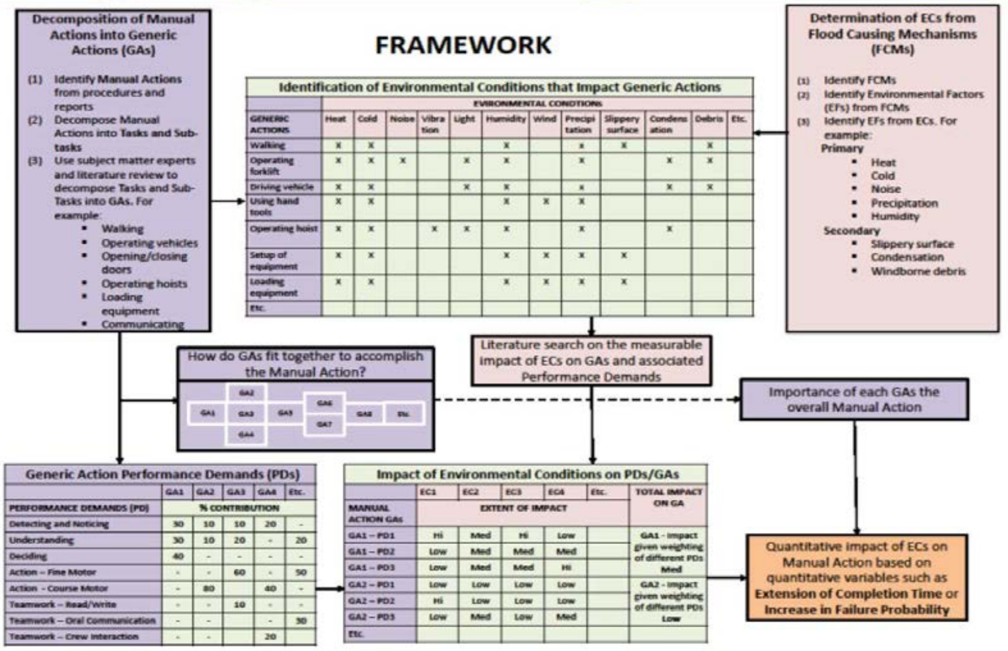
Impact Assessment Framework



FRAMEWORK

Decomposition of Manual Actions into Generic Actions (GAs)

(1) Identify Manual Actions from procedures and reports
(2) Decompose Manual Actions into Tasks and Sub-tasks
(3) Use subject matter experts and literature review to decompose Tasks and Sub-Tasks into GAs. For example:
  - Walking
  - Operating vehicles
  - Opening/closing doors
  - Operating hoists
  - Loading equipment
  - Communicating

Identification of Environmental Conditions that Impact Generic Actions

	ENVIRONMENTAL CONDITIONS											
GENERIC ACTIONS	Heat	Cold	Noise	Vibration	Light	Humidity	Wind	Precipitation	Slippery surface	Condensation	Debris	Etc.
Walking	x	x				x		x	x		x	
Operating forklift	x	x	x		x	x		x		x	x	
Driving vehicle	x	x			x	x		x		x	x	
Using hand tools	x	x				x	x	x				
Operating hoist	x	x		x	x	x		x		x		
Setup of equipment	x	x				x	x	x	x			
Loading equipment	x	x				x	x	x	x			
Etc.												

Determination of ECs from Flood Causing Mechanisms (FCMs)

(1) Identify FCMs
(2) Identify Environmental Factors (EFs) from FCMs
(3) Identify EFs from ECs. For example:
Primary
  - Heat
  - Cold
  - Noise
  - Precipitation
  - Humidity

Secondary
  - Slippery surface
  - Condensation
  - Windborne debris

How do GAs fit together to accomplish the Manual Action?

Literature search on the measurable impact of ECs on GAs and associated Performance Demands

Importance of each GAs the overall Manual Action

Generic Action Performance Demands (PDs)

	GA1	GA2	GA3	GA4	Etc.
PERFORMANCE DEMANDS (PD)	% CONTRIBUTION				
Detecting and Noticing	30	10	10	20	-
Understanding	30	10	20	-	20
Deciding	40	-	-	-	-
Action – Fine Motor	-	-	60	-	50
Action – Course Motor	-	80		40	-
Teamwork – Read/Write	-	-	10	-	-
Teamwork – Oral Communication	-	-		-	30
Teamwork – Crew Interaction	-	-		20	

Impact of Environmental Conditions on PDs/GAs

	EC1	EC2	EC3	EC4	Etc.	TOTAL IMPACT ON GA
MANUAL ACTION GAs	EXTENT OF IMPACT					
GA1 – PD1	Hi	Med	Hi	Low		GA1 - impact given weighting of different PDs Med
GA1 – PD2	Low	Med	Med	Med		
GA1 – PD3	Low	Med	Med	Hi		
GA2 – PD1	Low	Low	Low	Low		GA2 - impact given weighting of different PDs Low
GA2 – PD2	Hi	Low	Low	Low		
GA2 – PD3	Low	Med	Low	Med		
Etc.						

Quantitative impact of ECs on Manual Action based on quantitative variables such as **Extension of Completion Time** or **Increase in Failure Probability**

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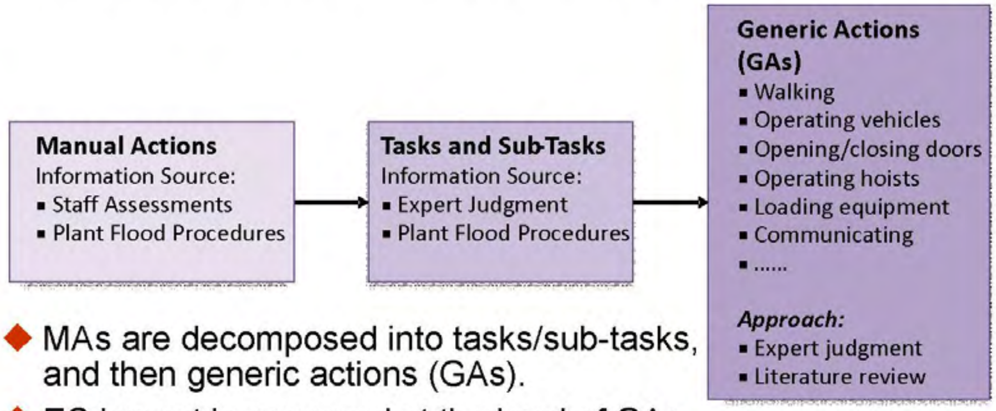
Characterization of Manual Actions

- Manual actions (MAs) are actions taken away from the Main Control Room.
  - We define and MA as a distinct group of inter-related tasks that are performed outside the main control room to achieve an operational goal.
  - MAs were compiled from
    - NRC Staff Assessments of licensees' Flooding Walkdown Reports
    - Available site-specific Flood Protection and Mitigation procedures
- Key assumptions
  1. Differences between/among individuals are minimal
  2. Staffing levels are appropriate and adequate
  3. Procedures are established and appropriate
  4. Staff are provided with and know how to use necessary equipment
  5. Staff are trained
  6. Staff are fit for duty

Decomposing Manual Actions

- MAs are often complex, consisting of multiple steps, involving sequential movements or a combination of motor and cognitive functions and processes, and requiring more than one task location and varying levels of automation and/or need for tools or equipment.



Manual Actions
Information Source:
- Staff Assessments
- Plant Flood Procedures

Tasks and Sub-Tasks
Information Source:
- Expert Judgment
- Plant Flood Procedures

Generic Actions (GAs)
- Walking
- Operating vehicles
- Opening/closing doors
- Operating hoists
- Loading equipment
- Communicating
- ……

Approach:
- Expert judgment
- Literature review

- MAs are decomposed into tasks/sub-tasks, and then generic actions (GAs).
- EC impact is assessed at the level of GAs.

Characterizing GAs with Performance Demands

- Performance demands are the physical and/or cognitive exertions required for performing a GA by an operator.
- We developed a taxonomy of performance demands by integrating performance capabilities from NUREG/CR-5680 (Echeverria et al. 1994), taxons (O'Brien et al. 1992), and cognitive functions in NUREG-2114 (Whaley et al. 2013).
- We used performance demands to characterize GAs for assessing the impact of ECs on operator performance.

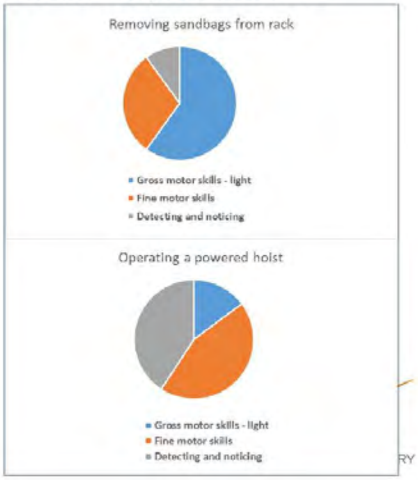
Performance Demands

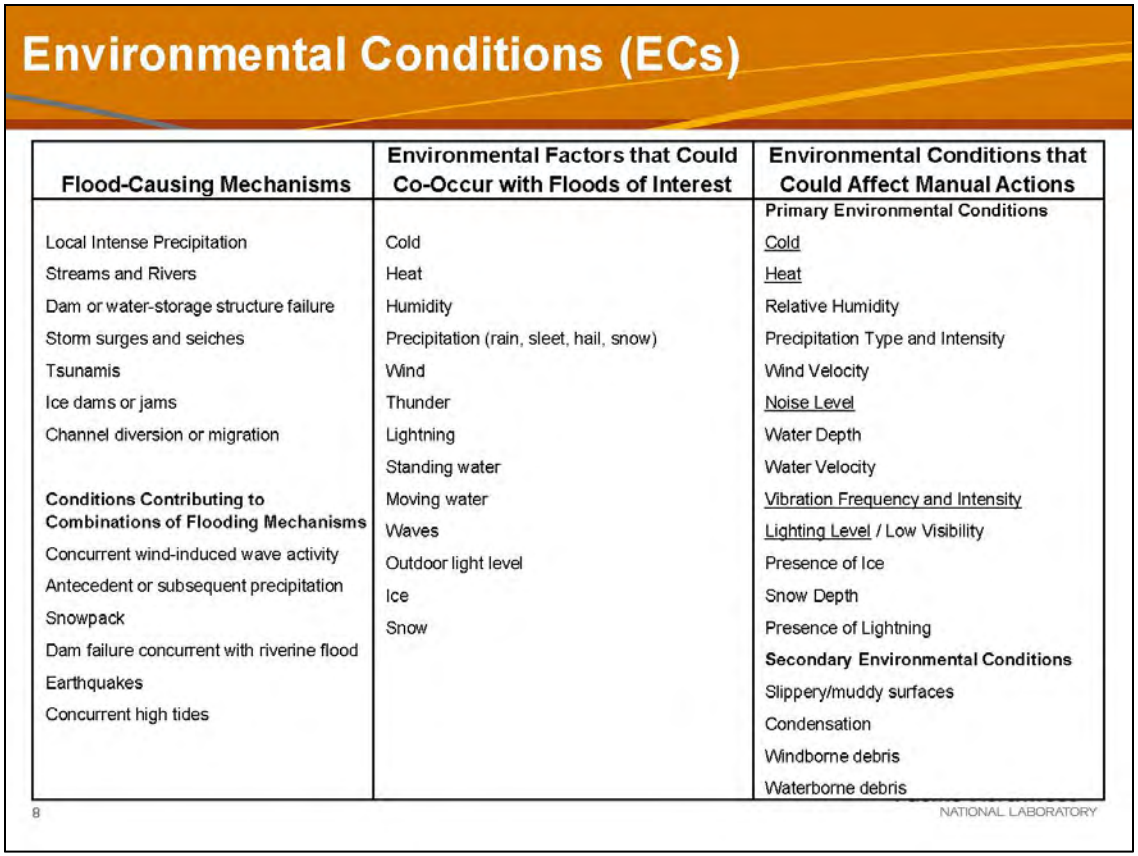
- **Detecting and Noticing**
- **Understanding**
- **Decision Making**
- **Action**
  - Fine motor
  - Gross motor
  - Other neurophysiological functions
- **Teamwork**
  - Read/Write
  - Oral communication
  - Crew interaction

Representing GAs with Performance Demands

- Each GA can be represented as a combination of one or more performance demands.
- The % contribution represents the weight associated with a performance demand. Different GAs require different varying types and magnitudes of performance demands.
- For each GA, the total contributions from its constituent performance demands should be 100%.

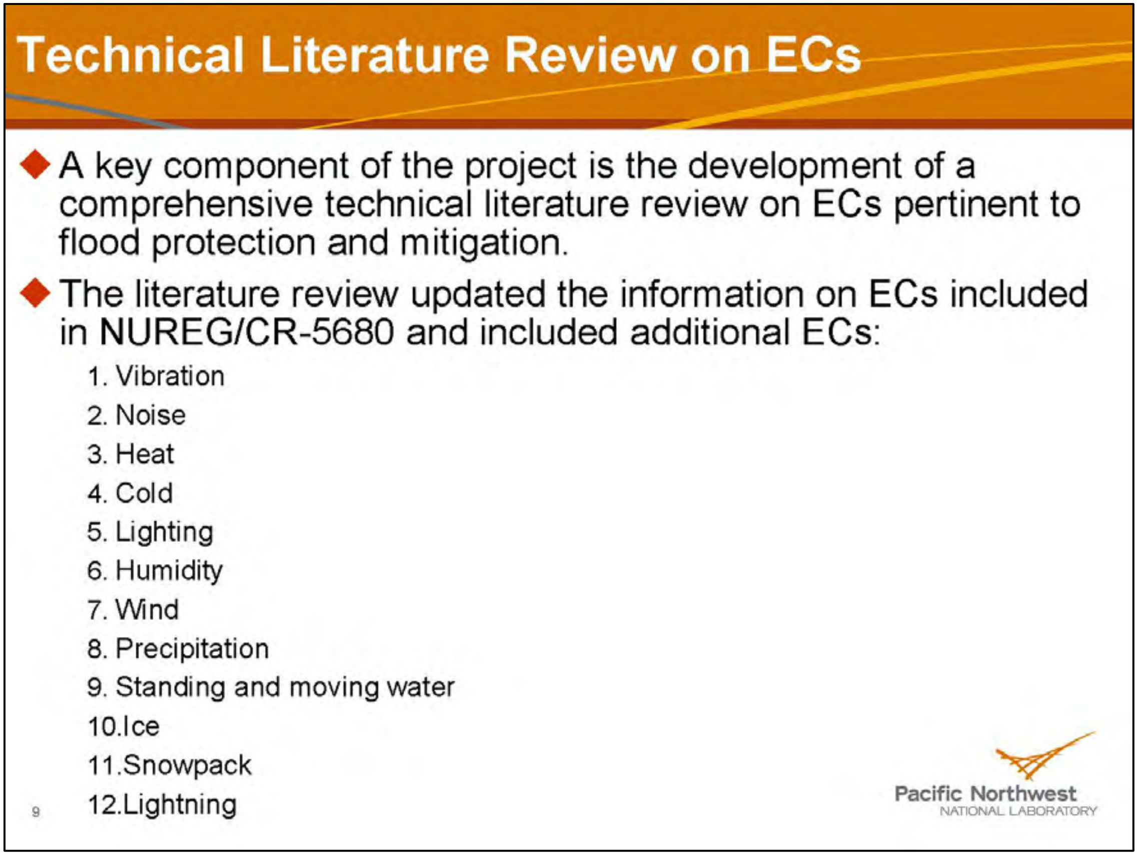
Generic Action Performance Demands (PDs)					
	GA1	GA2	GA3	GA4	……
Performance Demands (PD)	% CONTRIBUTION				
Detecting and Noticing	30	10	10	20	-
Understanding	30	10	20	-	20
Decision Making	40	-	-	-	-
Action – Fine Motor	-	-	60	-	50
Action – Gross Motor	-	80		40	-
Action – Other	-	-	-	-	-
Teamwork – Read/Write	-	-	10	-	-
Teamwork – Oral Communication	-	-		-	30
Teamwork – Crew Interaction	-	-		20	
Sum of Contributions	100	100	100	100	100





Environmental Conditions (ECs)

Flood-Causing Mechanisms	Environmental Factors that Could Co-Occur with Floods of Interest	Environmental Conditions that Could Affect Manual Actions
		Primary Environmental Conditions
Local Intense Precipitation	Cold	Cold
Streams and Rivers	Heat	Heat
Dam or water-storage structure failure	Humidity	Relative Humidity
Storm surges and seiches	Precipitation (rain, sleet, hail, snow)	Precipitation Type and Intensity
Tsunamis	Wind	Wind Velocity
Ice dams or jams	Thunder	Noise Level
Channel diversion or migration	Lightning	Water Depth
	Standing water	Water Velocity
Conditions Contributing to Combinations of Flooding Mechanisms	Moving water	Vibration Frequency and Intensity
	Waves	Lighting Level / Low Visibility
Concurrent wind-induced wave activity	Outdoor light level	Presence of Ice
Antecedent or subsequent precipitation	Ice	Snow Depth
Snowpack	Snow	Presence of Lightning
Dam failure concurrent with riverine flood		**Secondary Environmental Conditions**
Earthquakes		Slippery/muddy surfaces
Concurrent high tides		Condensation
		Windborne debris
		Waterborne debris

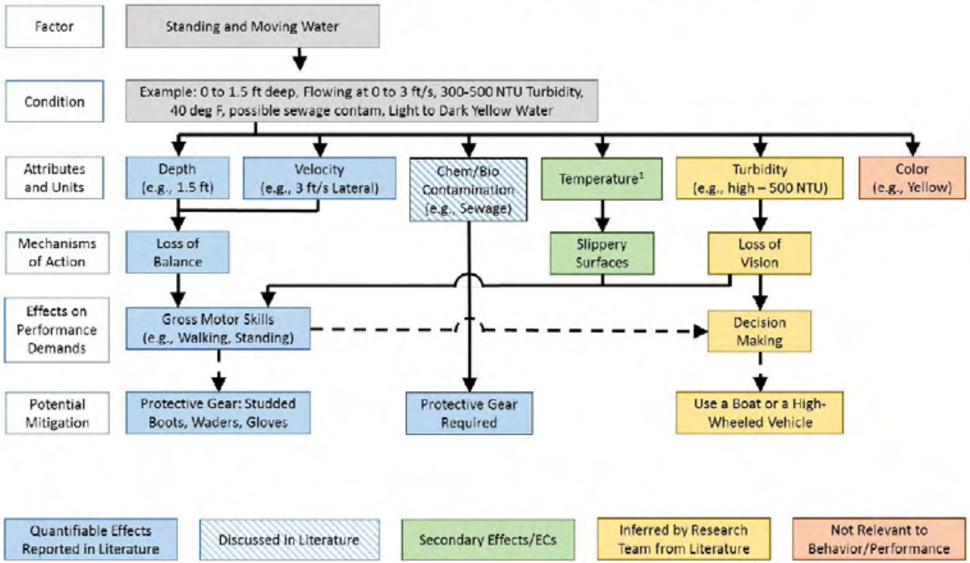


Technical Literature Review on ECs

- A key component of the project is the development of a comprehensive technical literature review on ECs pertinent to flood protection and mitigation.
- The literature review updated the information on ECs included in NUREG/CR-5680 and included additional ECs:
  1. Vibration
  2. Noise
  3. Heat
  4. Cold
  5. Lighting
  6. Humidity
  7. Wind
  8. Precipitation
  9. Standing and moving water
  10. Ice
  11. Snowpack
  12. Lightning

Literature Review Approach: Example of Standing and Moving Water

EF: Standing and Moving Water, EC: Water Depth and Flow Velocity



Factor

Standing and Moving Water

Condition

Example: 0 to 1.5 ft deep, Flowing at 0 to 3 ft/s, 300-500 NTU Turbidity, 40 deg F, possible sewage contam, Light to Dark Yellow Water

Attributes and Units

Depth (e.g., 1.5 ft)

Velocity (e.g., 3 ft/s Lateral)

Chem/Bio Contamination (e.g., Sewage)

Temperature[1]

Turbidity (e.g., high – 500 NTU)

Color (e.g., Yellow)

Mechanisms of Action

Loss of Balance

Slippery Surfaces

Loss of Vision

Effects on Performance Demands

Gross Motor Skills (e.g., Walking, Standing)

Decision Making

Potential Mitigation

Protective Gear: Studded Boots, Waders, Gloves

Protective Gear Required

Use a Boat or a High-Wheeled Vehicle

Quantifiable Effects Reported in Literature

Discussed in Literature

Secondary Effects/ECs

Inferred by Research Team from Literature

Not Relevant to Behavior/Performance

[1] See COLD and HEAT EC Figures.

Leveraging Literature Review for Impact Assessment

- Information identified from the literature review was classified into 4 categories in terms of what level of information is available and how it might be used in impact assessment.

Four Levels of Information

1. **Quantitative information that is directly applicable** to determining the quantitative impact of an EC on a performance demand and can be directly used to support the proof-of-concept approach.

2. **Quantitative information** that is of some applicability in determining the degree impact of an EC on a performance demand (e.g., in some cases, EC severity limits may be available - below a lower limit, there is no discernible impact and above an upper limit, an operator cannot perform an activity at all). Under certain assumptions regarding the variation of impacts with changing severity between the two limits, this information might be used with the proof-of-concept model to provide useable information.

3. **Qualitative information.** General agreement exists that the EC affects a performance demand, but the measured impacts are not reported in literature, not even for limits. A performance demand may also be affected because a critical cognitive function is primarily impaired. This information might be used to inform a sensitivity analysis using the proof-of-concept model.

4. **No information** (i.e., a literature gap).

Example of EC Literature Review Summary Table – Standing and Moving Water

- For each EC, the available literature was summarized by performance demands and coded based on the 4 levels of information.

Performance Requirements for Standing/Moving Water	Level of Information Related to Impacts	Assumptions and Limitations on Applicability
Detection and Noticing		
Attention, memory, vigilance, switching, acuity, perception and threshold perception	3	(b)
Sensation and visual recognition	3	(b)
Understanding		
Pattern recognition, discrimination, understanding, evaluating, hypothesizing, diagnosing, and integrating	3	(b)
Decision Making		
Reasoning, computation, interpreting, classifying, goal setting, planning, adapting, and evaluating and selecting options	3	(b)
Action		
Fine motor skills - discrete and motor continuous, and manual dexterity	3	(b)
Gross motor skills - heavy and light	1	(a)
Other neurophysiological functions	3	(b)
Teamwork		
Reading and writing	3	(b)
Oral face-to-face and electronic communication	3	(b)
Cooperation, crew interaction, and command and control	3	(b)

(a) Toppling risk is very quantifiable for models, but any individual's toppling tendency may depend on additional factors including fitness, loose or form fitting clothing, shoe gripping abilities, etc.

(b) It can be assumed that once an individual topples in moving water, none of the other manual or cognitive tasks will be possible.

- Information levels were not cleanly cut and expert judgment was used to make coding decisions.

1 = Quantitative information that is directly applicable to determining the quantitative impact of an EC on a performance demand and can be directly used to support the proof-of-concept approach.

3 = Qualitative information

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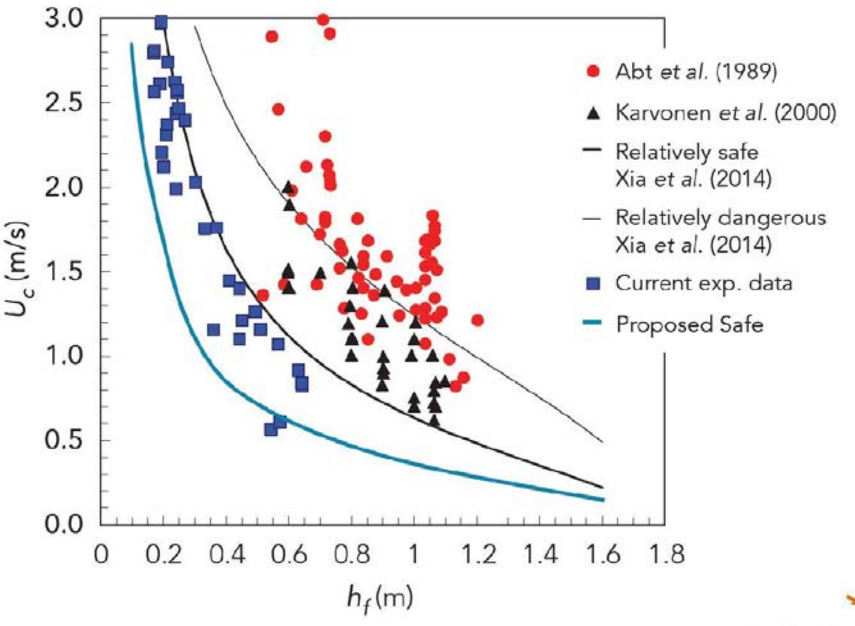
Example of Level 1 EC Information in Literature – Standing and Moving Water



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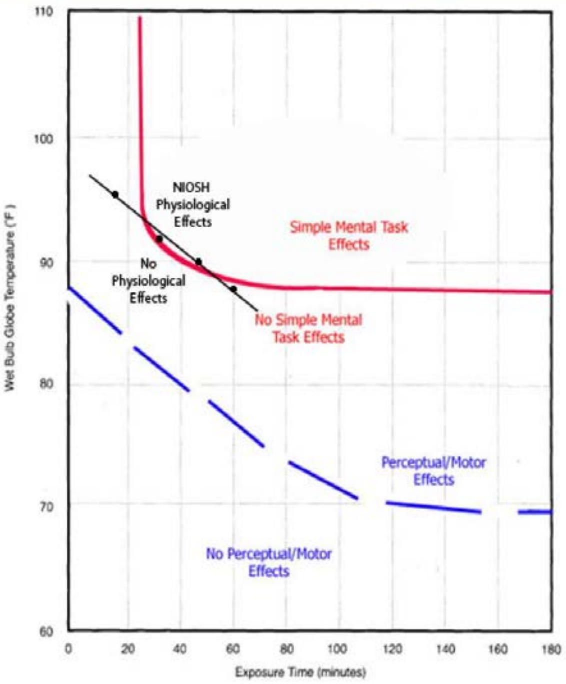
Example of Level 2 EC Information in Literature – Heat



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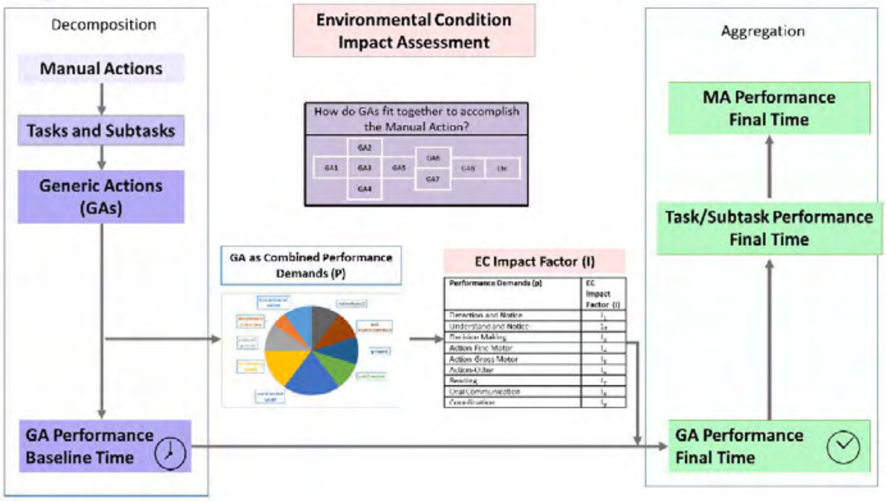
Assessing Impacts of ECs on Performance of MAs

- Developed a method to leverage the decomposition approach and assess EC impact on GAs via performance demands. The resulting GA-level impact is aggregated up to the MA level.
- The method focused on time as the primary performance measure but accuracy and other measures can also be assessed.



Decomposition

Manual Actions

Tasks and Subtasks

Generic Actions (GAs)

GA Performance Baseline Time

Environmental Condition Impact Assessment

How do GAs fit together to accomplish the Manual Action?

GA as Combined Performance Demands (P)

EC Impact Factor (I)

Performance Demands (p)	EC Impact Factor (I)
Detection and Notice	I_1
Understand and Notice	I_2
Decision Making	I_3
Action Fine Motor	I_4
Action Gross Motor	I_5
Action-Other	I_6
Reading	I_7
Oral Communication	I_8
Coordination	I_9

Aggregation

MA Performance Final Time

Task/Subtask Performance Final Time

GA Performance Final Time

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Overview of Impact Assessment Approaches

- In Human Reliability Analysis, ECs have been used as Performance Shaping or Influencing Factors (PSFs/PIFs), and function as multipliers affecting Human Error Probabilities for varying levels of stress (e.g., extreme, high, and nominal).

$HEP_{overall} = HEP_{nominal} * PSF$	$0 < PSF < 1$	$HEP_{overall} < HEP_{nominal}$	Enhancing reliability
	$PSF = 1$	$HEP_{overall} = HEP_{nominal}$	No impact on reliability
	$PSF > 1$	$HEP_{overall} > HEP_{nominal}$	Reducing reliability

- In IMPRINT, ECs are Performance Degradation Factors (PDFs) affecting performance time/accuracy through their impact on taxons.

Time/Accuracy adjustment = (PDF associated with a taxon – 1) x weight assigned to the taxon
Final time/accuracy = (1 + time/accuracy adjustment) x baseline time/accuracy

- **IMPRINT includes nine taxons**: (1) visual cognition/visual discrimination, (2) numerical analysis, (3) information processing/problem solving, (4) fine motor discrete, (5) fine motor continuous, (6) gross motor light, (7) gross motor-heavy, (8) oral communication, and (9) written communication

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A Proof-of-Concept Method for Impact Assessment: Conceptual Representation

- For each GA, performance time is assumed to be longer than the baseline if an EC adversely impacts performance.
- Among the performance demands required by a GA, an EC could impact different performance demands differently.
- For performing each GA,

Affected Time = (1 + Combined Time Adjustment) * Baseline Time

- For each performance demand within a GA,

Combined Time Adjustment = Sum of Time Adjustments across all performance demands encompassed in a GA

Time Adjustment = (EC Impact Factor -1) * Performance Demand Weight

- Baseline Time can be estimated from flood protection procedures and/or expert opinion.
- EC Impact Factor is a quantitative measure representing the magnitude of the impact on a performance demand resulting from a specific EC. It can be estimated from relevant literature and/or by expert judgment.
- Performance Demand Weight is the relative contribution of a performance demand toward completing a GA that comprises the performance demand.

A Proof-of-Concept Method for Impact Assessment: Single Prevailing EC

The impact of an EC E_j on the GA G_k, as measured by time, is the difference between affected time (TG_k^*) and baseline time (TG_k).

$$TG_k = \sum_{i=1}^{9} T_{i,k}$$

the affected time for G_k, given only one prevailing EC E_j, is:

$$TG_k^* = \sum_{i=1}^{9} T_{i,k}^* = \sum_{i=1}^{9} (1 + \Delta_{i,j,k}) T_{i,k}$$

Where

G_k = a GA, where $k = 1,2,3, \dots n_G$

i = a performance demand required by G_k, where $_i$ ranges from 1 to 9

w_i = weight for performance demand $_i$, where $w_i \in [0,1]$ and $\sum_{i=1}^{9} w_i = 1$

E_j = an EC, where $j = 1,2,3, \dots n_E$

$I_{i,j,k}$ = impact factor for performance demand $_i$ from prevailing E_j within G_k

TG_k= baseline time for performing G_k

$T_{i,k}$= baseline time associated with performance demand $_i$ within G_k (which is $w_i TG_k$)

$\Delta_{i,j,k}$= time adjustment for performance demand $_i$ from prevailing E_j within G_k ($\Delta_{i,j,k} = I_{i,j,k} - 1$)

TG_k^*= affected time for performing G_k

$T_{i,k}^*$= affected time associated with performance demand $_i$ within G_k

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A Proof-of-Concept Method for Impact Assessment: Multiple Prevailing ECs

- To account for the impact of multiple ECs, the impact factor $I_{i,j,k}$ could be combined (three examples):

a) Simple additive combination, where n_E is the number of prevailing ECs while performing G_k

$$I_{i,k} = \sum_{j=1}^{n_E} I_{i,j,k}$$

b) Multiplicative combination, where n_E is the number of prevailing ECs while performing G_k

$$I_{i,k} = \prod_{j=1}^{n_E} I_{i,j,k}$$

c) Power function combination, where α_j, j _ $1,2,3, \dots n_E$ are the different exponents for prevailing ECs' impacts while performing G_k

$$I_{i,k} = \prod_{j=1}^{n_E} (I_{i,j,k})^{\alpha_j}$$

- Thus, the affected time for G_k, given multiple prevailing ECs, is expressed below, where I_k^* is the impact factor for the kth GA, appropriately weighted by performance demand weights.

$$TG_k^* = \sum_{i=1}^{9} T_{i,k}^* = \sum_{i=1}^{9} (1 + \Delta_{i,k}) T_{i,k} = \sum_{i=1}^{9} I_{i,k} w_i TG_k = I_k^* \, TG_k$$

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A Proof-of-Concept Method for Impact Assessment: Aggregation from GA to MA

◆ Based on the affected time for GAs, affected times for tasks/subtasks and MAs can be estimated:

- **Task/Subtask**: a task or subtask S_l can consist of one more GAs, (i.e., $S_l = \{G_k\}, k = 1,2,3 \ldots n_G$), baseline time TS_l and affected time TS_l^* for a task S_l are, assuming GAs are performed sequentially

$$TS_l = \sum_{k=1}^{n_G} TG_k \qquad TS_l{}^* = \sum_{k=1}^{n_G} TG_k{}^* = \sum_{k=1}^{n_G}\sum_{i=1}^{9}(1+\Delta_{i,k})\,T_{i,k} = \sum_{k=1}^{n_G}\sum_{i=1}^{9} I_{i,k}\,T_{i,k} = \sum_{k=1}^{n_G} I_k^*\,TG_k$$

- **MAs:** a manual action M_o typically consists of one or more tasks (and subtasks), (i.e., $M_o = \{S_l\}, l = 1,2,3 \ldots n_S$), baseline time TA_o and affected time TA_o^* for M_o are, assuming tasks are performed sequentially

$$TA_o = \sum_{l=1}^{n_S} TS_l \qquad TA_o{}^* = \sum_{l=1}^{n_S} TS_l^*$$

Method Application: an example

Example MA: Fastening Barriers onto Intake Structure Walls

Task 1. Fabricate steel plates

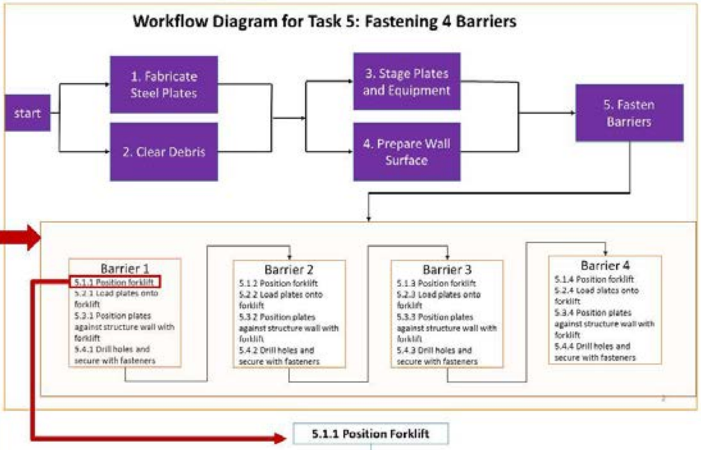
Task 2. Clear debris – could be done parallel to #1

Task 3. Stage plates and equipment – must be done sequential with # 1 and # 2

Task 4. Prepare wall surface – could be parallel to # 3

Task 5. Fasten 4 Barriers

- Subtask 5.1 Position Forklift
  - *GA 5.1.a Walking*
  - *GA 5.1.b Getting forklift*
  - *GA 5.1.c Driving forklift*
- Subtask 5.2 Load plates onto forklift
  - *GA 5.2.a Operating forklift (picking up)*
- Subtask 5.3 Position plates against structure wall with forklift
  - *GA 5.3.a Operate forklift (lifting the plate)*
  - *GA 5.3.b Communicate and coordinate*
  - *GA 5.3.c Operate forklift (pinning the plate)*
  - *GA 5.3.d Manually adjust plate position against wall*
- Subtask 5.4 Drill holes and secure with fasteners
  - *GA 5.4.a Hand tools (drill)*
  - *GA 5.4.b Hand tools (concrete bolts)*



Workflow Diagram for Task 5: Fastening 4 Barriers

5.1.1 Position Forklift

5.1.a Walking	
1.Detect and Notice	4.2 Action – Gross Motor
0.25	0.75

5.1.b. Getting in forklift		
1. Detect and Notice	2. Understand	4.2 Action - Gross Motor
0.25	0.25	0.5

5.1.c. Driving			
1. Detect and Notice	2. Understand	3. Decision Making	4.1. Action Fine Motor
0.167	0.167	0.167	0.5

Method Application: an example (cont'd)

Performance Demands Associated with Each GA under Task 5

S_5: Task 5. Fasten 4 Barriers		Performance Demand Weights (*w*)								
		w_1 1. Detection and Noticing	w_2 2. Understanding	w_3 3. Decision Making	4. Action			5. Teamwork		
Subtask	GAs				w_4 4.1 Fine Motor	w_5 4.2 Gross Motor	w_6 4.3 Other	w_7 5.1 Reading' /writing	w_8 5.2 Oral Comm.	w_9 5.3 Crew Interaction
B_1: 5.1 Position forklift	G_1: 5.1.a. walking	0.25	0	0	0	0.75	0	0	0	0
	G_2: 5.1.b. getting in forklift	0.25	0.25	0	0	0.5	0	0	0	0
	G_3: 5.1.c. driving	0.17	0.17	0.17	0.5	0	0	0	0	0
B_2: 5.2 Load plates onto forklift	G_1: 5.2.a loading plates	0.17	0.17	0.17	0.5	0	0	0	0	0
B_3: 5.3 Position plates against structure wall with forklift	G_1: 5.3.a. Position plates/driving	0.17	0.17	0.17	0.5	0	0	0	0	0
	G_2: 5.3.b. communicating the position	0	0	0	0	0	0	0	0.5	0.5
	G_3: 5.3.c. pinning with forklift	0.17	0.17	0.17	0.5	0	0	0	0	0
	G_4: 5.3.d. manual adjustment	0.33	0	0	0.33	0.33	0	0	0	0
B_4: 5.4 Drill holes and secure with fasteners	G_1: 5.4.a drilling (hand tool)	0.33	0.33	0	0.33	0	0	0	0	0
	G_2: 5.4.b. bolting (hand tool)	0.33	0.33	0	0.33	0	0	0	0	0

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Method Application: an example (cont'd)

GA Baseline Times, Impact Factors, and Affected Times

Task 5. Fasten 4 Barriers		Baseline Time TG_k (min)	Nominal GA Impact Factor I_k^* (Primary EC only)	Affected Time TG_k^* (Primary EC Only)
Sub-Tasks	**GAs**			
5.1 Position forklift	5.1.a. walking	5	1.15	5.75
	5.1.b. getting in forklift	1	1.15	1.15
	5.1.c. driving	9	1.23	11.10
5.2 Load plates onto forklift	5.2.a loading plates	15	1.23	18.50
5.3 Position plates against structure wall with forklift	5.3.a. Position plates/driving	10	1.23	12.33
	5.3.b. communicating the position	10	1.25	12.50
	5.3.c. pinning with forklift	20	1.23	24.67
	5.3.d. manual adjustment	20	1.23	24.67
5.4 Drill holes and secure with fasteners	5.4.a drilling (hand tool)	15	1.23	18.50
	5.4.b. bolting (hand tool)	15	1.23	18.50
Total Time		**120**		**147.67**

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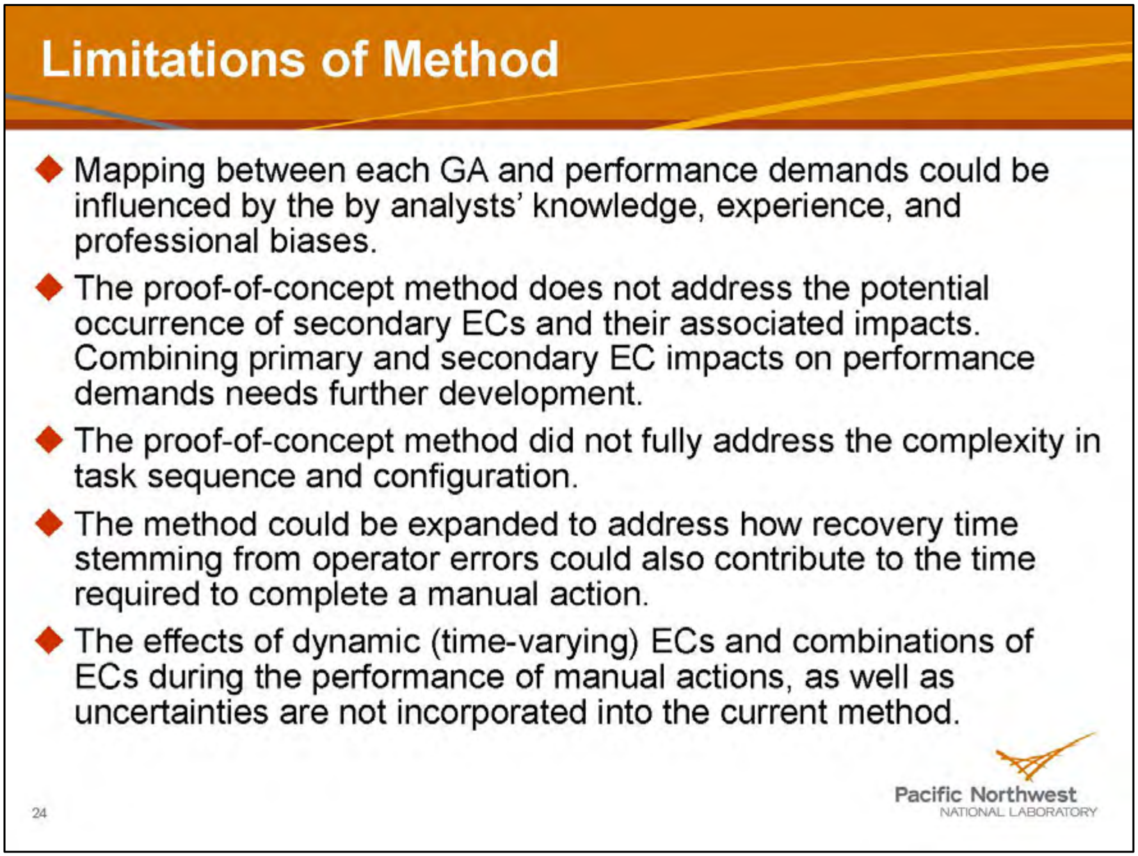
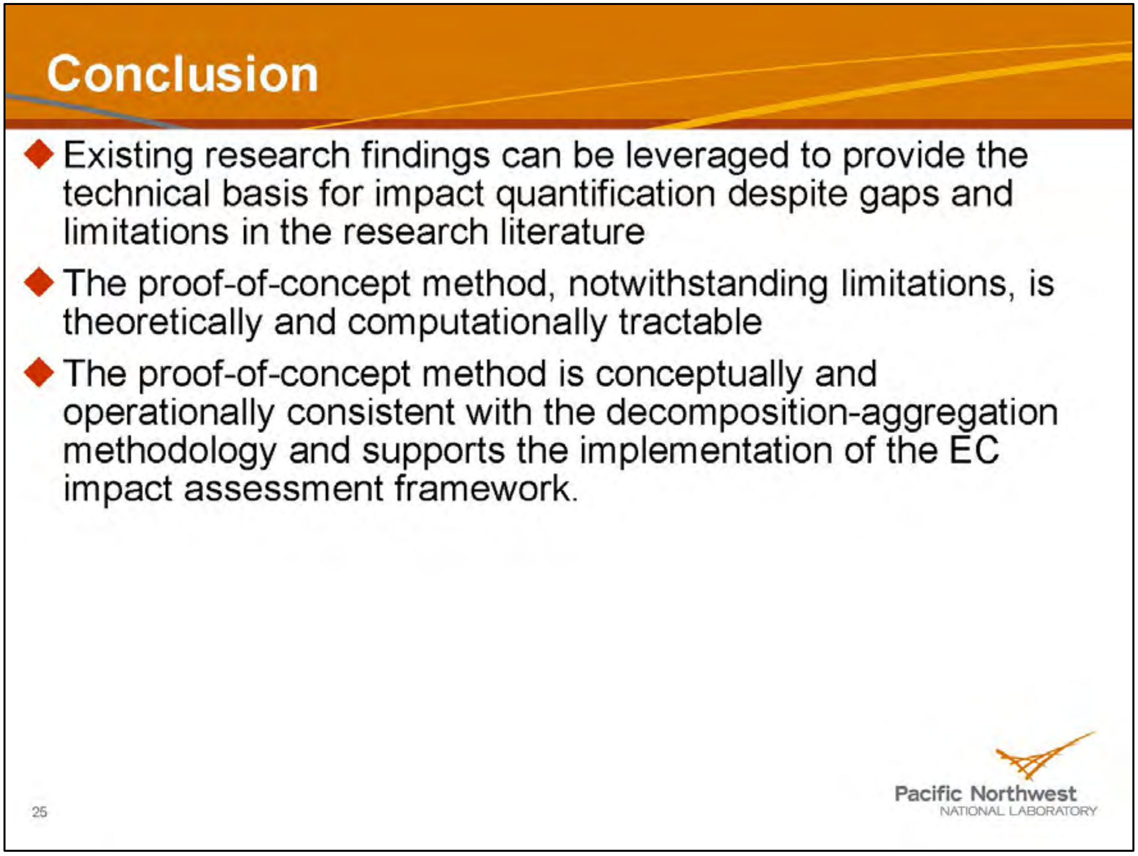


Limitations of Method

- Mapping between each GA and performance demands could be influenced by the by analysts' knowledge, experience, and professional biases.
- The proof-of-concept method does not address the potential occurrence of secondary ECs and their associated impacts. Combining primary and secondary EC impacts on performance demands needs further development.
- The proof-of-concept method did not fully address the complexity in task sequence and configuration.
- The method could be expanded to address how recovery time stemming from operator errors could also contribute to the time required to complete a manual action.
- The effects of dynamic (time-varying) ECs and combinations of ECs during the performance of manual actions, as well as uncertainties are not incorporated into the current method.



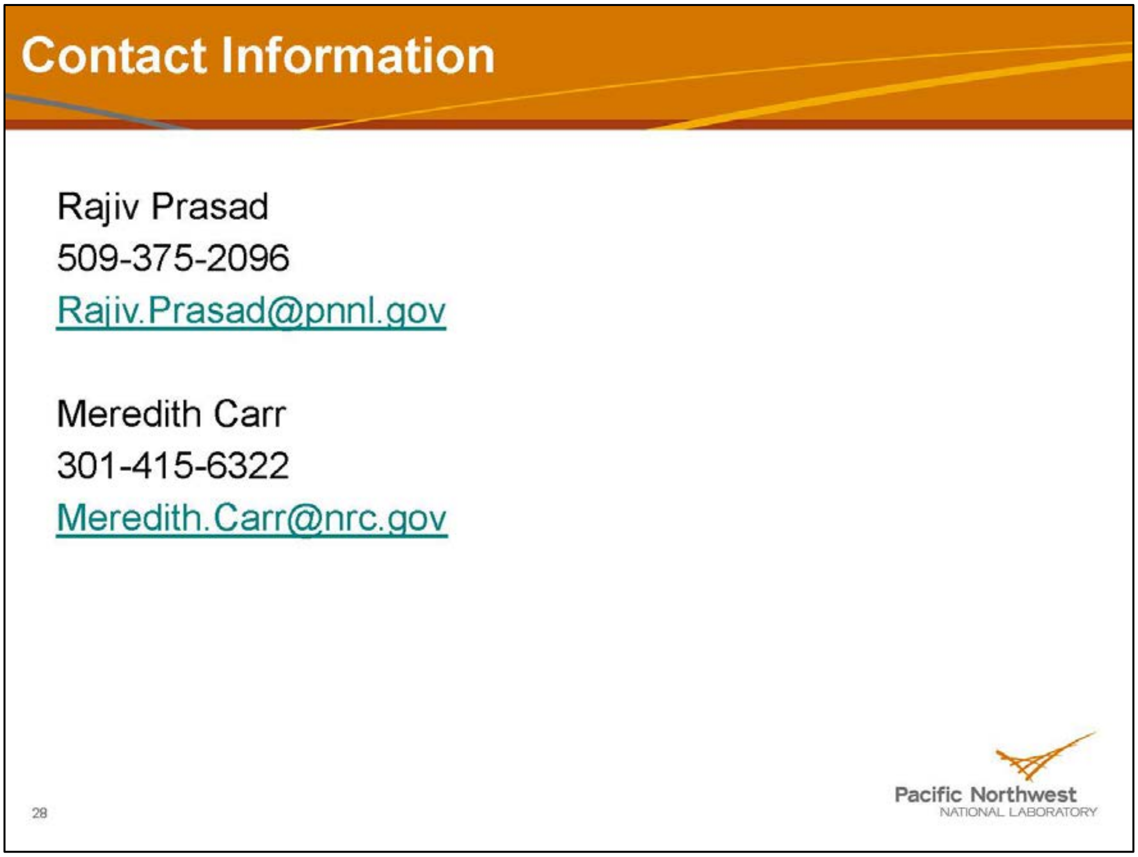
Conclusion

- Existing research findings can be leveraged to provide the technical basis for impact quantification despite gaps and limitations in the research literature
- The proof-of-concept method, notwithstanding limitations, is theoretically and computationally tractable
- The proof-of-concept method is conceptually and operationally consistent with the decomposition-aggregation methodology and supports the implementation of the EC impact assessment framework.

Directions for Future Research

- Adapting the model to account for both primary and secondary EC impacts on performance
- Modeling complexity in task sequence and crew performance;
- Expanding the approach to model the time it takes to recover from critical operator errors Modeling effects of multiple, simultaneously-occurring ECs
- Modeling the effects of dynamic ECs;
- Address uncertainties in model parameters
- Addressing additional factors (e.g., fatigue, stress, and learning) that might influence performance.

Questions?



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2.3.8.1.3 Questions and Answers

Question:

IMPRINT is not available to the public. The framework seems to lead to a deterministic “yes/no” answer rather than trying to establish the probability that an action is successful. However, the probabilistic information is important, and “definitive” answers on the time required are not needed on a generic basis because of the site-specific nature of actions. We developed a simple model and structure that cover some of these.

Response:

IMPRINT, which is a stochastic tool, provides statistics, and the Monte Carlo simulation can give probability information. The result is site specific and condition specific depending on the site (access road, obstacle, etc.). Lead time is important.

Question:

It would be a valuable tool. How would it handle the intersection between an emergency condition (or isolated condition) and a sunny-day version (nonemergency condition)? It seems that key assumptions for emergency conditions are more or less vulnerable.

Response:

We did not look at emergency conditions in the current scope of work (e.g., stress or perception of fear); we focused on what is in the literature and conceptual framework; those issues would be part of the next steps. We needed the simple example to show things could be done.

Question:

How do emergency conditions effect the “key assumptions?”

Response:

Those are some things that need to be worked through [in another scope] (e.g., when crew members are not available to go out and perform tasks). This might actually be best to look at from a design point of view and assess feasibility to make procedures work.

Comment:

If the control room personnel believe the water is dangerous, they will not send people out (or vice versa). Perception may be more important than actual conditions.

Also, there is a hierarchy, in that the “top three” adverse conditions might be the most controlling, so all factors do not need to be considered.

Question:

Secondary effects are also important. For example, even a small elevation of water (from a local intense precipitation event) in a switch gear room with energized equipment would be an issue. Although there are not a lot of “forces” from the water, the energized equipment poses a larger risk. How can this be translated into probabilities of basic events?

Response:

Many of the “secondary effects” are very site specific, along with the “perception of fear.” This framework can allow analysts to “plug in” to a human reliability analysis or PRA framework that allows for the determination of when actions are not feasible, and mitigation is required.

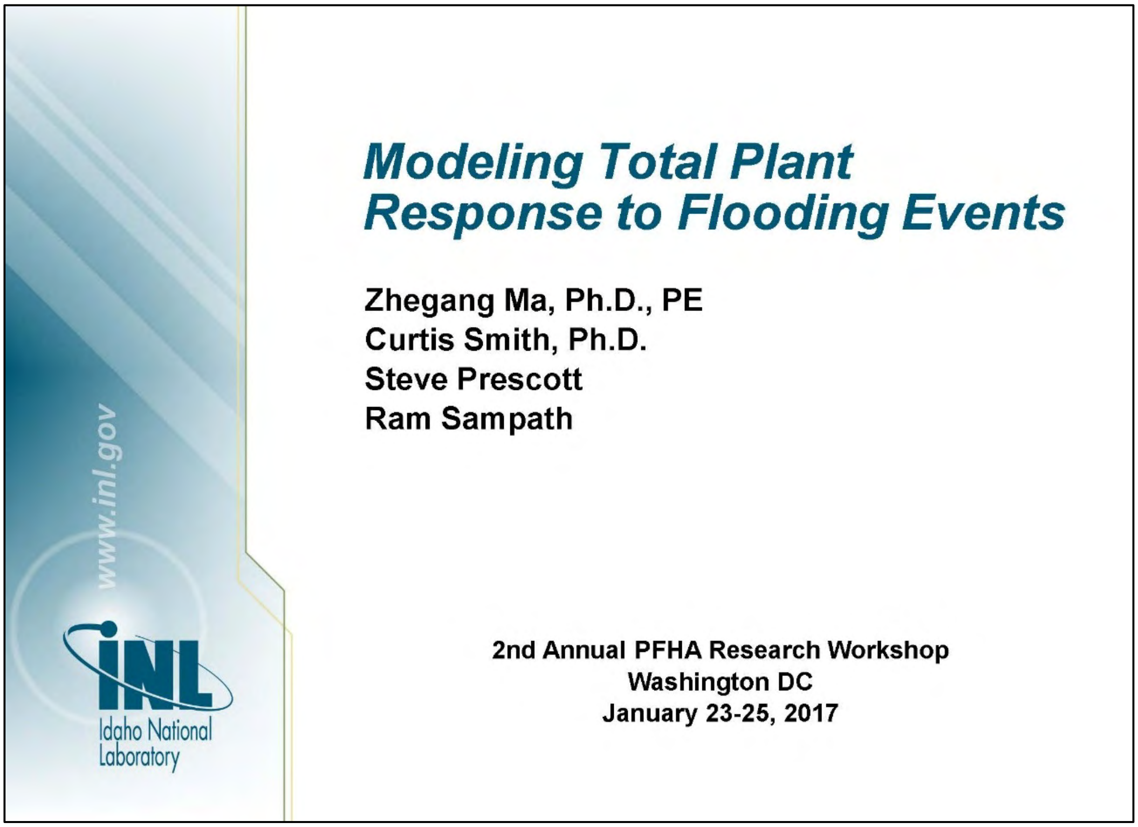
2.3.8.2 Modeling Total Plant Response to Flooding Events, Zhegang Ma*, Ph.D., P.E., Curtis L. Smith, Ph.D. and Steven R. Prescott, Idaho National Laboratory, Risk Assessment and Management Services; and Ramprasad Sampath, Centroid PIC, Research and Development (Session 3-A2; ADAMS Accession No. ML17054C518)

2.3.8.2.1 Abstract

All NPPs must consider external flooding risks, such as local intense precipitation (LIP), riverine flooding, flooding due to upstream dam failure, and coastal flooding due to storm surge or tsunami. These events have the potential to challenge offsite power, threaten plant systems and components, challenge the integrity of plant structures, and limit plant access. Detailed risk assessments of external flood hazard are often needed to provide significant insights to risk-informed decisionmakers. Many unique challenges exist in modeling the complete plant response to the flooding event. Structures, systems, and components (SSCs); flood protection features; and flood mitigation measures to external flood may be highly spatial and time dependent and subject to the hydrometeorological, hydrological, and hydraulic characteristics of the flood event (antecedent soil moisture, precipitation duration and rate, infiltration rate, surface water flow velocities, inundation levels and duration, hydrostatic and hydrodynamic forces, debris impact forces, etc.). Simulation-based methods and dynamic analysis approaches are believed to be a great tool to model the performance of SSCs and operator actions during an external flooding event. In support of the NRC PFHA research plan, INL was tasked to develop such new approaches and demonstrate a proof of concept for the advanced representation of external flooding analysis. This project developed a work plan and framework to perform a simulation-based dynamic flooding analysis. This framework was applied to a LIP event as a case study. A three-dimensional (3D) plant model for a typical pressurized-water reactor and 3D flood simulation models for the LIP event were developed. A state-based PRA modeling tool, Event Model Risk Assessment using Linked Diagrams (EMRALD), was used to incorporate time-related interactions from both 3D time-dependent physical simulations and stochastic failures into traditional PRA logic models. An example state-based PRA model was developed to represent two accident sequences in a simplified traditional general transient event tree, along with incorporating 3D simulation elements into the logic so that the PRA model could communicate with the 3D simulation models. This integrated EMRALD model was run with 34 3D dynamic simulations and millions of Monte Carlo simulations. The EMRALD model results were compared with the corresponding traditional PRA model results. Insights and lessons learned from the project are documented for future research and applications.

The project shows that dynamic approaches could be used as an important tool to investigate total plant response to external flooding events with their appealing features. They can provide visual demonstration of component or system behavior during a highly spatial- and time-dependent flood event. They could provide additional important insights to risk-informed decisionmakers. The dynamic approaches could also play a supplemental role by supporting the development or enhancement of a static PRA with the insights from the dynamic analysis or by performing a standalone analysis that focuses on specific issues with limited sequences and components (e.g., FLEX).

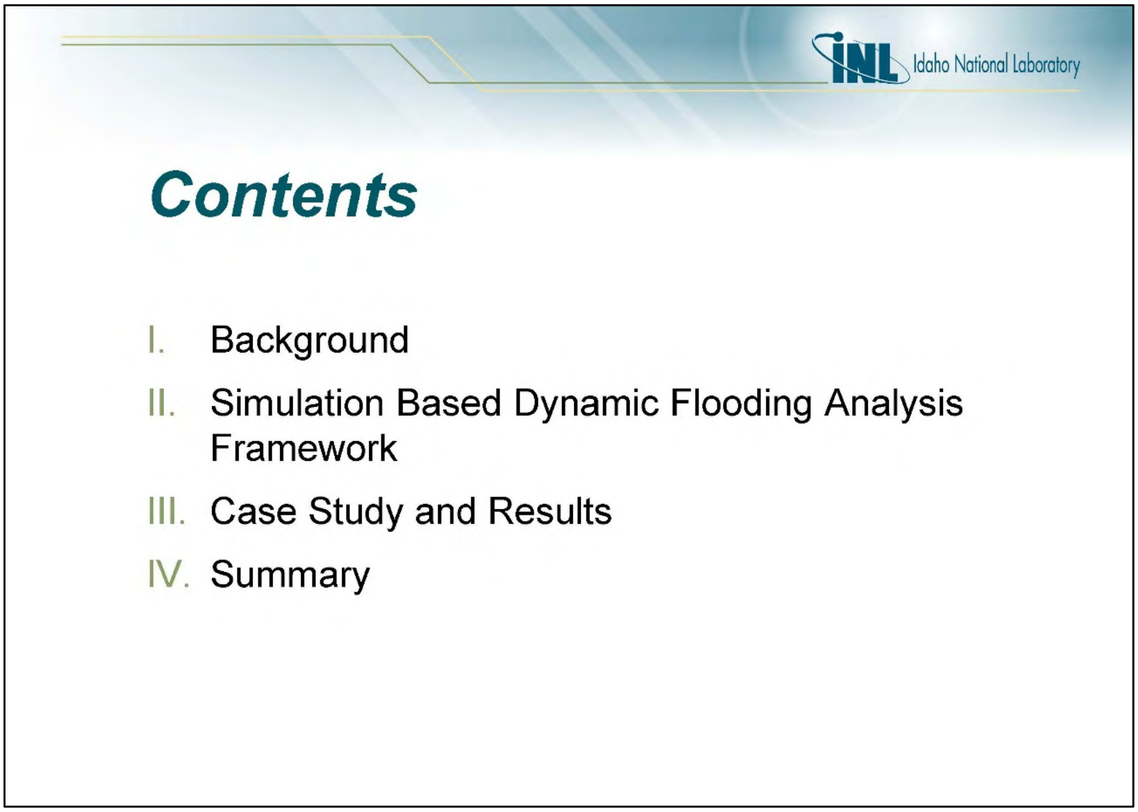
2.3.8.2.2 Presentation



Modeling Total Plant Response to Flooding Events

Zhegang Ma, Ph.D., PE
Curtis Smith, Ph.D.
Steve Prescott
Ram Sampath

2nd Annual PFHA Research Workshop
Washington DC
January 23-25, 2017



Contents

I. Background
II. Simulation Based Dynamic Flooding Analysis Framework
III. Case Study and Results
IV. Summary

I. Background

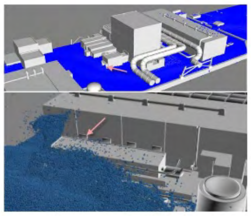
- External Flood hazard could interrupt offsite power, threaten safety important SSCs and limit plant access
- They have often been qualitatively assessed as risk insignificant and screened out from detailed evaluation in the past
- Total plant response should be evaluated to ensure that flood protection features and mitigation measures are adequate

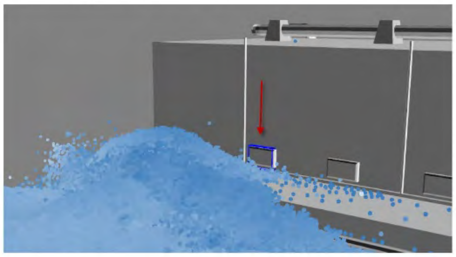
I. Background (Cont.)

- Unique challenges exist for a comprehensive external flooding analysis:
  - Flood protection may be a function of flooding levels (spatial)
  - Degree of flooding may influence the rate of stochastic or common cause failures (dynamic)
  - Response relies heavily on procedures and manual actions
  - Feasibility and reliability of actions can be impacted by the flooding (dynamic and spatial)
  - Duration of the flooding event can be quite long and onsite conditions may change throughout the event
- Might be difficult to capture in static models

I. Background (Cont.)

- This project explores dynamic analysis approaches that depict scenarios through simulation methods
  - an alternative for representing highly time- and location-dependent nature of flooding response
- Proof-of-concept project
- Local Intense Precipitation (LIP) as the case study
- Focus on total plant response to external flooding, not details of hazard or fragility analysis



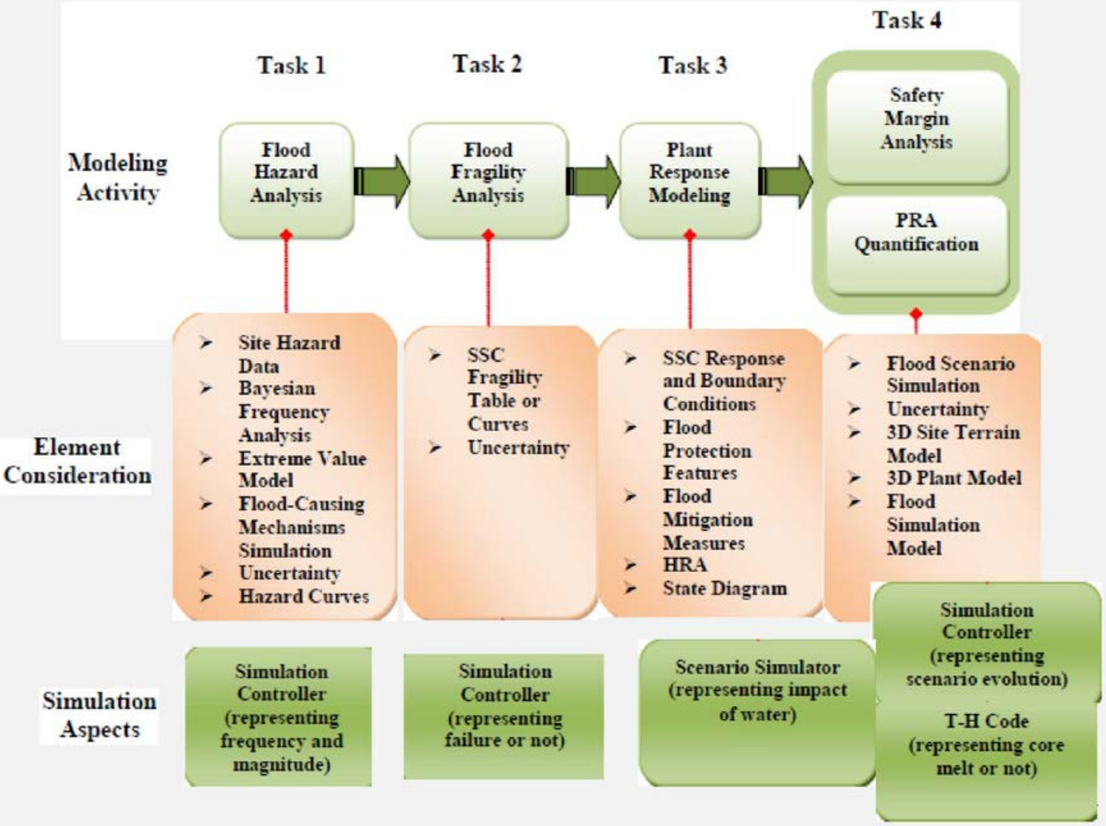


I. Background (Cont.)

- The project started September 2014
  - NRC COR is Dr. Joseph Kanney
  - INL PI is Dr. Curtis Smith
- The project has four specific tasks
  - Task 1 - Work Plan Development
    - Completed in March 2015
  - Task 2 - Margins Assessment Approach for Local Intense Precipitation External Flooding Events
    - Completed in September 2015
  - Task 3 - PRA Approach for Local Intense Precipitation External Flooding Events
    - Completed in September 2016
  - Task 4 - Knowledge Transfer
    - Seminar – completed in October 2016
    - PFHA Research Workshop – January 2017
    - NUREG/CR Report – April 2017

II. Simulation Based Dynamic Flooding Analysis Framework

- External Flood Hazard Analysis
  - Evaluates the frequency that parameters representing flood magnitude (e.g., flood elevation) will be exceeded at a site based on site-specific probabilistic evaluation
- External Flood Fragility Analysis
  - Identify plant SSCs that are susceptible to the effects of external floods
  - Determine their plant-specific failure probabilities as a function of the magnitude of the external flood
- External Flood Plant Response Analysis
  - Develop plant response model to address the initiating events and other failures resulting from the effects of external flood that can lead to core damage or large early release
- External Flood 3D Simulations and PRA Quantification
  - Develop 3D flood scenario simulations that represent component or system behavior, as well as human actions
  - Interact with plant response model by providing flood-induced failures
  - Quantify plant response model



Task 1 | Task 2 | Task 3 | Task 4

Modeling Activity
- Task 1: Flood Hazard Analysis
- Task 2: Flood Fragility Analysis
- Task 3: Plant Response Modeling
- Task 4: Safety Margin Analysis; PRA Quantification

Element Consideration
- Task 1:
  - Site Hazard Data
  - Bayesian Frequency Analysis
  - Extreme Value Model
  - Flood-Causing Mechanisms Simulation
  - Uncertainty
  - Hazard Curves
- Task 2:
  - SSC Fragility Table or Curves
  - Uncertainty
- Task 3:
  - SSC Response and Boundary Conditions
  - Flood Protection Features
  - Flood Mitigation Measures
  - HRA
  - State Diagram
- Task 4:
  - Flood Scenario Simulation
  - Uncertainty
  - 3D Site Terrain Model
  - 3D Plant Model
  - Flood Simulation Model

Simulation Aspects
- Task 1: Simulation Controller (representing frequency and magnitude)
- Task 2: Simulation Controller (representing failure or not)
- Task 3: Scenario Simulator (representing impact of water)
- Task 4: Simulation Controller (representing scenario evolution); T-H Code (representing core melt or not)

II. SBDFA Framework (Cont.)

- Develop plant response model that includes
  - External flood-caused initiating events
  - External flood-induced SSC failures
  - Unavailabilities and failures not induced by external flood
  - Human errors
- Two-stage response model
  - External plant response – flood protection features
    - As-designed features (site drain system, water-tight doors and penetration seals, etc.)
    - Temporary features (portable pumps, sandbag barriers, etc.)
  - Internal plant response
    - Plant mitigation measures and manual actions to maintain key safety functions and prevent core damage and large early release

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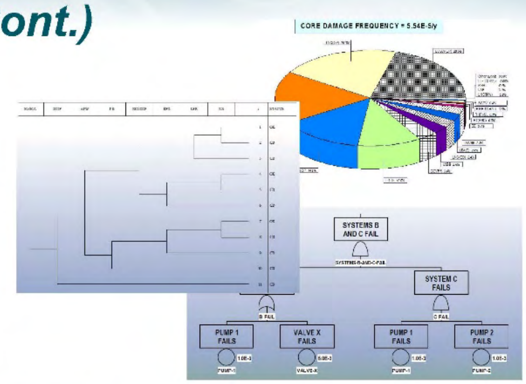
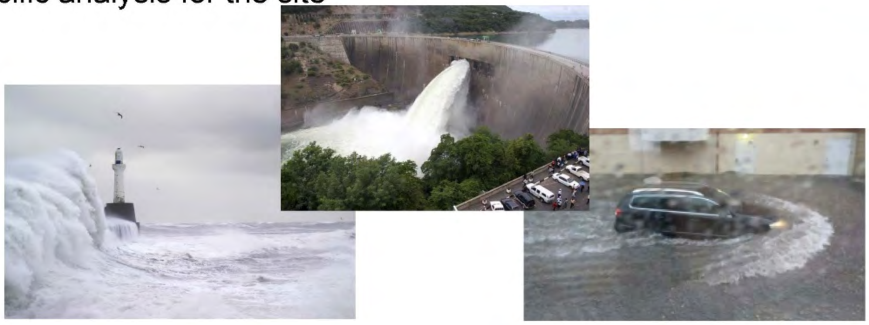
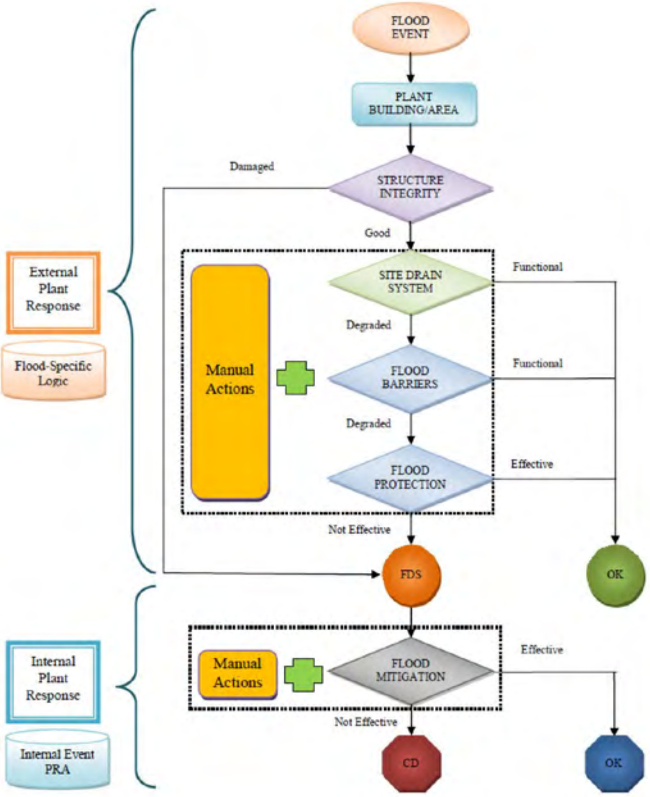
II. SBDFA Framework (Cont.)



- Internal plant response modeling could use existing at-power, internal event (including internal flooding) PRA model as the basis and modify as necessary
- External plant response modeling may need new, flood mechanism-specific analysis for the site

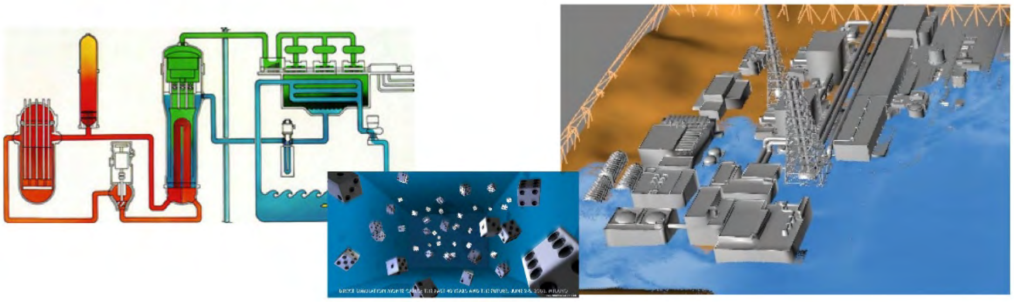




- Two-stage response model
  - External plant response – flood protection features
  - Internal plant response - flood protection and/or mitigation measures

II. SBDFA Framework (Cont.)

- It may be challenge for static models to represent highly time- and spatial-dependent flooding events
- Simulation-based dynamic analysis can be helpful
  - Integrates simulation and time elements into the logic models
  - Advanced 3D modeling and simulations
  - Monte Carlo simulations, 3D physical simulations, and mechanistic analysis are coupled together



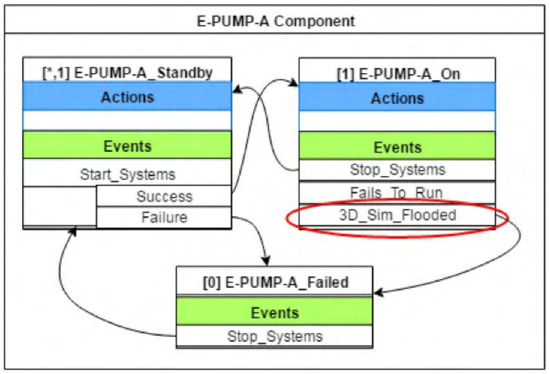
II. SBDFA Framework (Cont.)

- EMRALD – Event Model Risk Assessment using Linked Diagrams
- Uses “states” to represent and track the conditions of the SSCs in the model
- A set of states is represented at any given moment within the mission time
- The set of current states could change over the time until a terminal state is reached
- The model can represent the flooding event dynamically and determine
  - Which components fail?
  - When components fail?
  - What caused their failure?
  - What impact these failures have on the systems?
  - What impact system failure have on the overall plant?

II. SBDFA Framework (Cont.)

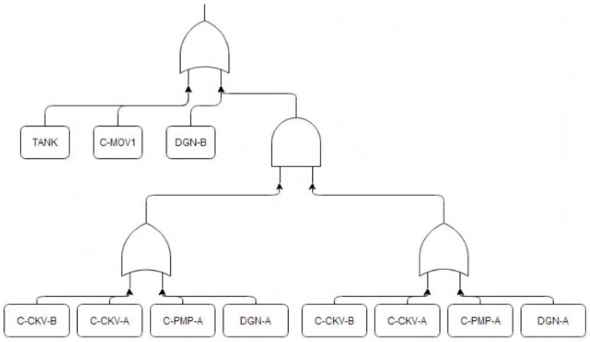
- State-Based Component Modeling

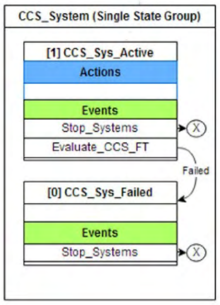
- Standby, On, Failed states
- Designation [1] for success
  [0] for failure
- Monte Carlo Sampling
  - Fail-to-start probability
  - Fail-to-run probability
    - Timer for mission time
- 3D flood simulation failure feedback



II. SBDFA Framework (Cont.)

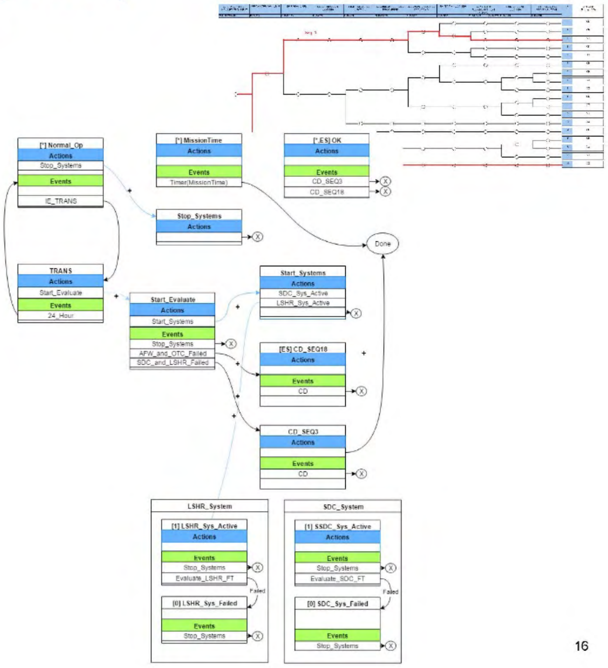
- State-Based System Modeling
- Active, Failed states
- Evaluate system logic diagram
  - Component-specific basic events in EMRALD:
    C-PMP-A, …
  - Failure mode-specific basic events in SAPHIRE:
    C-PMP-A-FS, C-PMP-A-FR, …





II. SBDFA Framework (Cont.)

- State-Based Accident Sequence Modeling
- No explicit accident sequence modeling such as event tree in EMRALD
- Implicitly represented in the plant state diagram with the flow paths between the initiating event states, system or component states, and key/end states

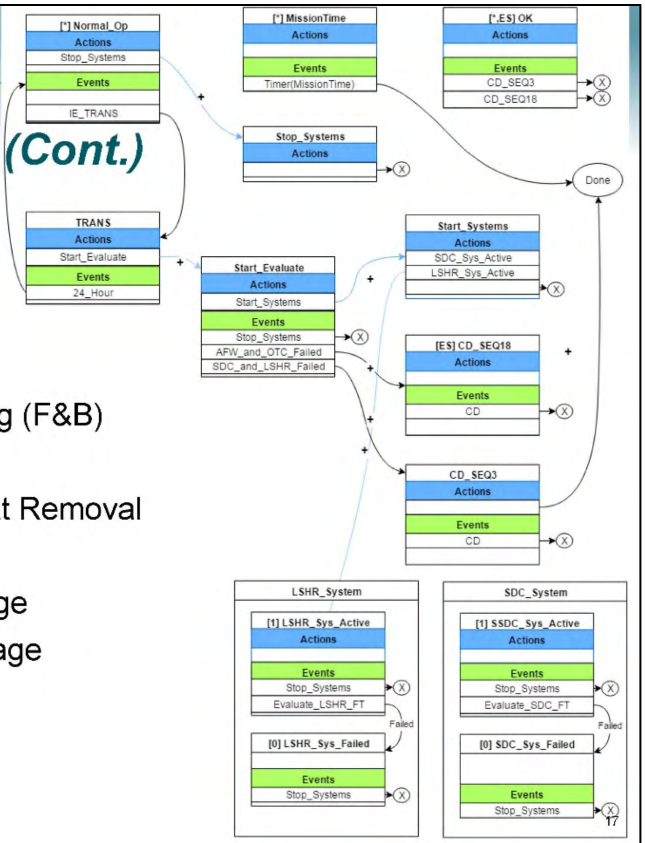


II. SBDFA Framework (Cont.)

- Plant State Diagram

  (Without 3D flooding IE)
- General Transient event
- AFW – Auxiliary Feedwater
- OTC – Once Through Cooling (F&B)
- SDC – Shutdown Cooling
- LSHR – Late Secondary Heat Removal

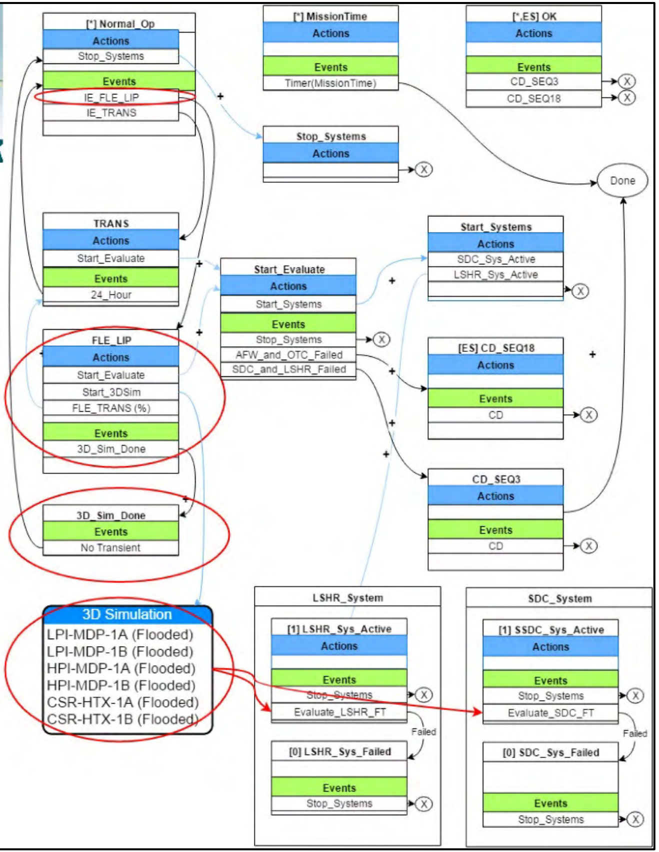
- IE*AFW*OTC -> Core Damage
- IE*SDC*LSHR -> Core Damage



II. SBDFA Framework

- Plant State Diagram

  (With 3D flooding IE)
- External Flood (LIP) IE added
- Flood-caused failures added
- New human actions added
- System logic revised
- 3D simulation results added

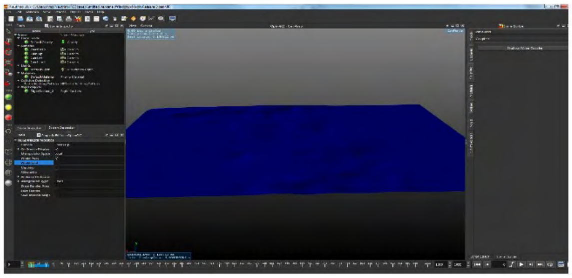


III. Case Study

- A LIP event occurred in a U.S PWR
  - Heavy rainfall plus degraded site drain system
  - Water accumulated on the ground of Building C
  - Water entered underground pipe tunnel when the level exceeds the height of the curb of man hole
  - Flood seal of one penetration between the pipe tunnel and the Auxiliary Building was missing, and water began entering -0.5 ft level of AB
  - Water entered into ECCS pump room sumps at the -10.0 ft level of AB from the -0.5 ft floor drains
  - When pump sump level triggered high-high alarms, operators closed ECCS sump isolation valves to prevent flooding of the ECCS pump rooms
  - However, the water level in -0.5 ft level of AB continued to rise
  - Operators control the AB flooding by cycling ECCS sump isolation valves
  - The event was terminated after the rains subsided and the storm drain was working
  - No safety related equipment inoperable during the event

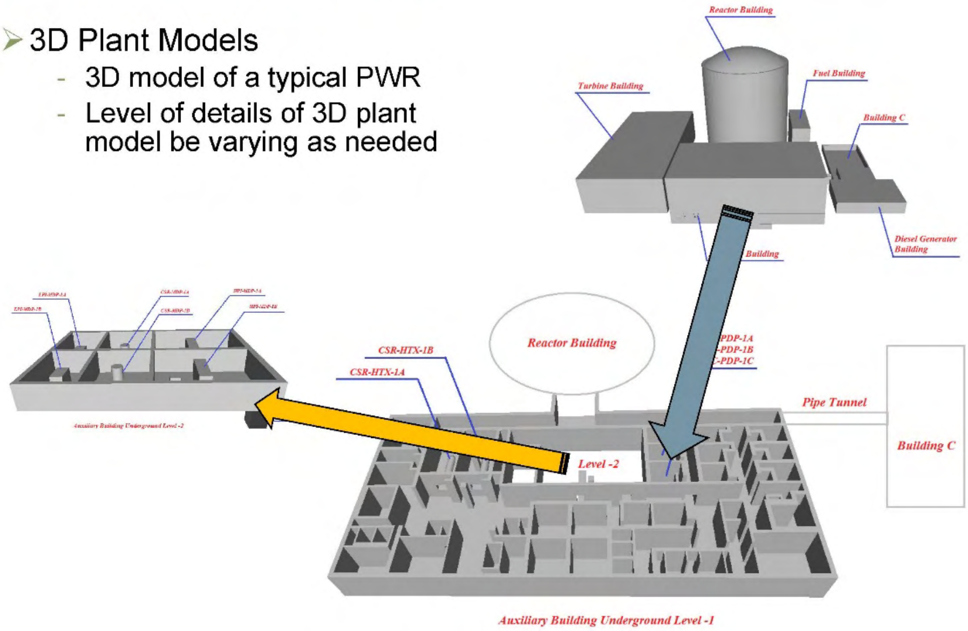
III. Case Study (Cont.)

- 3D Site Terrain Model
  - Developed a web-based Web Terrain Mapper API
  - Using public available Google Maps Elevation API
  - Used for this proof of concept project



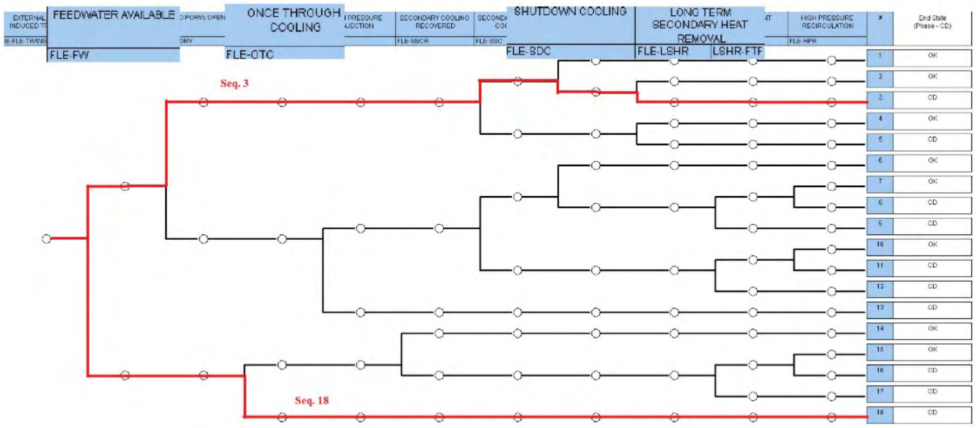
III. Case Study (Cont.)

- 3D Plant Models
  - 3D model of a typical PWR
  - Level of details of 3D plant model be varying as needed



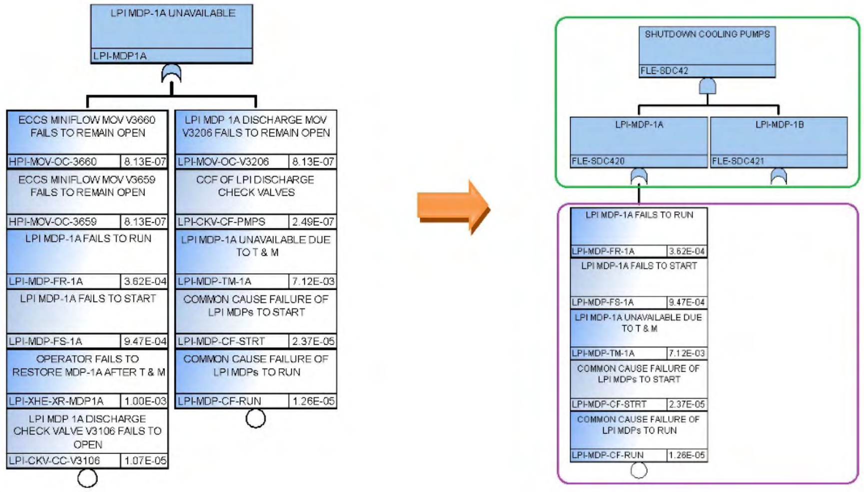
III. Case Study (Cont.)

- Simplified SAPHIRE Model for the flood event
  - External Flood-Caused Transient Event Tree
  - Two Sequences for analysis
  - Seq. 3: IE * /FW * /PORV * /SSC * SDC * LSHR (failure of shutdown cooling and long term secondary heat removal)
  - Seq. 18: IE * FW * OTC (failure of feedwater and feed & bleed)



III. Case Study (Cont.)

- Convert SAPHIRE Model to EMRALD Model
  - Convert fault trees in SAPHIRE to component state diagrams and system state diagrams

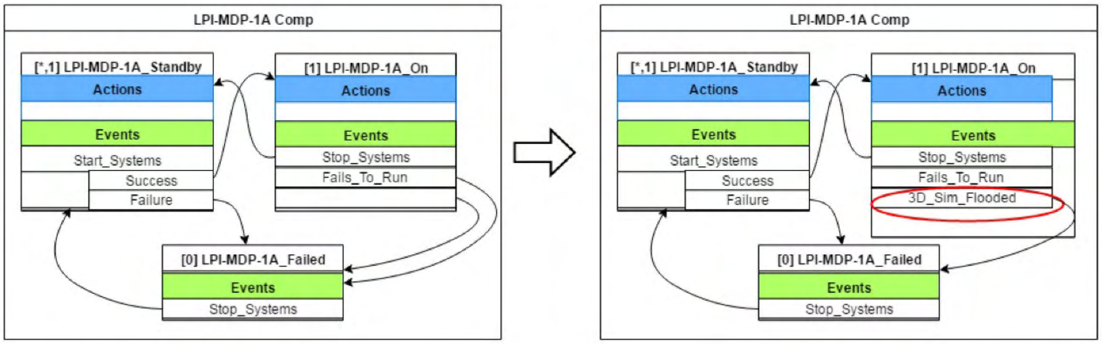


Used for System Logic Diagram Design

Used for Component State Diagram Design

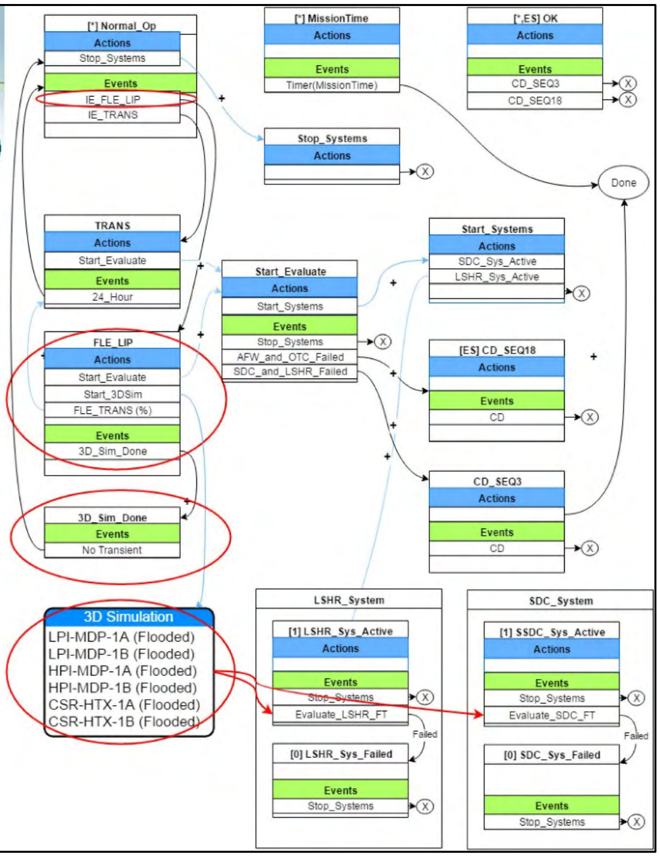
III. Case Study (Cont.)

- Add External Flood Elements into the EMRALD Model
  - Add external flood-induced failure events to component state diagrams



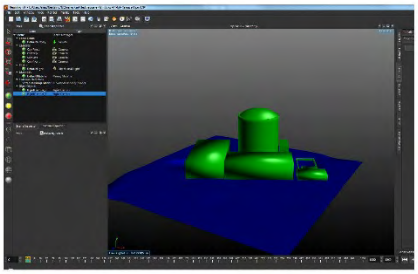
III. Case Study (Cont.)

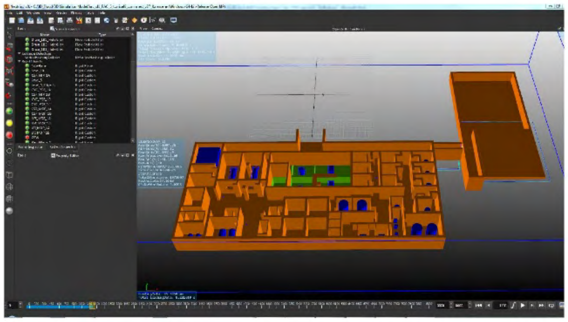
- Add External Flood Elements into the EMRALD Model
  - Add external flood-caused initiating event to plant state diagram
  - Add the tokens of 3D simulation results to plant state diagram



III. Case Study (Cont.)

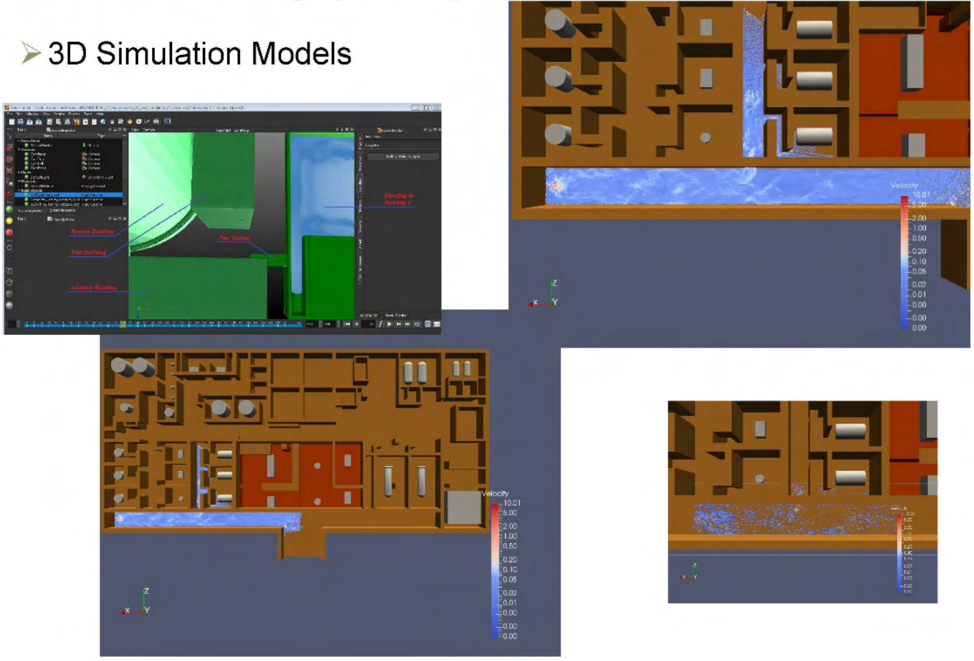
- 3D Simulation Models
- Neutrino software was used for this project
  - Smooth Particle Hydrodynamics (SPH)
  - Handle memory requirements for large simulations
  - Measure flooding parameters such as flood height, flow rate, pressure, etc.
- Potential area of future research





III. Case Study (Cont.)

- 3D Simulation Models



III. Case Study (Cont.)

- EMRALD with 3D Simulation Model Results
  - Run on 5 clustered Windows-based PC servers (Minion 1 – 5) for 3D flood simulations
  - 3D simulation results returned back to EMRALD for model quantification
  - A part of the quantification results

3-D Sim. Run	Flood Rate (gpm)	Seq. 18 Prob.	Seq. 3 Prob.	Component Failure
1-2	1010	1.1E-05	3.5E-06	CSR_MDP_1A_Failed, CSR_MDP_1B_Failed, HPI_MDP_1A_Failed, HPI_MDP_1B_Failed, LPI_MDP_1A_Failed, LPI_MDP_1B_Failed
1-3	919	2.0E-07	2.0E-07	CSR_MDP_1A_Failed, CSR_MDP_1B_Failed, HPI_MDP_1B_Failed, LPI_MDP_1A_Failed, LPI_MDP_1B_Failed
1-4	731	7.0E-07	0.0E+00	CSR_MDP_1B_Failed, HPI_MDP_1B_Failed
1-5	737	4.0E-07	0.0E+00	CSR_MDP_1B_Failed, HPI_MDP_1B_Failed, LPI_MDP_1B_Failed
1-7	702	4.0E-07	0.0E+00	CCW_HTX_1B_Failed, CSR_MDP_1B_Failed, HPI_MDP_1B_Failed
1-8	700	2.0E-07	0.0E+00	CSR_MDP_1B_Failed, HPI_MDP_1B_Failed
2-1	763	3.0E-07	0.0E+00	CSR_MDP_1B_Failed, HPI_MDP_1B_Failed, LPI_MDP_1B_Failed
2-2	839	1.0E-07	1.0E-07	CSR_MDP_1B_Failed, HPI_MDP_1B_Failed, HPI_XHE_FB_Failed, LPI_MDP_1A_Failed, LPI_MDP_1B_Failed
2-3	609	2.0E-07	0.0E+00	
2-5	873	5.0E-07	1.0E-07	CSR_MDP_1B_Failed, HPI_MDP_1B_Failed, LPI_MDP_1A_Failed, LPI_MDP_1B_Failed
2-6	772	4.0E-07	0.0E+00	CSR_MDP_1B_Failed, HPI_MDP_1B_Failed, LPI_MDP_1B_Failed
2-7	668	5.0E-07	0.0E+00	HPI_MDP_1B_Failed
2-8	992	5.0E-07	5.0E-07	CSR_MDP_1A_Failed, CSR_MDP_1B_Failed, HPI_MDP_1B_Failed, LPI_MDP_1A_Failed, LPI_MDP_1B_Failed

III. Case Study (Cont.)

- Compare EMRALD results with SAPHIRE results
    - Grouping EMRALD results by the flow rate and failure components -> 6 scenarios
    - Quantify SAPHIRE model with proper change sets for the 6 scenarios
    - EMRALD results seem to be consistent to those of SAPHIRE

Scenario	Component Failure	Seq.	SAPHIRE	EMRALD
1	None	Seq. 18	2.3E-07	2.0E-07
		Seq.3	5.0E-10	0.0E+00
2	HPI-B pump failed	Seq. 18	2.7E-07	4.5E-07
		Seq.3	7.7E-10	0.0E+00
3	HPI-B, and CSR-B pumps failed	Seq. 18	2.7E-07	3.8E-07
		Seq.3	7.7E-10	0.0E+00
4	LPI-B, HPI-B, and CSR-B pumps failed	Seq. 18	2.7E-07	4.0E-07
		Seq.3	1.9E-09	0.0E+00
5	All LPI and CSR pumps and HPI-B pump failed	Seq. 18	2.7E-07	3.8E-07
		Seq.3	1.3E-07	2.0E-07
6	All LPI, HPI, CSR pumps failed	Seq. 18	8.6E-06	1.3E-05
		Seq.3	3.2E-06	3.8E-06

IV. Summary

- The objective of this project is to investigate dynamic approaches to model total plant response to flooding events
- Dynamic approaches could be used as an important tool
- EMRALD, the state based PRA modeling tool, could be an integrated dynamic PRA tool for external flood and other hazard analysis
- This proof-of-concept project is an exploratory research
- Not every element of flooding risk models can be simulated
- Simulation can also play a supplemental role
    - To support the development or enhancement of a static PRA with the insights from the dynamic analysis
    - To perform a stand alone analysis that focuses on specific issues with limited sequences and components (e.g., FLEX)
    - To validate or challenge some specific assumptions and inputs in the traditional static PRA models

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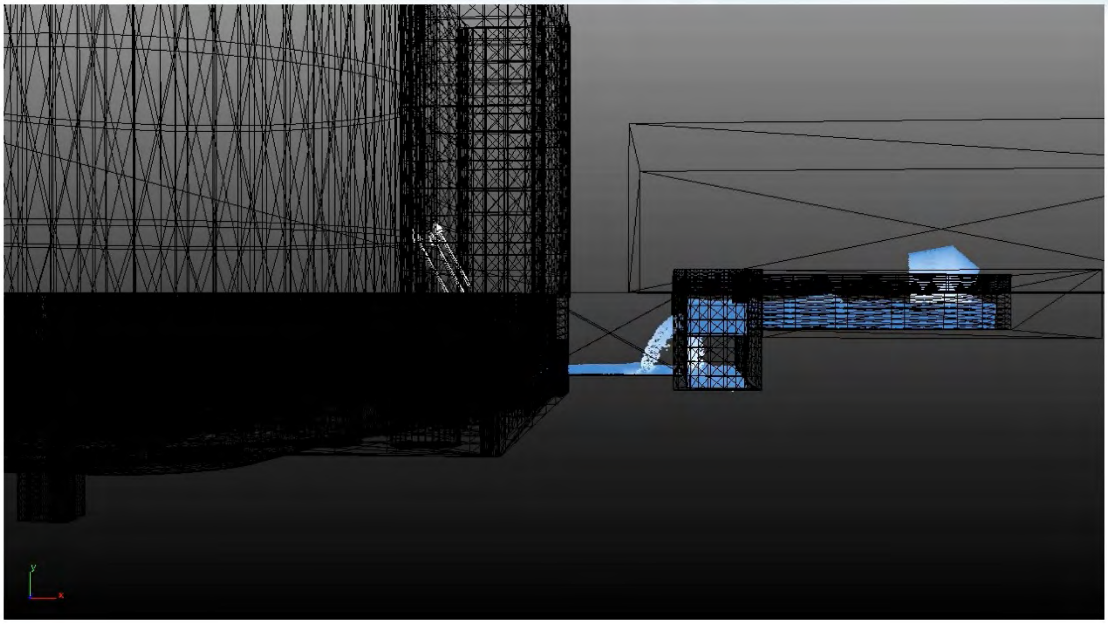

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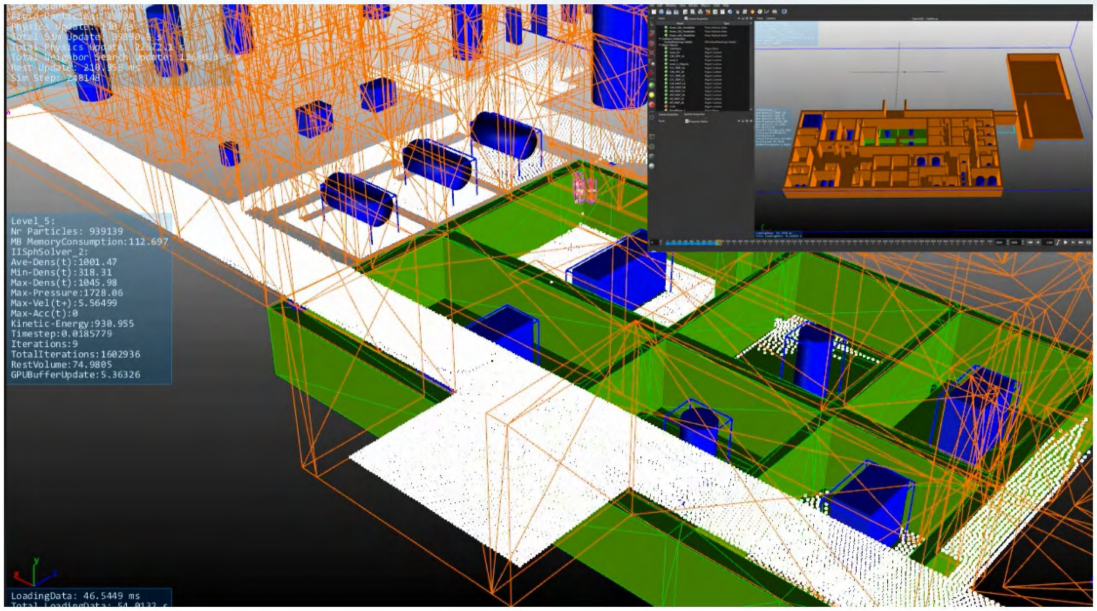

```
Level_5:
Nr Particles: 939139
MB MemoryConsumption:112.697
IISphSolver_2:
Ave-Dens(t):1001.47
Min-Dens(t):318.31
Max-Dens(t):1045.98
Max-Pressure:1728.06
Max-Vel(t+):5.56499
Max-Acc(t):0
Kinetic-Energy:930.955
Timestep:0.0185779
Iterations:9
TotalIterations:1602936
RestVolume:74.9805
GPUBufferUpdate:5.36326
```

```
LoadingData: 46.5449 ms
```

Questions?

Contact Info

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- Dr. Zhegang Ma (INL), Zhegang.Ma@inl.gov, 208-526-1069
- Dr. Joseph Kanney (NRC), Joseph.Kanney@nrc.gov, 301-415-1920

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2.3.8.2.3 *Questions and Answers*

Question:

Can the 3D modeling approach be applicable to seismic?

Response:

This is not part of the scope of this project, but there are some examples. It was done in a U.S. Department of Defense project, looking at a detailed piping network and internal flooding from an earthquake. It can also be applied to a high-wind case and atmospheric modeling, particle tracking, and other situations.

2.3.9 Day 3: Session 3B - Frameworks I

This session considered the development and demonstration of a PFHA framework for flood hazard curve estimation.

2.3.9.1 Technical Basis for Probabilistic Flood Hazard Assessment, Rajiv Prasad*, Ph.D., and Philip Meyer, Ph.D., Pacific Northwest National Laboratory (Session 3B-1; ADAMS Accession No. ML17054C482)

2.3.9.1.1 Abstract

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

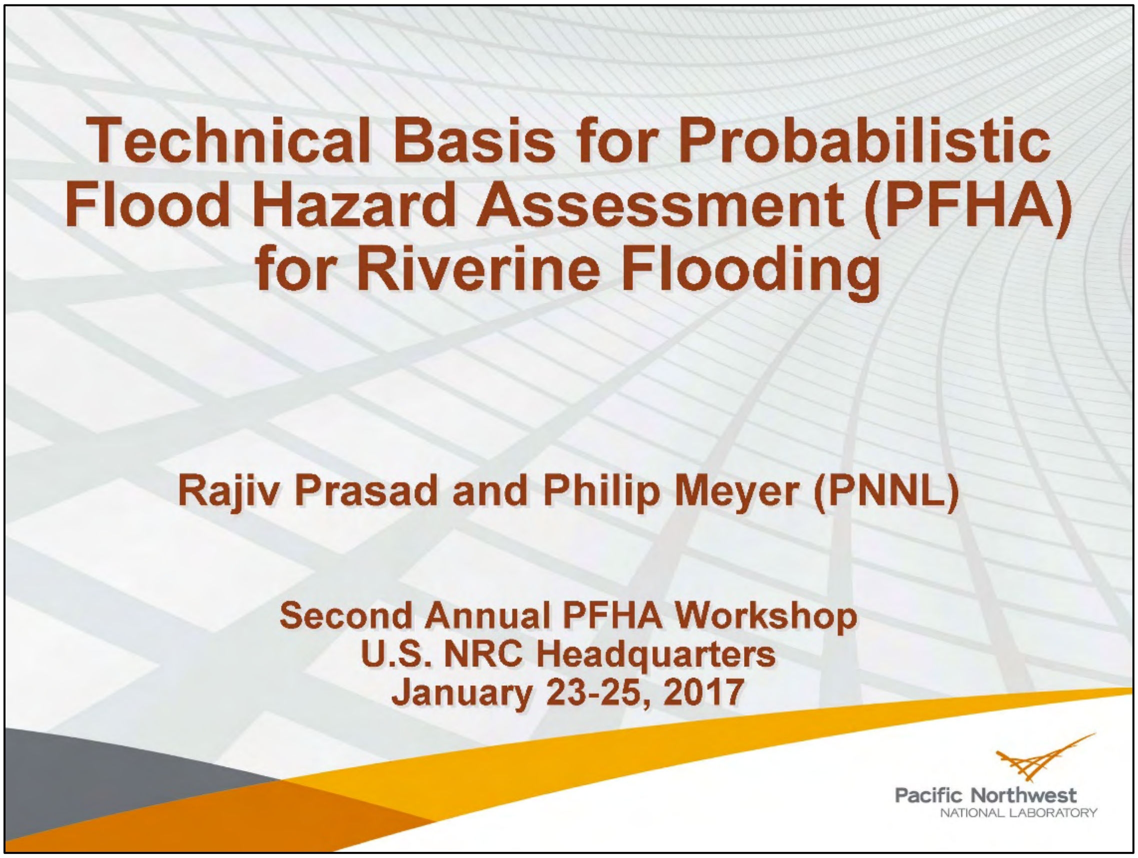
PFHA is defined as a site-specific, systematic evaluation of the probabilities and frequencies of exceedance of hazards generated by applicable flood mechanisms to which SSCs could be exposed during specified exposure times at an NPP site. Flood mechanisms are those hydrometeorological, geoseismic, or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

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

The project proposes a PFHA framework that is simulation based and includes a comprehensive evaluation of uncertainties. The framework uses three components: (1) a meteorological component that provides hydrometeorologic input data, (2) a hydrologic component that estimates runoff discharges from precipitation events given hydrometeorologic input data, watershed initial conditions, and physical watershed data, and (3) a hydraulic component that estimates hydraulic flood parameters, including floodwater-surface elevations and flood velocities given runoff discharges and physical river network properties. In addition, there may be another component to transform the watershed model outputs into the required flood parameters for which hazard curves are required. Aleatory uncertainties are associated with the hydrometeorologic inputs and with the watershed initial and boundary conditions. These quantities describe the primary

irreducible uncertainties affecting the occurrence of future flooding at a site: the depth and intensity of rainfall events in the future, and the watershed conditions at the time of those events. Epistemic uncertainties are associated with the parameters of the watershed model and describe the lack of knowledge in modeling the precipitation-runoff processes, in characterizing the watershed, and in determining appropriate parameter values for the models. These are the primary uncertainties that could be reduced by collecting additional data. By incorporating available data, a Bayesian approach is used to reduce the epistemic uncertainties. Watershed model outputs either directly represent the flood hazards of interest or may be transformed to them (e.g., hydrostatic and hydrodynamic loads, scour potential). The aleatory uncertainties result in a distribution of each flood hazard, which constitutes a hazard curve. Epistemic uncertainties contribute to the uncertainty in the quantiles of the distribution representing the hazard curve (e.g., the uncertainty in the exceedance probability of a given flood hazard value). The team expects to address issues related to implementing the proposed framework in the near future.

2.3.9.1.2 Presentation



Technical Basis for Probabilistic Flood Hazard Assessment (PFHA) for Riverine Flooding

Rajiv Prasad and Philip Meyer (PNNL)

Second Annual PFHA Workshop
U.S. NRC Headquarters
January 23-25, 2017

Pacific Northwest
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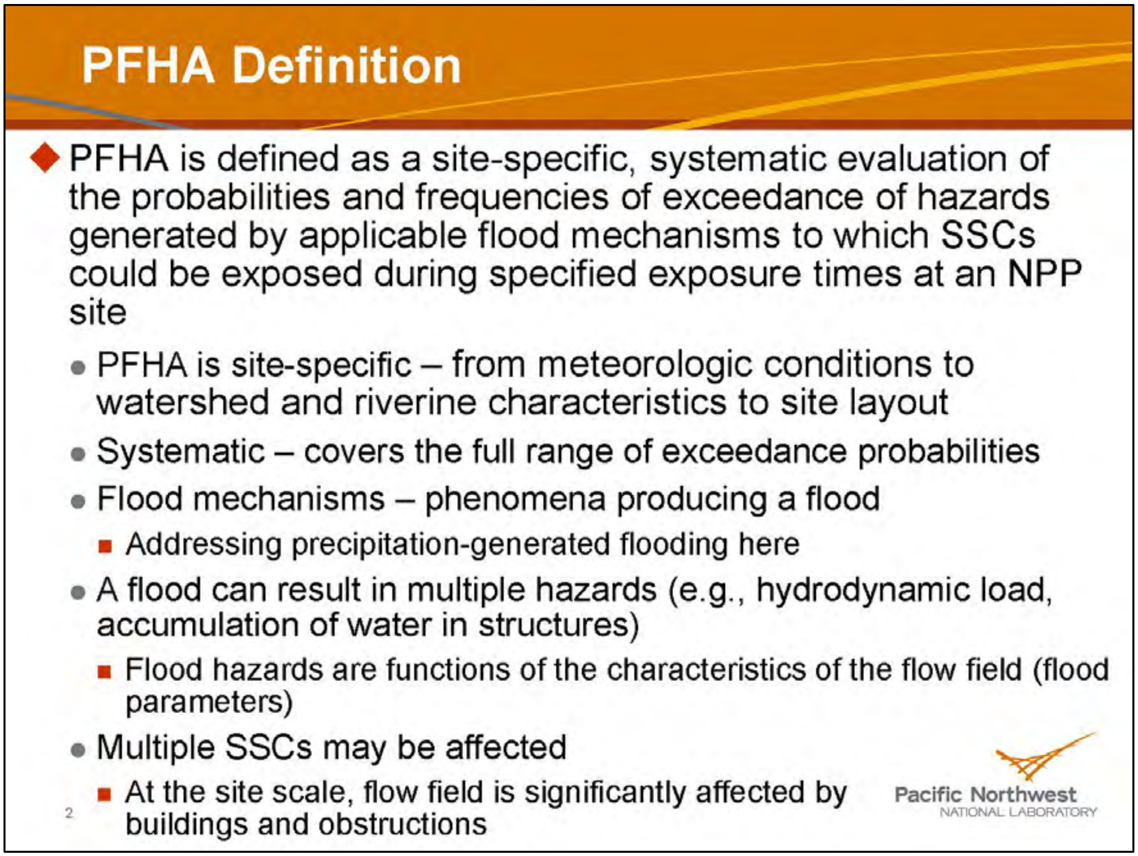
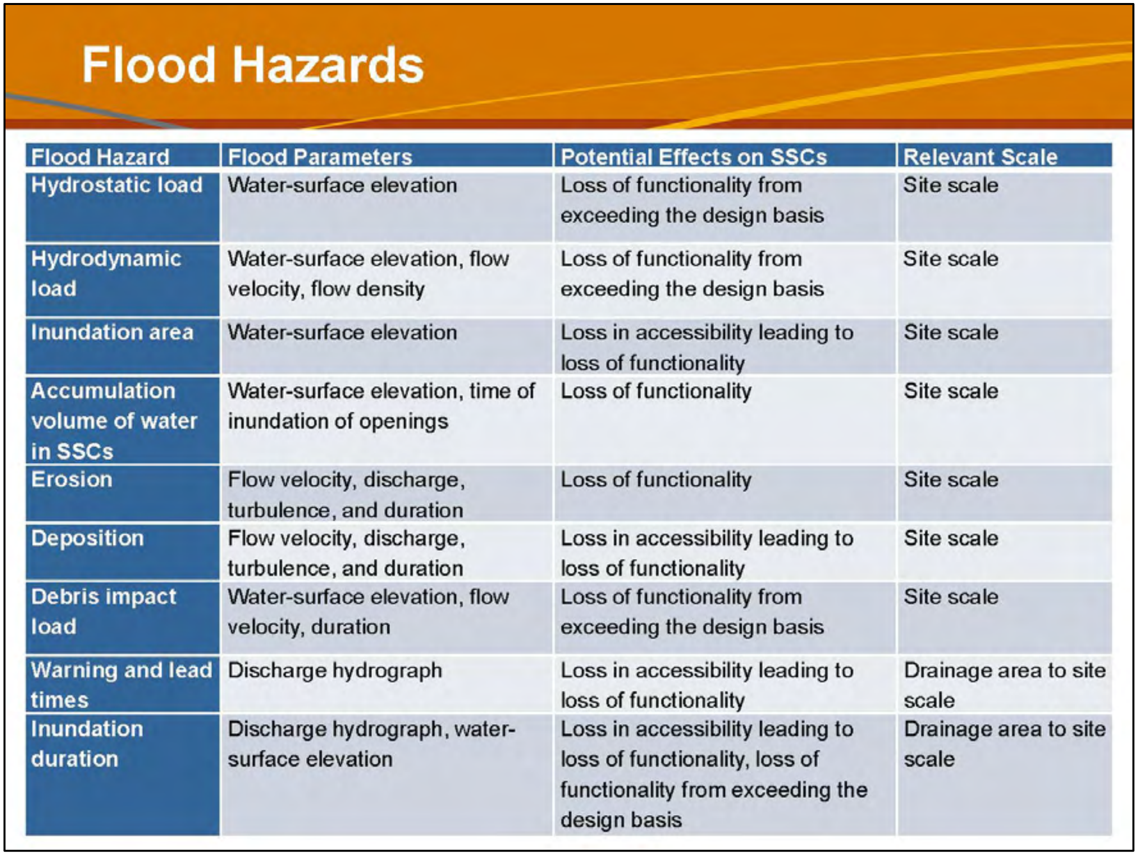


PFHA Definition

- PFHA is defined as a site-specific, systematic evaluation of the probabilities and frequencies of exceedance of hazards generated by applicable flood mechanisms to which SSCs could be exposed during specified exposure times at an NPP site
  - PFHA is site-specific – from meteorologic conditions to watershed and riverine characteristics to site layout
  - Systematic – covers the full range of exceedance probabilities
  - Flood mechanisms – phenomena producing a flood
    - Addressing precipitation-generated flooding here
  - A flood can result in multiple hazards (e.g., hydrodynamic load, accumulation of water in structures)
    - Flood hazards are functions of the characteristics of the flow field (flood parameters)
  - Multiple SSCs may be affected
    - At the site scale, flow field is significantly affected by buildings and obstructions



Flood Hazards

Flood Hazard	Flood Parameters	Potential Effects on SSCs	Relevant Scale
Hydrostatic load	Water-surface elevation	Loss of functionality from exceeding the design basis	Site scale
Hydrodynamic load	Water-surface elevation, flow velocity, flow density	Loss of functionality from exceeding the design basis	Site scale
Inundation area	Water-surface elevation	Loss in accessibility leading to loss of functionality	Site scale
Accumulation volume of water in SSCs	Water-surface elevation, time of inundation of openings	Loss of functionality	Site scale
Erosion	Flow velocity, discharge, turbulence, and duration	Loss of functionality	Site scale
Deposition	Flow velocity, discharge, turbulence, and duration	Loss in accessibility leading to loss of functionality	Site scale
Debris impact load	Water-surface elevation, flow velocity, duration	Loss of functionality from exceeding the design basis	Site scale
Warning and lead times	Discharge hydrograph	Loss in accessibility leading to loss of functionality	Drainage area to site scale
Inundation duration	Discharge hydrograph, water-surface elevation	Loss in accessibility leading to loss of functionality, loss of functionality from exceeding the design basis	Drainage area to site scale

PFHA Components

- Data collection and analysis
- Model selection
- Model parameter estimation
- Evaluation of variability and uncertainty
- Quantification of probabilistically-defined hazard, including uncertainties

Potentially Applicable Data

- Streamflow data
- Physical data
  - Topography, watershed area, subwatersheds, drainage connectivity, land use and cover, soil types, channel lengths, connectivity, cross sections
- Hydrometeorologic input data
  - Precipitation, air temperature, solar radiation, wind speeds and direction
- Snow cover and water content
- Soil Moisture
- Data types, temporal resolution, and spatial coverage are dictated by model requirements

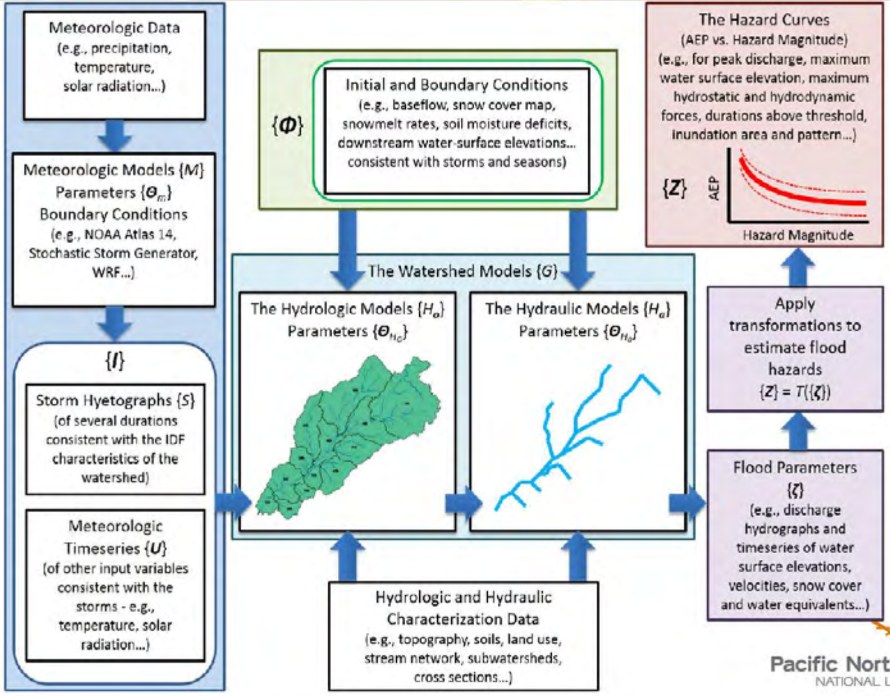
Potentially Applicable Models

- Statistical models (flood frequency analysis)
- Meteorologic models
  - Provides meteorologic input (e.g., a regional precipitation IDF curve)
- Watershed models
  - Hydrologic Model
    - Set up using physical watershed data (e.g., topography, subwatersheds, channel network, soils, land use and cover…)
    - Given input meteorologic data and initial conditions, predicts streamflow discharge hydrographs
  - Hydraulic Model
    - Set up using physical watershed data (e.g., topography, channel network, cross sections…)
    - Given initial conditions (baseflow) and streamflow discharge hydrographs, predicts flood characteristics (e.g., water-surface elevations, velocities…)

Multiple Model Alternatives

- Hydrologic Models
  - Lumped-parameter conceptual models (e.g., unit hydrograph)
  - Physically-based process models (e.g., Stanford Watershed Model, Sacramento Model, HSPF, IHDM, PRMS, HBV, TOPMODEL)
  - "Fully-distributed" physically-based models (e.g., SHE, DHSVM)
  - Semi-distributed, lumped-parameter models (e.g., HEC-HMS)
- Hydraulic Models
  - One-dimensional approximation (e.g., kinematic wave, diffusive wave)
  - Full one-dimensional dynamic wave models (e.g., NWS DWOPER, NWS DAMBRK, NWS FLDWAV, USACE HEC-RAS)
  - Two-dimensional hydraulic models (e.g., TUFLOW, Mike 21, TELEMAC)
- Varying data requirements
- Need calibration and validation

PFHA Framework: Model-based



Meteorologic Data
(e.g., precipitation, temperature, solar radiation...)

Meteorologic Models $\{M\}$
Parameters $\{\Theta_m\}$
Boundary Conditions
(e.g., NOAA Atlas 14, Stochastic Storm Generator, WRF...)

$\{I\}$

Storm Hyetographs $\{S\}$
(of several durations consistent with the IDF characteristics of the watershed)

Meteorologic Timeseries $\{U\}$
(of other input variables consistent with the storms - e.g., temperature, solar radiation...)

$\{\Phi\}$

Initial and Boundary Conditions
(e.g., baseflow, snow cover map, snowmelt rates, soil moisture deficits, downstream water-surface elevations... consistent with storms and seasons)

The Watershed Models $\{G\}$

The Hydrologic Models $\{H_o\}$
Parameters $\{\Theta_{H_o}\}$

The Hydraulic Models $\{H_a\}$
Parameters $\{\Theta_{H_a}\}$

Hydrologic and Hydraulic Characterization Data
(e.g., topography, soils, land use, stream network, subwatersheds, cross sections...)

The Hazard Curves
(AEP vs. Hazard Magnitude)
(e.g., for peak discharge, maximum water surface elevation, maximum hydrostatic and hydrodynamic forces, durations above threshold, inundation area and pattern...)

$\{Z\}$

Apply transformations to estimate flood hazards
$\{Z\} = T(\{\zeta\})$

Flood Parameters
$\{\zeta\}$
(e.g., discharge hydrographs and timeseries of water surface elevations, velocities, snow cover and water equivalents...)

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Model Parameter Estimation

◆ Evolution of methods

- Trial and error → automated calibration
- Single objective → multi-objective
- Local → global search
- Classical (least-squares, maximum likelihood) → Bayesian (prior parameter information)

◆ Extrapolation likely required even with best effort

- Observed data record on the order of 100 years – may not include low-probability events
- Best observations for parameter estimation may not include those for extreme floods

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Evaluation of Variability and Uncertainty

- Aleatory Uncertainty
  - Arises from the natural variability in a system; irreducible
  - For PFHA, the primary irreducible uncertainties affecting the occurrence of future flooding at a site are:
    - the depth and intensity of rainfall events in the future, and the
    - watershed conditions at the time of those events
    - associated with the hydrometeorologic inputs, $\boldsymbol{I}$, and with the watershed initial and boundary conditions, $\boldsymbol{\Phi}$
  - Aleatory uncertainties result in a distribution of each flood hazard (a hazard curve)

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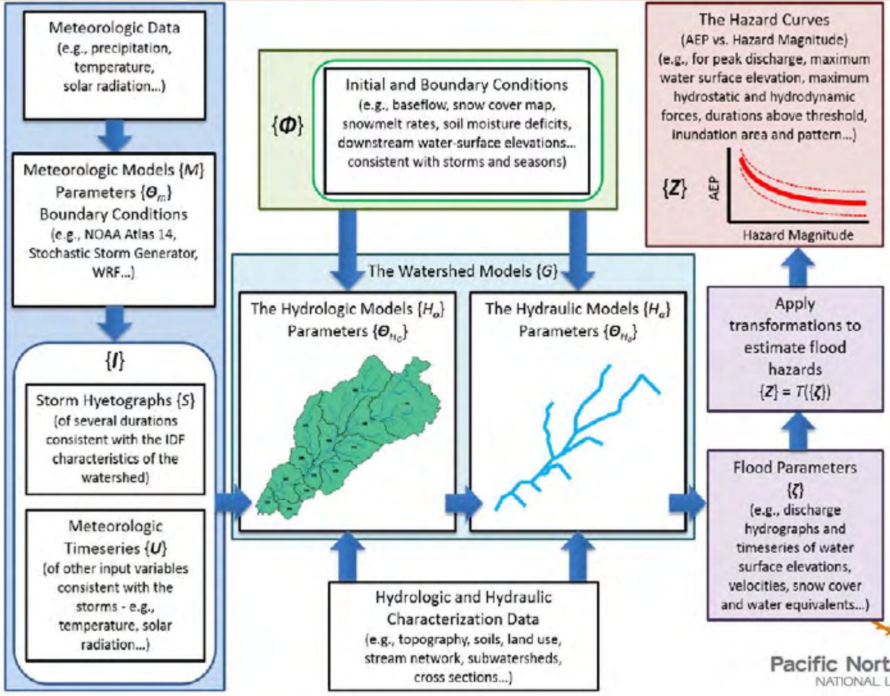
PFHA Framework: Model-based



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Parameters $\{\Theta_{H_c}\}$

The Hydraulic Models $\{H_a\}$
Parameters $\{\Theta_{H_a}\}$

Hydrologic and Hydraulic Characterization Data
(e.g., topography, soils, land use, stream network, subwatersheds, cross sections...)

The Hazard Curves
(AEP vs. Hazard Magnitude)
(e.g., for peak discharge, maximum water surface elevation, maximum hydrostatic and hydrodynamic forces, durations above threshold, inundation area and pattern...)

Apply transformations to estimate flood hazards
$\{Z\} = T(\{\zeta\})$

Flood Parameters
$\{\zeta\}$
(e.g., discharge hydrographs and timeseries of water surface elevations, velocities, snow cover and water equivalents...)

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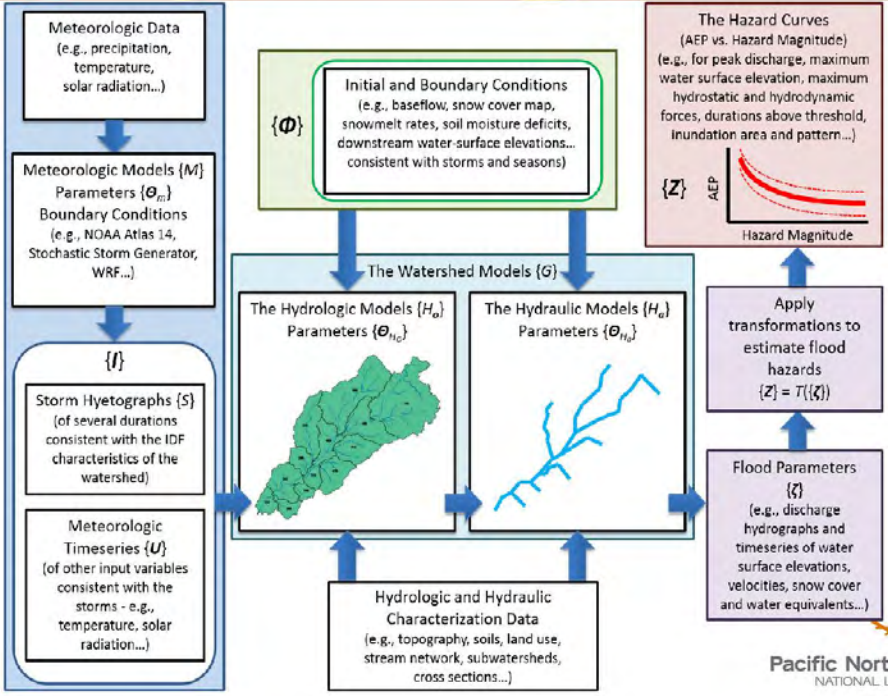
Evaluation of Variability and Uncertainty

◆ Epistemic Uncertainty

- Represents our lack of knowledge about a system; may be reducible with collection of additional data
- For PFHA, the primary epistemic uncertainties are in:
  - modeling the precipitation-runoff processes
  - characterizing the watershed
  - determining appropriate parameter values for the models.
  - May be represented as parameter probability distributions, alternative process representations, and alternative model structures (a discrete set of choices), all collected in the model parameters, $\boldsymbol{\Theta}$
- Epistemic uncertainties contribute to the uncertainty in the quantiles of the hazard distribution (e.g., the uncertainty in the exceedance probability of a given flood hazard value)

PFHA Framework: Model-based



Meteorologic Data
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Parameters $\{\Theta_m\}$
Boundary Conditions
(e.g., NOAA Atlas 14, Stochastic Storm Generator, WRF...)

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(e.g., baseflow, snow cover map, snowmelt rates, soil moisture deficits, downstream water-surface elevations... consistent with storms and seasons)

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Parameters $\{\Theta_{H_o}\}$

The Hydraulic Models $\{H_a\}$
Parameters $\{\Theta_{H_a}\}$

Hydrologic and Hydraulic Characterization Data
(e.g., topography, soils, land use, stream network, subwatersheds, cross sections...)

The Hazard Curves
(AEP vs. Hazard Magnitude)
(e.g., for peak discharge, maximum water surface elevation, maximum hydrostatic and hydrodynamic forces, durations above threshold, inundation area and pattern...)

Apply transformations to estimate flood hazards
$\{Z\} = T(\{\zeta\})$

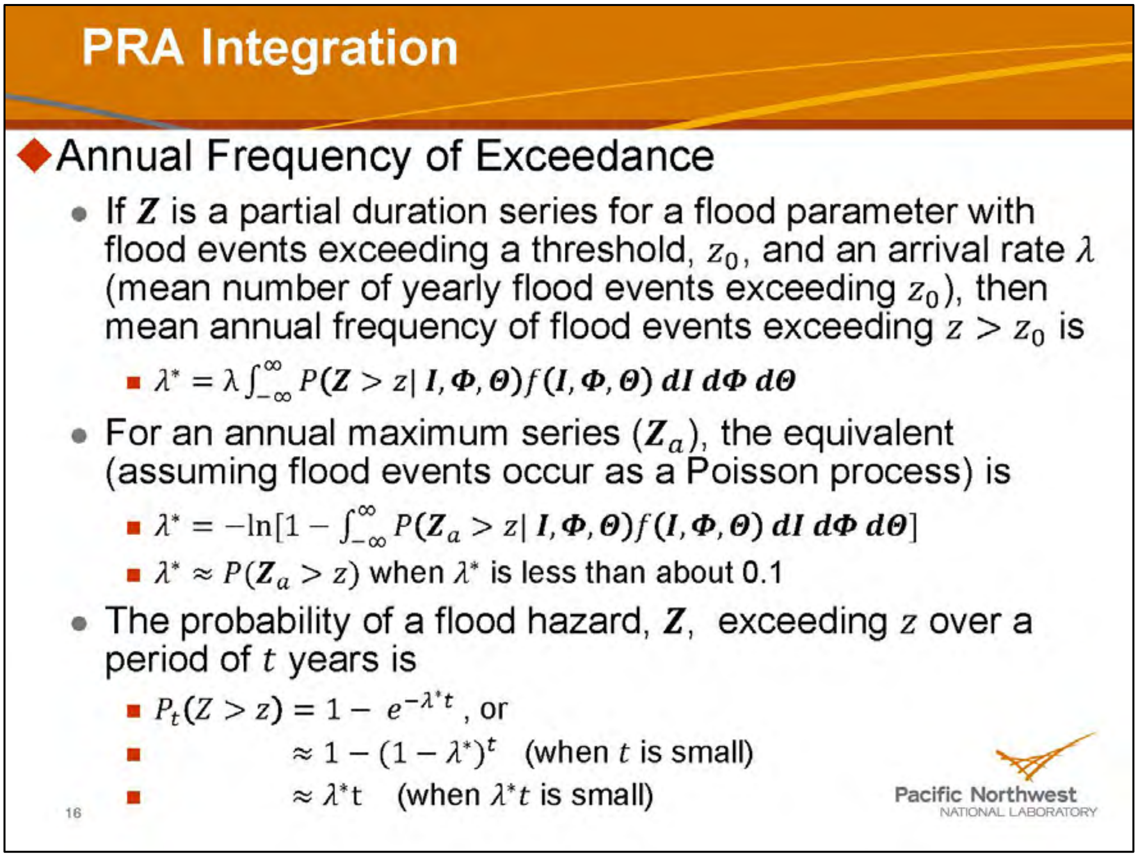
Flood Parameters
$\{\zeta\}$
(e.g., discharge hydrographs and timeseries of water surface elevations, velocities, snow cover and water equivalents...)

Quantifying the Hazard

- Consistent with the model-based PFHA framework, for a flood hazard $\boldsymbol{Z}$
  - $\boldsymbol{Z} = T[G(\boldsymbol{I}, \boldsymbol{\Phi}, \boldsymbol{\Theta}\ )]$
    - where
      - $\boldsymbol{Z}$ = the flood hazard
      - G = the watershed model
      - $\boldsymbol{I}$ = the hydrometeorologic input variables
      - $\boldsymbol{\Phi}$ = the initial and boundary conditions in the watershed
      - $\boldsymbol{\Theta} = \{\boldsymbol{\Theta}_{H_o}, \boldsymbol{\Theta}_{H_a}\}$ = the model parameters
      - T = any further transformation or analysis needed to estimate the flood hazard from primary flood parameters simulated by the watershed model
  - with
    - aleatory uncertainties, $\boldsymbol{I}$ and $\boldsymbol{\Phi}$
    - epistemic uncertainties, $\boldsymbol{\Theta}$ (possibly including discrete model process/structural uncertainties)

Probabilistically-defined Hazard

- Given the joint distribution of the aleatory and epistemic uncertainties, the hazard exceedance probability is
  - $P(\boldsymbol{Z} > z) = \int_{-\infty}^{\infty} P(\boldsymbol{Z} > z |\ \boldsymbol{I}, \boldsymbol{\Phi}, \boldsymbol{\Theta}) f(\boldsymbol{I}, \boldsymbol{\Phi}, \boldsymbol{\Theta})\ d\boldsymbol{I}\ d\boldsymbol{\Phi}\ d\boldsymbol{\Theta}$
    - which would generally be solved numerically
    - e.g., estimate $P(\boldsymbol{Z} > z)$ using $\hat{P}(z) = \frac{1}{N}\sum_{i=1}^{N} H(z_i - z)$
      - where $z_i = T[G(\boldsymbol{I}_i, \boldsymbol{\Phi}_i, \boldsymbol{\Theta}_i)]$ for $i = 1 \ldots, N$ samples from $f(\boldsymbol{I}, \boldsymbol{\Phi}, \boldsymbol{\Theta})$
      - and $H(z_i - z)$ is the Heaviside function
  - Reduce computational effort by
    - efficient sampling (e.g., latin hypercube, importance sampling)
    - simplifying the form of $G(\boldsymbol{I}, \boldsymbol{\Phi}, \boldsymbol{\Theta})$ (e.g., reduce model dimensions, simplify process representation, use surrogate model)
    - adopt a conservative approach for certain aspects of the analysis



PRA Integration

◆ Annual Frequency of Exceedance

- If $\boldsymbol{Z}$ is a partial duration series for a flood parameter with flood events exceeding a threshold, z_0, and an arrival rate λ (mean number of yearly flood events exceeding z_0), then mean annual frequency of flood events exceeding $z > z_0$ is
  - $\lambda^* = \lambda \int_{-\infty}^{\infty} P(\boldsymbol{Z} > z |\, \boldsymbol{I}, \boldsymbol{\Phi}, \boldsymbol{\Theta}) f(\boldsymbol{I}, \boldsymbol{\Phi}, \boldsymbol{\Theta})\, \boldsymbol{dI}\, \boldsymbol{d\Phi}\, \boldsymbol{d\Theta}$
- For an annual maximum series ($\boldsymbol{Z}_a$), the equivalent (assuming flood events occur as a Poisson process) is
  - $\lambda^* = -\ln[1 - \int_{-\infty}^{\infty} P(\boldsymbol{Z}_a > z |\, \boldsymbol{I}, \boldsymbol{\Phi}, \boldsymbol{\Theta}) f(\boldsymbol{I}, \boldsymbol{\Phi}, \boldsymbol{\Theta})\, \boldsymbol{dI}\, \boldsymbol{d\Phi}\, \boldsymbol{d\Theta}]$
  - $\lambda^* \approx P(\boldsymbol{Z}_a > z)$ when λ^* is less than about 0.1
- The probability of a flood hazard, $\boldsymbol{Z}$, exceeding z over a period of t years is
  - $P_t(Z > z) = 1 - e^{-\lambda^* t}$, or
  - $\approx 1 - (1 - \lambda^*)^t$ (when t is small)
  - $\approx \lambda^*$t (when $\lambda^* t$ is small)

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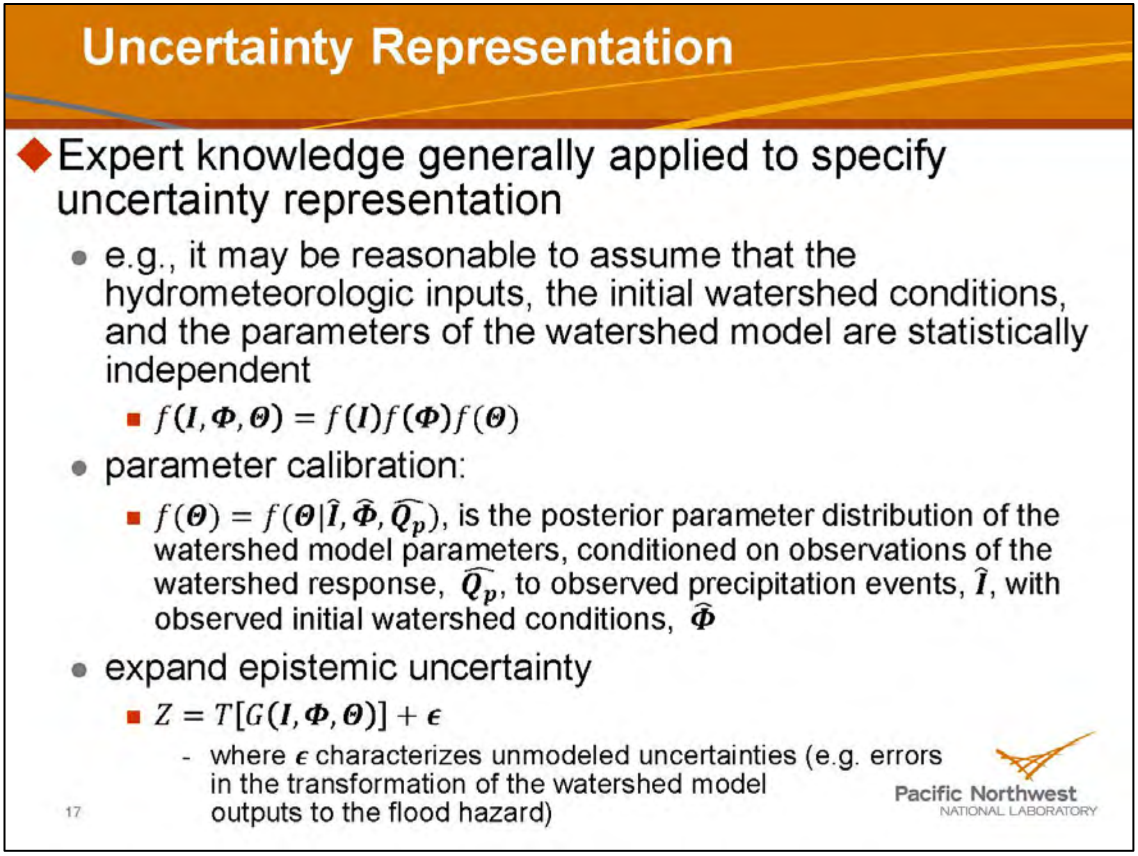

Uncertainty Representation

◆ Expert knowledge generally applied to specify uncertainty representation

- e.g., it may be reasonable to assume that the hydrometeorologic inputs, the initial watershed conditions, and the parameters of the watershed model are statistically independent
  - $f(\boldsymbol{I}, \boldsymbol{\Phi}, \boldsymbol{\Theta}) = f(\boldsymbol{I}) f(\boldsymbol{\Phi}) f(\boldsymbol{\Theta})$
- parameter calibration:
  - $f(\boldsymbol{\Theta}) = f(\boldsymbol{\Theta} | \hat{\boldsymbol{I}}, \hat{\boldsymbol{\Phi}}, \widehat{\boldsymbol{Q}_p})$, is the posterior parameter distribution of the watershed model parameters, conditioned on observations of the watershed response, $\widehat{\boldsymbol{Q}_p}$, to observed precipitation events, $\hat{\boldsymbol{I}}$, with observed initial watershed conditions, $\hat{\boldsymbol{\Phi}}$
- expand epistemic uncertainty
  - $Z = T[G(\boldsymbol{I}, \boldsymbol{\Phi}, \boldsymbol{\Theta})] + \epsilon$
    - where ϵ characterizes unmodeled uncertainties (e.g. errors in the transformation of the watershed model outputs to the flood hazard)

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Evaluation of Hazard Curve Uncertainty

◆ A single hazard curve representing the aleatory uncertainties would arise from the solution of

- $P(Z > z|\, \boldsymbol{\Theta}, \boldsymbol{\epsilon}) = \int_{(I,\Phi)} P(Z > z|\, \boldsymbol{I}, \boldsymbol{\Phi}, \boldsymbol{\Theta}, \boldsymbol{\epsilon}) f(\boldsymbol{I}, \boldsymbol{\Phi}|\boldsymbol{\Theta}, \boldsymbol{\epsilon})\, \boldsymbol{dI}\, \boldsymbol{d\Phi}$

◆ A family of hazard curves representing the epistemic uncertainties would be calculated by sampling repeatedly from the distribution of the epistemic uncertainties, $f(\boldsymbol{\Theta}, \boldsymbol{\epsilon})$, and solving the above expression

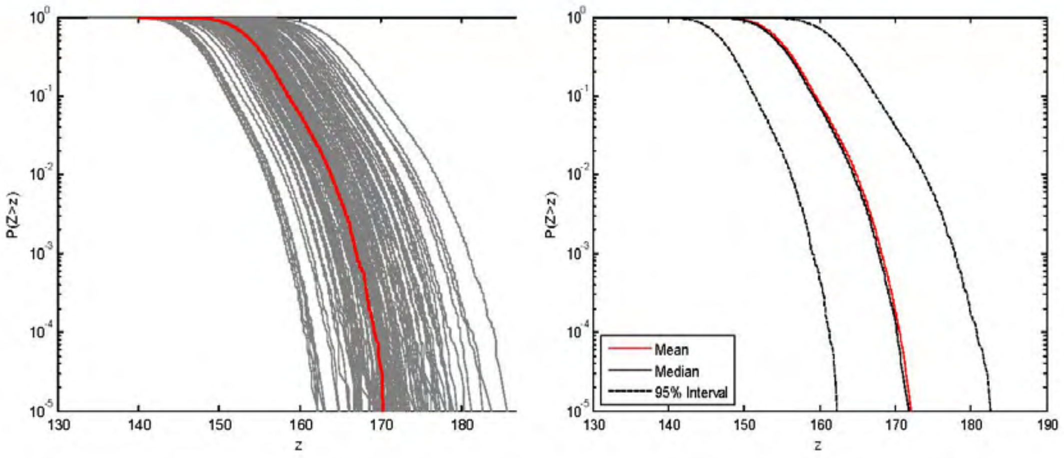
---

Evaluation of Hazard Curve Uncertainty

◆ Small hypothetical watershed example

- Aleatory uncertainties
  - $f(\boldsymbol{I})$, GEV distribution for the 1-hr annual maximum rainfall depth based on NOAA Atlas 14 results
  - $f(\boldsymbol{\Phi}|\boldsymbol{I})$, watershed initial condition, dependent on the rainfall depth
- Epistemic uncertainties
  - $f(\boldsymbol{\Theta})$, independent watershed model parameters
  - $f(\boldsymbol{\epsilon}|\boldsymbol{I}, \boldsymbol{\Phi}, \boldsymbol{\Theta})$, additional uncertainty dependent on the output of the watershed model
- Aleatory hazard curve (in red on following figure) from constant $\boldsymbol{\Theta}$ at mean values and $\boldsymbol{\epsilon} = 0$
- Gray curves sampled from epistemic uncertainty, $f(\boldsymbol{\Theta}, \boldsymbol{\epsilon}|\boldsymbol{I}, \boldsymbol{\Phi}) = f(\boldsymbol{\epsilon}|\boldsymbol{I}, \boldsymbol{\Phi}, \boldsymbol{\Theta}) f(\boldsymbol{\Theta})$

Evaluation of Hazard Curve Uncertainty



- Aleatory hazard curve (in red) from constant $\boldsymbol{\Theta}$ at mean values and $\epsilon = 0$
- Gray curves sampled from epistemic uncertainty,

$$f(\boldsymbol{\Theta}, \epsilon | \boldsymbol{I}, \boldsymbol{\Phi}) = f(\epsilon | \boldsymbol{I}, \boldsymbol{\Phi}, \boldsymbol{\Theta}) f(\boldsymbol{\Theta})$$

- Statistics (on right) computed from epistemic results

PFHA Framework – Next Steps

- Uncertainty representation
  - Valid generalizations
  - Valid simplifications
  - Integration of multiple sources of data/information
  - Treatment of nonstationarities
- Computational tools
  - Integration of applicable tools
  - Selective development
- Application/demonstration

Questions?

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2.3.9.1.3 Questions and Answers

Comment:

TVA recently finished a framework very similar to that described here. With regard to uncertainty, we recently decided that we are really mostly interested in the extremely rare end of the spectrum. At that end of the spectrum, for a 15-inch rainfall, a watershed model will probably give a result of 12 inches plus-or-minus a half an inch or similar. On the more frequent side of that band, 4 inches of rainfall might give a half an inch of runoff, or it might give 3.8 inches of runoff. The way we run our reservoirs on a given day (the normal operating day), we could make almost any decision on the river, so the uncertainty is huge. However, at the really rare end of the spectrum, we would spill 100 percent. The structure of your uncertainty very much changes depending on what part of the probability spectrum you are looking at. We felt confident with that approach: looking primarily at the uncertainty in the rainfall and, at least for now, glossing over some of the rainfall runoff model uncertainty and routing uncertainty, because at the extreme end they are comparatively small, while the rainfall uncertainty is extremely large at the rare end.

Response:

Those traits argue the site-specific nature of this analysis with regard to developing generalizations. Some of those concepts you expressed may or may not be generalized for the kind of reservoir TVA has. The type of evaluation you performed is what I meant when I talked earlier about applying expert judgment to simplify the problem and trying to establish generalizations.

Question:

This is a very impressive watershed modeling, including uncertainty analysis. How do you specify the initial and boundary conditions of the watershed?

Response:

In determining the initial and boundary conditions, we considered what data might be available and, because that may be model specific, what model will be used and what output is desired. In general, watershed modeling involves conditions such as soil moisture, initial streamflow, and baseflow; the conditions in a winter or springtime situation; and the amount of the snow on the ground. Datasets are available for different places in the country that could supply that information to the model, taking uncertainties into account. For example, these data might be measured infrequently or only available in certain locations and require you to extrapolate. This returns to the same issue of what data you have and how much characterization do they afford you in terms of that particular model. This project used spatially distributed datasets that have been maintained and that could be used at least initially to look at those conditions.

Question:

Listening to the descriptions of all these studies, it is clear that inferences are being made. Do today’s statistical methods have credibility for statistical inference? This whole process of very challenging inferences really needs to have statistical validation because it involves many assumptions concerning many different aspects of the uncertainty analysis, not only in the models, but also in the way in that uncertainty is defined. How are those models and uncertainties validated? Many different models are available. My own experience with many years of modeling is that you can fit just about anything to anything. You do not need to have very detailed models. You can take any polynomial with enough degrees of freedom and you can get a perfect fit. The issue really is how can you actually validate, with completely independent data, the particular model that you are using or the particular structure you are assuming for quantifying your uncertainties?

Response

Uncertainty is a big issue for us. We acknowledge that there are two parts to it. One could come from variabilities: things could be measured with certain degrees of uncertainty. The second relates to these model structures. We treat the model structures as the epistemic part of the analysis, which leads to model validation and to how much weight should be given to a model or to a parameter structure that leads to a different conceptual model that is faithful to what you have observed. It goes back to the quality of your conditioning based on observed data, which is all we have. Based on the observed data, how can you condition the model parameter set as well as these models? We are trying to put this whole framework into a Bayesian model, where the parameter estimation is constrained by all the observations that we can find for that particular analysis. That would allow us to build a posterior distribution that can have not only model parameters but also weighting for different model structures. As more and more data become available, the Bayesian framework allows you to include that dataset and try to update the model structure. We do not yet know how much difference it would make. However, we need to do some computations with this framework to determine whether we can actually reach a practical solution where we can address some of these issues.

Response

Validation is always a difficult topic. In any case, this issue will involve extrapolation because we are moving beyond the data to exceedance probabilities that are extreme. In terms of extrapolation, in order to validate your inferences, you are at the extreme end and you get data that are mostly less extreme. Therefore, you rely on expert knowledge and a physically based process that relies on the less extreme more than the more extreme parts of the process. You use what you have, and the more information, the better the approximation. We are relying on the knowledge of the process.

2.3.10 Day 3: Session 3C - Frameworks II

This session considers the development and demonstration of a PFHA framework for flood hazard curve estimation.

2.3.10.1 Evaluation of Deterministic Approaches to Characterizing Flood Hazards, John Weglian, EPRI (Session 3C-1; ADAMS Accession No. ML17054C483)

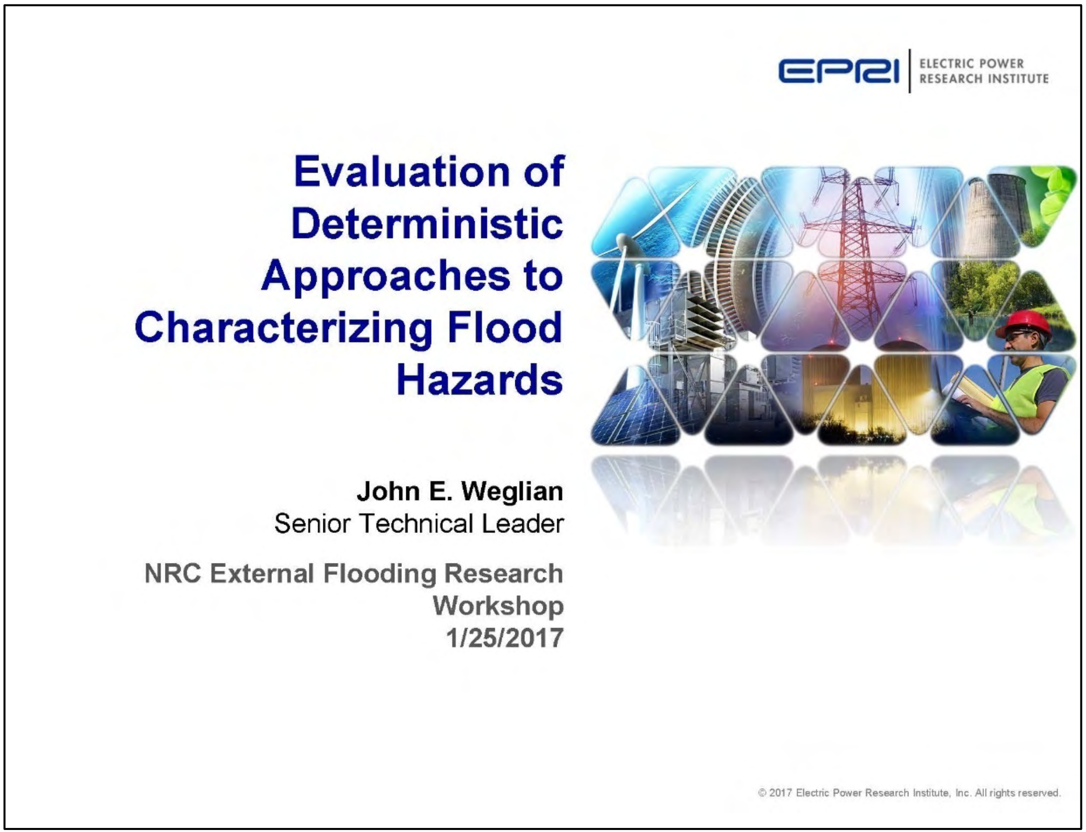
2.3.10.1.1 Abstract

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

Deterministic, bounding analyses are used to ensure that NPPs are protected from what is expected to be the worst-case flooding events that could impact a site. Utilities will typically use the most conservative and bounding assumptions when initially assessing the flood hazard to a site. If the site is not able to withstand the flood using those bounding assumptions, the analysis is refined using more realistic, but still bounding, assumptions. This process is known as the hierarchical hazard assessment. EPRI published the technical report, "Evaluation of Deterministic Approaches to Characterizing Flood Hazards," EPRI ID 3002008113, dated November 29, 2016 (http://www.epri.com/abstracts/Pages/ProductAbstract.aspx?ProductId=000000003002008113).

The report examines the assumptions, inputs, and methods used for assessing the external flooding hazards for the following flooding mechanisms: local intense precipitation, flooding of streams and rivers, dam breaches and failures, storm surge, wind-generated wave and runup, and hydrodynamic and debris loads. For each of these flood mechanisms, the report provides several areas where the analysis can be improved to provide a more realistic characterization of the flood hazard. Some examples are provided to describe some of these improvement opportunities. Utilities can use the report to identify opportunities to improve their bounding flood hazard analyses for existing or new plants.

2.3.10.1.2 Presentation



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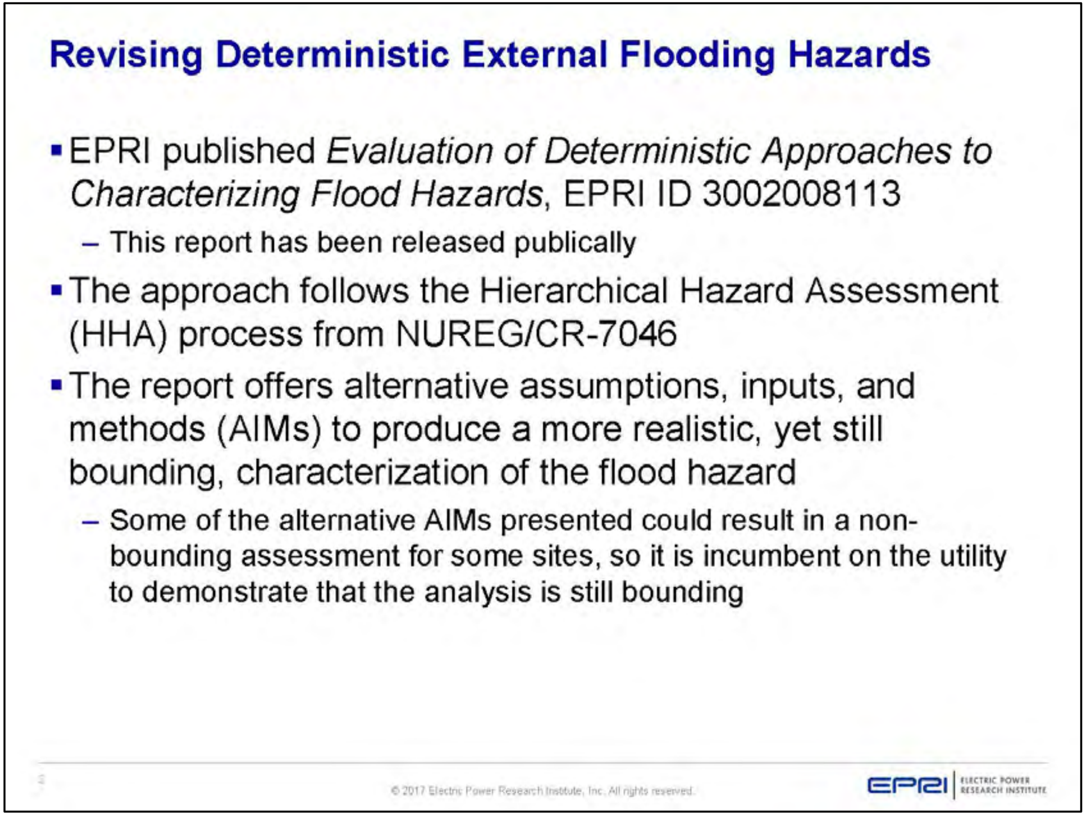
Evaluation of Deterministic Approaches to Characterizing Flood Hazards

John E. Weglian
Senior Technical Leader

NRC External Flooding Research Workshop
1/25/2017



Revising Deterministic External Flooding Hazards

- EPRI published *Evaluation of Deterministic Approaches to Characterizing Flood Hazards*, EPRI ID 3002008113
  - This report has been released publically
- The approach follows the Hierarchical Hazard Assessment (HHA) process from NUREG/CR-7046
- The report offers alternative assumptions, inputs, and methods (AIMs) to produce a more realistic, yet still bounding, characterization of the flood hazard
  - Some of the alternative AIMs presented could result in a non-bounding assessment for some sites, so it is incumbent on the utility to demonstrate that the analysis is still bounding

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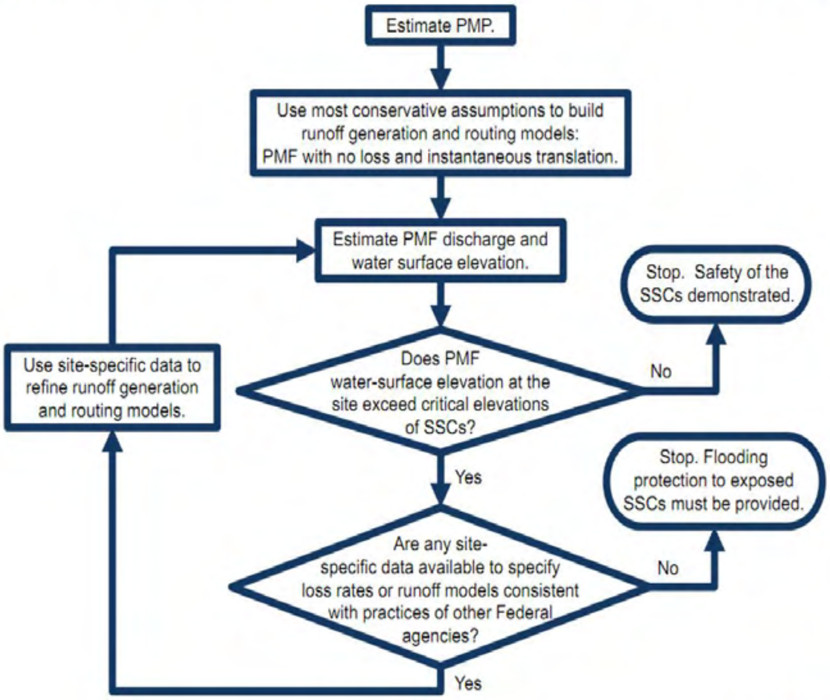
Example HHA Process from NUREG/CR-7046



Estimate PMP.

Use most conservative assumptions to build runoff generation and routing models: PMF with no loss and instantaneous translation.

Estimate PMF discharge and water surface elevation.

Does PMF water-surface elevation at the site exceed critical elevations of SSCs?

No

Stop. Safety of the SSCs demonstrated.

Yes

Are any site-specific data available to specify loss rates or runoff models consistent with practices of other Federal agencies?

No

Stop. Flooding protection to exposed SSCs must be provided.

Yes

Use site-specific data to refine runoff generation and routing models.

Flooding Mechanisms Covered in the Report

- Local Intense Precipitation
- Flooding in Rivers and Streams
- Dam Breaches and Failure
- Storm Surge
- Wind-Generated Waves and Runup
- Hydrodynamic and Debris Loads

Presentation Details

- The report gives alternative AIMs for each flood hazard that could be applied to improve the realism in the analysis
- For some of these alternatives, the report provides an example of how it might be used
- This presentation will list all of the alternatives in the report, but it will only cover one or two items from each flooding mechanism

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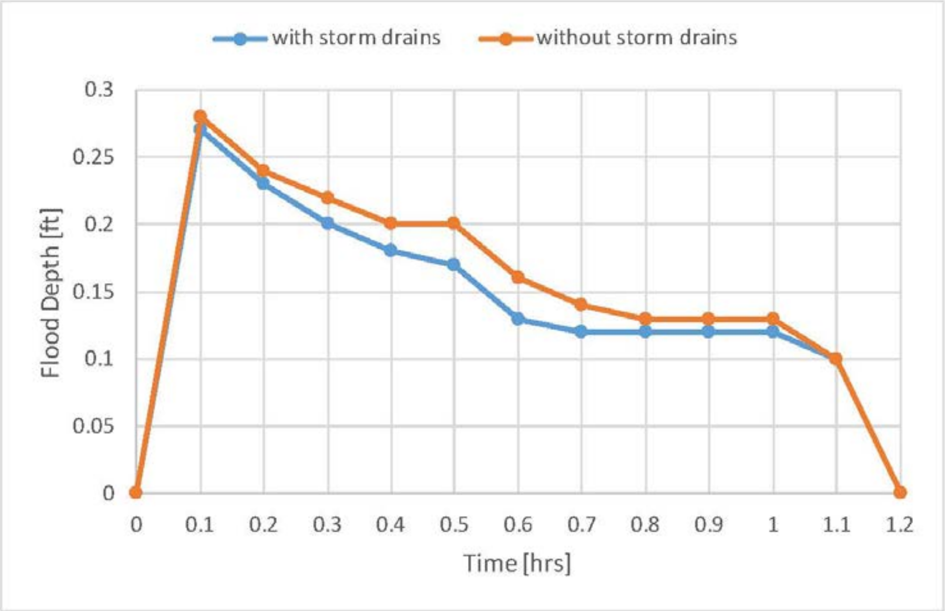
Local Intense Precipitation (LIP)

LIP Alternative AIMs

- Characterization of rainfall depth-area-duration
- Local intense precipitation event duration
- Boundary conditions
- One-dimensional vs. two-dimensional modeling
- Crediting drainage system conveyance
- Modeling effects of vehicle or security barriers
- Storage and attenuation on roofs

LIP - Crediting Drainage System

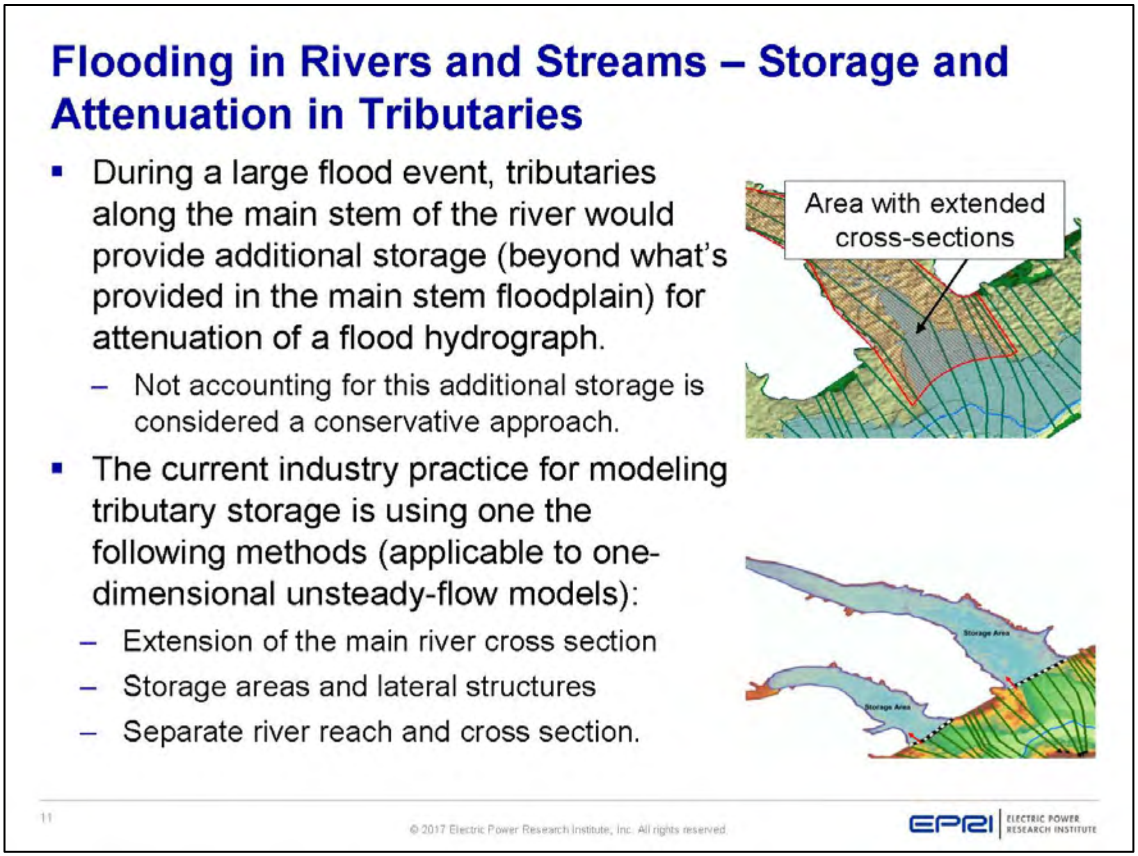


Flood Depth vs. Time Graph

Flooding in Rivers and Streams

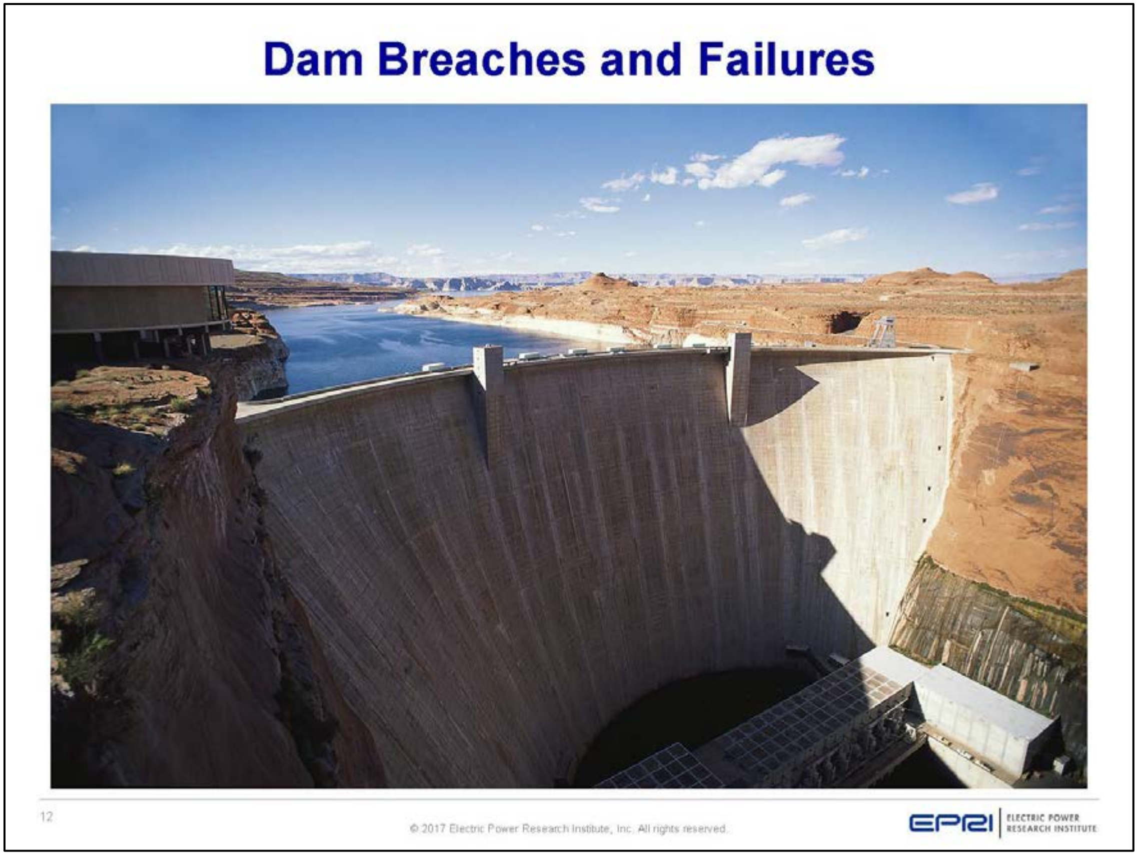
Riverine Flooding Alternative AIMs

- Characterization of rainfall depth-area-duration
- Use of SCS curve number method for long-duration and/or sequential storms
- Estimating constant losses
- Nonlinearity adjustments to the unit hydrograph
- Tributary storage in river reach routing
- Selection of Manning roughness coefficients
- Selection of modeling technique for complex hydraulics
- Treatment of ineffective flow areas
- Selection of expansion and contraction loss coefficients
- Dry period between sequential storms



Flooding in Rivers and Streams – Storage and Attenuation in Tributaries

- During a large flood event, tributaries along the main stem of the river would provide additional storage (beyond what's provided in the main stem floodplain) for attenuation of a flood hydrograph.
  - Not accounting for this additional storage is considered a conservative approach.
- The current industry practice for modeling tributary storage is using one the following methods (applicable to one-dimensional unsteady-flow models):
  - Extension of the main river cross section
  - Storage areas and lateral structures
  - Separate river reach and cross section.



Dam Breaches and Failures

Dam Failure Alternative AIMs

- Dam breach assumptions during probable maximum flood
- Failure of critical dams
- River reach routing for dam breach flood waves
- Selection of breach parameters
- Inconsequential dams
- Hypothetical dams
- Initial dam water surface elevation
- Gate operations
- Timing of peak outflow from multiple dam failures
- Cascading dam failures

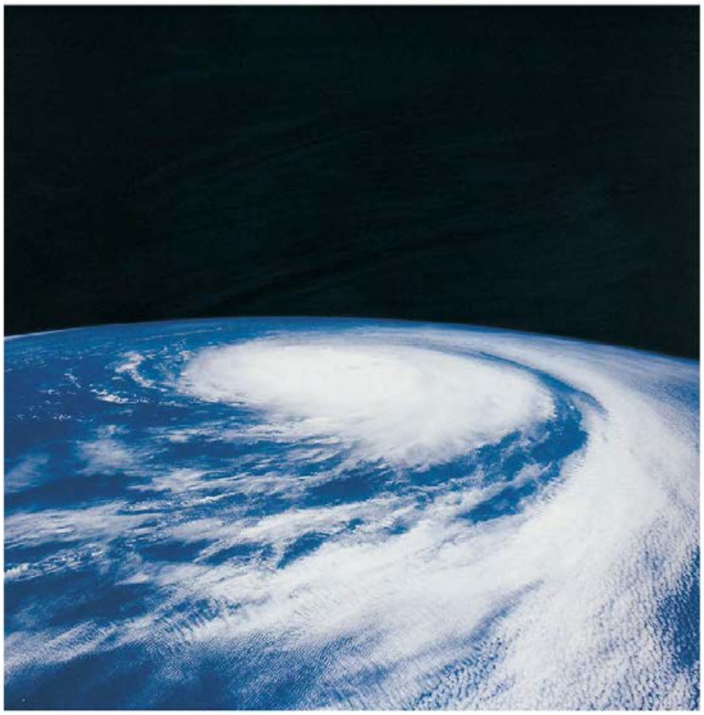
Dam Breaches and Failures – Dam Breach Assumptions during Probable Maximum Flood

- Main causes of hydrologic dam failure include overtopping, structural overstressing, and surface erosion due to high velocity flow and wave action.
- Unless a dam can withstand its basin-specific PMF, it should be failed (JLD-ISG-2013-01).
- During a watershed-wide PMF-type flood, most dams do not experience a flood that approaches the design flood.
- Variance from JLD-ISG-2013-01 could be considered and non-failure of these assumed by providing justification in the form of H&H modeling results showing significant margin, inspection records, and geotechnical analyses.

Dam Breaches and Failures – Failure of Critical Dams

- Screening process in JLD-ISG-2013-01 groups dams into three categories: inconsequential, non-critical, and critical.
- All critical dams are subject to further evaluation and can be assumed to not fail with proper justification.
- Some utilities may have failed all critical dams to reduce effort.
- Licensees could utilize studies performed by Federal or State agencies to provide justification for non-failure.

Storm Surge



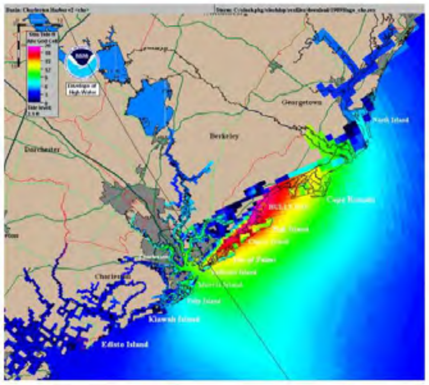
Storm Surge Alternative AIMs

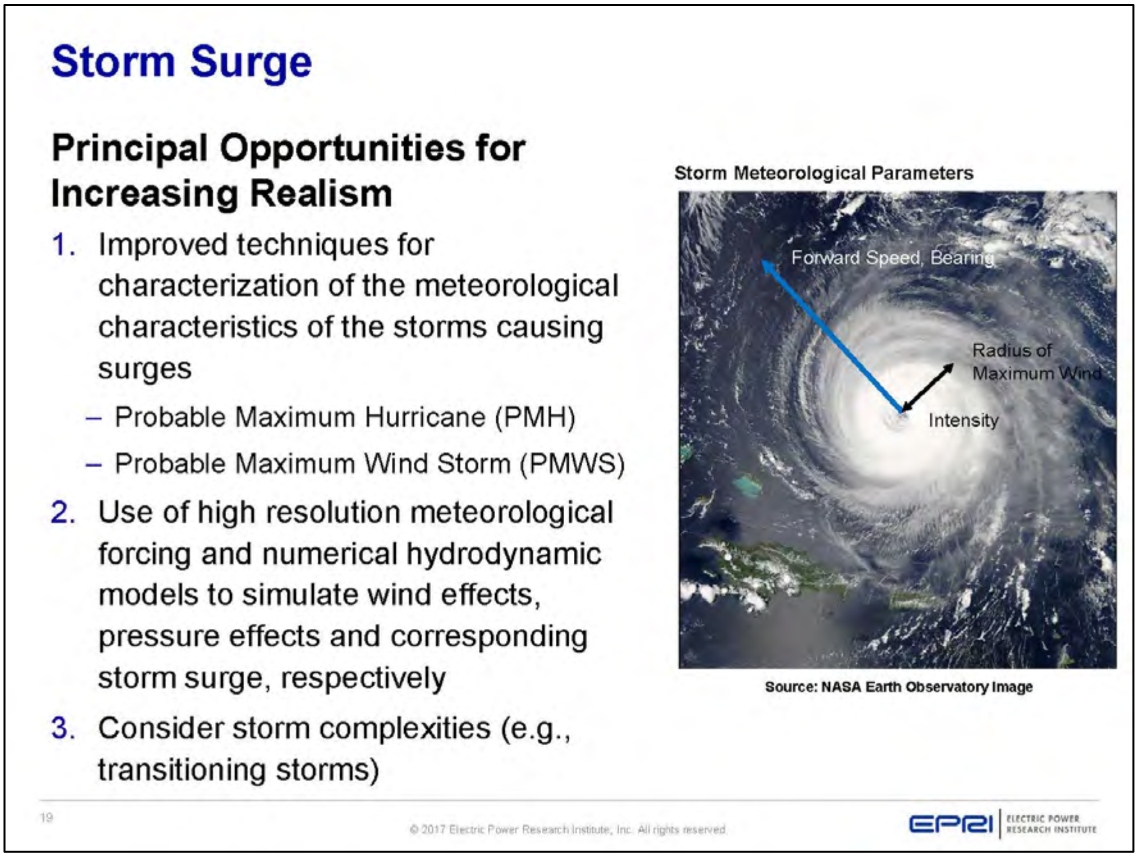
- Characterization of meteorological storm parameters
  - Probable maximum hurricane
  - Probable maximum wind storm
  - Moving squall lines
  - Numerical hydrodynamic models

Storm Surge

Factors Affecting Storm Surge:

- Intensity, size and speed of storm
- Characteristics and shape of shoreline (affects height of surge)
- Width and slope of ocean bottom (gradual sloping ocean bottoms creates larger surges)
- Angle of storm approach and relative position from storm track to site location:
- Combination of storm surge and coincident tides, waves and freshwater input (near deltas and bays)





Storm Surge

Principal Opportunities for Increasing Realism

1. Improved techniques for characterization of the meteorological characteristics of the storms causing surges
   - Probable Maximum Hurricane (PMH)
   - Probable Maximum Wind Storm (PMWS)
2. Use of high resolution meteorological forcing and numerical hydrodynamic models to simulate wind effects, pressure effects and corresponding storm surge, respectively
3. Consider storm complexities (e.g., transitioning storms)

Storm Meteorological Parameters

Source: NASA Earth Observatory Image

Wind-Generated Wave and Runup

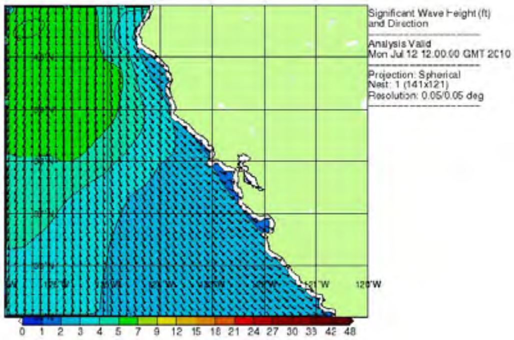
Wind-Generated Waves and Runup Alternative AIMs

- Wind-generated wave characteristics
    - Numerical wave models
    - Modeling transient conditions
    - Wave transformation
    - Wave spectra
    - Wave breaking characteristics
- Wave setup
- Wave runup and overtopping

Wind-Generated Waves and Runup

Increasing Realism in Wind-Generated Wave Characteristics

- Simplified analytical and/or inapplicable empirical methods introduce unnecessary conservatism
- Numerical wave models (i.e., STWAVE (STeady state spectral WAVE) and SWAN (Simulating Waves Nearshore)
    - Can be used independently or coupled with storm surge models (i.e., ADCIRC) to increase realism and accurately reflect transient time series effects
    - Account for complex bathymetry and shoreline features to capture wave transformations
- Wave spectra and wave breaking characteristics should be incorporated to provide more realistic representation of wave effects



Source:
http://cordc.ucsd.edu/projects/hires/ - SWAN model output provided by John Cook <cook@hrts.nrl.navy.mil> at NRL

Hydrodynamic and Debris Loads

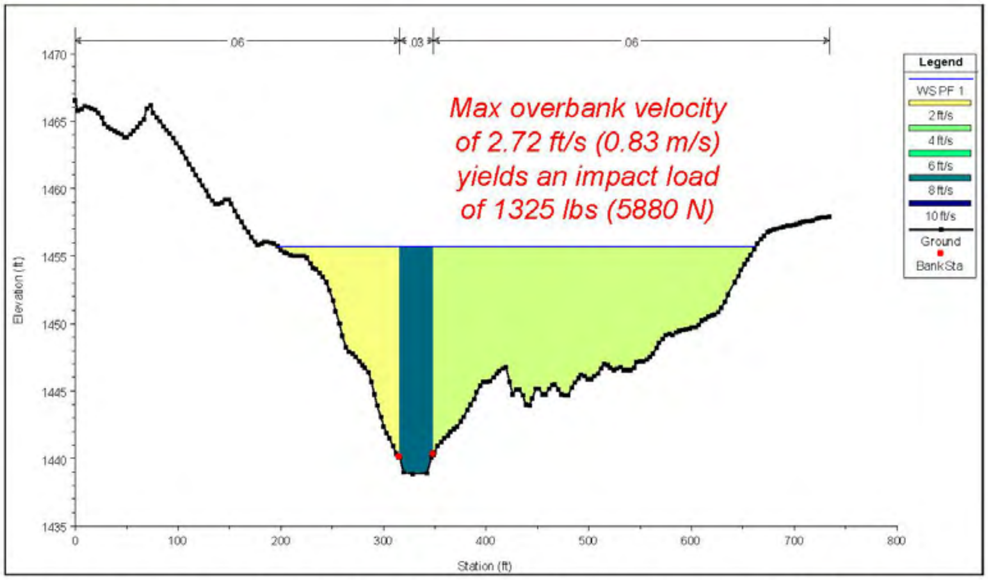
Hydrodynamic and Debris Load Alternative AIMs

- Debris weights and types
- Debris velocities
- Inertia
- Shielding effects of structures

Hydrodynamic and Debris Loads – Debris Velocities

- Unrealistic debris velocities that do not correspond to the velocities that are expected in the overbank areas during the PMF can significantly overestimate (and also underestimate) debris impacts on critical structures.
- Even 1-D models have the ability to provide a more refined velocity distribution in the floodplain.

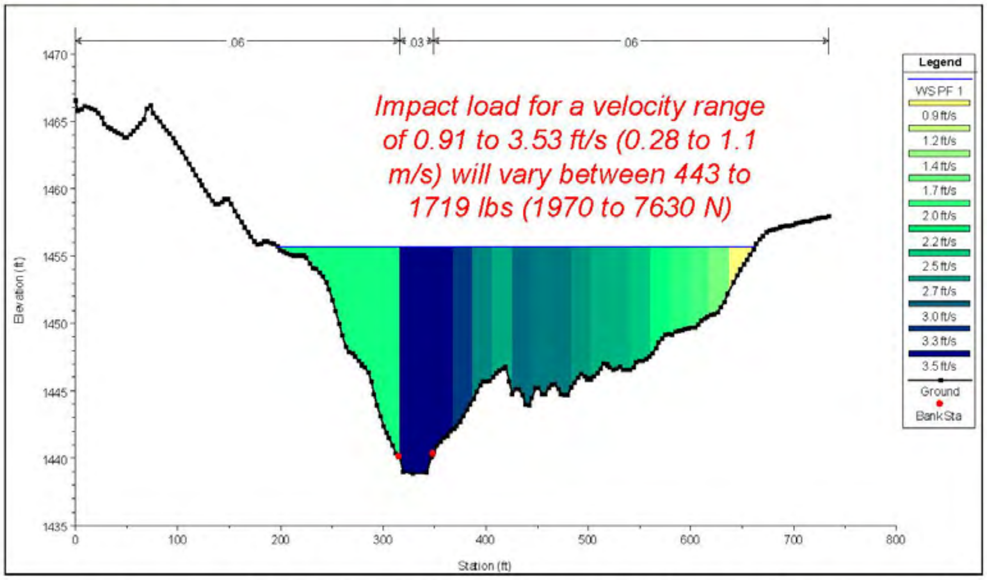
Hydrodynamic and Debris Loads – Debris Velocities



Max overbank velocity of 2.72 ft/s (0.83 m/s) yields an impact load of 1325 lbs (5880 N)

Output from a HEC-RAS Model (no velocity distribution)

Hydrodynamic and Debris Loads – Debris Velocities



Impact load for a velocity range of 0.91 to 3.53 ft/s (0.28 to 1.1 m/s) will vary between 443 to 1719 lbs (1970 to 7630 N)

Output from a HEC-RAS Model (with velocity distribution)

Together…Shaping the Future of Electricity

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2.3.10.1.3 Questions and Answers

Question:

Is this approach really deterministic in the sense that many of the models that are deployed in this application setting are calibrated?

Response:

This is not a probabilistic approach, with the exception of storm surge, which most likely will have some probabilistic aspects. It would still be considered a deterministic analysis. In terms of the Manning roughness coefficient, it is not sufficient to look in a book and decide that while I am in this kind of area, this is what I am going to use. You have to look at the area upstream of your particular plant and identify the kinds of flow restrictions that are there. It is still a deterministic type of approach because you have to make sure that you are being bounding. Some of this could be accomplished with sensitivity studies. You would identify a site-specific refinement and run the model again with that piece a little higher or lower and see if it changes your results.

Question:

In terms of project scope, are you looking at some of these conservatisms and analyzing what value they add, because introducing more realism can also increase the extent of cost-benefit thinking on what to target. We acknowledge that every site is different, and hazards are different. Second question, the PRA models related to National Fire Protection Association Standard 805, "Performance-Based Standard for Fire Protection for Light Water Reactor Electric Generating Plants," have brought debate on conservatisms. Sometimes a deterministic aspect being debated is what is ultimately influencing, or even distorting, the realism in the PRA. This work, even though you are calling it deterministic, could ultimately also translate into conservatism in a more risk-informed approach.

Response:

Some of these approaches could also be used to obtain the most realistic result possible for use in the PRA model. However, that was not the intent of this approach or this paper. The genesis of this effort is responding to 10 CFR 50.54(f) letters on the flooding hazards. The Nuclear Energy Institute (NEI) is having a workshop on the approach for addressing those in NEI-16-05, "External Flooding Assessment Guidelines," Revision 1, issued June 2016. This involves the option to revise your flood hazard as your starting point. Where do you start in your analysis to show whether you are protected? Do you need to rely on your mitigating strategy? EPRI did not begin with the assumption that everything that we might do will result in a reduction in the flood hazard. Some things in the approach can be considered conservative or nonconservative. Vehicle barriers are a great example. During a local intense precipitation event, the giant cement wall put in for security purposes may hold the water in and result in higher water levels that might have otherwise occurred. The project did not begin with that assumption that we are only reducing conservatism, but instead sought to say objectively what can we do to improve the realism but still maintain it as bounding? We received great feedback from the NRC, and I made some significant adjustment to some of the wording to account for some of the concerns that the agency had on the draft version. It should now be a much better product from both the NRC and industry standpoints.

2.3.10.2 Probabilistic Flood Hazard Assessment Framework Development, Brian Skahill*, Ph.D.; U.S. Army Corps of Engineers, Engineer Research and Development Center, Coastal and Hydraulics Laboratory, Hydrologic Systems Branch, Watershed Systems Group (Session 3C-2; ADAMS Accession No. ML17054C484)

2.3.10.2.1 Abstract

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

- literature review
- warm season rainfall and local intense precipitation
- cool season rainfall, snow, and snowpack
- site-scale flooding from local intense precipitation
- riverine flooding —rainfall or rainfall and snowmelt
- riverine flooding —hydrologic dam/levee failure
- knowledge transfer

This presentation summarized features of a current draft, proposed PFHA framework for warm season rainfall, which outlines the use of a spatiotemporal Bayesian Hierarchical Model (BHM) embedded within a multimodel averaging technique to leverage the capacities of Bayesian inference while generalizing the problem of extreme rainfall model selection. The Bayesian inference methodology was selected not only because it supports a probabilistic analysis of extreme rainfall, but also because it is a flexible means by which to combine all available and relevant complementary data. These characteristics of Bayesian inference are either required or highly desirable for extreme rainfall analysis, particularly given the application focus wherein quantile estimates are necessary for low exceedance probabilities. For example, additional data that could be combined with a given station's systematic record for a local or regional analysis of extreme rainfall are data from surrounding stations, information derived from expert elicitation, or included in a nonstationary climate index. An additional attractive feature of the Bayesian inference methodology is that it supports the capacity to compute the predictive posterior distribution for a future observation. Several demonstrations of the proposed PFHA framework for warm season rainfall not only reinforced various aspects of the key framework elements, but they also underscored the flexibility of the framework to accommodate different data scenarios. The first four demonstrations in aggregate emphasized the importance of data analysis, model selection, and inference methodology for the evaluation of extreme rainfall risk at a given location. The fifth demonstration emphasized the flexibility of the Bayesian inference methodology to accommodate treatment of nonstationarity in an analysis of extreme rainfall. The sixth demonstration profiled application of a BHM for the analysis of extreme daily rainfall using annual maxima data from 68 stations located within and surrounding the 11,478-square-mile Willamette River Basin in northwestern Oregon. The final demonstration briefly profiled two multimodel averaging techniques to generalize the problem of extreme rainfall model selection. The

presentation concluded with a brief summary of ongoing framework development for the probabilistic modeling of cool season rainfall processes.

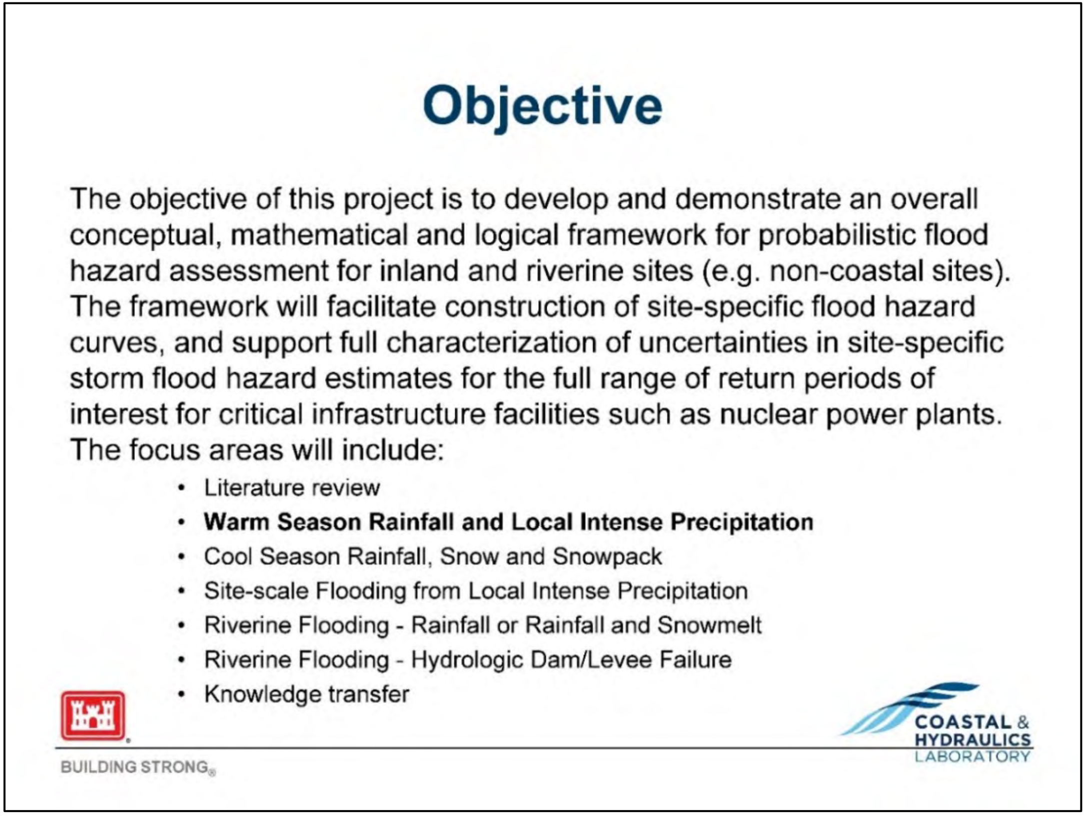
2.3.10.2.2 Presentation

Probabilistic Flood Hazard Assessment Framework Development

ERDC
Engineer Research and Development Center

Brian Skahill
US Army Corps of Engineers Engineer R&D Center
Coastal and Hydraulics Laboratory
Hydrologic Systems Branch
Watershed Systems Group

January 25, 2017



Objective

The objective of this project is to develop and demonstrate an overall conceptual, mathematical and logical framework for probabilistic flood hazard assessment for inland and riverine sites (e.g. non-coastal sites). The framework will facilitate construction of site-specific flood hazard curves, and support full characterization of uncertainties in site-specific storm flood hazard estimates for the full range of return periods of interest for critical infrastructure facilities such as nuclear power plants. The focus areas will include:

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

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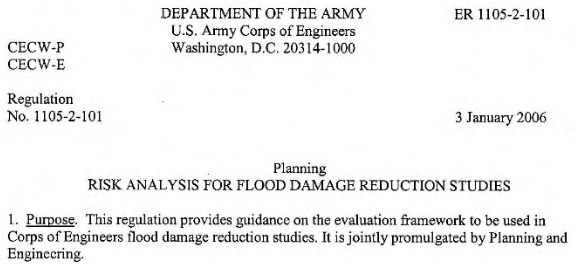
Context

General Requirement. For inland nuclear facility sites a PFHA must be able to incorporate probabilistic models for a variety of processes (e.g., precipitation, runoff, stream flow, operation of water control structures), allow for characterization and quantification of aleatory and epistemic uncertainties, facilitate propagation of uncertainties, and facilitate sensitivity analysis.



DEPARTMENT OF THE ARMY
U.S. Army Corps of Engineers
Washington, D.C. 20314-1000

ER 1105-2-101

CECW-P
CECW-E

Regulation
No. 1105-2-101

3 January 2006

Planning
RISK ANALYSIS FOR FLOOD DAMAGE REDUCTION STUDIES

1. Purpose. This regulation provides guidance on the evaluation framework to be used in Corps of Engineers flood damage reduction studies. It is jointly promulgated by Planning and Engineering.

USACE Engineering Regulation requires the performance of risk and uncertainty analyses in the process of planning, design, and operation of all civil works flood risk management projects.

The ultimate goal of the policy guidance is probabilistic analysis of “all key variables, parameters, and components of flood damage reduction studies.”

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Hydrologic Hazard Curve Definition / *Principles*

- A Hydrologic Hazard Curve is a graph of peak flow, volume (for specified duration), or reservoir elevation versus Annual Exceedance Probability (AEP) ***(< 1 in 10,000 for risk assessment)***
- AEP estimates are made for peak flows, runoff volumes and reservoir elevations
- Portray full range of values, with uncertainty, needed for risk-based dam safety decision making for a portfolio or to evaluate a specific facility
- Used to evaluate specific Potential Failure Modes (PFMs)

- *Multiple Methods*
- *Lots of Data*
- *Explicitly Quantify Uncertainty*
- *Research and Development needed-Data/Methods*

- *Temporal Information*
- *Spatial information*
- *Causal information*

- *We need to be more deliberate to include each concept, and include more information on hydrological processes and hydrological reasoning*
- *Extreme flood and storm data representative of extreme process we're trying to predict?*
- *Combine data evidence from each piece to do this*

From England, John. "Hydrologic Hazard Workshop Lecture 1.2 - Introduction". Hydrologic Hazards for Risk Assessments Training Workshop. August 31 - September 3, 2015. USACE Risk Management Center, Lakewood, CO.

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PFHA Framework Development: Extreme Rainfall Analysis

- Task requirements
  - Continuous and discrete representation of rainfall
  - Temporal and spatial dependence
  - Characterization and modeling of uncertainty
  - Build upon recent advances in modeling of extreme rainfall
  - Adapt existing tools to meet the demonstration needs
    - Project focus is not tools development

Selected Inference Methodology

While there exists many different approaches to estimate the parameters of a statistical model selected for the analysis of extreme rainfall data, the Bayesian inference methodology was selected for PFHA framework development for several reasons

- Probabilistic analysis; uncertainties are consistent with everyday interpretations
- Flexibly combines data
- Accommodates treatment of non-stationarity
- Hierarchical modeling framework can support regional extreme rainfall analysis
- Can compute the predictive posterior distribution for a future observation

The focus of the approach is to update knowledge about the unknowns, θ, on the basis of observations y, with revised knowledge expressed in the posterior density $p(\theta|y)$. The sample of observations y being analyzed provides new information about the unknowns, while the prior density $p(\theta)$ of the unknowns represents accumulated knowledge about them before observing or analyzing data

$$\underset{\substack{\uparrow \\ \text{updated} \\ \text{evidence}}}{p(\theta|y)} \propto \underset{\substack{\uparrow \\ \text{data} \\ \text{evidence}}}{p(y|\theta)}\,\underset{\substack{\uparrow \\ \text{historic} \\ \text{evidence}}}{p(\theta)}$$

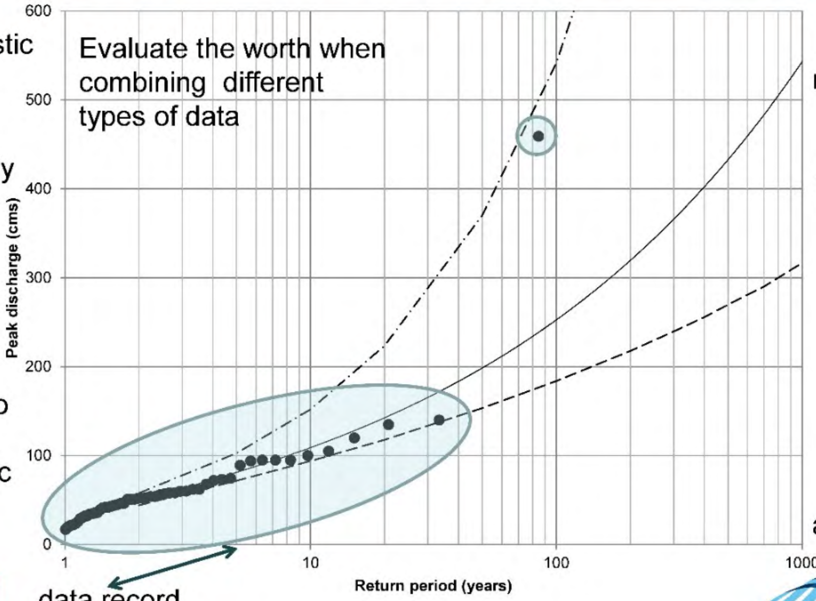
θ = extremal model parameters

y = observed extreme values

Selected Inference Methodology

Probabilistic analysis

Coherently and flexibly combine different types of data in addition to the systematic record



Evaluate the worth when combining different types of data

data record

Assumptions made explicit; analysis is repeatable and revisable

Extract the maximum amount of information from all available data

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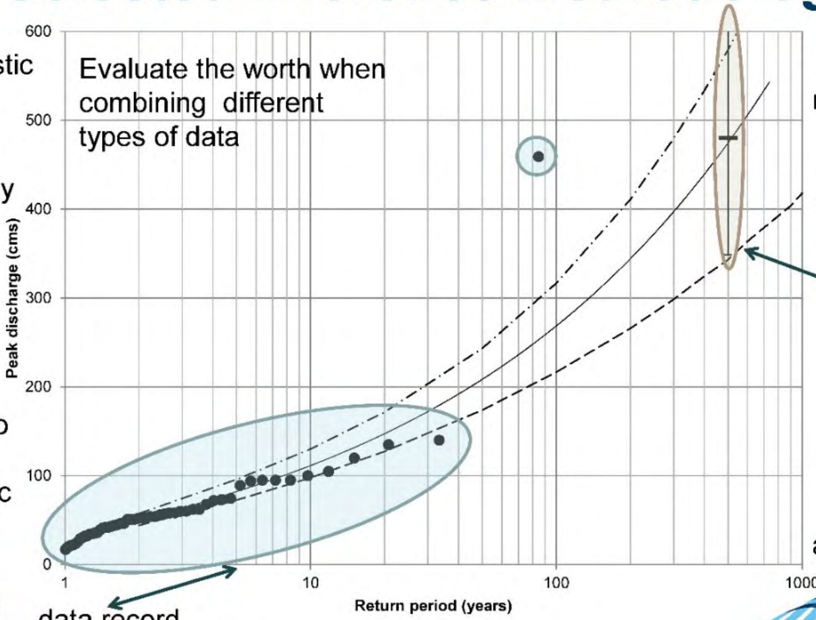
Selected Inference Methodology

Probabilistic analysis

Coherently and flexibly combine different types of data in addition to the systematic record



Evaluate the worth when combining different types of data

data record

Assumptions made explicit; analysis is repeatable and revisable

Info. derived via expert elicitation

Extract the maximum amount of information from all available data

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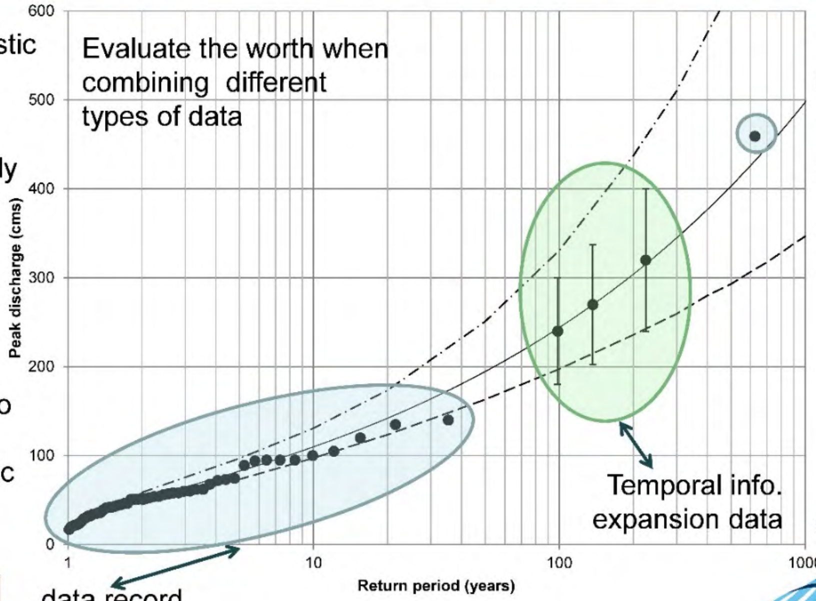
Selected Inference Methodology

Probabilistic analysis

Coherently and flexibly combine different types of data in addition to the systematic record



Evaluate the worth when combining different types of data

Temporal info. expansion data

data record

Assumptions made explicit; analysis is repeatable and revisable

Extract the maximum amount of information from all available data

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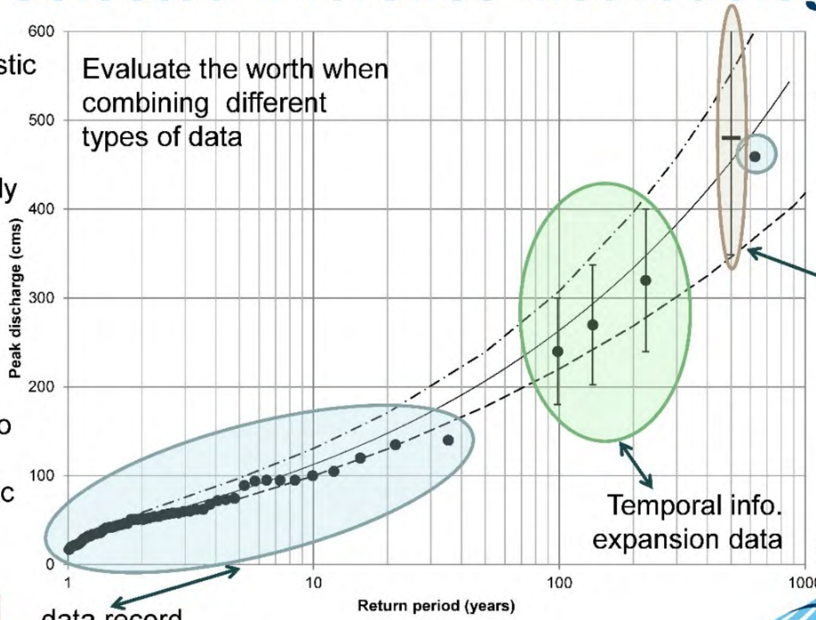
Selected Inference Methodology

Probabilistic analysis

Coherently and flexibly combine different types of data in addition to the systematic record



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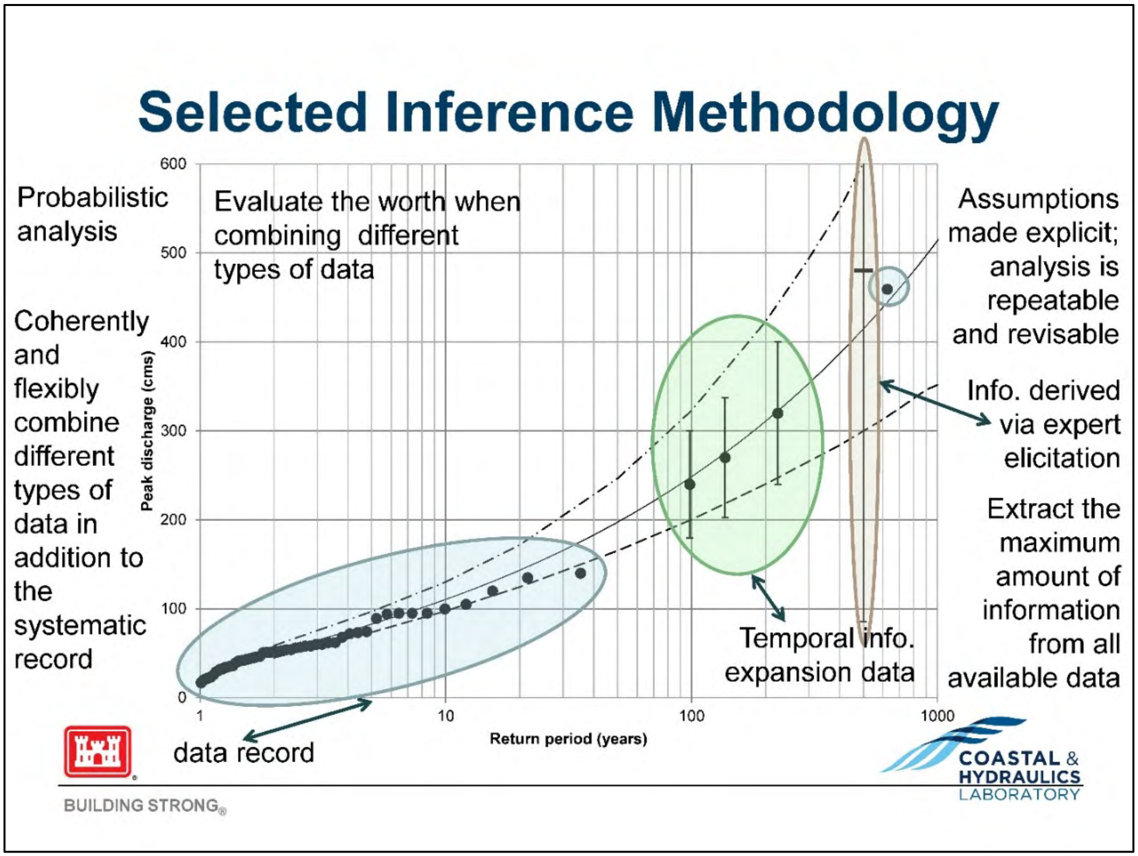

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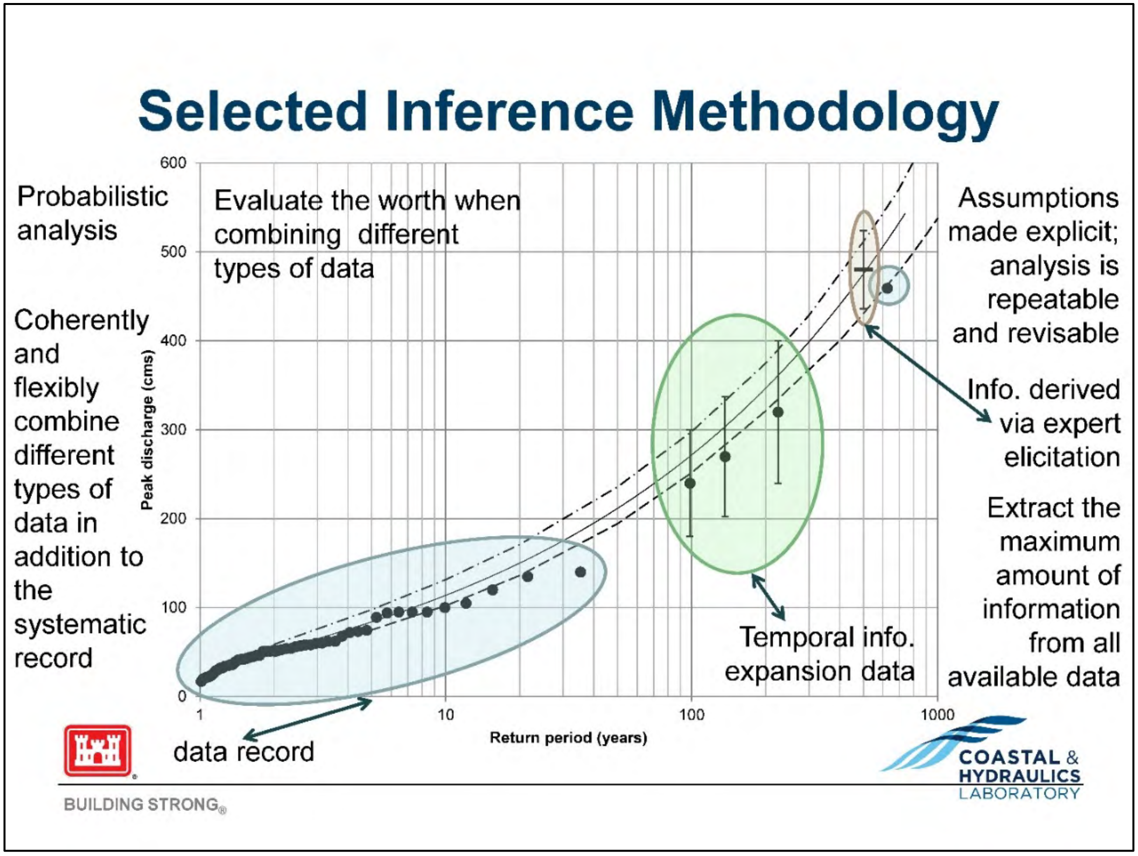

Selected Inference Methodology

Probabilistic analysis

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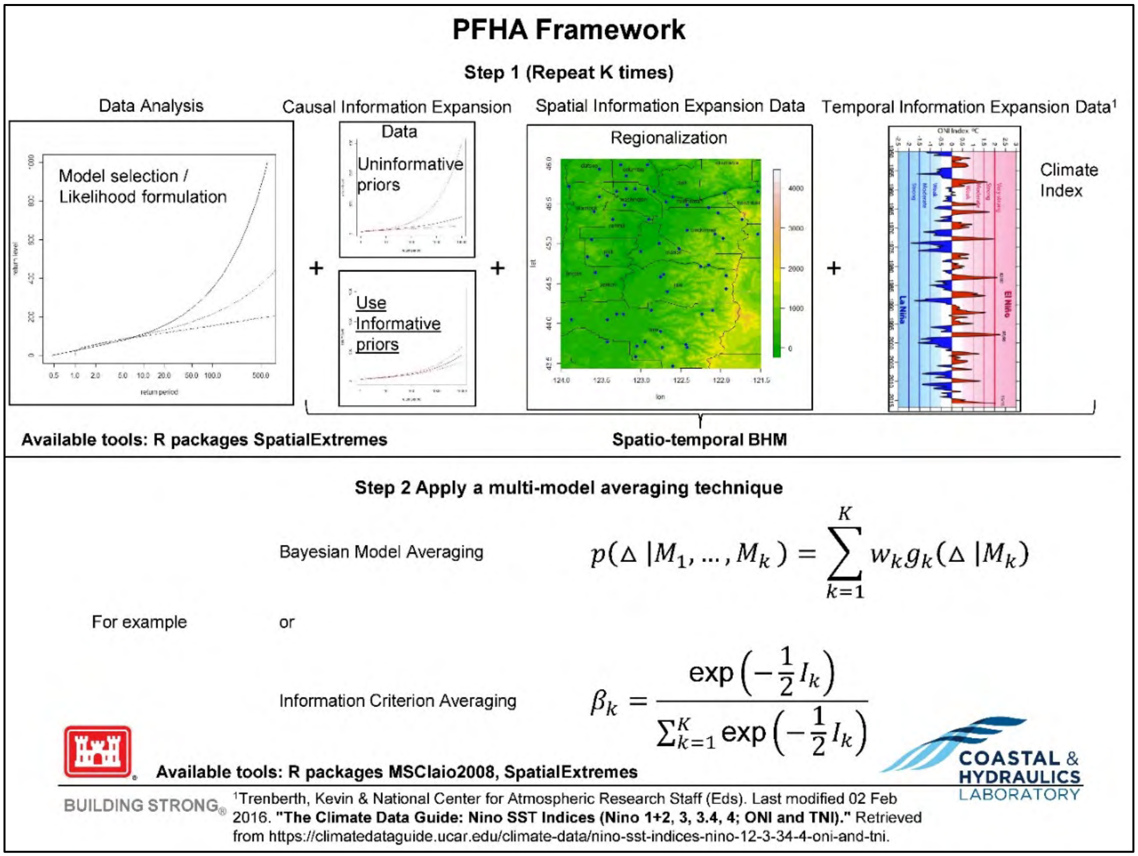
data record



PFHA Framework

Step 1 (Repeat K times)

Data Analysis

Model selection / Likelihood formulation

Causal Information Expansion

Data

Uninformative priors

Use Informative priors

Spatial Information Expansion Data

Regionalization

Temporal Information Expansion Data[1]

Climate Index

Available tools: R packages SpatialExtremes

Spatio-temporal BHM

Step 2 Apply a multi-model averaging technique

For example

Bayesian Model Averaging

$$p(\Delta\,|M_1,\ldots,M_k) = \sum_{k=1}^{K} w_k g_k(\Delta\,|M_k)$$

or

Information Criterion Averaging

$$\beta_k = \frac{\exp\left(-\frac{1}{2}I_k\right)}{\sum_{k=1}^{K}\exp\left(-\frac{1}{2}I_k\right)}$$

Available tools: R packages MSClaio2008, SpatialExtremes

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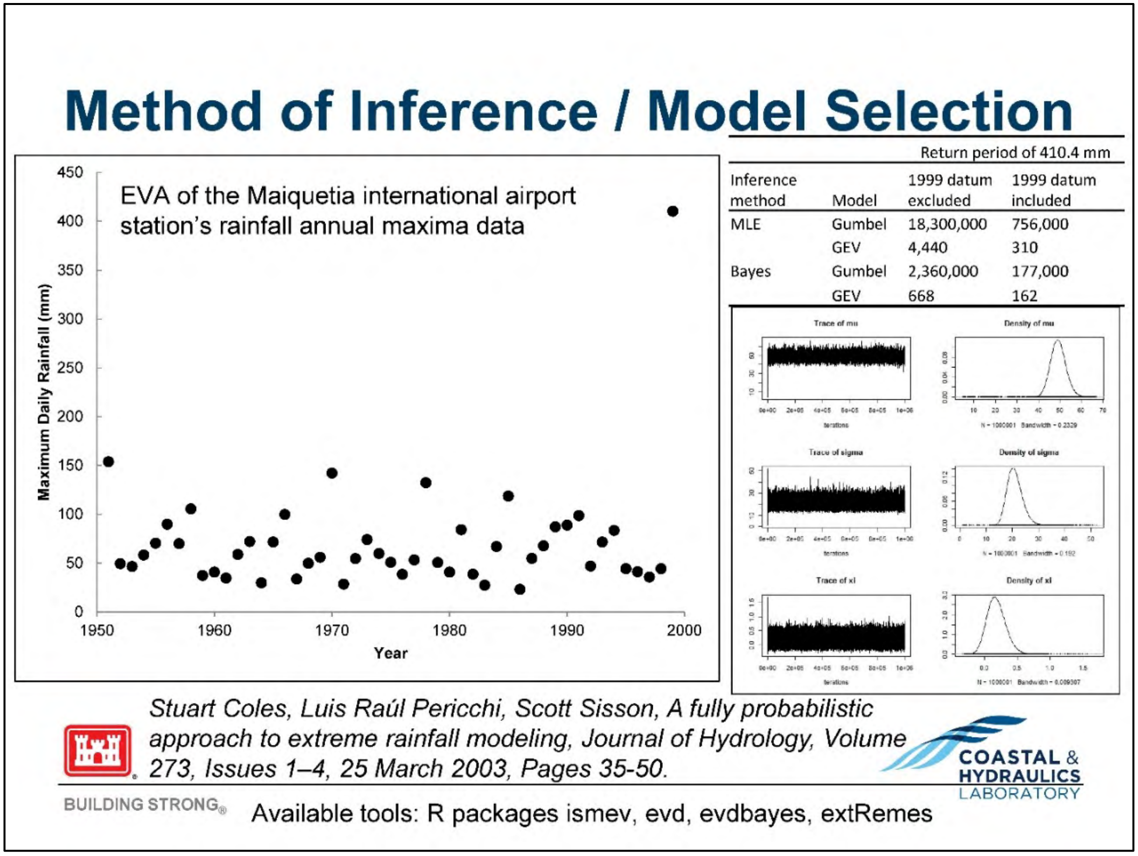
[1] Trenberth, Kevin & National Center for Atmospheric Research Staff (Eds). Last modified 02 Feb 2016. **"The Climate Data Guide: Nino SST Indices (Nino 1+2, 3, 3.4, 4; ONI and TNI)."** Retrieved from https://climatedataguide.ucar.edu/climate-data/nino-sst-indices-nino-12-3-34-4-oni-and-tni.



Method of Inference / Model Selection

EVA of the Maiquetia international airport station's rainfall annual maxima data

		Return period of 410.4 mm	
Inference method	Model	1999 datum excluded	1999 datum included
MLE	Gumbel	18,300,000	756,000
	GEV	4,440	310
Bayes	Gumbel	2,360,000	177,000
	GEV	668	162

Stuart Coles, Luis Raúl Pericchi, Scott Sisson, A fully probabilistic approach to extreme rainfall modeling, Journal of Hydrology, Volume 273, Issues 1–4, 25 March 2003, Pages 35-50.

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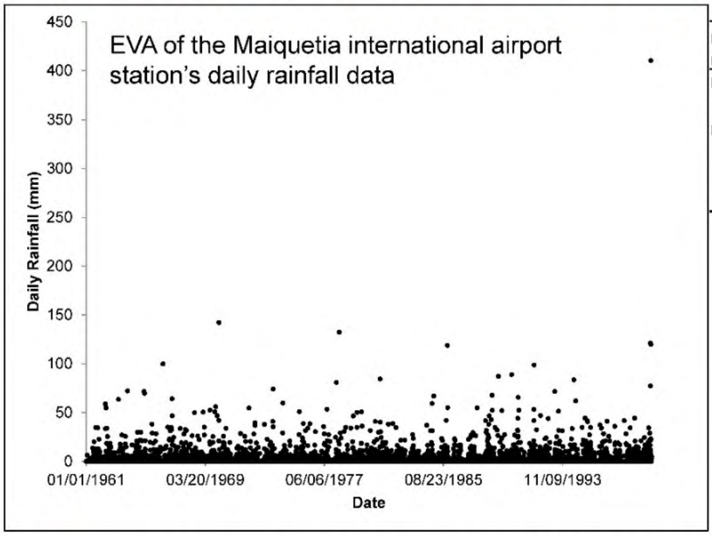
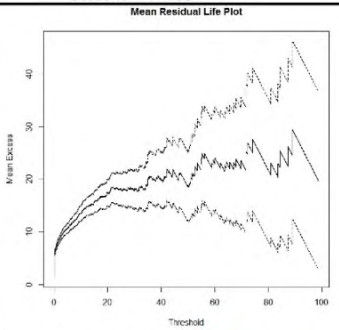
Available tools: R packages ismev, evd, evdbayes, extRemes

Method of Inference / Model Selection



		Return period of 410.4 mm	
Inference method	Model	1999 datum excluded	1999 datum included
MLE	Gumbel	18,300,000	756,000
	GEV	4,440	310
Bayes	Gumbel	2,360,000	177,000
	GEV	668	162
	PP (daily)	338	
	Seasonal PP	133	



Stuart Coles, Luis Raúl Pericchi, Scott Sisson, A fully probabilistic approach to extreme rainfall modeling, Journal of Hydrology, Volume 273, Issues 1–4, 25 March 2003, Pages 35-50.

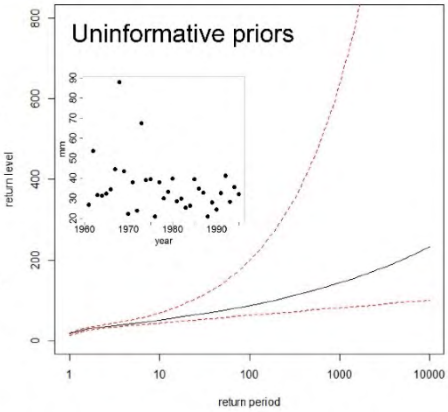
Available tools: R packages ismev, evd, evdbayes, extRemes

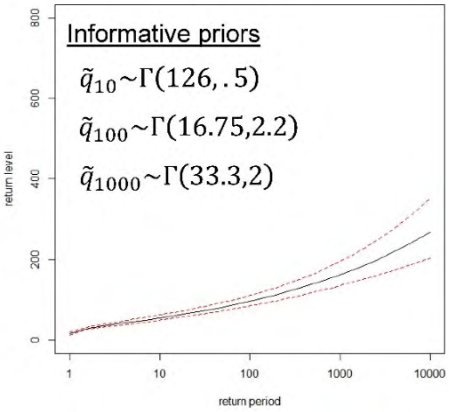
Expert Elicitation

Coles and Tawn (1996) elicited prior information in terms of three distinct ordered return levels, but worked with their differences. The $\tilde{q}_i$, $i = 1,2,3$, are specified by gamma distributions whose parameters are determined by way of the expert elicitation.

Leverage the full capabilities of Bayesian inference

Sensitivity analysis: Evaluate the worth of additional data





Informative priors

$\tilde{q}_{10} \sim \Gamma(126, .5)$

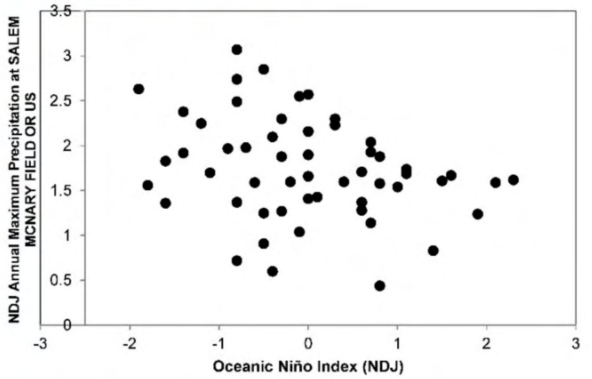
$\tilde{q}_{100} \sim \Gamma(16.75, 2.2)$

$\tilde{q}_{1000} \sim \Gamma(33.3, 2)$

Stuart G. Coles and Jonathan A. Tawn (1996), A Bayesian Analysis of Extreme Rainfall Data, Journal of the Royal Statistical Society. Series C (Applied Statistics), Vol. 45, No. 4(1996), pp. 463-478.

Available tools: Web tool for eliciting probability distributions from experts (http://optics.eee.nottingham.ac.uk/match/uncertainty.php) & the R package evdbayes

Temporal Covariates



Economou T, Stephenson DB, Ferro CAT. (2014) SPATIO-TEMPORAL MODELLING OF EXTREME STORMS,*ANNALS OF APPLIED STATISTICS*, volume 8, no. 4, pages 2223-2246, DOI:10.1214/14-AOAS766.

NDJ = November, December, January

	log l	D		
M_0	-46.0924			
M_1	-43.5732	5.0384		
M_2	-38.5446	15.09564	10.05724	
M_3	-28.2434	35.6981	30.6597	20.60246

$$\mu = \mu_0 + \mu_1 \mathrm{ONI}(t)$$

$$\sigma = \sigma_0 + \sigma_1 \mathrm{ONI}(t)$$

$$\xi = \xi_0 + \xi_1 \mathrm{ONI}(t)$$

Likelihood Ratio test: $D = -2\{l(\mu_0, \mu_1, \sigma, \xi) - l(\mu, \sigma, \xi)\}$

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http://www.cpc.ncep.noaa.gov/products/analysis_monitoring/ensostuff/ensoyears.shtml

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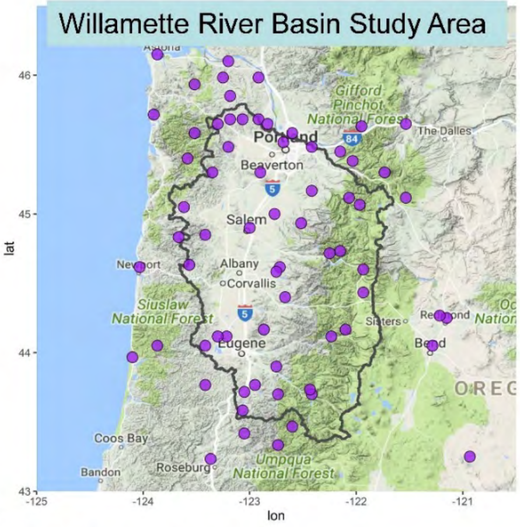
Regionalization

The 11,478 square mile WRB contains approximately two-thirds of Oregon's population and 20 of the 25 most populous cities in the state. The U.S. Army Corps of Engineers (USACE) Portland District operates thirteen dams in the WRB.

Extreme rainfall estimates are required to support risk-informed hydrologic analyses for the USACE Dam Safety Program.

Profile an alternate methodology to a regional frequency analysis (RFA), which was developed in 2008 due to the lack of an official NOAA Atlas 14 update for the state of Oregon.

In contrast with RFA, BHM does not require the decomposition of the study region into homogeneous sub-regions, it includes the spatial components of the data, it is robust in the treatment of uncertainty, and it can be easily adapted to accommodate treatments of non-stationarity.



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Regionalization

Let $\mathcal{S}$ denote the spatial region of interest and $s \in \mathcal{S}$ a specific site within $\mathcal{S}$. Let y_{ts} denote the maximum annual rainfall of a given duration at location s for a year t. We assume the y_{ts} follow a GEV distribution with spatially dependent parameters; viz.,

$$y_{ts} \sim GEV(\mu_s, \sigma_s, \xi_s),\ \ \mu_s = \boldsymbol{x}_s^{\mathrm{T}} \boldsymbol{\theta}^{\mu} + \tau_s^{\mu},\ \ \kappa_s = \boldsymbol{x}_s^{\mathrm{T}} \boldsymbol{\theta}^{\kappa} + \tau_s^{\kappa},\ \ \xi_s = \boldsymbol{x}_s^{\mathrm{T}} \boldsymbol{\theta}^{\xi} + \tau_s^{\xi}$$

with $\kappa_s = 1/\sigma_s$, and $\boldsymbol{x}_s$, $\boldsymbol{\theta}^{\nu}$, $\nu \in \{\mu, \kappa, \xi\}$, and τ_s^{ν} denoting the covariates, the linear model parameters, and spatial random effects terms, respectively. Each GEV model parameter is defined by a linear model of the covariates plus a spatial random effects term that accounts for residual spatial association not captured by the covariates. One or more of the extremal model parameters may also be indexed in time to support the development of a spatio-temporal BHM (Economou et al. 2014). The spatial random effects term is assumed to be a zero-centered Gaussian spatial process. $d_{s_t s_r}$ is the Euclidean distance between locations s_t and s_r

$$\tau_s^{\nu} \sim GP(\alpha^{\nu}, \lambda^{\nu}),\ \nu \in \{\mu, \kappa, \xi\} \quad E(\tau_{s_t}^{\nu}) = 0 \quad cov(\tau_{s_t}^{\nu}, \tau_{s_r}^{\nu}) = \frac{1}{\alpha^{\nu}} exp\left(-\frac{d_{s_t s_r}}{\lambda^{\nu}}\right)$$

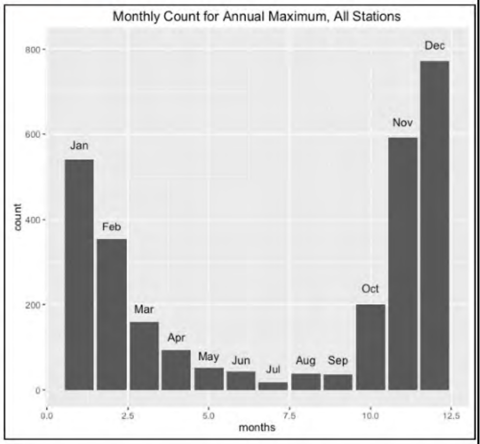
Economou T, Stephenson DB, Ferro CAT. (2014) SPATIO-TEMPORAL MODELLING OF EXTREME STORMS,*ANNALS OF APPLIED STATISTICS*, volume 8, no. 4, pages 2223-2246, DOI:10.1214/14-AOAS766.

Available tools: R packages spatial.gev.bma, SpatialExtremes

Regionalization

The likelihood is given by
$p(\boldsymbol{y}|\{\mu_s, \kappa_s, \xi_s\}_{s \in \mathcal{S}}) = \prod_{s \in \mathcal{S}_o} \prod_{t=1}^{T_s} p(y_{ts}|\mu_s, \kappa_s, \xi_s)$, where $\boldsymbol{y}$ and $\mathcal{S}_o \subset \mathcal{S}$ denote the entire set of block maxima observations and the set of observation locations, respectively. The likelihood definition does imply that y_{ts} and $y_{t\acute{s}}$ are conditionally independent for any $s \neq \acute{s}$ where $s, s \acute{\in} \mathcal{S}$. Model inference is performed using MCMC.

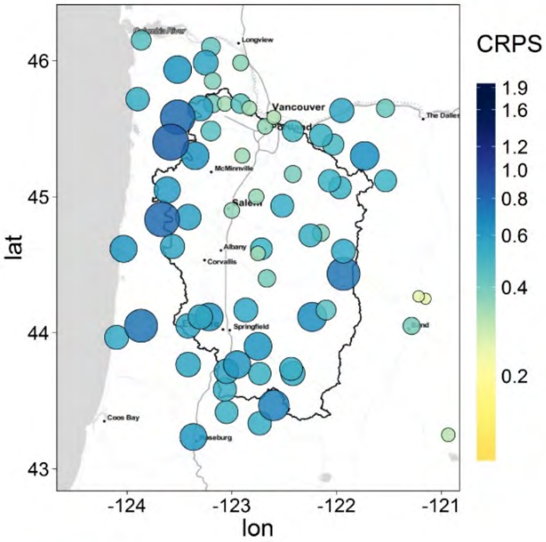
Prediction at locations $q \in \mathcal{S} \setminus \mathcal{S}_o$ using the post burn-in MCMC draws requires specification of the spatial random effects terms. If $\tau_s^{\nu} \sim GP(\alpha^{\nu}, \lambda^{\nu})$, then $\tau_q^{\nu} \big| \{\tau_s^{\nu}\}_{s \in \mathcal{S}_o} \sim N\left(\hat{\tau}_q^{\nu}, \hat{\kappa}_q^{\nu}\right)$



The Pacific Northwest region experiences warm, dry summers due to intensification of the Pacific subtropical high, and cool, wet winters as the polar jet stream dips southward bringing storms from the Gulf of Alaska. Winter storms that occur between October and March typically make up to 75-80% of the region's annual precipitation

Available tools: R packages spatial.gev.bma, SpatialExtremes

Regionalization



Willamette River Basin (WRB)	
Covariates	**Mean CRPS**
Lat., Lon.	0.5777
Lat., Lon., Elevation	0.5670
Lat., Lon., Elevation, $P_1,P_2,P_3,P_4,P_5,P_6,P_7,P_8,P_9,P_{10},P_{11},P_{12}$, Td_A, $Tmean_A$	0.5152
Lat., Lon., Elevation, P_*, Td_*, $Tmean_*$,$(P_*)^c$, $(Td_*)^c$,$(Tmean_*)^c$	**0.5120**
Lat., Lon., Elevation, $P_1,P_2,P_3,P_4,P_5,P_6,P_7,P_8,P_9,P_{10},P_{11},P_{12}$, $Td_1,Td_2,Td_3,Td_4,Td_5,Td_6,Td_7,Td_8,Td_9,Td_{10},Td_{11},Td_{12},Tmean_1$, $Tmean_2,Tmean_3,Tmean_4,Tmean_5,Tmean_6,Tmean_7,Tmean_8$, $Tmean_9,Tmean_{10},Tmean_{11},Tmean_{12}$	0.5231
Lat., Lon., Elevation, P_A	0.5191
Lat., Lon., Elevation, P_*, Td_*, $Tmean_*$	0.5133
Lat., Lon., Elevation, P_A, Td_A, $Tmean_A$	0.5204

$$\overline{CRPS} = \frac{1}{n}\sum_{i=1}^{n}\int_{-\infty}^{\infty}\left(F_i^f(x) - F_i^o(x)\right)^2 dx$$

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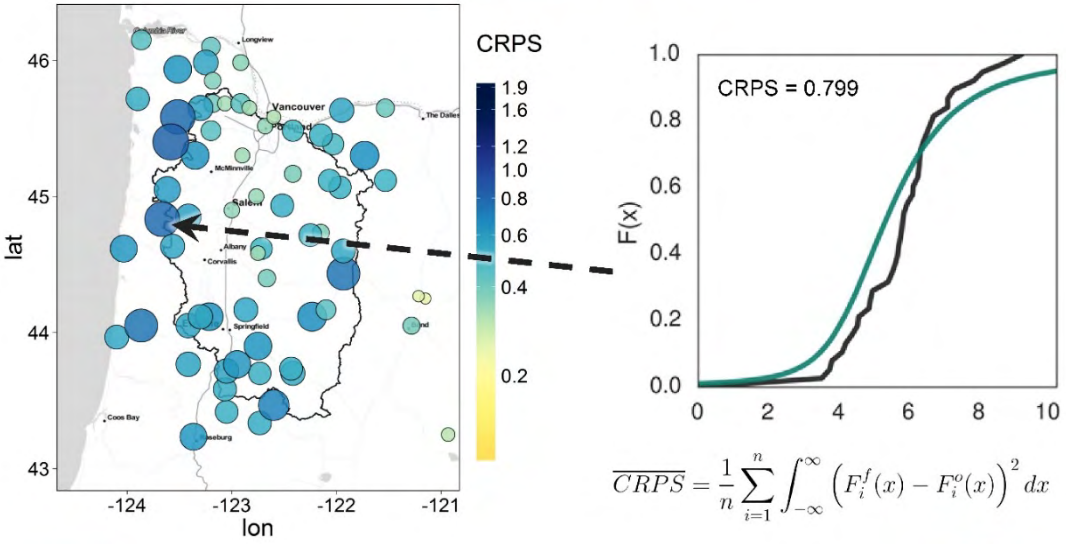
Available tools: R packages spatial.gev.bma, SpatialExtremes

Regionalization



$$\overline{CRPS} = \frac{1}{n}\sum_{i=1}^{n}\int_{-\infty}^{\infty}\left(F_i^f(x) - F_i^o(x)\right)^2 dx$$

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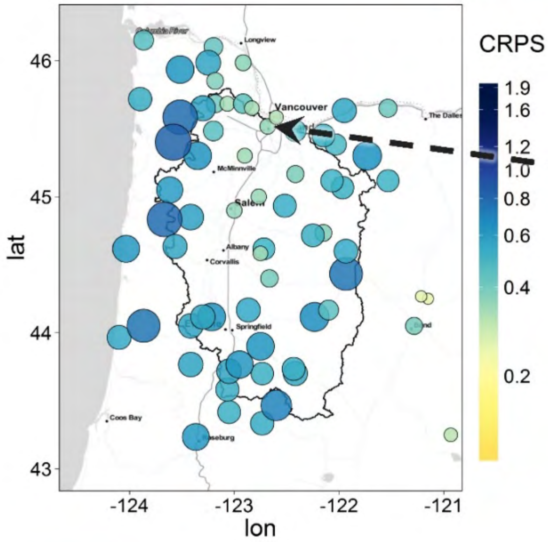
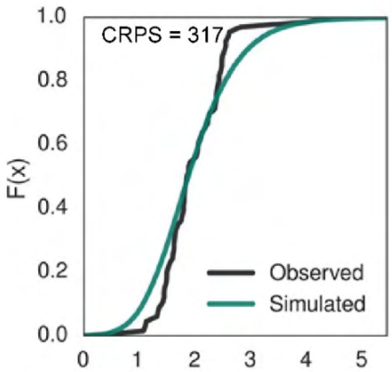
Available tools: R packages spatial.gev.bma, SpatialExtremes

Regionalization





$$\overline{CRPS} = \frac{1}{n}\sum_{i=1}^{n}\int_{-\infty}^{\infty}\left(F_i^f(x) - F_i^o(x)\right)^2 dx$$

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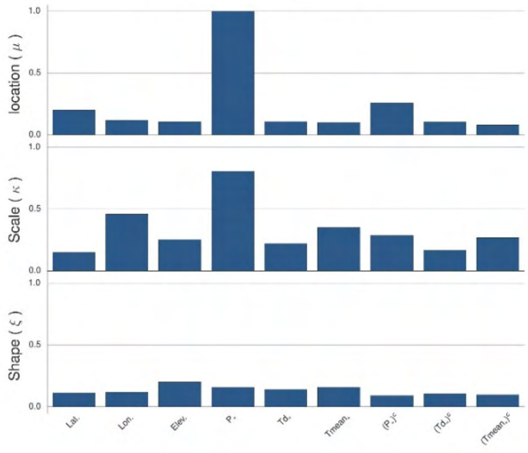
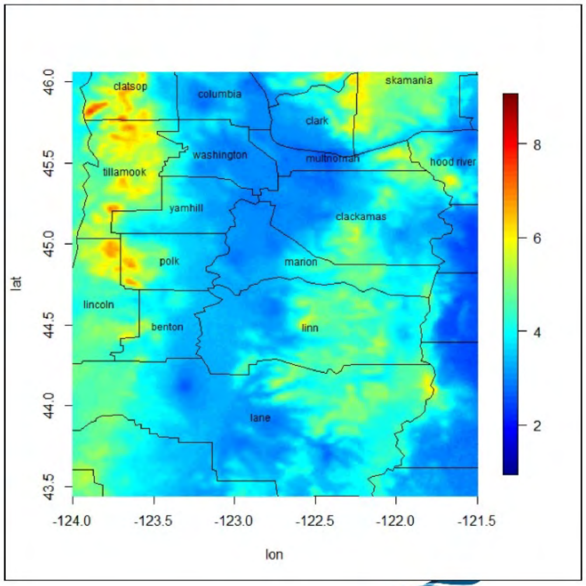
Available tools: R packages spatial.gev.bma, SpatialExtremes

Regionalization

Posterior Inclusion Probability by GEV parameter





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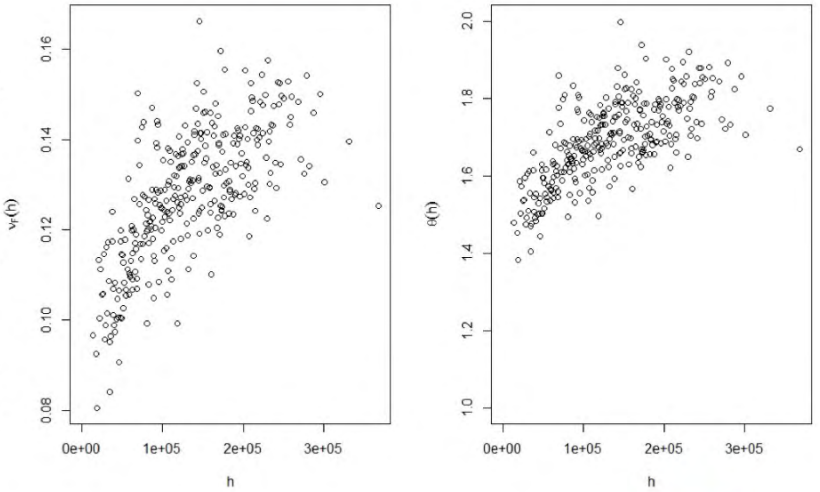
Available tools: R packages spatial.gev.bma, SpatialExtremes

Regionalization

Conditional independence assumption must be addressed to move further forward with the spatial analysis of hydrometeorological extremes

Treatment of spatial dependence among the extreme data



Reich, Brian J.; Shaby, Benjamin A. A hierarchical max-stable spatial model for extreme precipitation. Ann. Appl. Stat. 6 (2012), no. 4, 1430--1451. doi:10.1214/12-AOAS591.

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Available tools: R packages SpatialExtremes

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Regionalization

Conditional independence assumption must be addressed to move further forward with the spatial analysis of hydrometeorological extremes

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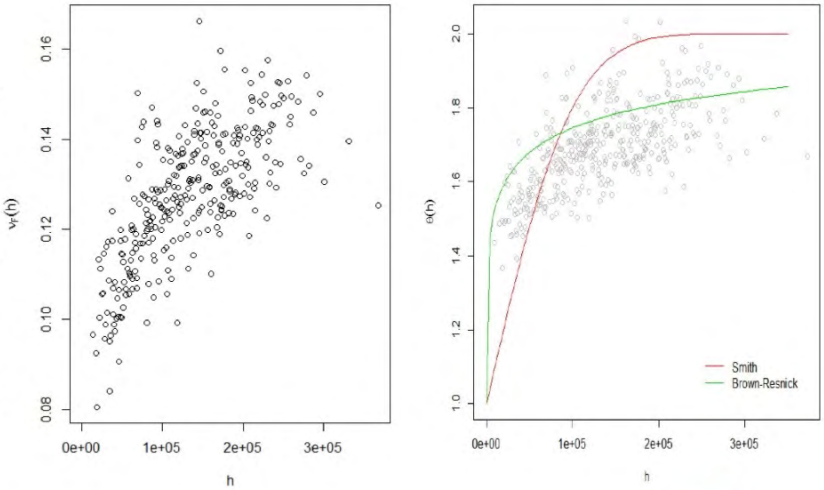

Reich, Brian J.; Shaby, Benjamin A. A hierarchical max-stable spatial model for extreme precipitation. Ann. Appl. Stat. 6 (2012), no. 4, 1430--1451. doi:10.1214/12-AOAS591.

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Available tools: R packages SpatialExtremes

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Generalization of Model Selection

The existence of multiple models for extreme rainfall analysis is a source of epistemic uncertainty. Model averaging is a straightforward, systematic, reproducible, and revisable means by which to account for the variability expressed across competing models selected for the analysis of extreme rainfall.

Model	Return period of 410.4 mm	Equal Weights	AIC	BIC
GEV	4,438	0.25	0.137	0.075
Gumbel	18,374,910	0.25	0.167	0.227
LN3	35,482	0.25	0.391	0.530
P3	1,567,614	0.25	0.305	0.168
Model Averge		4,995,611	3,564,577	4,445,779

$$\beta_k = \frac{\exp\left(-\frac{1}{2}I_k\right)}{\sum_{k=1}^{K}\exp\left(-\frac{1}{2}I_k\right)}$$

I_k is a function of data fit and model complexity.

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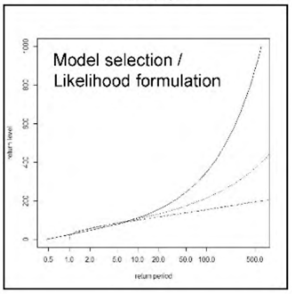
Available tools: R packages MSClaio2008, SpatialExtremes

PFHA Framework

Step 1 (Repeat K times)

Data Analysis



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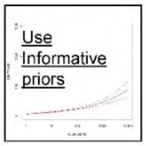
Causal Information Expansion Data



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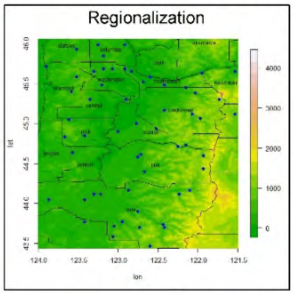
Spatial Information Expansion Data



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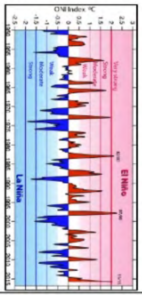
Temporal Information Expansion Data[1]



Climate Index

Available tools: R packages SpatialExtremes

Spatio-temporal BHM

Step 2 Apply a multi-model averaging technique

For example

Bayesian Model Averaging

$$p(\Delta \,|M_1, \ldots, M_k) = \sum_{k=1}^{K} w_k g_k(\Delta \,|M_k)$$

or

Information Criterion Averaging

$$\beta_k = \frac{\exp\left(-\frac{1}{2}I_k\right)}{\sum_{k=1}^{K}\exp\left(-\frac{1}{2}I_k\right)}$$

Available tools: R packages MSClaio2008, SpatialExtremes

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[1] Trenberth, Kevin & National Center for Atmospheric Research Staff (Eds). Last modified 02 Feb 2016. **"The Climate Data Guide: Nino SST Indices (Nino 1+2, 3, 3.4, 4; ONI and TNI)."** Retrieved from https://climatedataguide.ucar.edu/climate-data/nino-sst-indices-nino-12-3-34-4-oni-and-tni.

Probabilistic Flood Hazard Assessment Framework Development

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2.3.10.2.3 Questions and Answers

Questions were postponed until the end of the day.

2.3.10.3 Riverine Flooding and Structured Hazard Assessment Committee Process for Flooding (SHAC-F), Rajiv Prasad*, Ph.D., and Robert Bryce, Ph.D., Pacific Northwest National Laboratory; Kevin Coppersmith*, Ph.D., Coppersmith Consulting (Session 3C-3; ADAMS Accession No. ML17054C487)

2.3.10.3.1 Abstract

This research project is part of the NRC's PFHA research plan in support of development of a risk-informed analytical approach for flood hazards. The approach is expected to support estimation of flood hazards at new and existing facilities and enhance the NRC's capacity to support reviews of license applications, license amendment requests, and reactor oversight activities. Flood hazards at NPPs result from various flooding mechanisms, including local intense precipitation (LIP), precipitation and snowmelt in a river basin, dam failures, and storm surges and tsunamis. These flood events have the potential to challenge offsite power, threaten many onsite NPP SSCs, challenge the integrity of plant structures, and limit plant access. However, there is no widely accepted framework for performing a PFHA, and there are large uncertainties involved with estimating floods of magnitudes and frequencies of occurrence of interest for safety evaluations at NPPs. In 2013 and 2014, NRC-sponsored workshops discussed the available methods for conducting PFHAs and the development of a structured hazard assessment committee process

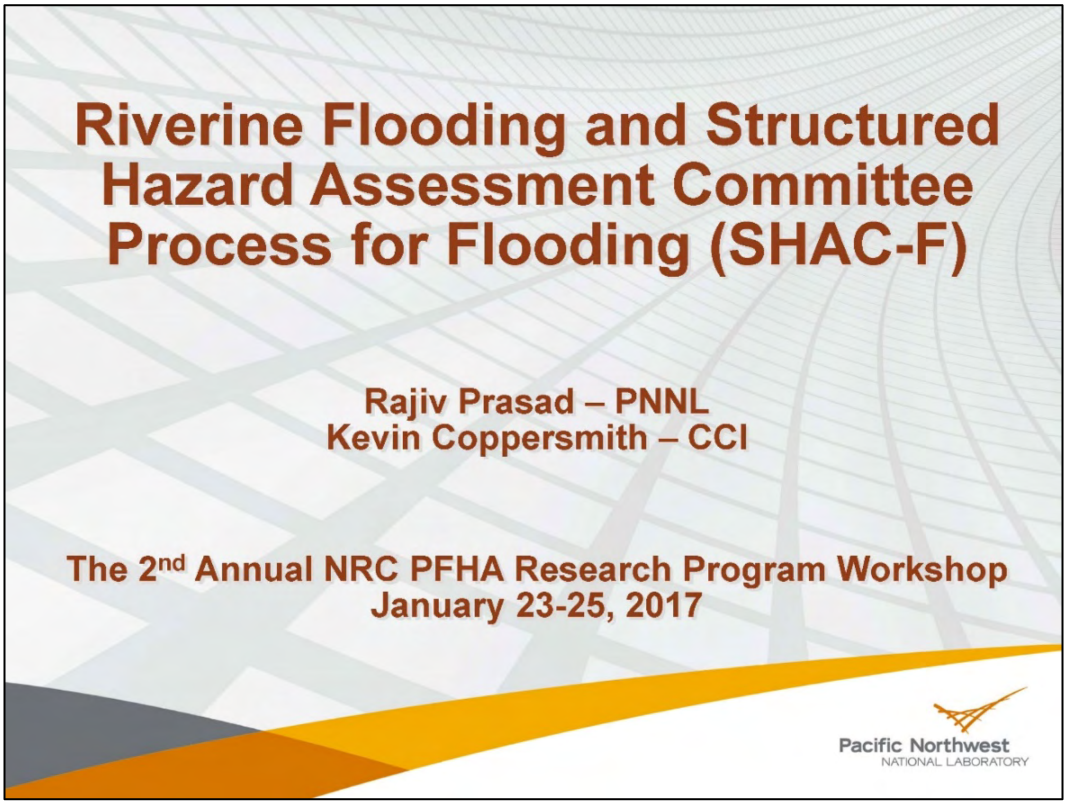
for flooding (SHAC-F). The need to develop implementation details of SHAC-F methodology was also recognized.

The objective of this project is to develop and apply the SHAC-F process to provide confidence that all data sets, models, and interpretations proposed by the larger technical community have been given appropriate consideration and that the inputs to the PFHA reflect the center, body, and range of technically defensible interpretations. The research team started with the overarching guidance from the Senior Seismic Hazard Analysis Committee (SSHAC) process (NUREG/CR-6372, "Recommendations for Probabilistic Seismic Hazard Analysis: Guidance on Uncertainty and Use of Experts," issued April 1997; and NUREG-2117, "Practical Implementation Guidelines for SSHAC Level 3 and 4 Hazard Studies, Revision 1, issued April 2012) used in probabilistic seismic hazard assessments and adapting them to the needs of flood hazard assessments. The SSHAC process is particularly well suited for structuring hazard assessments for purposes of risk analyses. For SHAC-F, the project adapted four levels, similar to SSHAC Levels 1–4. The virtual studies in the current project are carried out to simulate the full scope and activities that would accompany a full SHAC-F Level 3 PFHA. The project is investigating these aspects using virtual studies for LIP floods and riverine floods, excluding dam failures.

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

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

2.3.10.3.2 Presentation



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

Rajiv Prasad – PNNL
Kevin Coppersmith – CCI

The 2nd Annual NRC PFHA Research Program Workshop
January 23-25, 2017

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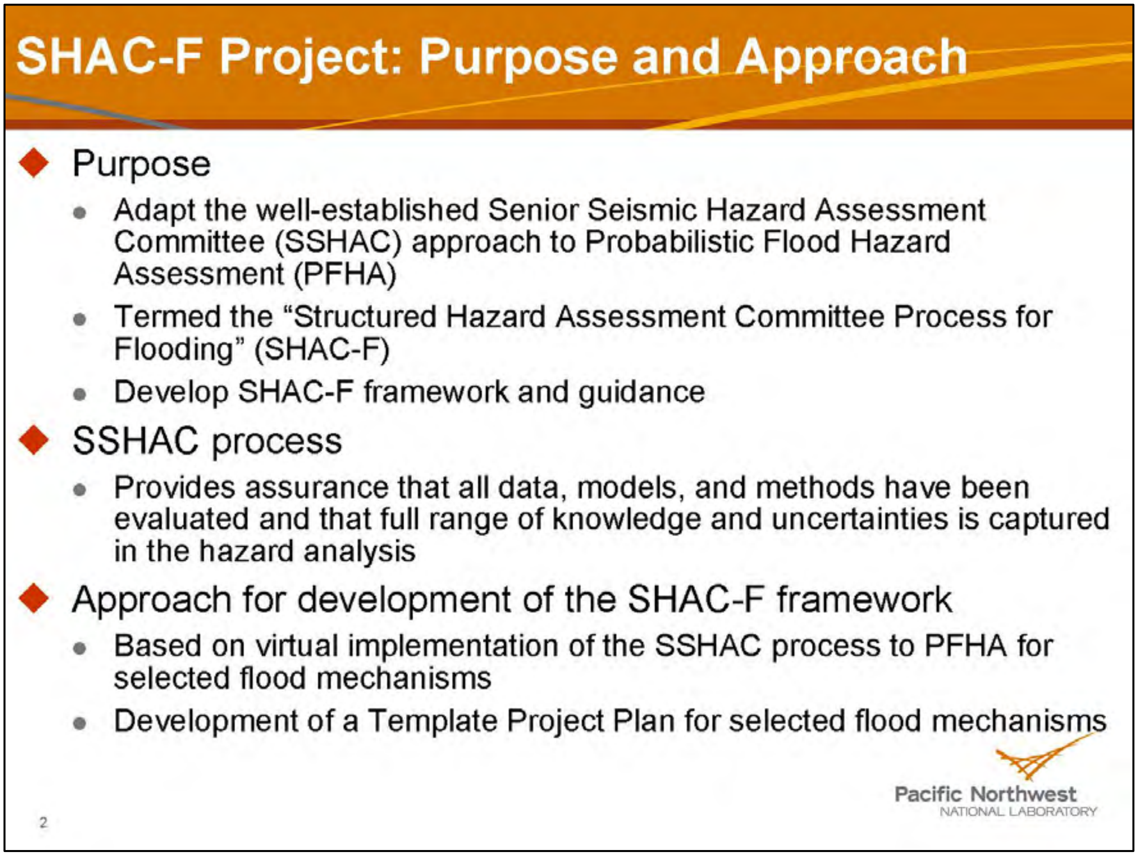

SHAC-F Project: Purpose and Approach

- Purpose
  - Adapt the well-established Senior Seismic Hazard Assessment Committee (SSHAC) approach to Probabilistic Flood Hazard Assessment (PFHA)
  - Termed the “Structured Hazard Assessment Committee Process for Flooding” (SHAC-F)
  - Develop SHAC-F framework and guidance
- SSHAC process
  - Provides assurance that all data, models, and methods have been evaluated and that full range of knowledge and uncertainties is captured in the hazard analysis
- Approach for development of the SHAC-F framework
  - Based on virtual implementation of the SSHAC process to PFHA for selected flood mechanisms
  - Development of a Template Project Plan for selected flood mechanisms

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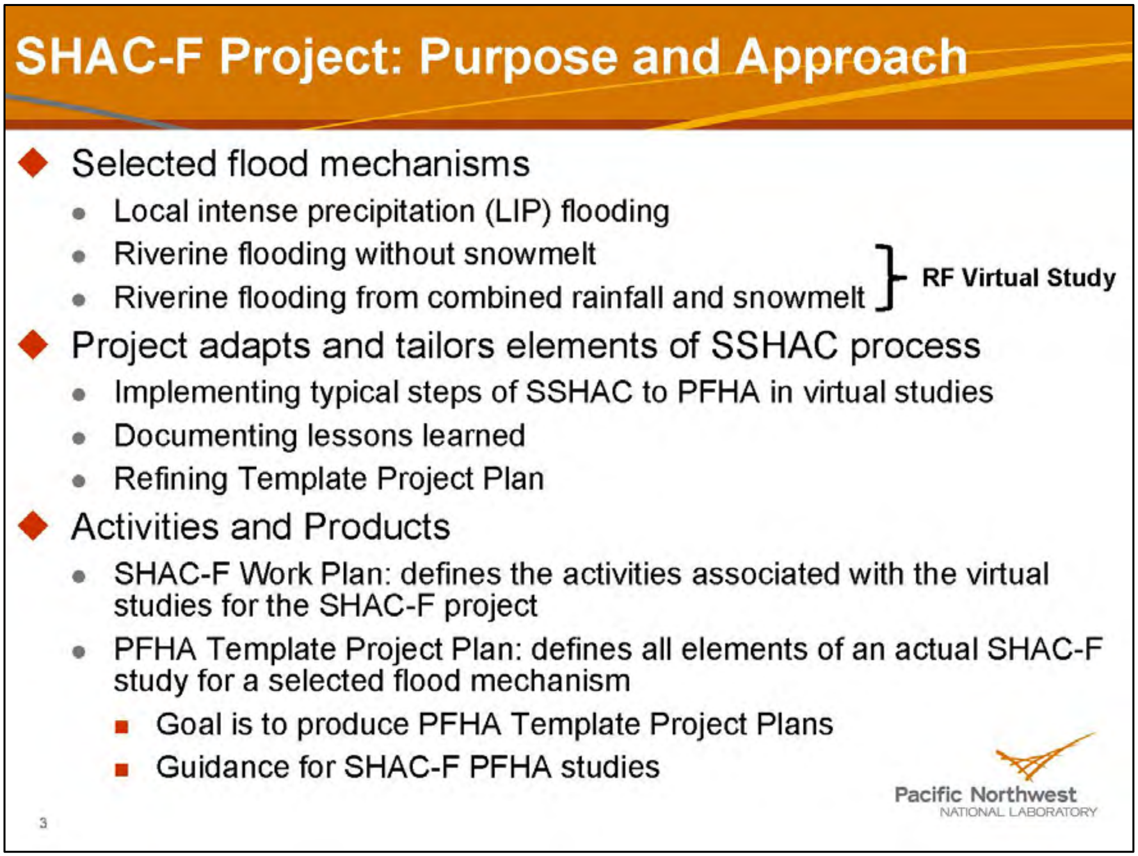

SHAC-F Project: Purpose and Approach

- Selected flood mechanisms
  - Local intense precipitation (LIP) flooding
  - Riverine flooding without snowmelt
  - Riverine flooding from combined rainfall and snowmelt

  } **RF Virtual Study**
- Project adapts and tailors elements of SSHAC process
  - Implementing typical steps of SSHAC to PFHA in virtual studies
  - Documenting lessons learned
  - Refining Template Project Plan
- Activities and Products
  - SHAC-F Work Plan: defines the activities associated with the virtual studies for the SHAC-F project
  - PFHA Template Project Plan: defines all elements of an actual SHAC-F study for a selected flood mechanism
    - Goal is to produce PFHA Template Project Plans
    - Guidance for SHAC-F PFHA studies

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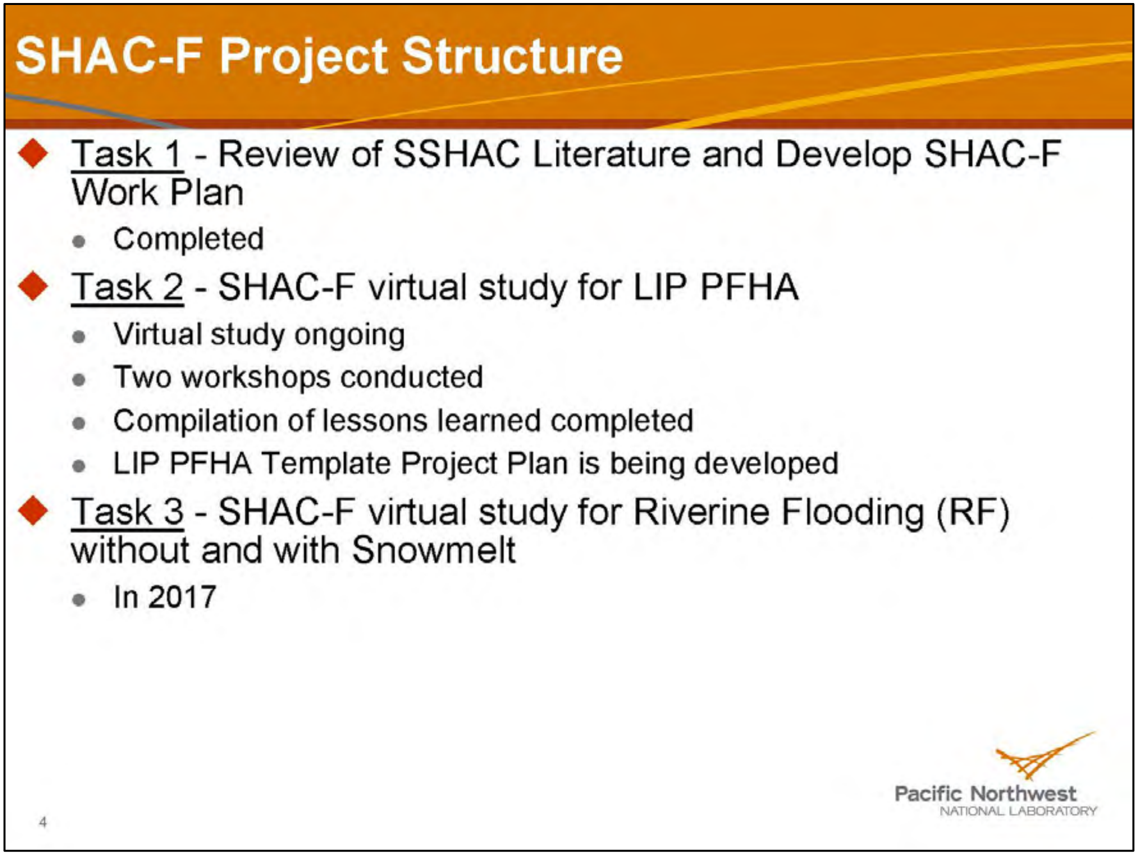

SHAC-F Project Structure

- Task 1 - Review of SSHAC Literature and Develop SHAC-F Work Plan
  - Completed
- Task 2 - SHAC-F virtual study for LIP PFHA
  - Virtual study ongoing
  - Two workshops conducted
  - Compilation of lessons learned completed
  - LIP PFHA Template Project Plan is being developed
- Task 3 - SHAC-F virtual study for Riverine Flooding (RF) without and with Snowmelt
  - In 2017

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Task 1a - Review of SSHAC Literature and Develop Work Plan

- Compilation and review of literature
  - SSHAC guidance documents
  - Project reports, mainly Probabilistic Seismic Hazard Assessments for nuclear facilities
  - Professional literature on case histories and lessons learned
- Summary table
  - Literature citations
  - Summary and lessons learned
  - Implications to SHAC-F
- Used as a tool during the development of SHAC-F Work Plan and LIP and RF PFHA Template Project Plans

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Literature review structure and example

Study/Year	Citation	Summary and Lessons Learned	Implications to SHAC-F Study
Lessons Learned from SSHAC Projects [2010 – 2014]	Coppersmith, K.J., J.J. Bommer, A.M. Kammerer, and J. Ake, 2010. Implementation Guidance for SSHAC Level 3 and 4 Processes, Proceedings, *10th International Probabilistic Safety Assessment & Management Conference*, Seattle, WA, June 7-11, 2010. Bommer, J.J., Coppersmith, K.J., Kammerer, A., Ake, J., 2010. The Value of SSHAC Level 3 and 4 Processes for Community-Based Seismic Hazard Assessments, Proceedings, SH3: Global, regional and local initiatives on seismic hazard assessment: Toward Setting New Standards, *European Seismological Commission, 32nd General Assembly*, Montpellier, France, September 6-10, 2010 Coppersmith, K.J., and Bommer, J.J., 2012. Use of the SSHAC Methodology within Regulated Environments: Cost-Effective Application for Seismic Characterization at Multiple Sites, *Nuclear Engineering and Design*, v. 245, p. 233– 240. Bommer, J.J., and Coppersmith, K.J., 2013. Lessons Learned from Application of the NUREG-2117 Guidelines for SSHAC Level 3 Probabilistic Seismic Hazard Studies for Nuclear Sites, *Structural Mechanics in Reactor Technology* (SMiRT-22) Conference Proceedings, San Francisco, CA, August 18-23, 2013	A number of papers and presentations have been given related to the lessons learned from actual application of the SSHAC process in projects. Most of the conclusions are procedural in nature, rather than related specifically to seismic issues, and are intended to assist those who are planning, conducting, or reviewing comparable studies. For example, the pros and cons of SSHAC Level 3 and 4 studies have been identified; the cost-effectiveness of conducting a regional SSHAC Level 3 study followed by site-specific studies conducted at a Level 2 is discussed; the advantages of promoting expert interactions within a SSHAC process is discussed relative to other expert elicitation procedures that frown on interaction; the need for clear roles and responsibilities of project participants to ensure proper team dynamics is discussed in the context of real experience, and the manner in which SSHAC studies can be tailored for the specific technical issue being addressed is also considered.	A careful consideration of the identified SSHAC processes that work and those that don't can lead to efficiencies in any studies going forward. Further, the adaptation and tailoring of the SSHAC process to deal with PFHA issues can be done in light of similar attempts to do so for other technical issues and actual projects. It is anticipated that the SHAC-F project will lead to those additional insights that allow the SSHAC process to be tailored to LIP and riverine PFHA.

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Task 1b - Develop SHAC-F Work Plan

- Methodology Development Team (MDT)
  - Rajiv Prasad (with expertise in flooding analysis)
  - Kevin Coppersmith (with expertise in probabilistic analysis of natural hazards using SSHAC processes)
  - Robert Bryce (with experience managing a recent large scale SSHAC analysis for a nuclear facility)
- SHAC-F Work plan
  - Steps based largely on required steps for SSHAC process, guidance, and experience
  - Roles, responsibilities, project structure, workshops
  - Virtual studies designed to arrive at procedural guidance, not hazard results
- Articulate project goals
  - Documentation of the SHAC-F project process and results
  - Lessons learned from virtual studies
  - Develop PFHA Template Project Plans

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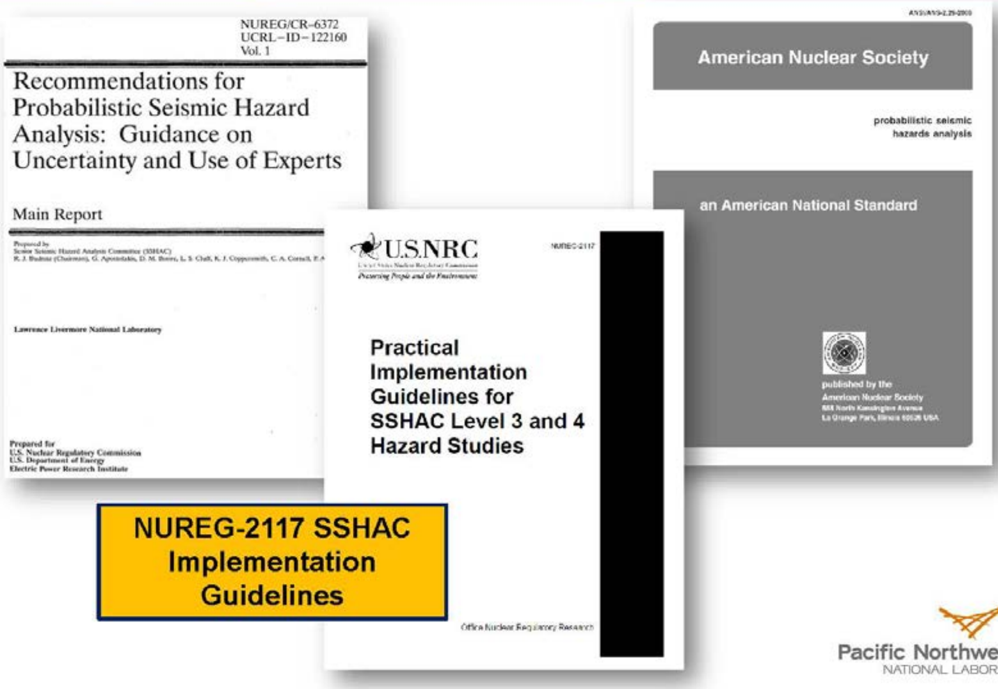
SSHAC Guidelines and Guidance



NUREG/CR-6372
UCRL–ID–122160
Vol. 1

Recommendations for Probabilistic Seismic Hazard Analysis: Guidance on Uncertainty and Use of Experts

Main Report

Prepared by
Senior Seismic Hazard Analysis Committee (SSHAC)
R. J. Budnitz (Chairman), G. Apostolakis, D. M. Boore, L. S. Cluff, K. J. Coppersmith, C. A. Cornell, P. A

Lawrence Livermore National Laboratory

Prepared for
U.S. Nuclear Regulatory Commission
U.S. Department of Energy
Electric Power Research Institute

U.S.NRC

NUREG-2117

Practical Implementation Guidelines for SSHAC Level 3 and 4 Hazard Studies

Office Nuclear Regulatory Research

American Nuclear Society

probabilistic seismic
hazards analysis

an American National Standard

published by the
American Nuclear Society

NUREG-2117 SSHAC Implementation Guidelines

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Goal of a SSHAC Process

- The fundamental goal of a SSHAC process is to properly carry out and completely document the activities of evaluation and integration, defined as:
  - 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 center, body, and range of technically defensible interpretations in light of the evaluation process (i.e., informed by the assessment of existing data, models, and methods)."

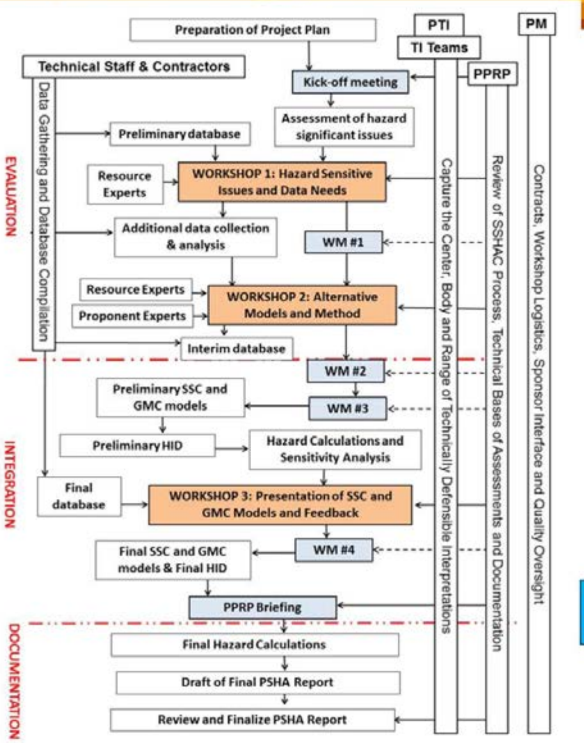
NUREG-2117 and ongoing updates

Roles in a SSHAC Level 3 Process

TI Team

EVALUATOR EXPERT	Impartial and objective evaluator of potentially applicable data, models, and methods
INTEGRATOR	Builds models that capture the full range of technically defensible interpretations
RESOURCE EXPERT	Has particular knowledge of a relevant data set, method or models
PROPONENT EXPERT	Advocates a particular hypothesis or technical position; will often promote a model that they have developed
SPECIALTY CONTRACTOR	Retrieves new data or undertakes new analyses to inform evaluators
PARTICIPATORY REVIEWER	Provides procedural and technical review; ensures capture of full range of views and robust technical justifications of integrated models

SSHAC Project Structure



NUREG-2117 and ongoing update

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Goals of an Actual SHAC-F PFHA and of the Virtual SHAC-F Study

◆ Actual SHAC-F PFHA

- Exercise the full SSHAC process
  - PTI, TI Leads and Teams, PPRP, Proponent and Resource Experts, Observers
  - Three multi-day workshops focused on established themes
  - Compilation and evaluation of actual data, models, and methods
  - Integration (model-building) by TI Teams to capture aleatory and epistemic uncertainties: feedback from PPRP
  - Full quantification and documentation of hazard

◆ Virtual SHAC-F Study

- Review the steps in SSHAC project to understand the roles and activities
  - Performed as a Level 3 project
  - Limited number of participants, must assume multiple roles
  - Step through the process with goal of identifying the process that is most suited to PFHA: not building an actual PFHA model
  - Arrive at a Template Project Plan for conducting an actual SHAC-F project
    - Defines roles and responsibilities, activities, schedule, deliverables
    - Project structure appropriate for PFHA for selected mechanisms

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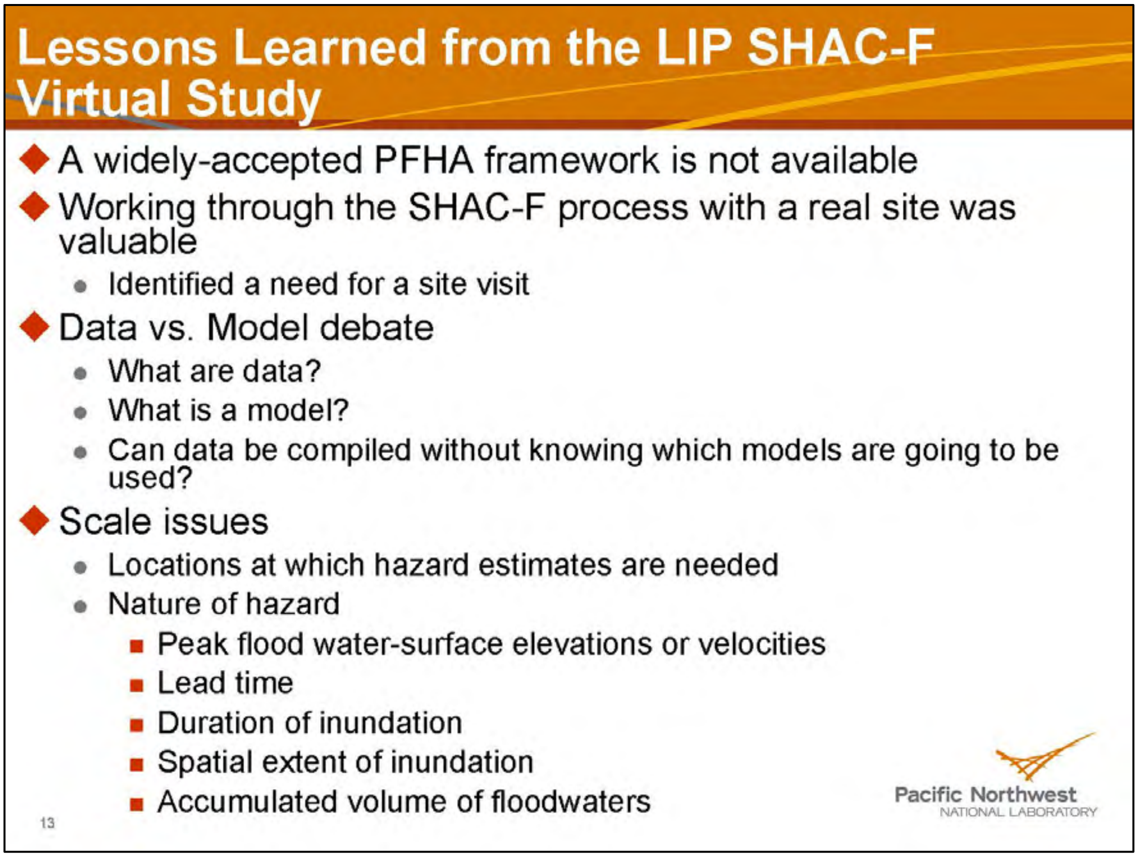

Lessons Learned from the LIP SHAC-F Virtual Study

- ◆ A widely-accepted PFHA framework is not available
- ◆ Working through the SHAC-F process with a real site was valuable
  - Identified a need for a site visit
- ◆ Data vs. Model debate
  - What are data?
  - What is a model?
  - Can data be compiled without knowing which models are going to be used?
- ◆ Scale issues
  - Locations at which hazard estimates are needed
  - Nature of hazard
    - Peak flood water-surface elevations or velocities
    - Lead time
    - Duration of inundation
    - Spatial extent of inundation
    - Accumulated volume of floodwaters

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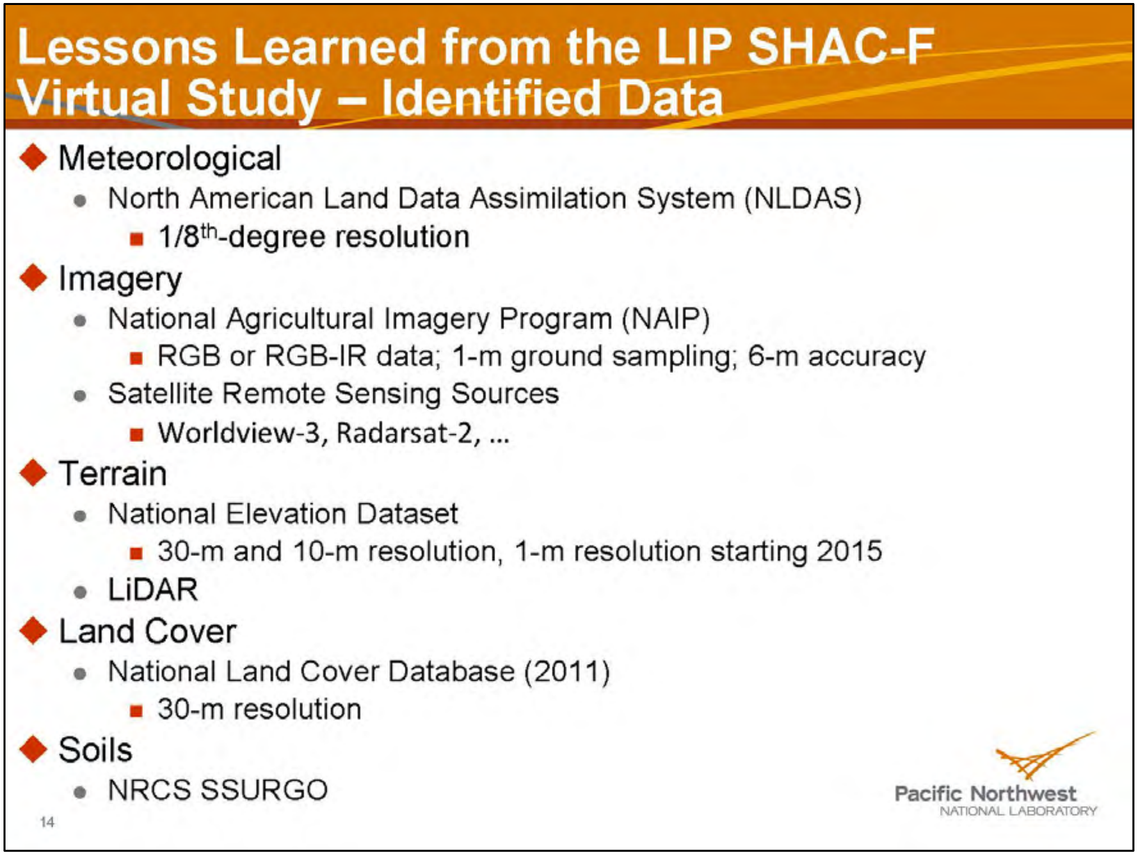

Lessons Learned from the LIP SHAC-F Virtual Study – Identified Data

- ◆ Meteorological
  - North American Land Data Assimilation System (NLDAS)
    - 1/8th-degree resolution
- ◆ Imagery
  - National Agricultural Imagery Program (NAIP)
    - RGB or RGB-IR data; 1-m ground sampling; 6-m accuracy
  - Satellite Remote Sensing Sources
    - Worldview-3, Radarsat-2, …
- ◆ Terrain
  - National Elevation Dataset
    - 30-m and 10-m resolution, 1-m resolution starting 2015
  - LiDAR
- ◆ Land Cover
  - National Land Cover Database (2011)
    - 30-m resolution
- ◆ Soils
  - NRCS SSURGO

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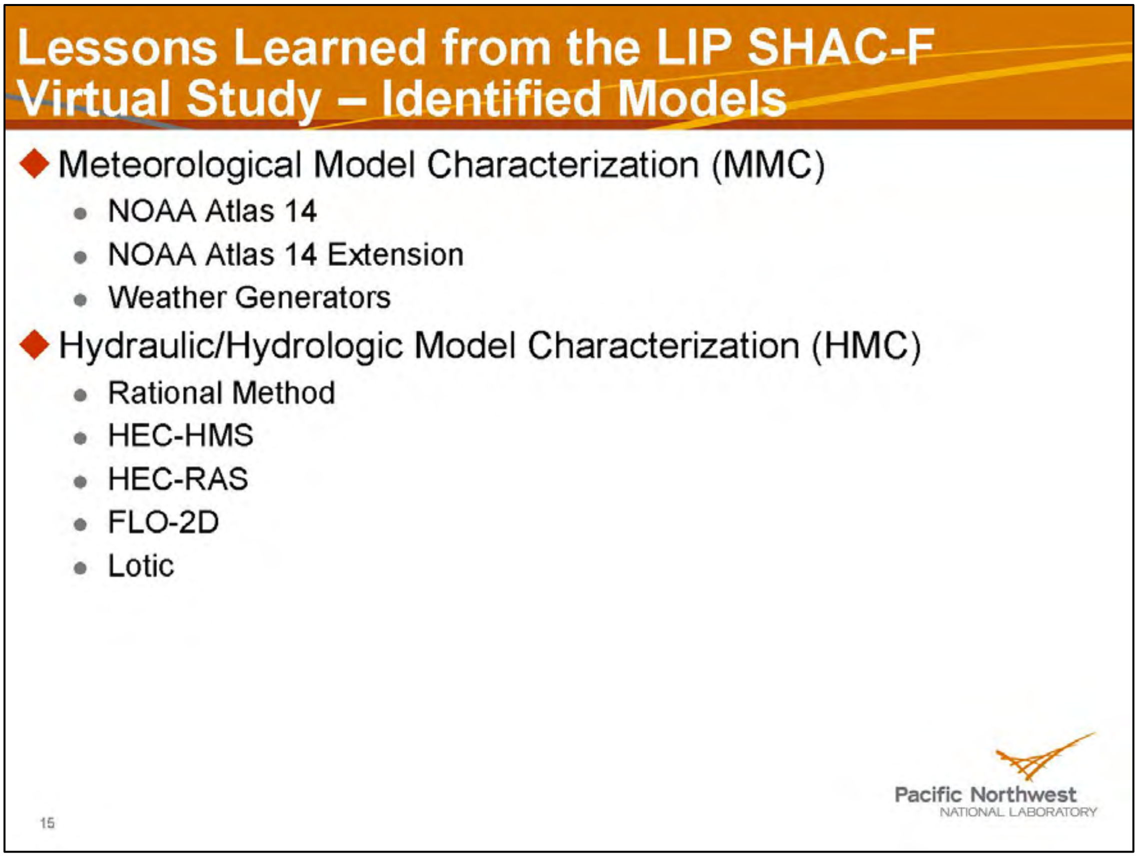
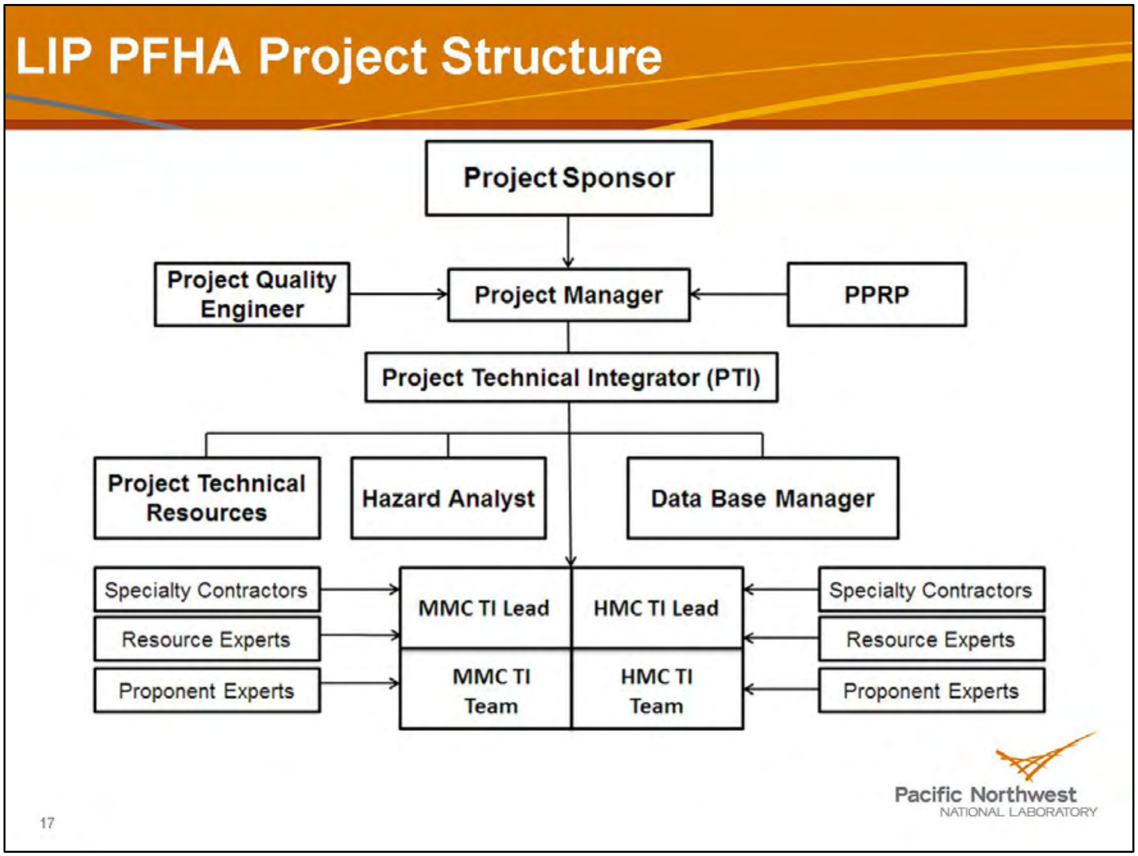


Lessons Learned from the LIP SHAC-F Virtual Study – Identified Models

- Meteorological Model Characterization (MMC)
  - NOAA Atlas 14
  - NOAA Atlas 14 Extension
  - Weather Generators
- Hydraulic/Hydrologic Model Characterization (HMC)
  - Rational Method
  - HEC-HMS
  - HEC-RAS
  - FLO-2D
  - Lotic

LIP PFHA Template Project Plan

- Topics addressed in the Template Project Plan
  - Selection of SHAC-F Level(s)
  - Development of Project Plan
  - Selection of Project Participants
  - Development of Project Databases
  - Compilation of Available Data
  - Collection of New Data
  - Data Dissemination
  - Workshops
  - Development of Models and Hazard Input Documents
  - Hazard Input Documents
  - Preliminary Hazard Calculations and Sensitivity Analyses
  - Final Hazard Calculations
  - Documentation and Peer Review



LIP PFHA Project Structure

Project Sponsor

Project Quality Engineer

Project Manager

PPRP

Project Technical Integrator (PTI)

Project Technical Resources

Hazard Analyst

Data Base Manager

Specialty Contractors

Resource Experts

Proponent Experts

MMC TI Lead

HMC TI Lead

MMC TI Team

HMC TI Team

Specialty Contractors

Resource Experts

Proponent Experts

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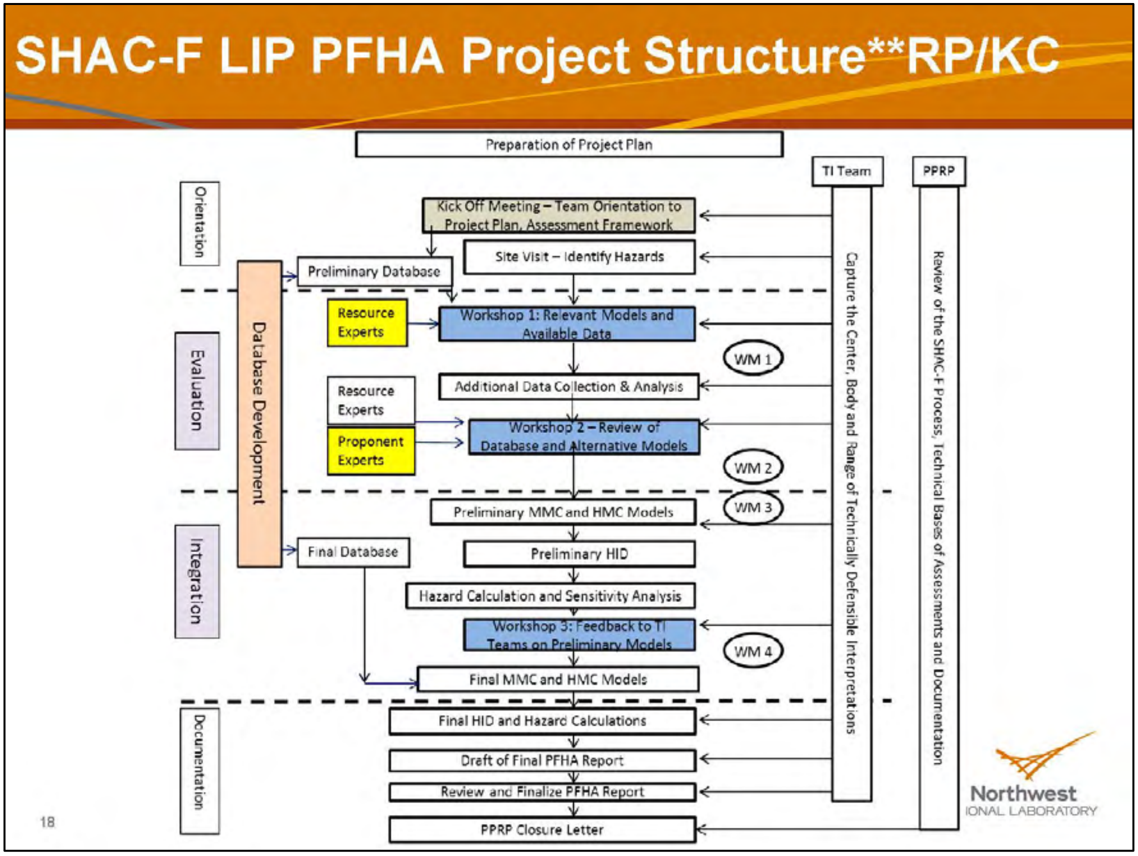

SHAC-F LIP PFHA Project Structure**RP/KC

Preparation of Project Plan

TI Team

PPRP

Orientation

Kick Off Meeting – Team Orientation to Project Plan, Assessment Framework

Site Visit – Identify Hazards

Preliminary Database

Database Development

Evaluation

Resource Experts

Workshop 1: Relevant Models and Available Data

WM 1

Additional Data Collection & Analysis

Resource Experts

Proponent Experts

Workshop 2 – Review of Database and Alternative Models

WM 2

WM 3

Integration

Preliminary MMC and HMC Models

Final Database

Preliminary HID

Hazard Calculation and Sensitivity Analysis

Workshop 3: Feedback to TI Teams on Preliminary Models

WM 4

Final MMC and HMC Models

Documentation

Final HID and Hazard Calculations

Draft of Final PFHA Report

Review and Finalize PFHA Report

PPRP Closure Letter

Capture the Center, Body and Range of Technically Defensible Interpretations

Review of the SHAC-F Process, Technical Bases of Assessments and Documentation

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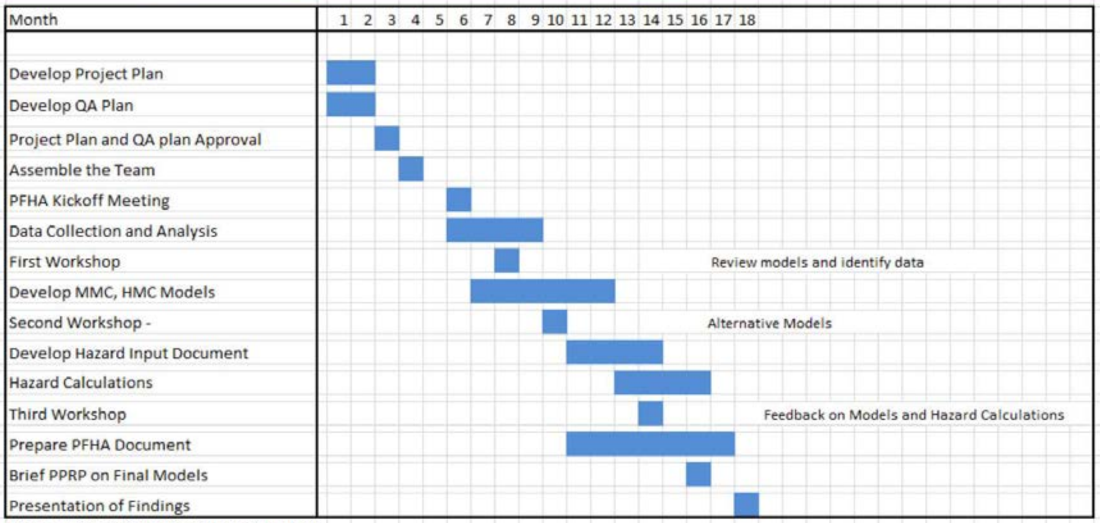
Idealized SHAC-F LIP PFHA Schedule of Activities**RP/KC



Month	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	
Develop Project Plan	■	■																	
Develop QA Plan	■	■																	
Project Plan and QA plan Approval			■																
Assemble the Team				■															
PFHA Kickoff Meeting						■													
Data Collection and Analysis						■	■	■	■										
First Workshop								■											Review models and identify data
Develop MMC, HMC Models							■	■	■	■	■	■							
Second Workshop -										■									Alternative Models
Develop Hazard Input Document											■	■	■	■					
Hazard Calculations													■	■	■	■			
Third Workshop														■					Feedback on Models and Hazard Calculations
Prepare PFHA Document											■	■	■	■	■	■	■		
Brief PPRP on Final Models																■			
Presentation of Findings																		■	

PFHA = Probabilistic Flood Hazard Analysis
MMC = meteorological model characterization
HMC = hydraulic/hydrologic model characterization

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SHAC-F Project Next Steps

- Complete the Workshop 2 report
  - Compile a list of example data sources for LIP analyses
  - Compile a list of models that may be appropriate for LIP analyses
  - Identify a list of resource and proponent experts that could be called on to work on an LIP study
  - Identify key points of contention and uncertainties
- Finalize the Template Project Plan for LIP PFHA
- Finalize Guidance for LIP PFHA

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SHAC-F Project Status and Conclusions

- Use of virtual approach to step through typical SSHAC steps is effective and insightful
- Presence and common understanding of PFHA framework is essential
- Certain elements of SSHAC process should be customized for LIP PFHA
- Template Project Plan for actual SHAC-F LIP PFHA is being developed and updated as project proceeds
    - A key deliverable
- Insights developed from LIP PFHA virtual study will benefit planning and implementation of SHAC-F Riverine PFHA virtual study
    - There is an opportunity to combine Riverine PFHA virtual study to address both floods without and with snowmelt

SHAC-F Riverine Flood Virtual Study

- Combine Riverine PFHA virtual study to address both floods without and with snowmelt
- Draw on lessons learned from LIP PFHA SHAC-F virtual study
    - Clearly articulate the probabilistic framework
    - Use a virtual site (the same virtual site used for the LIP PFHA SHAC-F virtual study)
        - Leverage some of the same data sources, site characterization, and understanding of hazards
- Characterize issues specific to riverine floods
    - Spatial extent and variability
        - MMC: expect to deal with multiple locations
        - MMC: expect to deal with variability and correlations within and among locations
        - HOMC/HAMC: initial and boundary conditions may vary in space
        - HOMC/HAMC: model parameters may vary in space
    - Temporal scales
        - Longer than an LIP flood
    - Watershed/river basin to site-scale flood progression
        - Different than an LIP flood
    - Nonstationarities

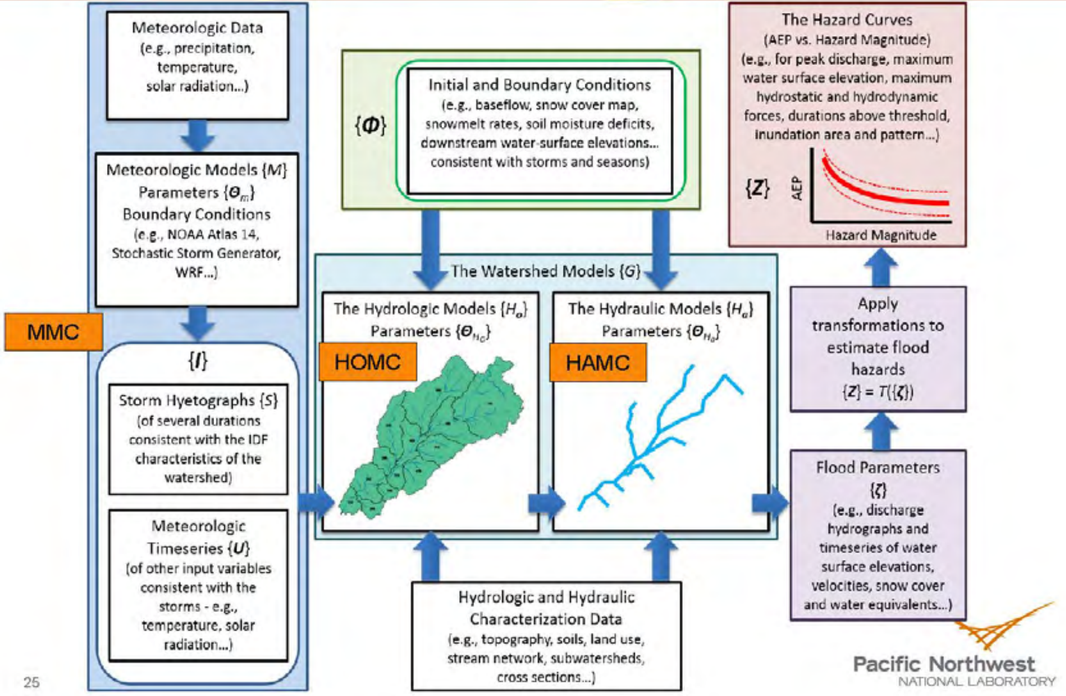
SHAC-F Riverine Flood Virtual Study (cont'd)

- Data specific to riverine floods
  - Clearly articulate raw data vs. modeled/derived data
    - Most models take input data that are derived from direct observations
  - Expect more observed/derived data to be available
    - Extent of the watershed or river basin (USGS)
    - Elevation (USGS)
    - Soil types (NRCS)
    - Land use and land cover (NRCS, NAIP)
    - Precipitation (NCEI)
    - Air temperature, solar radiation, humidity (NCEI)
    - Snowpack, snow water equivalent (NCEI, NRCS)
    - Soil moisture (NRCS)
    - Streamflow (USGS)
    - Stream channel characteristics (various)
    - Water storage and control (USACE, USGS)
  - Data related to nonstationarities
    - Changes in river basin (properties, urbanization, water management)
    - Changes in climate

SHAC-F Riverine Flood Virtual Study (cont'd)

- Models specific to riverine floods
  - HOMC
    - Lumped, semi-distributed, distributed models
  - HAMC
    - 1-D vs 2-D
    - Tightly or loosely coupled with HOMC model
    - Riverine to site-scale hydraulic model coupling (leverage LIP SHAC-F HMC?)

PFHA Framework – RF PFHA



Meteorologic Data (e.g., precipitation, temperature, solar radiation...)

Meteorologic Models $\{M\}$ Parameters $\{\Theta_m\}$ Boundary Conditions (e.g., NOAA Atlas 14, Stochastic Storm Generator, WRF...)

MMC

$\{I\}$

Storm Hyetographs $\{S\}$ (of several durations consistent with the IDF characteristics of the watershed)

Meteorologic Timeseries $\{U\}$ (of other input variables consistent with the storms - e.g., temperature, solar radiation...)

$\{\Phi\}$ Initial and Boundary Conditions (e.g., baseflow, snow cover map, snowmelt rates, soil moisture deficits, downstream water-surface elevations... consistent with storms and seasons)

The Watershed Models $\{G\}$

The Hydrologic Models $\{H_o\}$ Parameters $\{\Theta_{H_o}\}$

HOMC

The Hydraulic Models $\{H_a\}$ Parameters $\{\Theta_{H_a}\}$

HAMC

Hydrologic and Hydraulic Characterization Data (e.g., topography, soils, land use, stream network, subwatersheds, cross sections...)

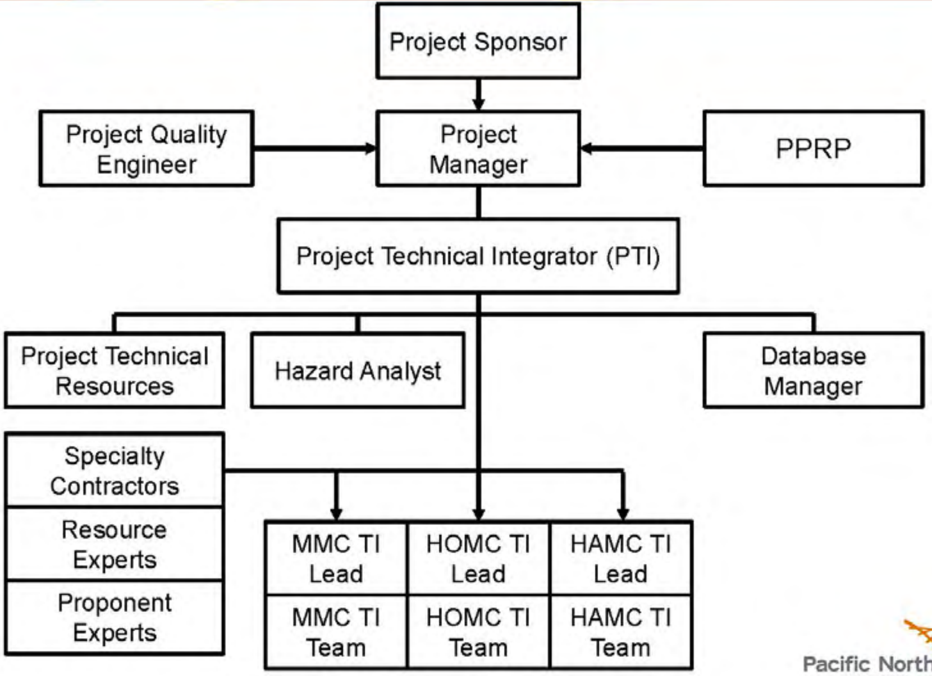
The Hazard Curves (AEP vs. Hazard Magnitude) (e.g., for peak discharge, maximum water surface elevation, maximum hydrostatic and hydrodynamic forces, durations above threshold, inundation area and pattern...)

$\{Z\}$

Apply transformations to estimate flood hazards $\{Z\} = T(\{\zeta\})$

Flood Parameters $\{\zeta\}$ (e.g., discharge hydrographs and timeseries of water surface elevations, velocities, snow cover and water equivalents...)

RF PFHA Project Structure



Project Sponsor

Project Quality Engineer

Project Manager

PPRP

Project Technical Integrator (PTI)

Project Technical Resources

Hazard Analyst

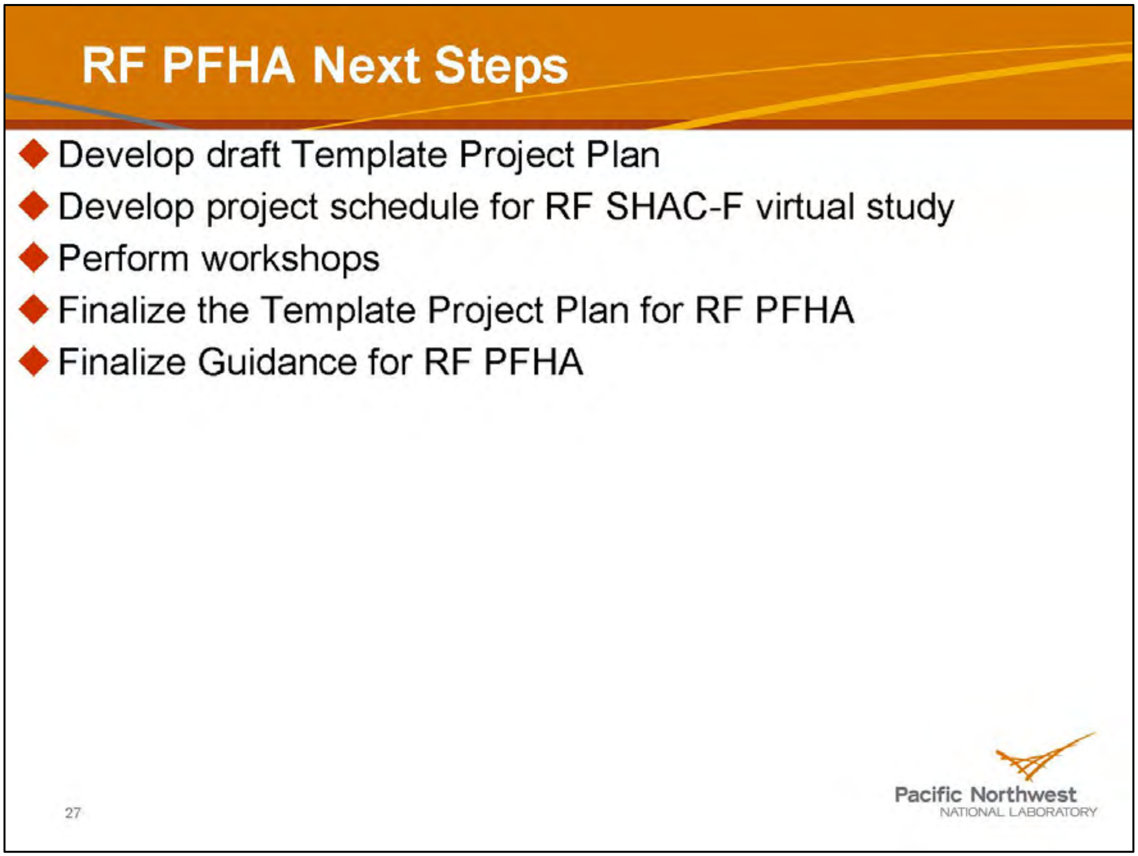
Database Manager

Specialty Contractors

Resource Experts

Proponent Experts

MMC TI Lead	HOMC TI Lead	HAMC TI Lead
MMC TI Team	HOMC TI Team	HAMC TI Team



RF PFHA Next Steps

- Develop draft Template Project Plan
- Develop project schedule for RF SHAC-F virtual study
- Perform workshops
- Finalize the Template Project Plan for RF PFHA
- Finalize Guidance for RF PFHA

Contact Information

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2.3.10.3.3 Questions and Answers

Comment:

I have no issue with your analysis or the approach, but I have a fundamental issue with expending the amount of resources that are required to do a SHAC Level 3 type of study for a site-specific implementation. Would you actually obtain new risk insights by going to that level of detail? We have talked earlier about which distribution to use when you find out at the end that all of them were within the 5th and 95th percentiles. Something similar can happen here, where many experts are spending a lot of time performing this analysis. Because the SHAC process does not lend itself to being amended, what happens if in the future you perform a paleoflood study and one of those pieces does not fit what the new data indicate. The present SHAC process, at least for seismic, would require you to go through the whole process again with these new data, again expending potential millions of dollars to get to this point. My storm surge study included an approach that was similar to a SHAC process and used logic trees. I would make that akin to a SHAC Level 1, but in my opinion, in a case that is very site specific, utilities will find it untenable to perform an analysis at a SHAC Level 3.

Response: NRC Program Manager

We are not recommending a specific level of SHAC, but, for the purposes of working through the ideas, we felt that at a SHAC Level 3 we can gain the insights and downselect to identify what would be needed for a SHAC Level 2 or Level 1. If we had done this at a SHAC Level 2, we would not have gleaned any information about what a Level 3 might require. The purpose of this project was not to decide what level of SHAC is needed for any particular analysis, whether site specific or not. We chose SHAC Level 3 because we thought that was the right level to gain the desired insights.

Response: Rajiv Prasad:

With regard to the new data, that is one of the reasons we want to use a Bayesian framework, under which you do not need to perform the whole study again. You can basically say that I already have my prior historical inferencing and I need to update that. The updating could be done at a lower level than the SHAC Level 3.

Question:

Does a SHAC Level 3 for flood really need to mirror the same level of effort and time required for a SHAC Level 3 for seismic? Looking at the big picture and fully recognizing the project’s purpose of adding structure, how does this apply in the sense that hydrology and meteorology are imbedded as part of the analysis? A seismic analysis is easier in that you can do a SHAC at one site and that will require considering the full gamut of issues, including the hydrologic response, versus asking whether we perform a SHAC at the level of a localized area? Do we develop a hazard aspect only on precipitation or a very specific subset of that?

Response:

In a seismic analysis, you have the advantage that you have a source and it could include an entire region. Flooding is rather site specific. Even in a large watershed, you have to make sure that watershed analysis is appropriate for each particular site of interest, which makes it more complicated. Your point is well taken in asking whether we need to follow all of those steps that the seismic community does. Apart from the issue of data versus model, one challenge is whether the hydrologists understand what they need to do. The nuclear community has performed such analyses for a while, but the hydrologists do not quite know what we mean, for example, for local intense precipitation, in some cases. We also note the lack of a framework. On the seismic side, over the years, experts have come to an agreement on what the framework looks like for performing the probabilistic seismic hazard assessments. We do not have such an agreed-upon framework for flooding, and that needs to be worked through with all of the experts to give the context for the analysis. In addition, such a framework needs to represent the community, not the personal bias of a particular hydrologist. In SHAC, we want to represent the full body and range of the technically informed community. We might come to the conclusion that we will have to tailor SHAC even more for flooding than we already have. The project document will include some of the lessons learned, and this will be an ongoing process. When we perform a SHAC in a real situation, we will work through the practical nature of the computations. These include how many models and how many people should be involved, what resources should be devoted? Is SHAC Level 1 sufficient, or is Level 2 needed? Do we need to go to SHAC Level 3? What is the risk significance in the first place? All of these need to be worked through as we continue the project, develop these terminologies and this whole approach, and try to apply it.

Question:

My question relates to the variation in the data and how they fit, as well as the data quality objectives. As presented, the SHAC process lacks explicit actual review of the data quality objectives and whether the data fit. You mentioned that if the data do not fit the model, the data could be rejected. However, this means that you are relying on data and that you try to strive to obtain more data to compare to the model rather than relying on the specific analysis. Ultimately, you need to consider the data quality and the data quality objectives and how everything fits your objectives for the analysis. I agree that you are looking for a risk, but now you are dealing with hazard, which is different from risk. The risk includes different types of uncertainties and impacts, and this could be specific to the actual conditions that you are addressing. I also suggest that you include the data quality objectives process in order to accept or reject the data. It is possible that you may reject data that are very important and significant, and you may call certain data outliers that are actually important.

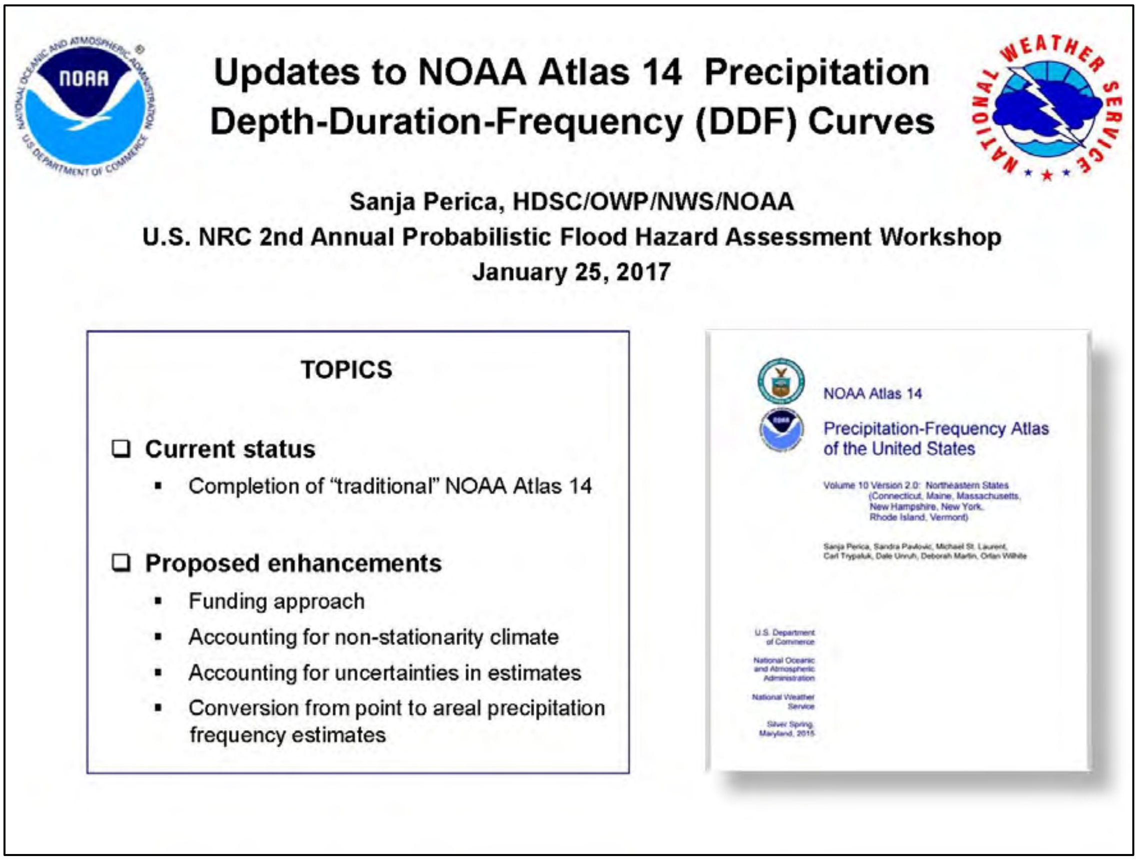
Response:

Quality assurance, which relates not only to data, takes place throughout the process. We will apply the process from the seismic side to the flood side. Sometimes we obtain Federal agency data from the agency’s Web site, and the agency indicates that it has already applied a data quality control process and only publishes processed data. We sometimes rely on such assurances, but, in addition, whenever there is a project activity that transforms the data and tries to use them in the analysis, we will subject the data to quality control. With regard to your statement that we are only dealing with that hazard and not the risk, I completely agree that this is a hazard analysis. We are trying to determine a probabilistic description of the hazard. The framework that I presented this morning tries to do this and we are trying to use the best information and tools available to try to build a sound foundational basis in probability and statistics. We will then go from there to say that we have come up with uncertainties that in the SHAC process allow you to say that you have considered all sources of uncertainties that can arise, not only from variabilities, but also from people's personal opinions and the way they do modeling. The question still remains on how to take these hazard assessments and then interface with the risk community. What products do we need to give you to be able to use them in a human reliability analysis or PRA, and where are those interfaces? We need to have further conversation between the risk community and the hazard community.

2.3.11 Day 3: Session 3D - Panel Discussion

This session included panel presentations and discussion on Probabilistic Flood Hazard Assessment Research Activities in Partner Agencies, chaired by Joseph Kanney of the NRC.

2.3.11.1 National Oceanic and Atmospheric Administration/National Weather Service (NOAA/NWS), Sanja Perica, Ph.D. (Session 3D-1-A; ADAMS Accession No. ML17054C488)



Updates to NOAA Atlas 14 Precipitation Depth-Duration-Frequency (DDF) Curves

Sanja Perica, HDSC/OWP/NWS/NOAA
U.S. NRC 2nd Annual Probabilistic Flood Hazard Assessment Workshop
January 25, 2017

TOPICS

❑ **Current status**
  - Completion of "traditional" NOAA Atlas 14

❑ **Proposed enhancements**
  - Funding approach
  - Accounting for non-stationarity climate
  - Accounting for uncertainties in estimates
  - Conversion from point to areal precipitation frequency estimates

NOAA Atlas 14

Precipitation-Frequency Atlas of the United States

Volume 10 Version 2.0: Northeastern States
(Connecticut, Maine, Massachusetts,
New Hampshire, New York,
Rhode Island, Vermont)

Sanja Perica, Sandra Pavlovic, Michael St. Laurent,
Carl Trypaluk, Dale Unruh, Deborah Martin, Orlan Wilhite

U.S. Department of Commerce

National Oceanic and Atmospheric Administration

National Weather Service

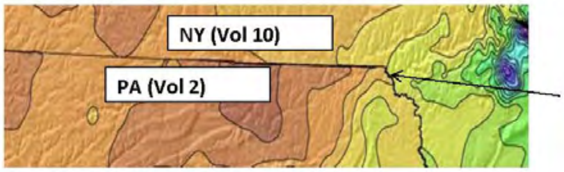
Silver Spring, Maryland, 2015

NOAA Atlas 14 current status

- ☐ Funding: work performed at request of users and funded by users

- ☐ Vol 1 (2004); data up to 2001
- ☐ Vol 11 (2018); data up to 2017 (+16 years)
- ☐ Vol 12 for remaining 5 NW states (funding not secured yet). Latest updates from 1964 & 1973.

- ☐ Approach causes inconsistencies at boundaries of adjacent volumes



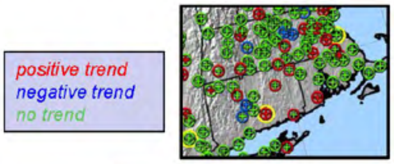
100-yr 24-hr estimate (inches):
4.4 (Vol 2) vs 7.1 (Vol 10)

Need to secure funding to update estimates for the whole contiguous US simultaneously!

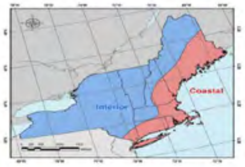
Accounting for non-stationary climate. Testing NA14 assumption of stationary AMS

☐ NA14 TESTS

At gauged locations.
Applying parametric and non-parametric tests for trends in AMS mean and variance



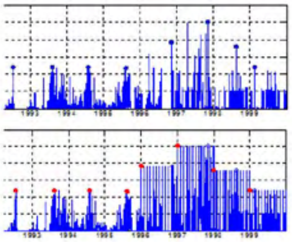
Regional.
Testing H0: no serial correlation at 5% level in normalized AMS regressed against time



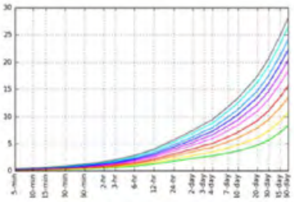
No spatially consistent trends in AMS data in Vols 1 -10, but could it be the data?

☐ AMS vs PDS

- AMS-based analysis not sensitive to change in **frequency** of heavy events.
- Replace AMS with PDS?



No difference in AMS



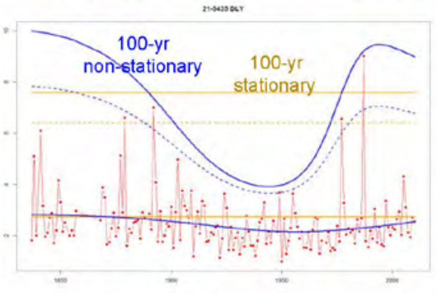
No difference in DDF

Accounting for non-stationary climate.
Preliminary findings, unresolved questions

❑ METHODOLOGY CHANGE

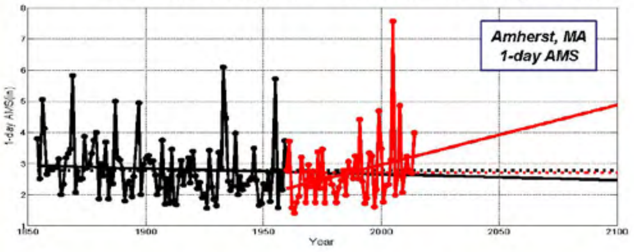
LMOM (in)	MLE (in)	MLE(t) (in)	LMOM vs MLE % change	MLE(t) vs MLE %change
15.0	20.0	20.7	33%	4%

❑ SELECTION OF NON-STATIONARY MODEL



❑ CHOICE OF PERIOD OF RECORD & DESIGN LIFETIME

- What period of record to use in the analysis?
- How much extrapolation to account for design lifetime?



❑ INCORPORATING CLIMATE PROJECTIONS

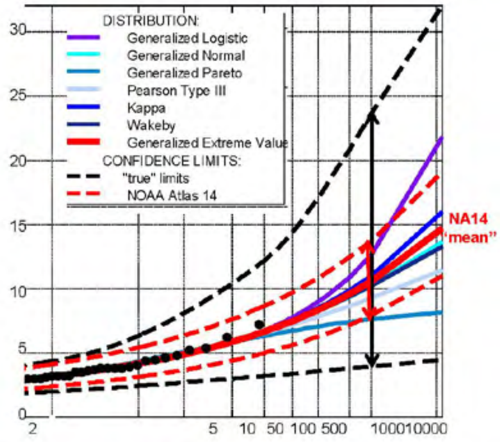
- Need to develop scientifically defensible methods
- Could this product provide useful information about extreme precipitation at spatial (point) and temporal scales of interest (sub-daily)?

Need to ensure we are not doing more harm than good!

Accounting for uncertainty in estimates – confidence intervals

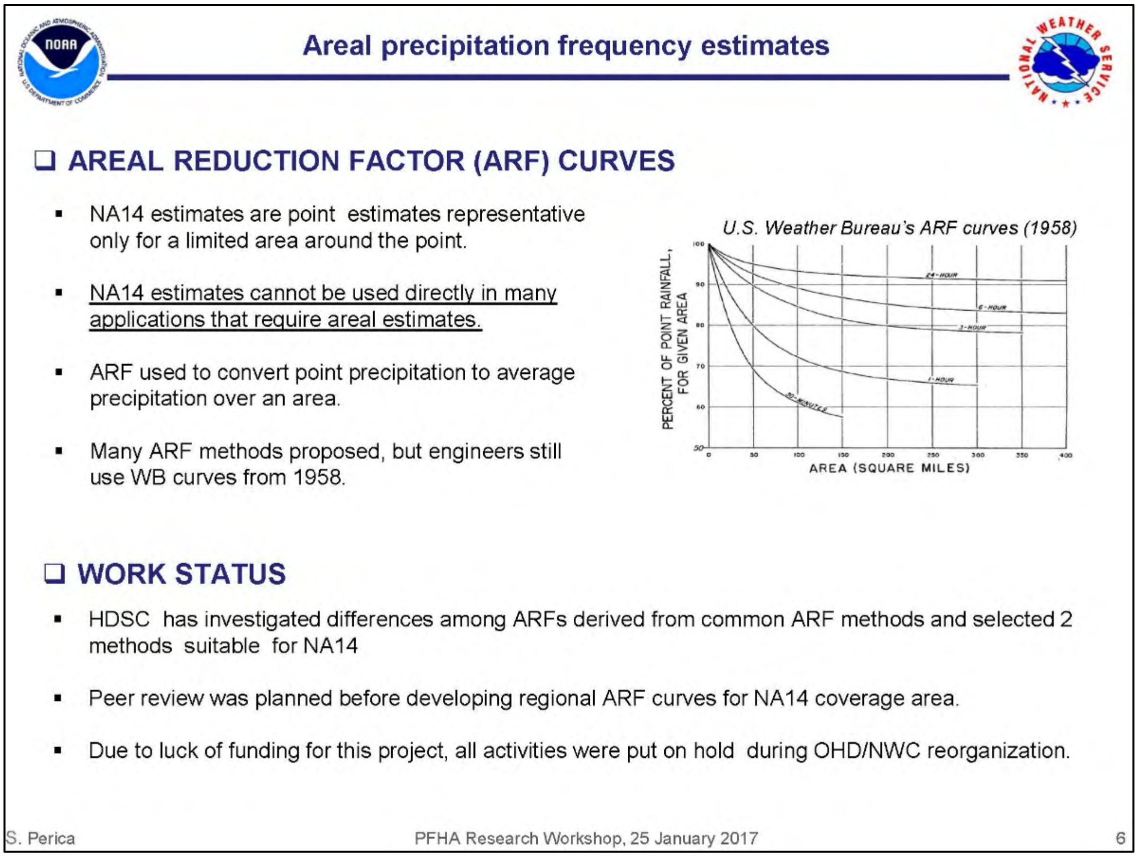
❑ NA14 CONFIDENCE INTERVALS

- Many users consider only "mean values" and don't consider uncertainties.
- NA14 does take into account many factors: degree of confidence, sample size, exceedance probability, spatial correlation, …
- NA14 <u>does not account for all uncertainties</u>: distribution selection, parameterization method, … ➔ NA14 confidence intervals underestimate the "true" confidence intervals.



SHOULD WE EXTRAPOLATE ESTIMATES BEYOND 200-YR (500-YR) USING NA14 METHODS?
NO, BUT…

- In mid-2000 HDSC considered not publishing estimates above 200-yr; solicited opinions from users
- Users' responses summarized here: http://hdsc.nws.noaa.gov/hdsc/pfds/docs/1000-yr_responses.pdf
- Some users routinely extrapolate NA14 estimates up to 10,000-yr ARI or more



Areal precipitation frequency estimates

❑ AREAL REDUCTION FACTOR (ARF) CURVES

- NA14 estimates are point estimates representative only for a limited area around the point.
- NA14 estimates cannot be used directly in many applications that require areal estimates.
- ARF used to convert point precipitation to average precipitation over an area.
- Many ARF methods proposed, but engineers still use WB curves from 1958.

U.S. Weather Bureau's ARF curves (1958)

❑ WORK STATUS

- HDSC has investigated differences among ARFs derived from common ARF methods and selected 2 methods suitable for NA14
- Peer review was planned before developing regional ARF curves for NA14 coverage area.
- Due to luck of funding for this project, all activities were put on hold during OHD/NWC reorganization.

S. Perica PFHA Research Workshop, 25 January 2017 6

2.3.11.2 *U.S. Army Corps of Engineers*, Christopher Dunn, P.E., D.WRE., Norberto Nadal-Caraballo, Ph.D., John England, Ph.D., P.E., P.H., D.WRE. (Session 3D-1-B; ADAMS Accession No. ML17054C489)

U.S. Army Corps of Engineers H&H Research Activities

2nd Annual PFHA Research Workshop

Christopher Dunn, P.E., D.WRE
Hydrologic Engineering Center
Institute for Water Resources

John England, Ph.D, P.E., P.H., D. WRE
Risk Management Center
Institute for Water Resources

Norberto Nadal-Caraballo, Ph.D
Coastal Hydraulics Laboratory
Engineer Research and Development Center

January 25, 2017

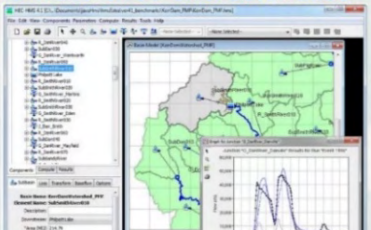
US Army Corps of Engineers
BUILDING STRONG®
www.hec.usace.army.mil

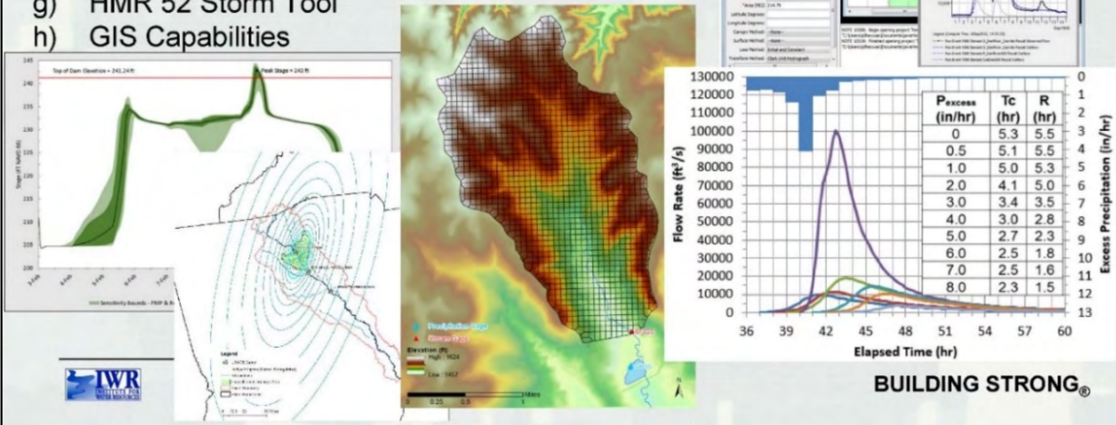
Hydrologic Modeling System

HEC-HMS R&D Efforts

a) Energy Balance Snowmelt
b) Sampling Starting Snow Water Equivalent (meteorologic variables)
c) Classical MC and New MCMC Optimization and Uncertainty
d) Variable Clark UH
e) 2D Overland Flow and 2D sediment Transport
f) Flood Forecasting
g) HMR 52 Storm Tool
h) GIS Capabilities

Computes streamflow throughout a river basin given precipitation and watershed characteristics





P_{excess} (in/hr)	Tc (hr)	R (hr)
0	5.3	5.5
0.5	5.1	5.5
1.0	5.0	5.3
2.0	4.1	5.0
3.0	3.4	3.5
4.0	3.0	2.8
5.0	2.7	2.3
6.0	2.5	1.8
7.0	2.5	1.6
8.0	2.3	1.5

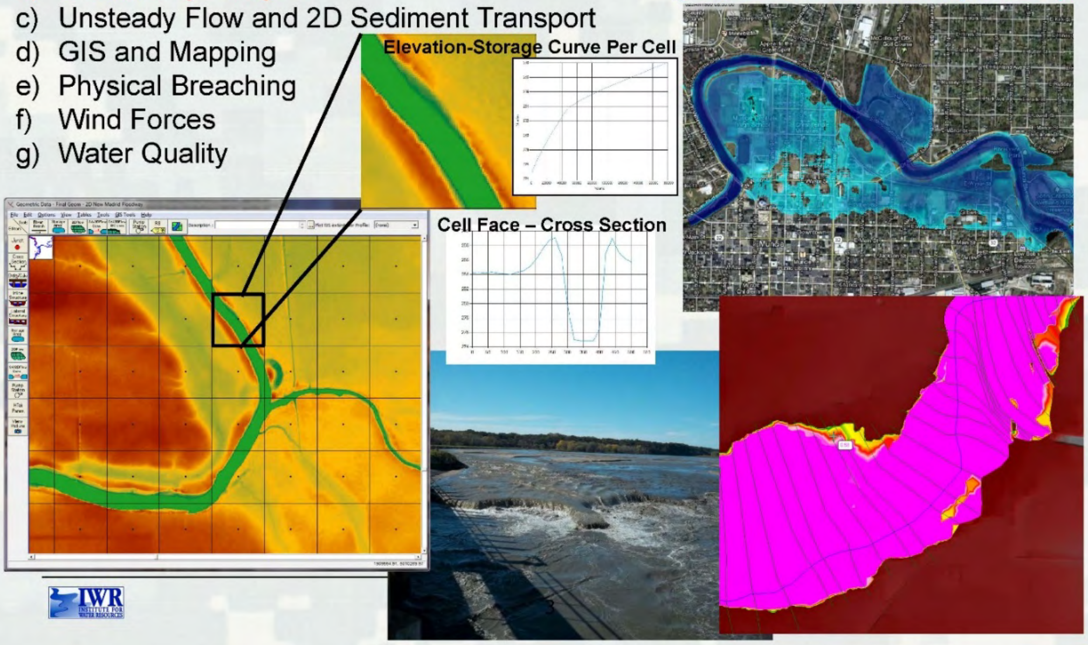
BUILDING STRONG®

River Analysis System

HEC-RAS R&D Efforts

a) 2D Hydraulics
b) Uncertainty Analysis
c) Unsteady Flow and 2D Sediment Transport
d) GIS and Mapping
e) Physical Breaching
f) Wind Forces
g) Water Quality

Computes river velocities, stages, profiles, and inundated areas given stream flow and geometry

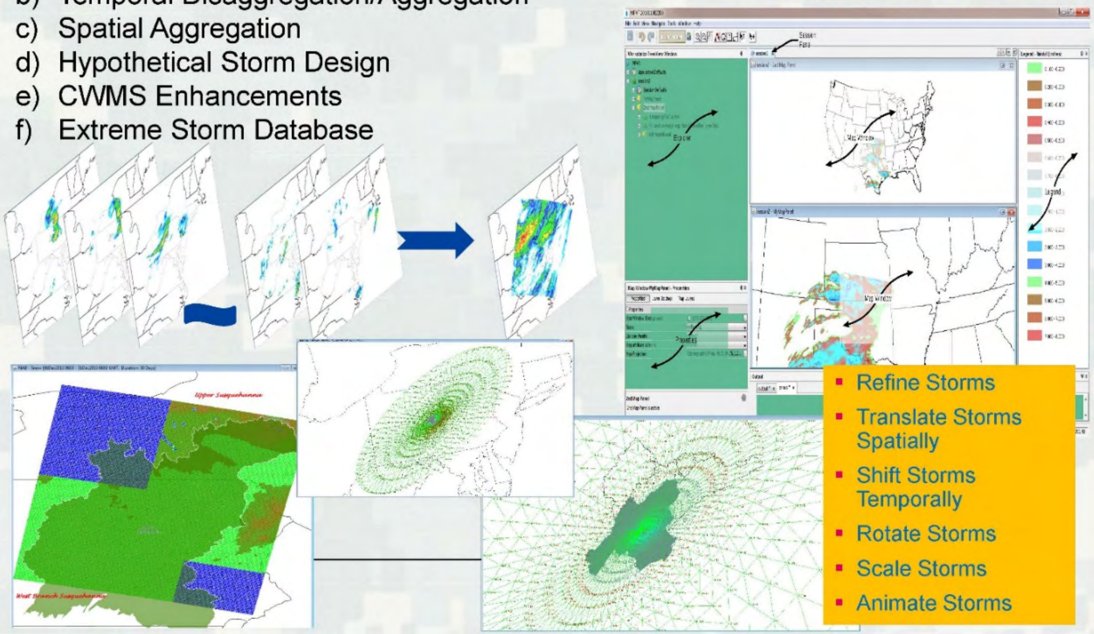


Meteorologic Visualization Utility Engine

HEC-MetVue R&D Efforts

a) Data Manipulation to Create Modified Storms
b) Temporal Disaggregation/Aggregation
c) Spatial Aggregation
d) Hypothetical Storm Design
e) CWMS Enhancements
f) Extreme Storm Database

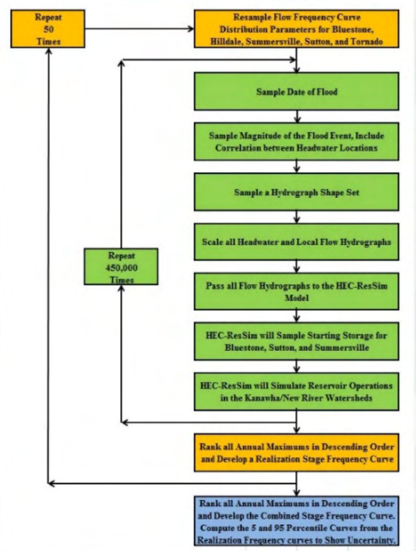
Visualize storm events and computes optimal/standardized design storms given historic events

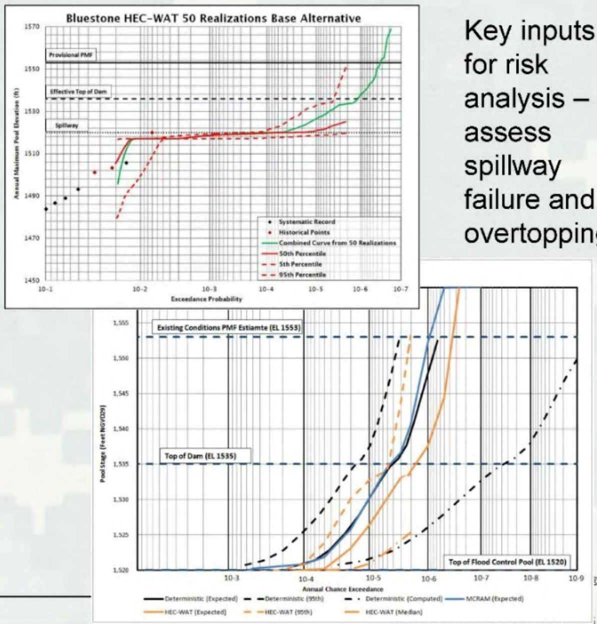


- Refine Storms
- Translate Storms Spatially
- Shift Storms Temporally
- Rotate Storms
- Scale Storms
- Animate Storms

Hydrologic Hazard Team
Bluestone Dam, WV Example DSMS

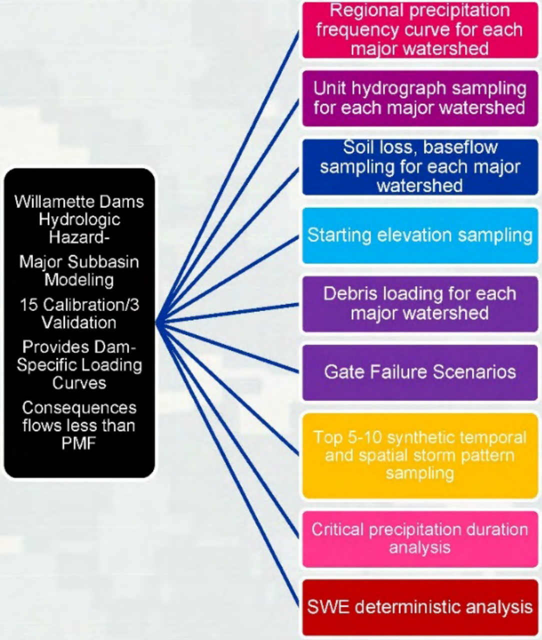
Flow and Reservoir Pool Frequency (HEC-WAT), subsequent MCRAM runs





Key inputs for risk analysis – assess spillway failure and overtopping

Willamette Dams, OR
Hydrologic Hazards



Willamette Dams Hydrologic Hazard-

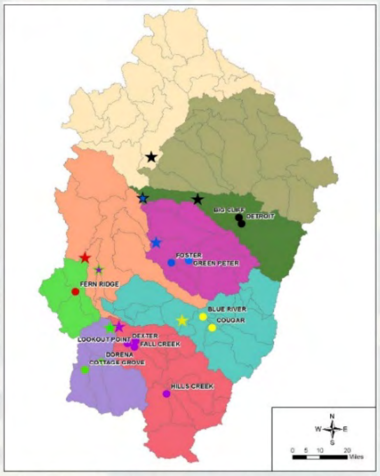
Major Subbasin Modeling

15 Calibration/3 Validation

Provides Dam-Specific Loading Curves

Consequences flows less than PMF

- Regional precipitation frequency curve for each major watershed
- Unit hydrograph sampling for each major watershed
- Soil loss, baseflow sampling for each major watershed
- Starting elevation sampling
- Debris loading for each major watershed
- Gate Failure Scenarios
- Top 5-10 synthetic temporal and spatial storm pattern sampling
- Critical precipitation duration analysis
- SWE deterministic analysis

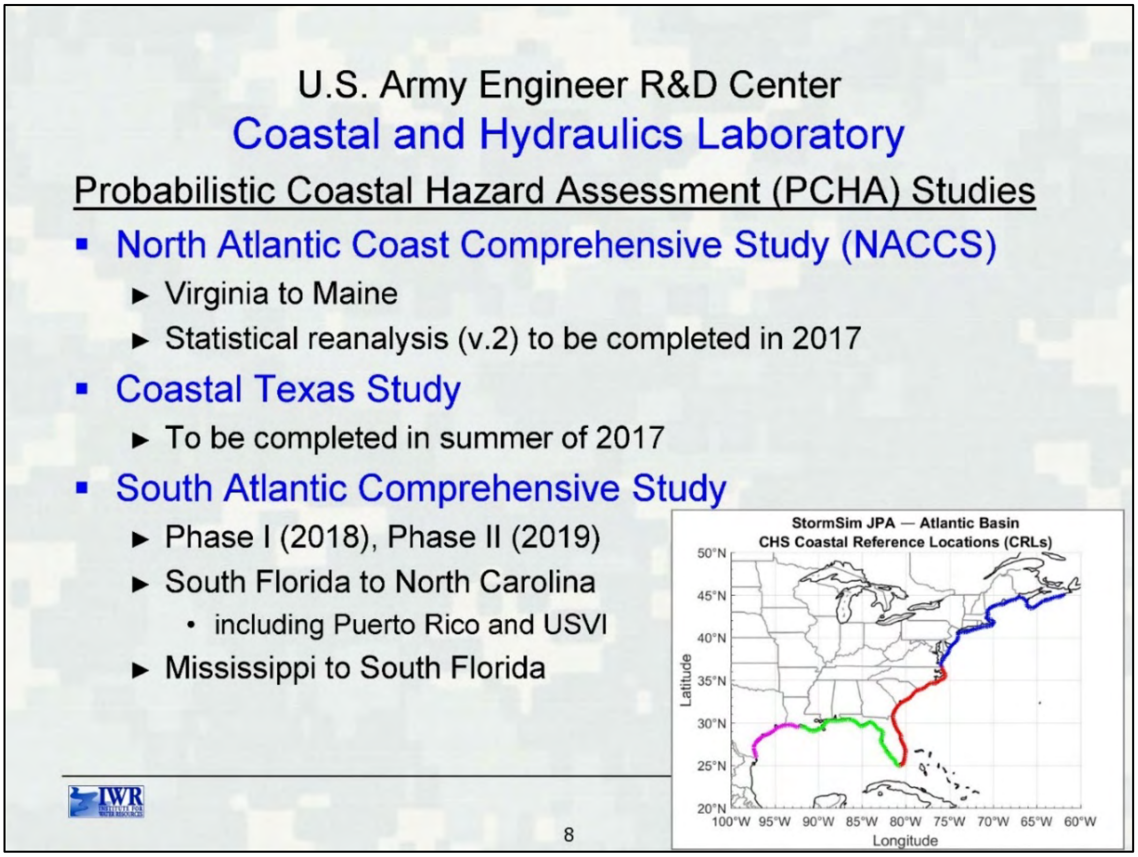


Hydrologic risk estimates – 7 key dams
HEC-WAT (HMS, ResSim, sampler)
System operations

U.S. Army Engineer R&D Center
Coastal and Hydraulics Laboratory

Probabilistic Coastal Hazard Assessment (PCHA) Products

- StormSim – stochastic storm simulation system
  - Used for joint probability analysis of coastal storm hazards.
  - GUI in development for select statistical tools.
- CSTORM modeling system
  - Standardizes application of high-resolution, highly skilled numerical models.
  - Consists of WAM for deep water waves, and tightly two-way coupled ADCIRC and STWAVE for storm surge and nearshore waves.
- Coastal Hazards System (CHS)
  - National coastal storm hazard data resource, spanning practical probability and forcing-parameter spaces.
  - Contains numerical and probabilistic modeling results including storm surge, astronomical tide, waves, currents, and wind.



U.S. Army Engineer R&D Center

Coastal and Hydraulics Laboratory

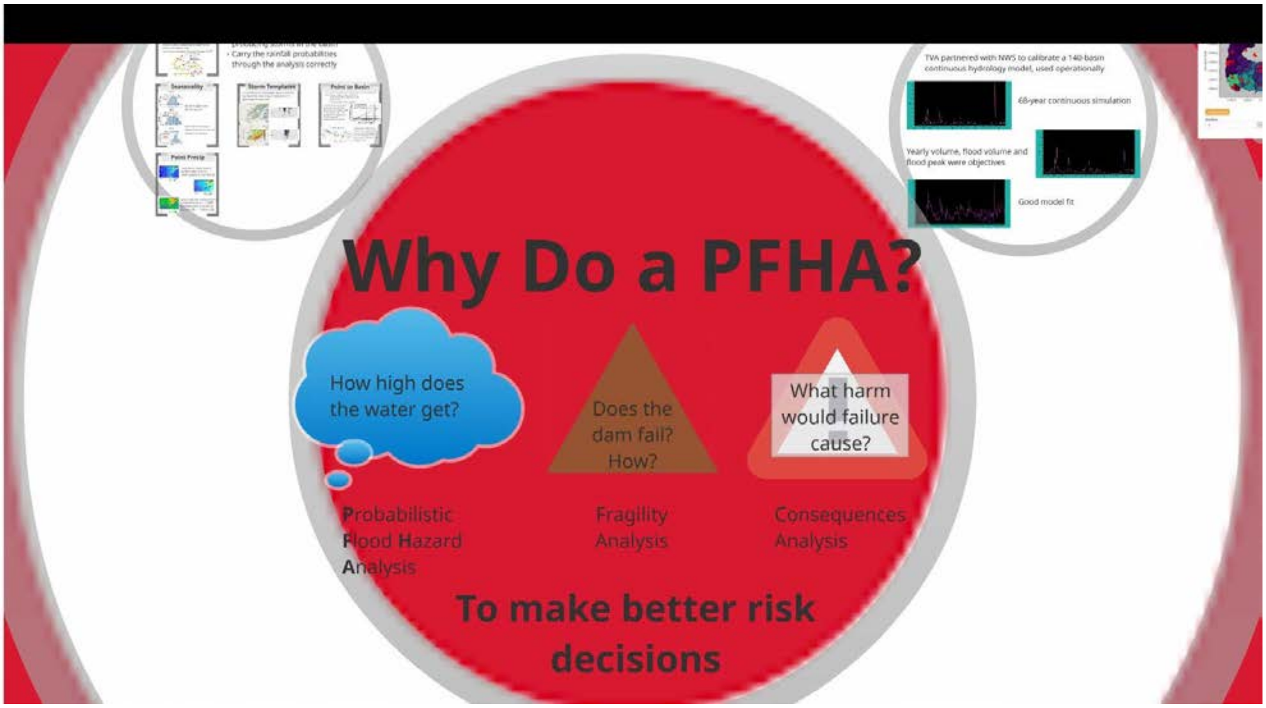
Probabilistic Coastal Hazard Assessment (PCHA) Studies

- North Atlantic Coast Comprehensive Study (NACCS)
  - Virginia to Maine
  - Statistical reanalysis (v.2) to be completed in 2017
- Coastal Texas Study
  - To be completed in summer of 2017
- South Atlantic Comprehensive Study
  - Phase I (2018), Phase II (2019)
  - South Florida to North Carolina
    - including Puerto Rico and USVI
  - Mississippi to South Florida

StormSim JPA — Atlantic Basin
CHS Coastal Reference Locations (CRLs)

8

2.3.11.3 *Tennessee Valley Authority (TVA)*, Curt Jawdy, P.E. (Session 3D-1-C; ADAMS Accession No. ML17054C490)



- Carry the rainfall probabilities through the analysis correctly

TVA partnered with NWS to calibrate a 140-basin continuous hydrology model, used operationally

68-year continuous simulation

Yearly volume, flood volume and flood peak were objectives

Good model fit

Why Do a PFHA?

How high does the water get?

Does the dam fail? How?

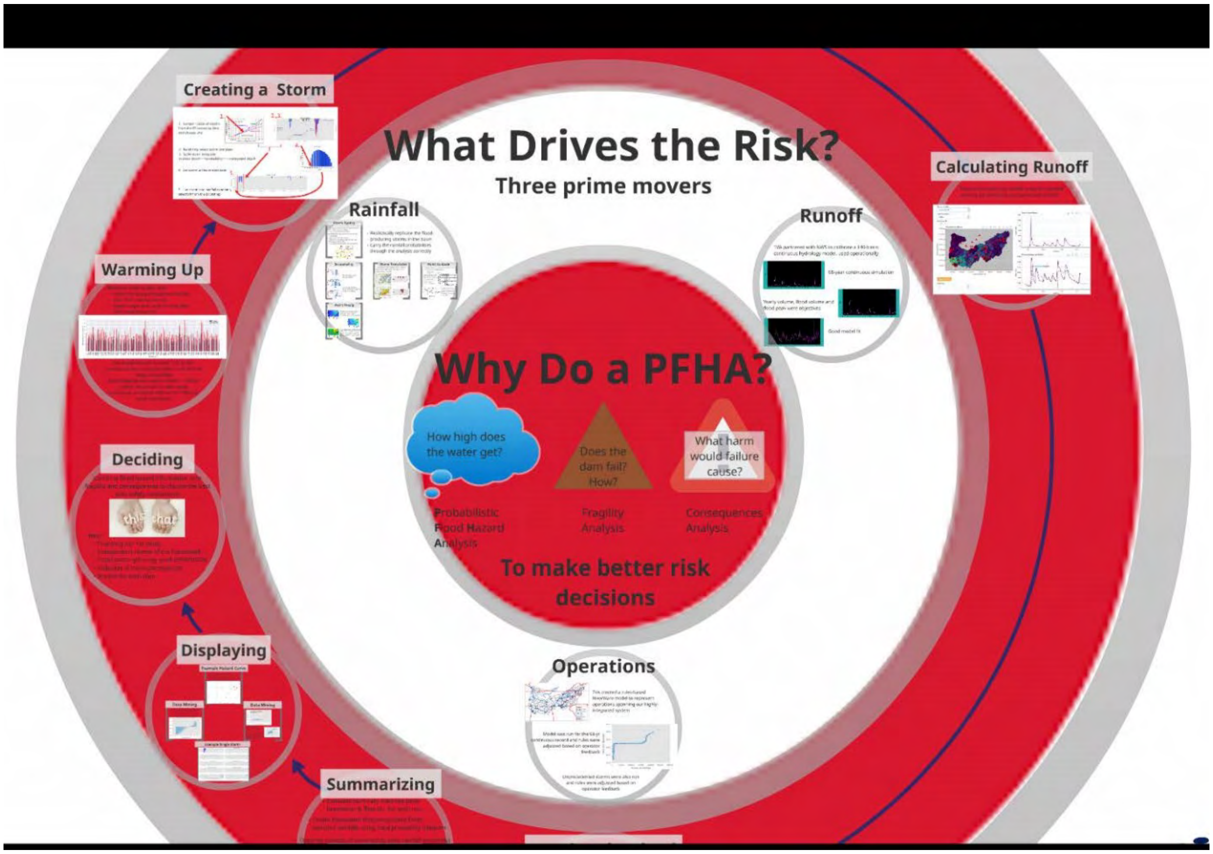
What harm would failure cause?

Probabilistic Flood Hazard Analysis

Fragility Analysis

Consequences Analysis

To make better risk decisions



What Drives the Risk?

Three prime movers

Creating a Storm

Calculating Runoff

Rainfall

Runoff

Warming Up

Why Do a PFHA?

How high does the water get?

Does the dam fail? How?

What harm would failure cause?

Probabilistic Flood Hazard Analysis

Fragility Analysis

Consequences Analysis

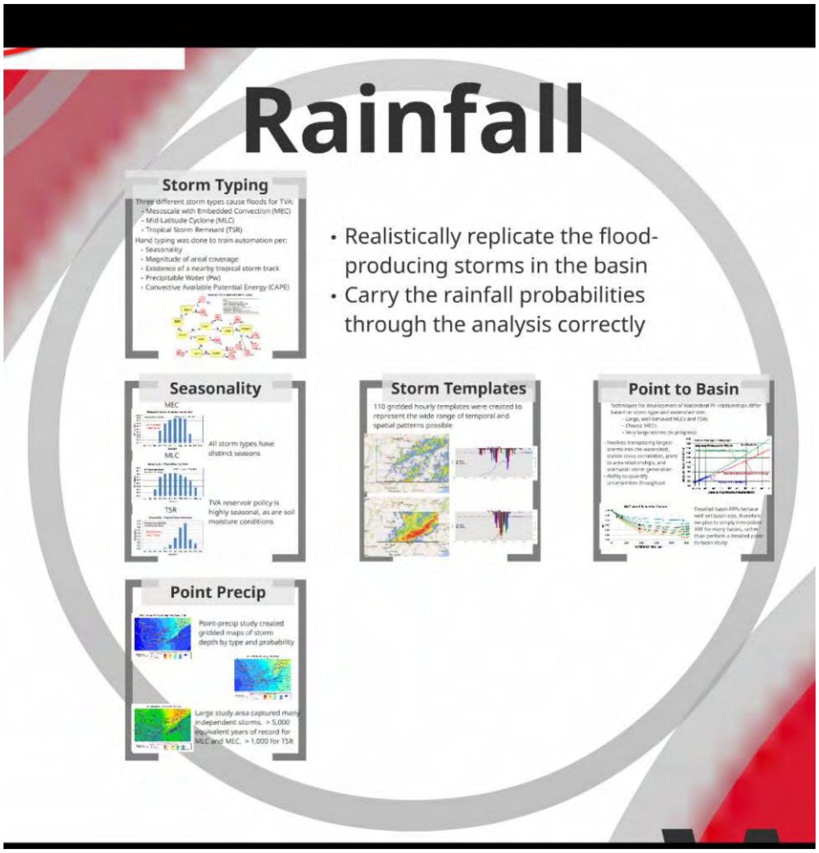
To make better risk decisions

Deciding

Displaying

Operations

Summarizing



Rainfall

- Realistically replicate the flood-producing storms in the basin
- Carry the rainfall probabilities through the analysis correctly

Storm Typing

Three different storm types cause floods for TVA:
- Mesoscale with Embedded Convection (MEC)
- Mid-Latitude Cyclone (MLC)
- Tropical Storm Remnant (TSR)

Hand typing was done to train automation per:
- Seasonality
- Magnitude of areal coverage
- Existence of a nearby tropical storm track
- Precipitable Water (Pw)
- Convective Available Potential Energy (CAPE)

Seasonality

All storm types have distinct seasons

TVA reservoir policy is highly seasonal, as are soil moisture conditions

Storm Templates

110 gridded hourly templates were created to represent the wide range of temporal and spatial patterns possible

Point to Basin

Techniques for development of Watershed PF relationships differ based on storm type and watershed size:
- Large, well-behaved MLCs and TSRs
- Chaotic MECs
- Very large storms (in progress)

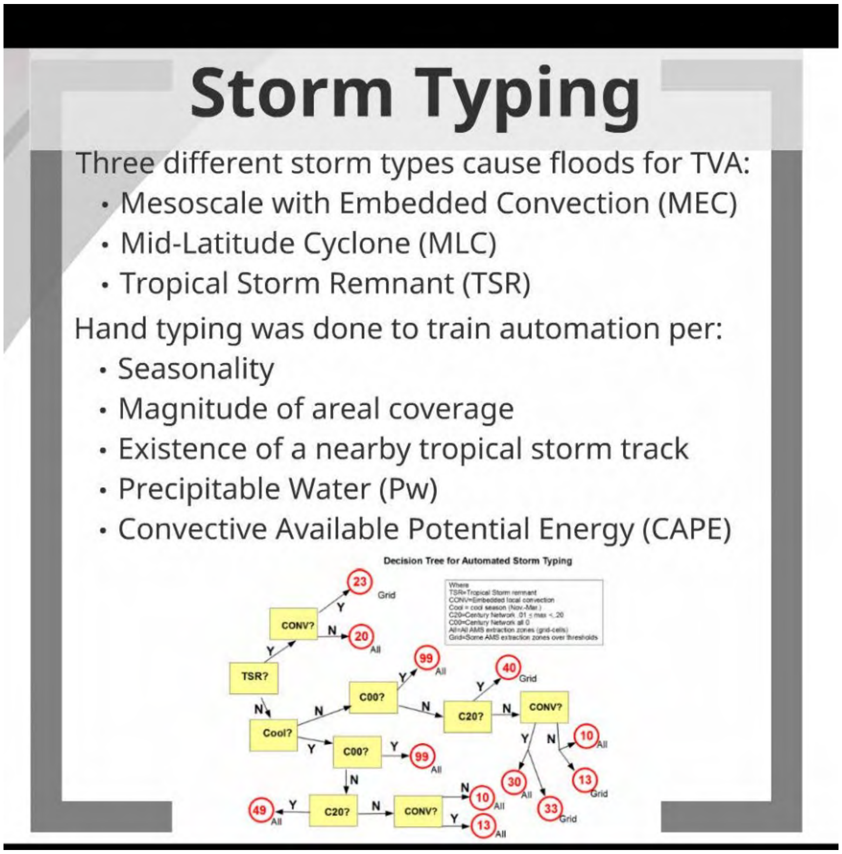
- Involves transposing largest storms into the watershed, station cross correlation, point to area relationships, and stochastic storm generation
- Ability to quantify uncertainties throughout

Detailed basin ARFs behave well wrt basin size, therefore we plan to simply interpolate ARF for many basins, rather than perform a detailed point to basin study

Point Precip

Point-precip study created gridded maps of storm depth by type and probability

Large study area captured many independent storms. > 5,000 equivalent years of record for MLC and MEC. > 1,000 for TSR



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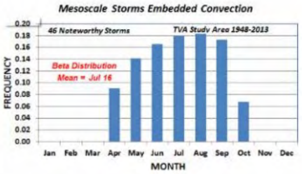
Decision Tree for Automated Storm Typing

Where
TSR=Tropical Storm remnant
CONV=Embedded local convection
Cool = cool season (Nov.-Mar.)
C20=Century Network .01 ≤ max <.20
C00=Century Network all 0
All=All AMS extraction zones (grid-cells)
Grid=Some AMS extraction zones over thresholds

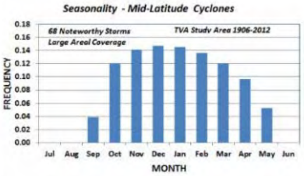
Seasonality

MEC

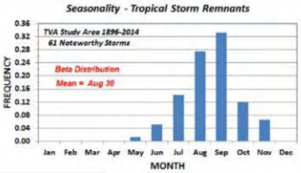


All storm types have distinct seasons

MLC



TSR



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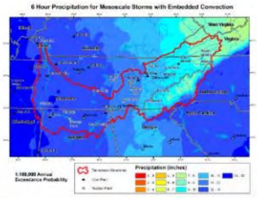

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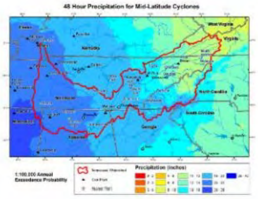

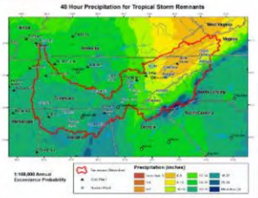

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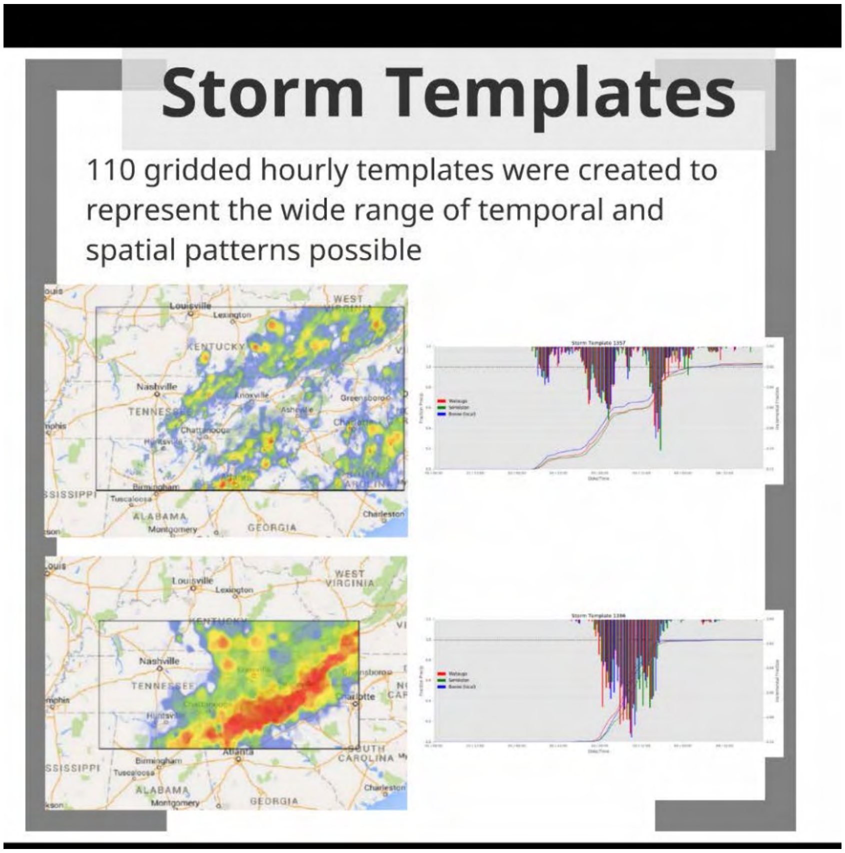
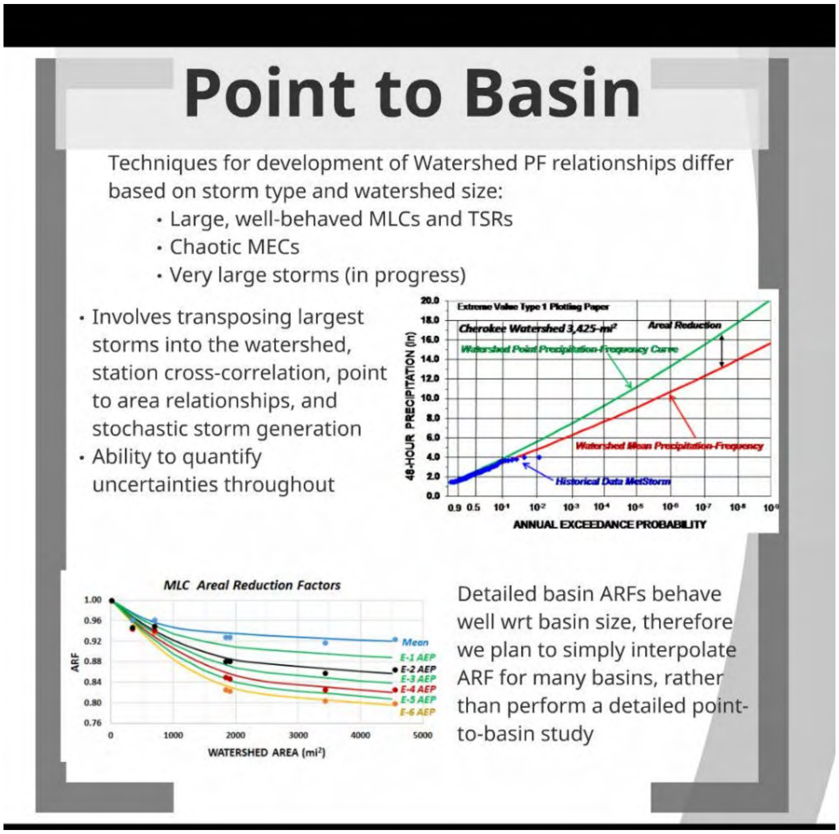


Storm Templates

110 gridded hourly templates were created to represent the wide range of temporal and spatial patterns possible



Point to Basin

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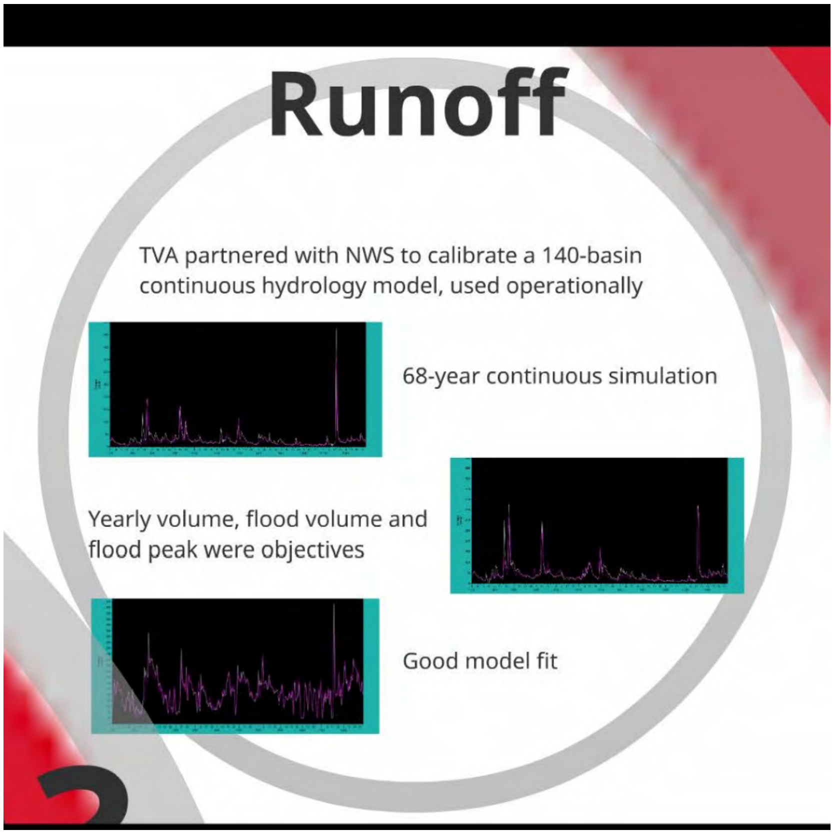

Runoff

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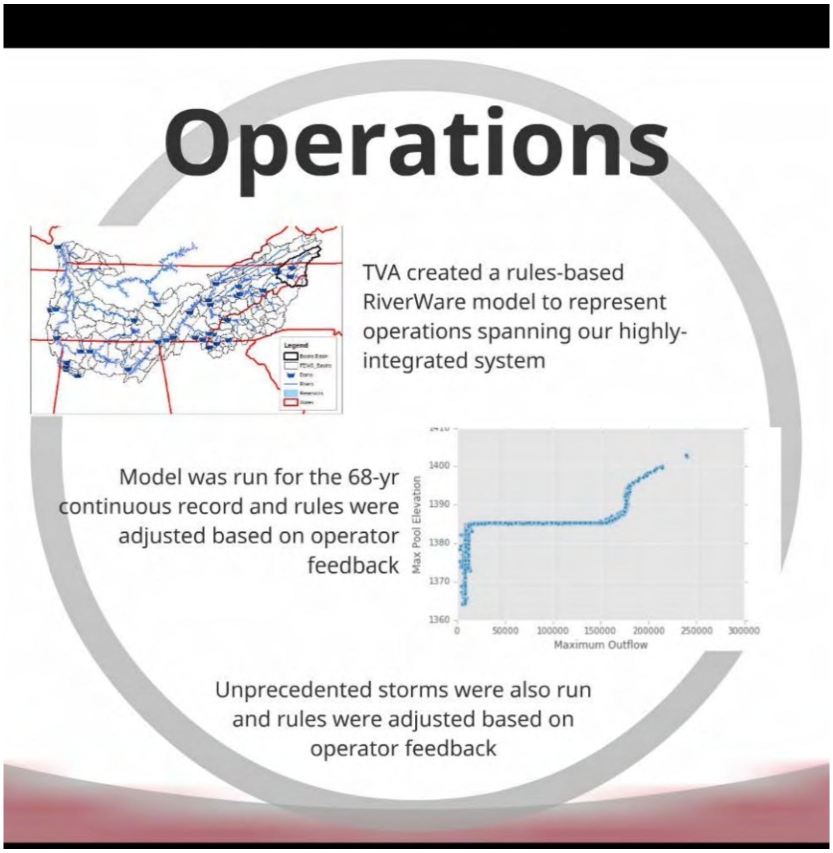
68-year continuous simulation

Yearly volume, flood volume and flood peak were objectives

Good model fit

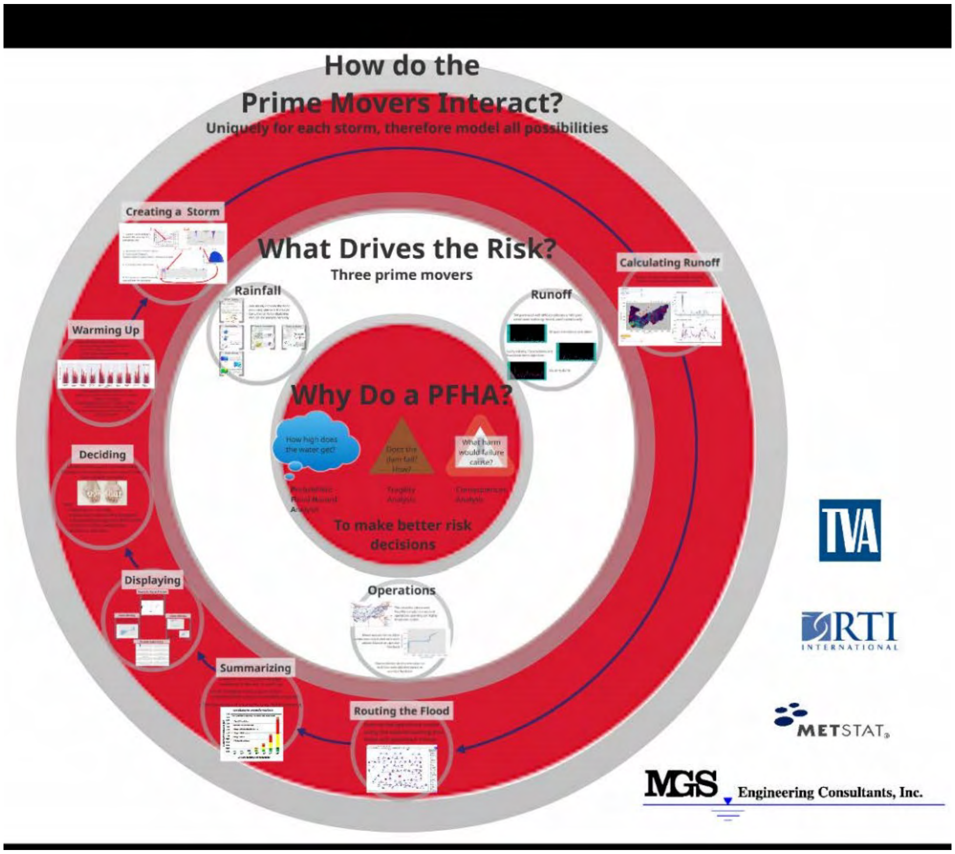


Operations

TVA created a rules-based RiverWare model to represent operations spanning our highly-integrated system

Model was run for the 68-yr continuous record and rules were adjusted based on operator feedback

Unprecedented storms were also run and rules were adjusted based on operator feedback



How do the Prime Movers Interact?

Uniquely for each storm, therefore model all possibilities

What Drives the Risk?

Three prime movers

Why Do a PFHA?

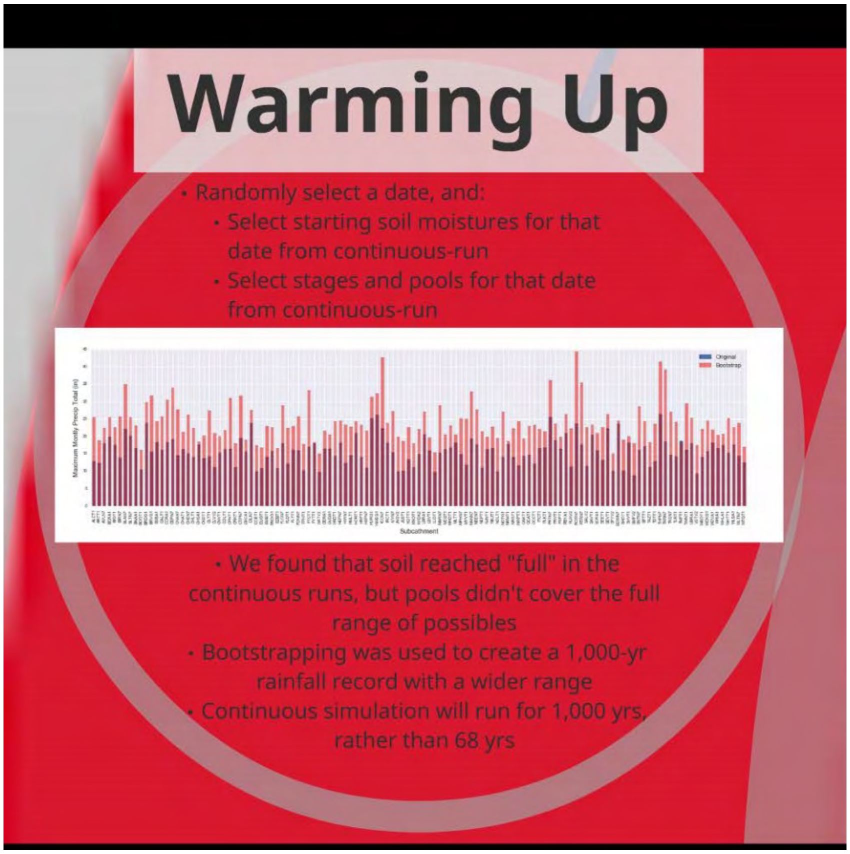
To make better risk decisions

TVA

RTI INTERNATIONAL

METSTAT

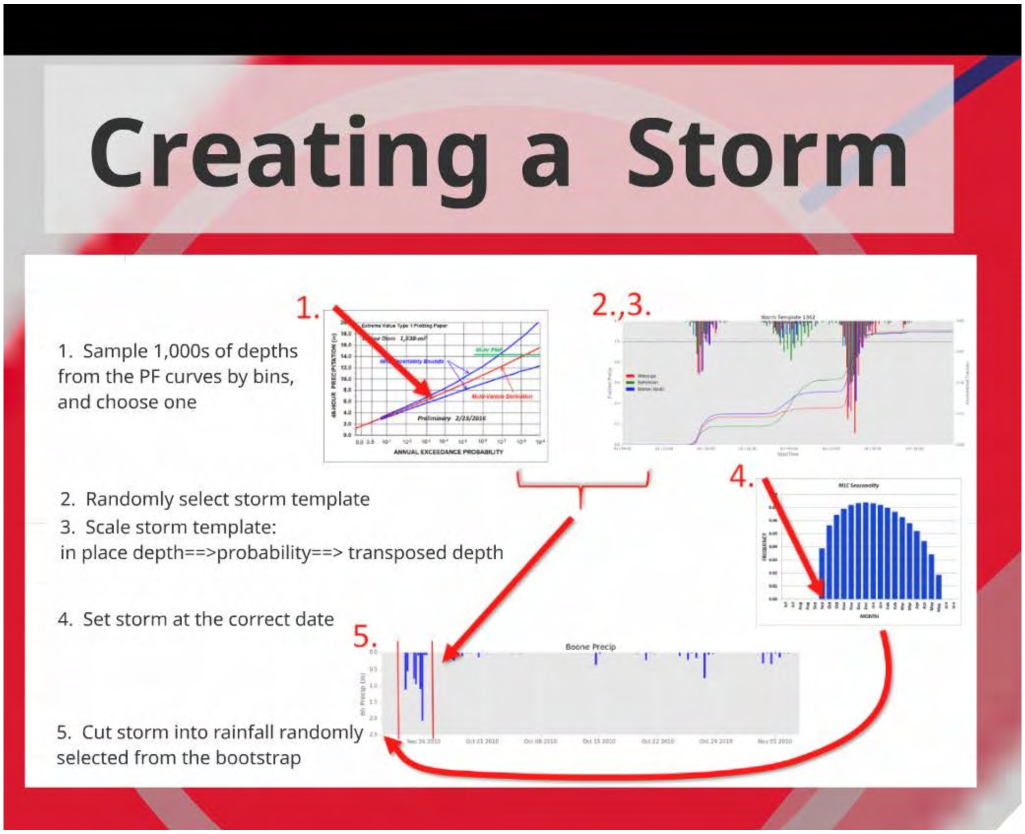
MGS Engineering Consultants, Inc.



Warming Up

- Randomly select a date, and:
  - Select starting soil moistures for that date from continuous-run
  - Select stages and pools for that date from continuous-run

- We found that soil reached "full" in the continuous runs, but pools didn't cover the full range of possibles
- Bootstrapping was used to create a 1,000-yr rainfall record with a wider range
- Continuous simulation will run for 1,000 yrs, rather than 68 yrs



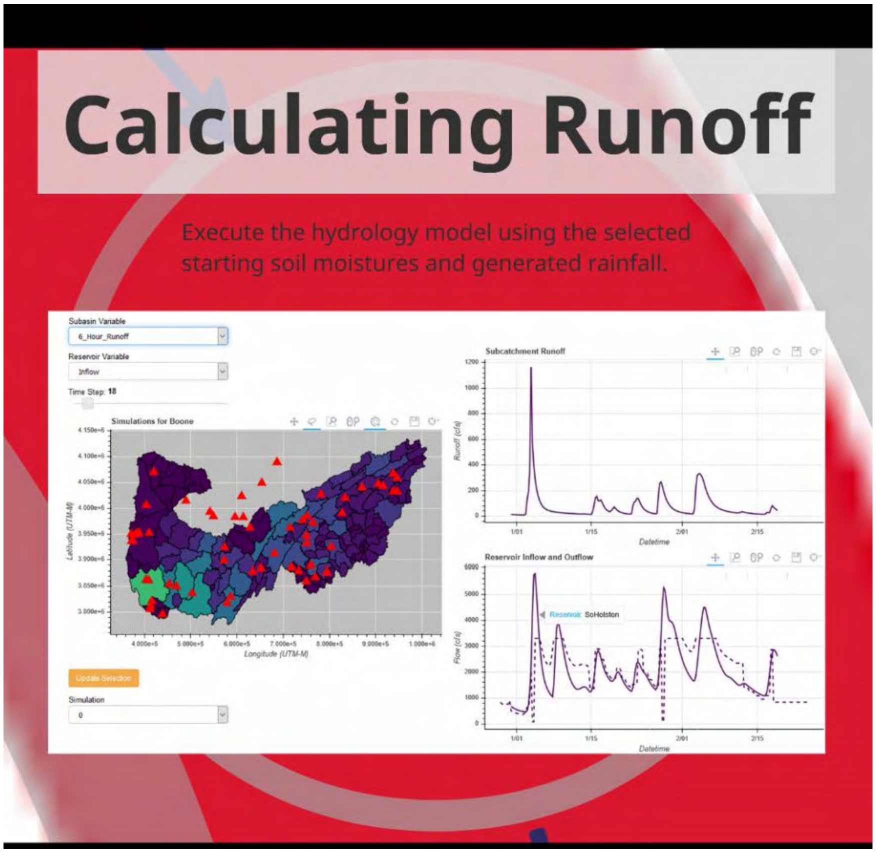
Creating a Storm

1. Sample 1,000s of depths from the PF curves by bins, and choose one

2. Randomly select storm template
3. Scale storm template:
in place depth==>probability==> transposed depth

4. Set storm at the correct date

5. Cut storm into rainfall randomly selected from the bootstrap



Calculating Runoff

Execute the hydrology model using the selected starting soil moistures and generated rainfall.

Subasin Variable: 6_Hour_Runoff

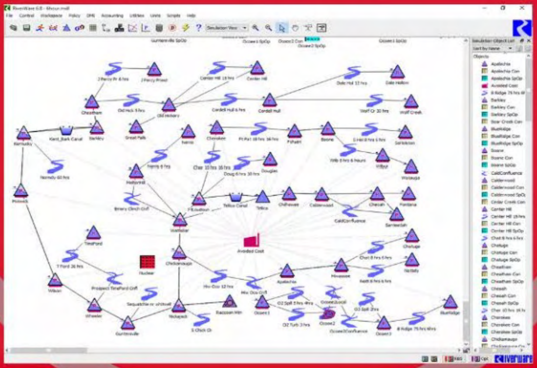
Reservoir Variable: Inflow

Time Step: 18

Simulation: 0

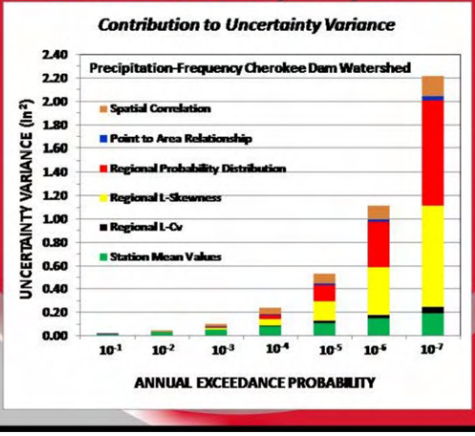
Routing the Flood

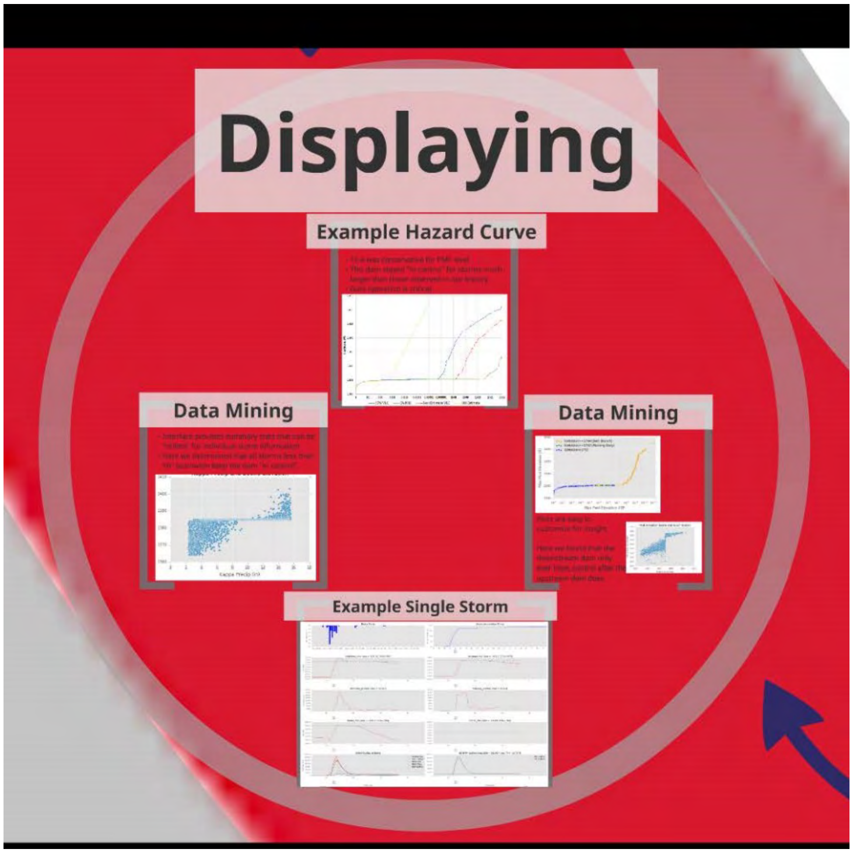
Execute the operations model using the selected starting pool levels and generated inflows.



Summarizing

- Calculate summary stats like peak headwater & flow etc. for each run
- Create headwater frequency curve from sampled rainfalls using total probability theorem
- Describe sources of uncertainty (only rainfall presently)





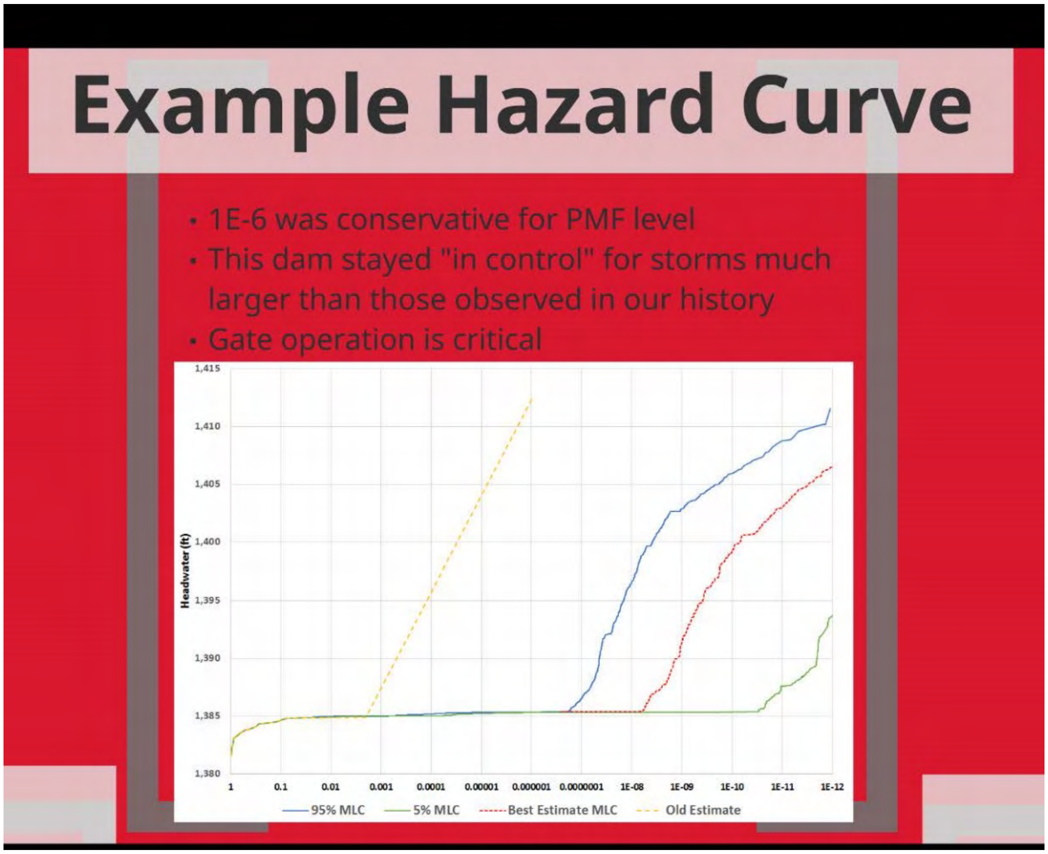
Displaying

Example Hazard Curve

Data Mining

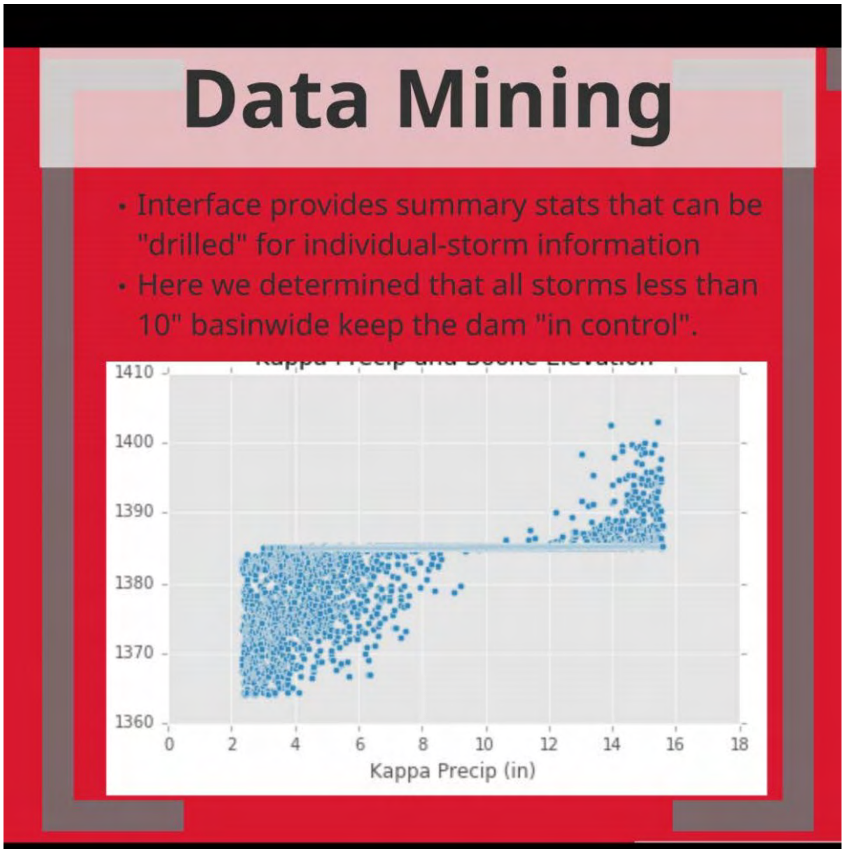
Data Mining

Example Single Storm



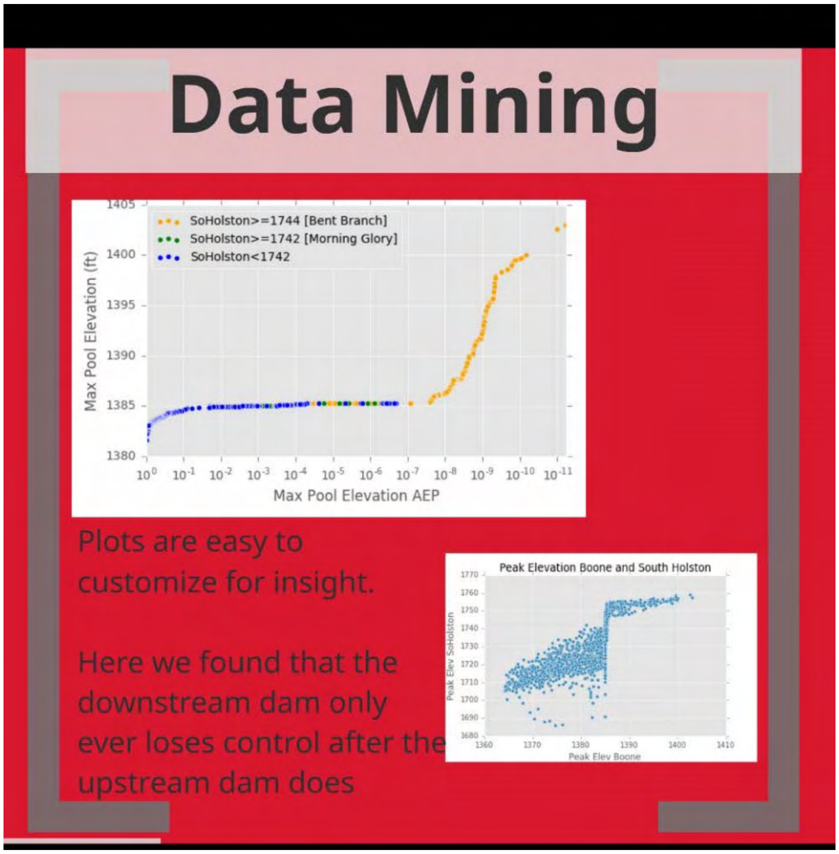
Example Hazard Curve

- 1E-6 was conservative for PMF level
- This dam stayed "in control" for storms much larger than those observed in our history
- Gate operation is critical



Data Mining

- Interface provides summary stats that can be "drilled" for individual-storm information
- Here we determined that all storms less than 10" basinwide keep the dam "in control".

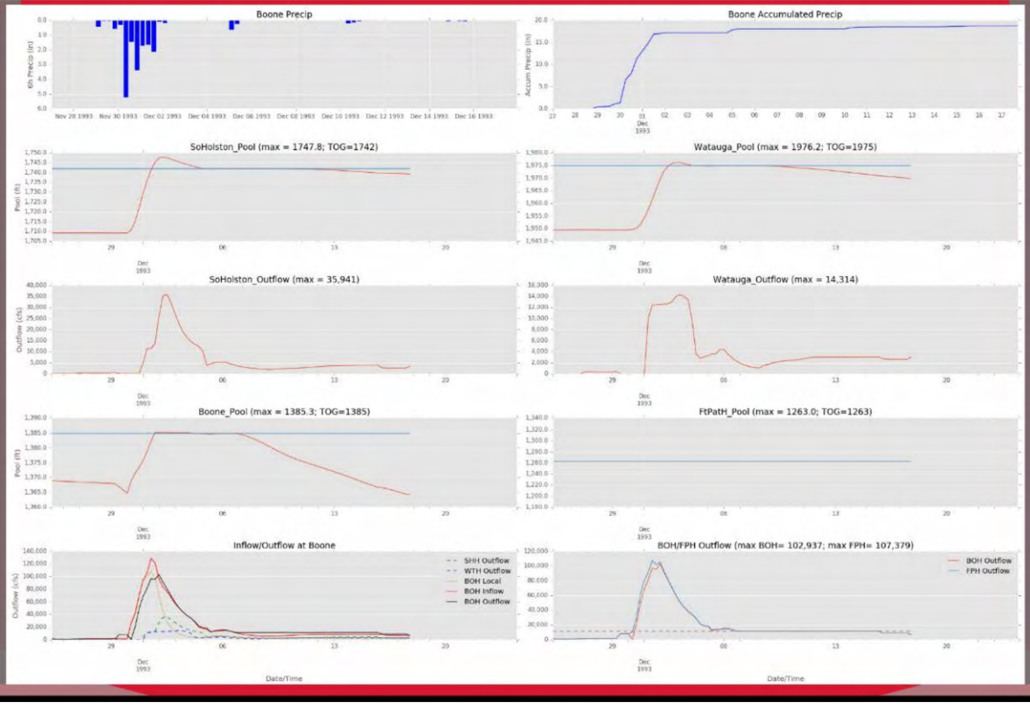


Data Mining

Plots are easy to customize for insight.

Here we found that the downstream dam only ever loses control after the upstream dam does

Example Single Storm



Deciding

Combine flood hazard information with fragility and consequences to choose the best dam safety investments

Next:

- Finalizing our 1st study
- Independent review of the framework
- Initial paleohydrology work (EPRI/USGS)
- Inclusion of more uncertainties
- Studies for each dam

2.3.11.4 U.S. Department of Energy (DOE), Curtis Smith, Ph.D., Idaho National Laboratory (Session 3D-1-D; ADAMS Accession No. ML17054C491)

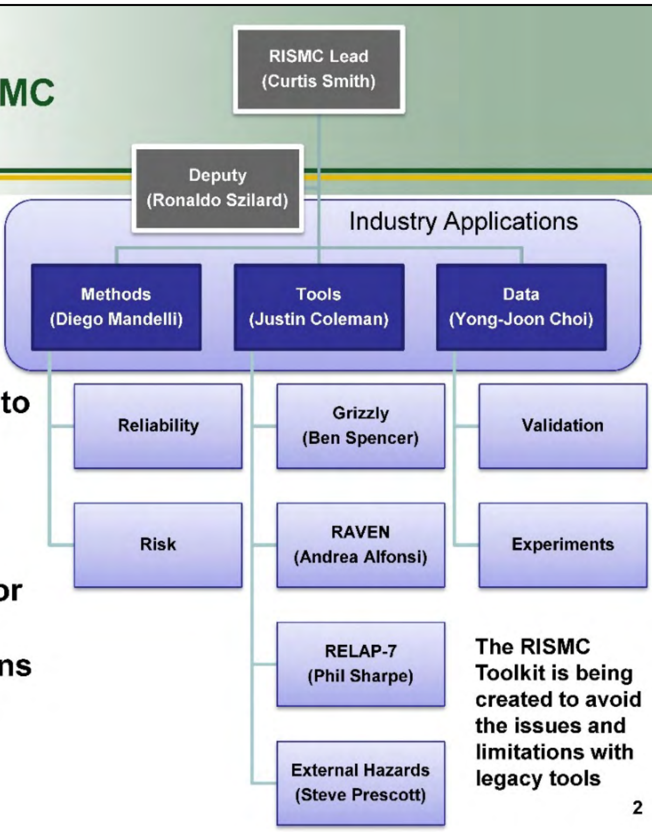
U.S. DEPARTMENT OF ENERGY | Nuclear Energy

DOE Risk Informed Safety
Margin Characterization (RISMC)
Flooding Research

Curtis L. Smith
RISMC Pathway Lead
Idaho National Laboratory

RISMC

- **The RISMC R&D activities are divided into**
  - **Methods**
  - **Tools**
  - **Data**
- **These come together for specific uses**
  - **Industry Applications**



The RISMC Toolkit is being created to avoid the issues and limitations with legacy tools

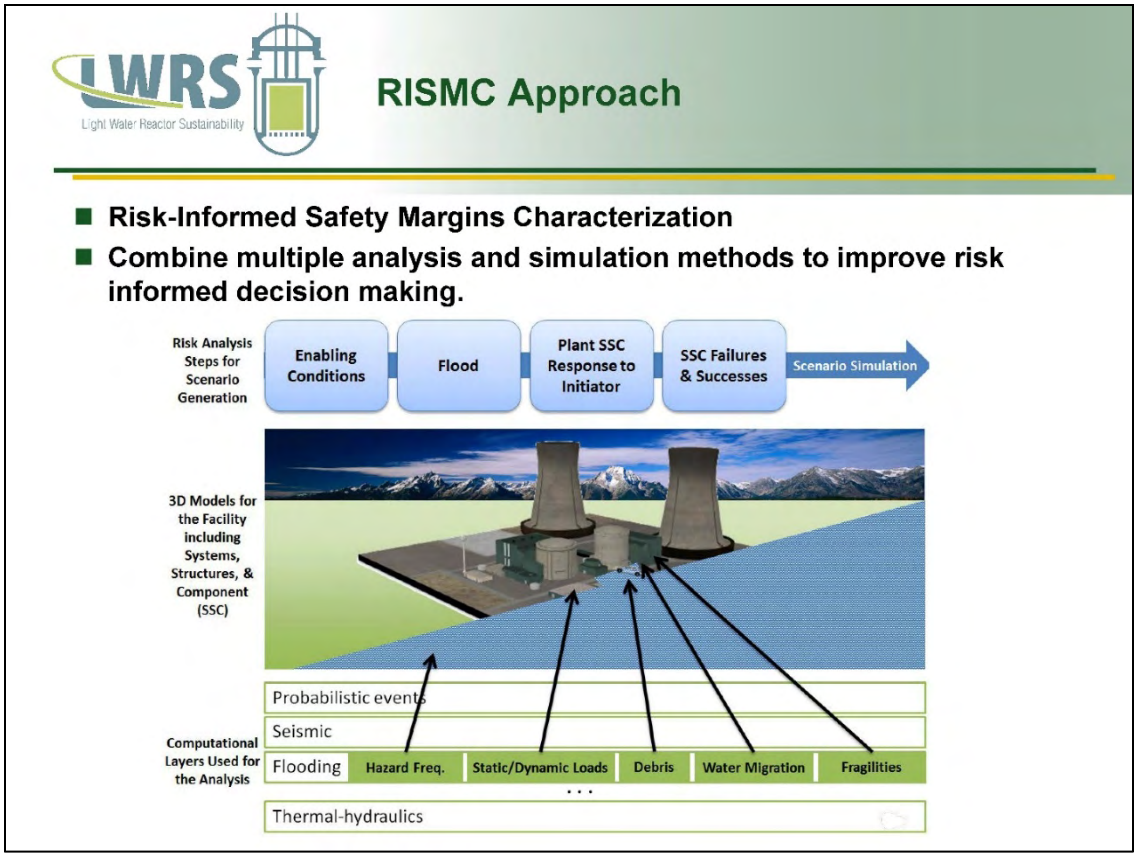
---

Factors for enhanced risk analysis methods

- **What are the factors that characterize system complexity?**
  - Four factors (or characteristics) have been identified:

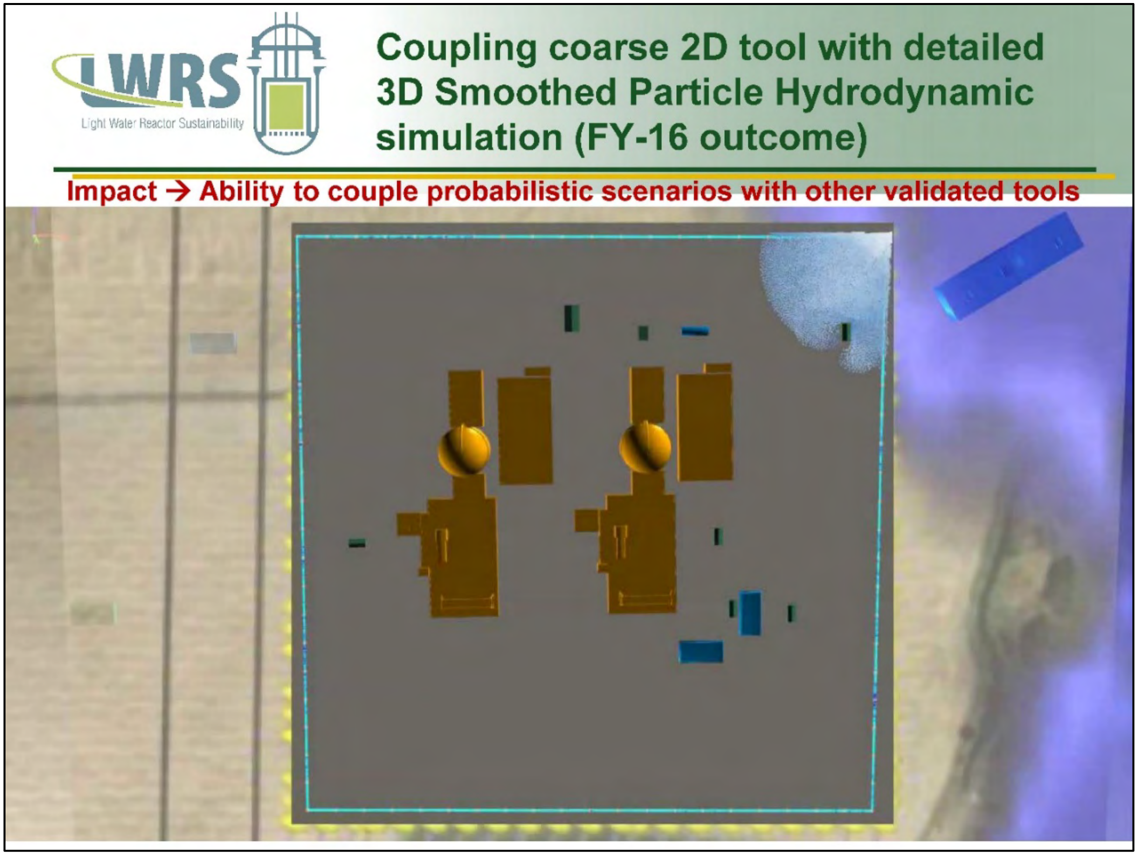
Temporal ***(timing issues)***	**Spatial** ***(location issues)***
Mechanistic ***(physics issues)***	**Topology** ***(complexity issues)***

- **If (at least) one attribute above is of interest for an issue then simulation-based risk assessment probably should be used for analysis**
- **The more attributes that are invoked, the larger the need is for simulation-based approaches**
  - **Leads us to Computational Risk Assessment (CRA)**
  - **CRA = Probabilistic (scenarios) + Mechanistic (physics)**
  - **External hazards invoke several of these**



RISMC Approach

- Risk-Informed Safety Margins Characterization
- Combine multiple analysis and simulation methods to improve risk informed decision making.

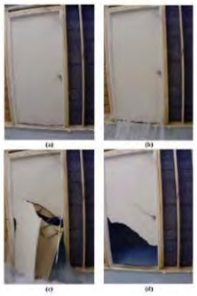


Coupling coarse 2D tool with detailed 3D Smoothed Particle Hydrodynamic simulation (FY-16 outcome)

Impact → Ability to couple probabilistic scenarios with other validated tools

External hazards experimental testing

- **We have run into technology gaps that need to be filled by testing**
  - Performing safety/reliability experimental testing specific to seismic and flooding external hazards
- **Partnership between INL, other national laboratories, and universities to perform necessary experiments**
- **External hazard experiments will include**
  - Determining failure probabilities for components during flooding conditions
  - Determining dependencies of component failures during seismic events
  - Will be used to provide data to validate physics-based external hazards numerical methods and tools
- **Testing has started last year**
  - Door flooding fragility and seismic laminar box testing
  - Extending this year to doors and penetrations
  - Idaho State U. is taking the lead on this activity



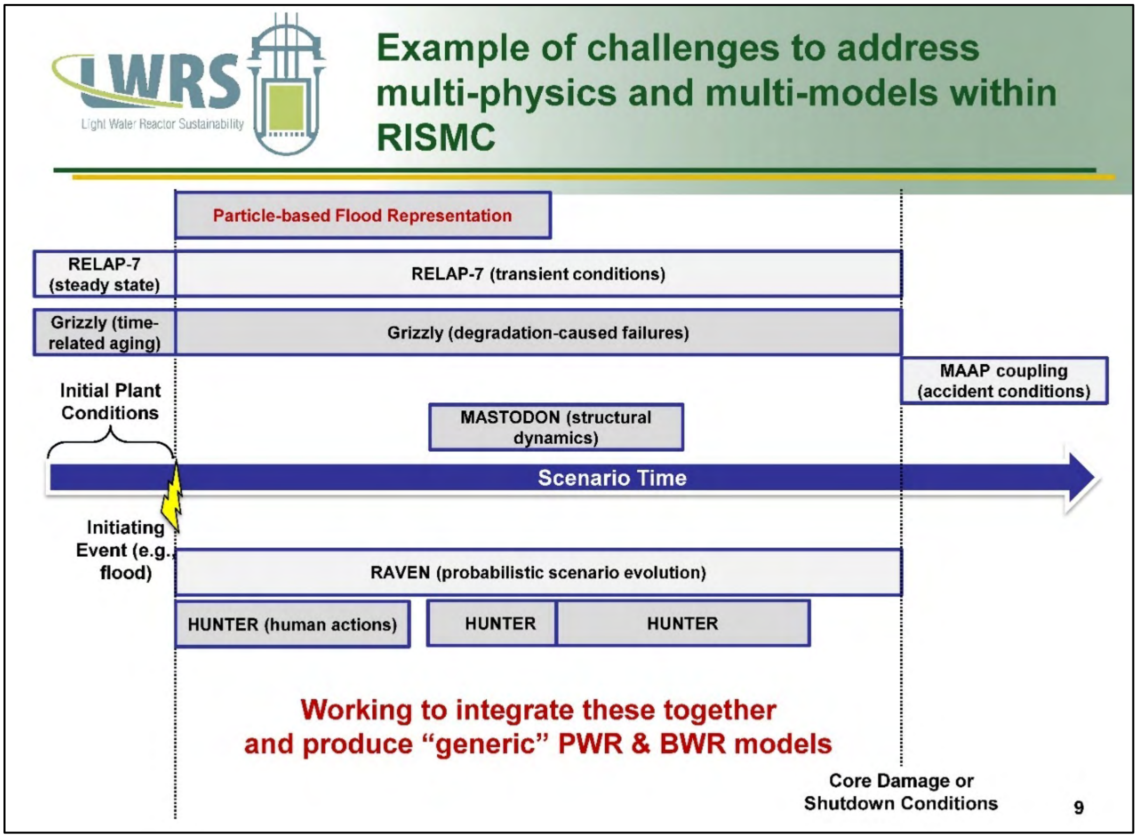
Conclusions

- **RISMC supports LWR Sustainability through enhanced methods, tools, and data**

- **Modernizing nuclear industry safety analysis**
  - Provide an improved understanding of safety margins
  - Provide enhanced tools for the next-generation of engineers
  - Provide efficiencies in the application of risk/safety analyses
  - Provide ways to integrate various technical domains
  - Provide ways to address key industry decisions

- **Collaborations increasing both domestically and internationally**

- **RISMC can be a key piece to bring science into decision-making**



Example of challenges to address multi-physics and multi-models within RISMC

Particle-based Flood Representation

RELAP-7 (steady state)

RELAP-7 (transient conditions)

Grizzly (time-related aging)

Grizzly (degradation-caused failures)

MAAP coupling (accident conditions)

Initial Plant Conditions

MASTODON (structural dynamics)

Scenario Time

Initiating Event (e.g. flood)

RAVEN (probabilistic scenario evolution)

HUNTER (human actions)

HUNTER

HUNTER

Working to integrate these together and produce "generic" PWR & BWR models

Core Damage or Shutdown Conditions

2.3.11.5 Institut de Radioprotection et de Sûreté Nucléaire (France's Radioprotection and Nuclear Safety Institute (IRSN)), Vincent Rebour*, Claire-Marie Duluc (Session 3D-1-E; ADAMS Accession No. ML17054C492)

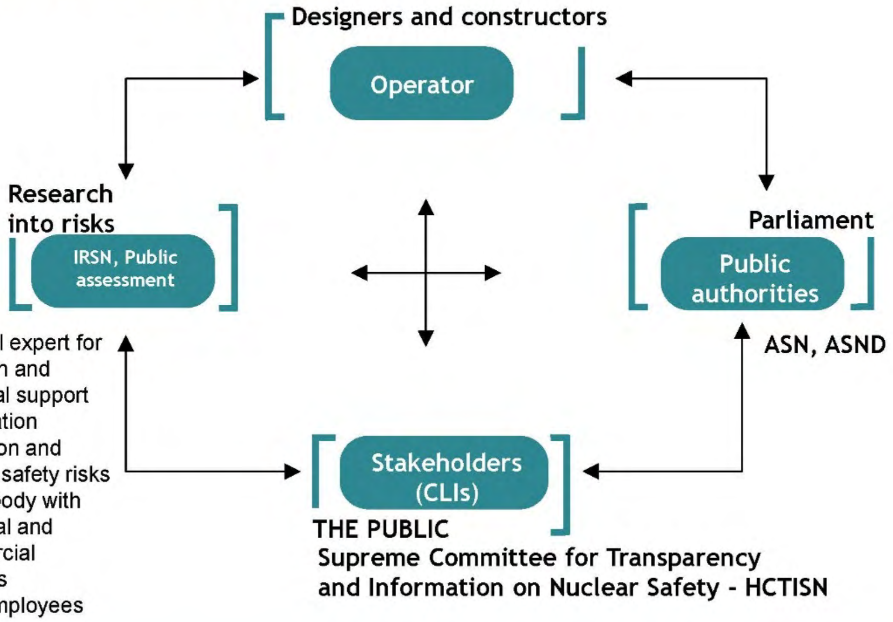
Probabilistic Flood Hazard Assessment Research Activities in IRSN

2nd Annual Probabilistic Flood
Hazard Assessment Research
Workshop

Rockville, Maryland,
January 23-25, 2017

Vincent Rebour IRSN/PRP-DGE/SCAN
Claire-Marie Duluc IRSN/PRP-DGE/SCAN/BEHRIG

Institutional environment



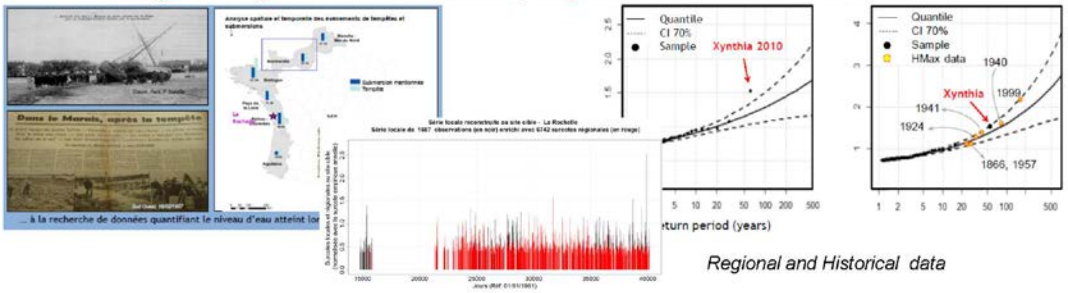
IRSN

- National expert for research and technical support on radiation protection and nuclear safety risks
- Public body with industrial and commercial activities
- 1800 employees

Objectives of the research activity on flood in IRSN

- Maintain and improve our expertise for review activity
- Develop our ability to perform independent calculations in key domains
- Develop basis for evolution of guidances

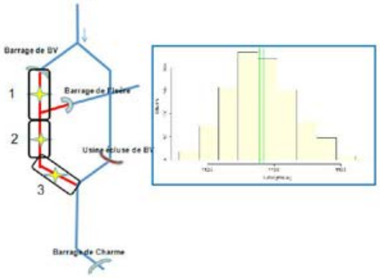
Background Topic 1 – Statistical methods, frequency analysis (extreme value theory)



Regional and Historical data

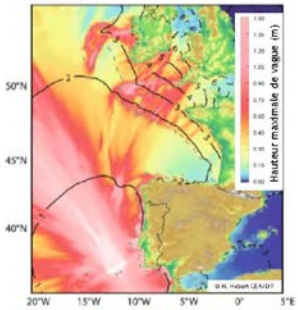
Background Topic 2 – Run-off/flood plain modelling, uncertainties propagation

River



Urban run-off

Tsunami



PFHA: Preliminary studies (2015-6) + PhD Thesis (2016-9) + European research projects (?)

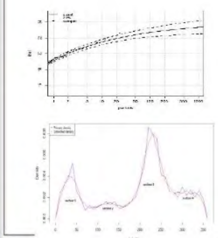
- Development of an integrated set of tools necessary to derive flood hazard curves
- Based on statistical modelling, hydraulic modelling, and PSHA experiences of the team and partners
- Developing new tools where needed
- Through real site studies
- With exchanges with PSA 1 and PSA 2 experts

Keys points

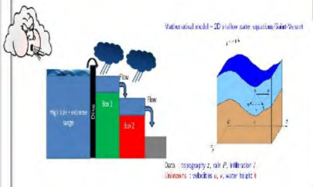
Phenomena → **Probabilisation** → **Propagation** → **Aggregation**

- Rain
- River flood
- Waves
- Clapoti
- ...

- Distribution functions
- Bounded density functions
- Join probabilities



- Appropriate models
- Uncertainties



- Capture of dependencies

$$P(H_{max} > H) = \sum_{i=1}^{N} \int_{Q_1}^{Q_2} f_i(Q) \times P(h \geq h_0/Q) . dQ \quad (1)$$

$P(H_{max} > H)$: *Annual exceedance probability*

H_{max} : max *water depth* ;

f_i : *density value of* Q;

Q : *parameter associated to a phenomenon*

Hope you are not flooded...

Thanks for your attention

2.3.11.6 Discussion

Question:

The USBR report on hydrologic hazard estimation discussed the Logan Workshop 1999 effort that led to that table that gives the limits of credible extrapolation with outside data, regional data, paleoflood data, and others. Where are we today within that scope? That report talks about Bayesian and other methods that have been presented in the last few days. Are we trying to establish better understanding of the credibility of these more rare or extreme events—are we trying to narrow down better on those limits?

Curt Jawdy, TVA

From TVA's perspective as a dam safety owner, TVA has a portfolio of 49 dams to keep as safe as possible. As a result, we have to prioritize our portfolio of projects in the best way. Therefore, we want to obtain the absolute value of the flood loading that is as accurate as we possibly can. For this reason, we put all this work into storm typing and understanding our uncertainties and breaking the system down as finely as possible. Ultimately, we have a decision to make, whether we have great data or not. For us, it is more about the relative value of dam A investment or dam B investment or dam C investment. While the absolute value is important, from a portfolio perspective, it is just as important to compare them to help make decisions.

John England, USACE:

Data on Australian rainfall and runoff are available on the Web, including a new 2016 version that has the same table I have worked on over the years with [Rory] Nathan [University of Melbourne] and David Bowles [Utah State University], who were both at the 2013 NRC PFHA workshop. We are working on implementing tools to make those probabilities as credible as possible with full uncertainty and then propagate that to decisions. The first step is to achieve credible estimates and quantify that uncertainty, which is large, and then second to roll it into a decision framework that USACE and USBR are managing. The framework is an f-*n* chart [estimated life loss vs. annualized failure probability plot]. As a result, in a dam safety construct decision framework, given some fixed set of consequences, you can state that the consequence estimate is 1 and you use lives lost as the surrogate for consequences. You do not need to go to 10^{-5} to 10^{-6} to use the process to focus on other locations in your inventory of dams. The key is combining information to obtain the best estimate you can with the information you have to help make a decision for the portfolio across an inventory. When considering specific dams or levees in USACE , you need to take a harder look, and sometimes you just have to make a call to do what is best for the decision of that organization. This may include collecting additional paleoflood information or performing additional rainfall studies such as storm typing, or you can decide that, given other factors, we can assess them in almost a deterministic standard, such as the probable maximum flood(PMF) for overtopping in the case of a dam, and take some sort of action based on that. In my opinion, we have not really made very particular progress on the tables, which have been criticized a lot over the years. We have not made much particular progress in refining those numbers. Instead, we have focused on the tools and data that go into making those numbers and quantifying that uncertainty. As Brian Skahill (USACE) mentioned earlier on combining disparate data types. The hydraulic hazard community is trying to grow PFHA skills. USBR has focused on trying to include site data with regional information, expand the information in space and time, and bring in causative mechanisms. This is within a Bayesian framework in the research area that is used within USACE. But holistically, those are the pieces of information the community is still grappling with how to apply practically. In the meantime, we are making decisions with the best information we have at the time.

Brian Skahill, USACE:

The spatial statistics of extremes is an active area research. Some papers in the past 5 years are pivotal for how we will look at the statistics of hydrometeorological extremes. Academia and government agencies are involved in active research to advance tool development and increase capacity to use those tools. The capability to combine all that information is being worked on within the PFHA framework development activity for the NRC.

Question:

The last two presentations tried to address the actual risk impacts to NPPs, which is of primary importance. My question is related to the integration of uncertainties from the hazard event. The hazard relates to analysis of the flood event itself, including when and how it will take place. Unfortunately, we do not have the qualifications to do that, so how do we determine the kind of consequences? The consequences of the hazard are really the risk. When we talk about risk at the NRC, we know about the risk triplet: the hazard itself, the probability of the hazard, and the consequences. Consequence is not dealt with much. This can be called “the scenario” or “the impact scenario.” Could you elaborate on the consequence analysis and how the uncertainties from the event itself (flood, in this case) and those of the consequence (scenario uncertainty) can be integrated together in order to achieve the results of the risk analysis we are trying to achieve? Second, how will we deal with the data? Although we did not talk much about the independence of the data, our colleague from IRSN did address the independence of the parameters in the uncertainty analysis. Our discussion of risk also did not give much consideration to data independence. These are important factors in a risk analysis that pertains to flood events.

Curtis Smith*, *INL for DOE

Once we get to the risk analysis part, it will be building on accepted practices, including industry and NRC PRA models. Some of the uncertainties for factors such as the hazard curves for a specific magnitude of floods are not really much different than some of the initiating events we already have in the models that we use for decisions every day. For example, the medium- and large-break LOCAs have frequencies down to 10^{-4}, 10^{-5}, and 10^{-6}, with a fair amount of uncertainties. However, we do not really question that those came from work in the 1980s and 1990s, and we just continue to use them with those large uncertainties. This is a similar case, although a flood has some unique features in that it is the kind of a failure that might knock out many components that a LOCA may not. However, the models being produced, whether an event tree/fault tree or a more dynamic kind of a model, are equipped to handle the dependency specific to external hazards. That element sometimes is a challenge. This is just another tool in a scenario that is in a larger kind of model.

Question:

Is MetVue publicly available?

Christopher Dunn, USACE:

MetVue is not yet publicly available but will be in the future. The goal was to release it by the end of 2016, so that could take place sometime in 2017[5].

Follow-up Question:

You talked about transposing and moving storms in MetVue. Are there any adjustments made to the precipitation amount as that is done, such as to take into account storms passing over changes in elevation or orographics? Or is it just strictly moving that spatial pattern to a new spot?

***Christopher Dunn, USACE*:**

Currently, MetVue does not do that. Users will have a lot of discretion in how to use it. You could potentially move a storm to another area where it does not make physical sense. Users will need to be careful when manipulating events, moving them around, and transposing them to ensure that they are doing something that is physically possible.

Question:

When will USACE release Hydrologic Modeling System (HMS) 4.3, including the Markov chain Monte Carlo method (MCMC) capability?

Christopher Dunn, USACE:

This is planned for September 2017[6].

Christopher Dunn, USACE:

The NRC's research themes have focused in part on epistemic uncertainties and understanding them from a framework of different interpretations of data models and methods, which has not been a big focus in the flooding field. Will the work the NRC is funding improve the state of practice with respect to the treatment of epistemic uncertainties? How that will help in applications that are not related to NPPs?

Curtis Smith*, *INL for DOE:

People appear to be agreeing on the different kinds and drivers of uncertainty, and the community of practice is moving forward. I would encourage it to keep moving forward and also consider what the NRC does for the other hazards. For example, we have a Bayesian distribution for the frequency of a large-break LOCA as an initiating event. If we want to use something like flooding hazards as an initiating event or a probabilistic PRA-type of initiating event, we would want to have an apples to apples kind of model. This appears to be an issue of concern among participants. We have that issue with a loss of offsite power, in terms of how far back in history we should consider, given that the practices of the grid have changed over last 20 to 30 years. This is the challenging question, as we are discussing climate and floods from 500 years ago, so going far back in history may be necessary. But the idea of having Bayesian distribution and Bayesian

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[5] HEC MetVue was released publicly in summer 2019 and can be accessed at https://www.hec.usace.army.mil/software/hec-metvue/

[6] HEC-HMS 4.3 was released in September 2018 and includes the Monte Carlo Uncertainty tool https://www.hec.usace.army.mil/software/hec-hms/documentation.aspx

models and classifying uncertainty (aleatory, epistemic) very much fits into the NRC way of thinking. This is the case for many synergies with other activities in risk assessment.

Norberto Nadal-Caraballo*, *USACE:

The collaboration with the NRC has given us the chance to evaluate many methods and models that we had not even considered in the past, and we are applying a lot of the lessons learned. We are still learning a lot doing this study, and we are in the process of applying some of those lessons learned to USACE products. For example, before this study, we did not even contemplate considering some of the epistemic uncertainties whose importance we are now realizing. In previous studies by FEMA and USACE, we just computed, for example, the modeling errors. We compared high-water marks with the results from ADCIRC, and, although we incorporated those uncertainties in the hazard curve, we basically ignored everything else. We have seen that the uncertainty in the SRR models is significant and can impact the final hazard curve. This has been a very good opportunity for us to see that and to give us the chance to improve our products moving forward.

Question:

In terms of both the statistical analysis and the uncertainty in the riverine modeling, are you considering multiple models, multiple distributions in the statistical part of it or different physical mechanisms or models that contain different physical mechanisms in modeling uncertainty portions?

Vincent Rebour , ***IRSN:***

Our first objective is to identify the set of tools. The second step will be testing different methods of modeling.

Question:

What resolution are the researchers at the University of Illinois using in those climate models to make climate projections? Until you reach a very fine resolution, essentially going to a convection permitting climate model, there will be certain precipitation events that just cannot be modeled, for example.

Sanja Perica, ***NOAA/NWS:*** *Response unclear and not recorded.*

Brian Skahill*, *USACE:

Based on the ongoing work on **Error! Bookmark not defined.**development for the NRC and then the related work with HMS at the Hydrologic Engineering Center, I proposed to the HMS team and the supervisory chain at the Hydrologic Engineering Center that as we now have that capability encased in HMS, and given that the HMS tool has a lot of flexibility and an adaptable, user-friendly interface, it would not be too difficult to transition to looking at different loss mechanisms for basin modeling and different transformation methods. We could definitely leverage the sampler and MCMC sampler we now have in HMS to support treatment of the model generalization problem that was brought up in the last two questions.

Question:

What are the limitations of using maximum likelihood estimation for probabilities of less than 10^{-4} for a dam safety application?

Sanja Perica, NOAA/NWS:

Although I do not know the answer, under the maximum likelihood approach, L-moments approach, or whichever approach you choose, once you are at frequencies of 10^{-4}, there are of course many uncertainties. It is difficult to identify which approach will result in smaller uncertainties.

Follow-up Question:

Can others address the question in terms of dam safety assessment?

Curt Jawdy, TVA:

We are just starting to look into the uncertainties outside of rainfall, but we are seeing that most TVA dams are fairly well in control out to the 10,000-year event. When you are looking at a time out that far, the soil is full of moisture and it is all going to runoff no matter what model you use. The rainfall uncertainty is so high, the further out you go. Much of the operational uncertainty in the reservoir system and the runoff uncertainty in the hydrological model will likely be swamped by the rainfall uncertainty. As a result, we are taking the approach of tackling the uncertainties that seem to be the biggest first and working down.

John England, USACE:

USBR did this in practice in about 2002 when we were working with FloodFreq3. The code is available, and Brian Skahill's research now is moving in a more modern framework with R (a statistical package). We looked at model uncertainty. Some of the issues that William Asquith touched on (see Section 3.4.2) in a likelihood framework you could do a little more conveniently to exploit LP-III versus GEV in terms of the peak flow frequency. As a result, you can directly account for which models fit well and then include those and weight them to inflate the uncertainty to include some model uncertainty. A couple of journal articles were published on that, and USBR published a report for Folsom Dam in 2002. This gives a place for likelihood and makes it a little more convenient to include covariates. However, it is challenging for practitioners to understand, and so we are still trying to include long data sets, as well as the biggest rainfalls and the biggest floods in the analysis. That is really the first order problem on the data side, rather than arguing between L-moments and likelihood. It is important to include the really big events and know the physics you are trying to mimic with the statistical models.

Question:

Has the work on automated storm typing been published?

Curt Jawdy , TVA:

It has not been published in a journal yet. We are reviewing our entire framework in April and need to determine what is proprietary and what can be published.

Question:

Could you provide more detail on how you are tackling the debris loading and gate failure scenarios for the Willamette River Project?

John England, USACE:

With regard to the previous question, there is extensive information in the academic literature, namely hydrology system science, on patterning and typing in climate. From a research perspective, MGS Engineering Consultants work for TVA in terms of patterning and using typing to do storms is not unique but well founded in other academic literature, including SOMs. It is actually in the roots of NOAA/NWS Hydrometeorological Report No. 55a, "Probable Maximum **Error! Bookmark not defined.** Estimates—United States Between the Continental Divide and the 103rd Meridian," issued June 1988, with the storm classification system in its PMP .

With regard to the question in the probabilistic world about the debris and gates on the Willamette River, this is a new part of project, so we do not yet have clear documentation. We are essentially adopting a gate scenario, based on the fault tree work that was shared through USACE and **Error! Bookmark not defined.**'s Best Practices in Dam Safety Risk Analysis. That training course on mechanical reliability, offered for the past 5 or 6 years, contains a whole gate module, and we are now trying to take the step of moving those pieces into the hydrologic hazard analysis. We have not yet come to consensus on how to do it. We know gate reliability and debris are huge issues, and therefore we are sort performing the scenario analysis and looking at initiation nodes in an event tree.

2.3.12 Day 3: Session 3E - Future Work in PFHA

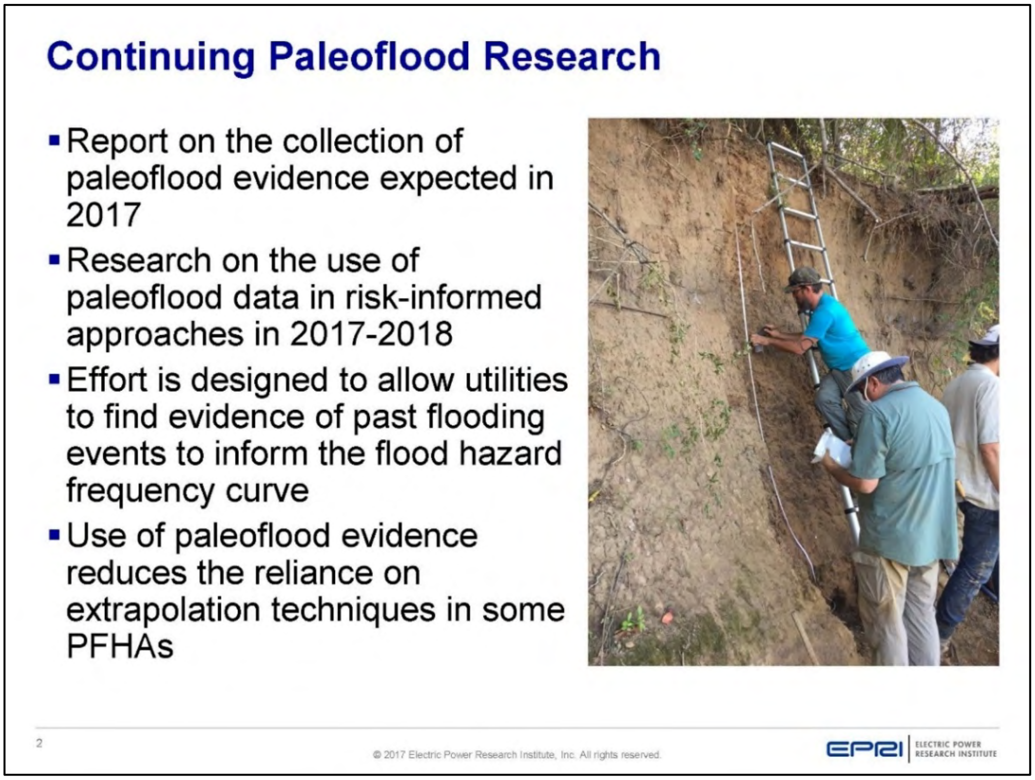
2.3.12.1 Future Work in PFHA at EPRI, John Weglian*, EPRI(Session 3E-1; ADAMS Accession No. ML17054C493)

2.3.12.1.1 Presentation

Future Work in PFHA at EPRI

John E. Weglian
Senior Technical Leader

NRC External Flooding Research Workshop
1/25/2017



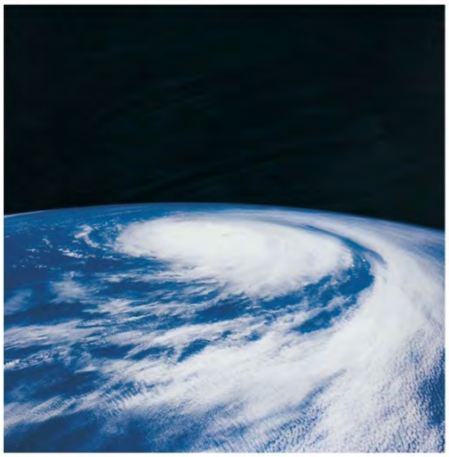
Continuing Paleoflood Research

- Report on the collection of paleoflood evidence expected in 2017
- Research on the use of paleoflood data in risk-informed approaches in 2017-2018
- Effort is designed to allow utilities to find evidence of past flooding events to inform the flood hazard frequency curve
- Use of paleoflood evidence reduces the reliance on extrapolation techniques in some PFHAs

2

Additional Storm Surge PFHA

- Estimation of frequency of hurricane-driven storm surge
  - Research in 2017
- Employs simulation of hurricane and Monte Carlo analysis to establish the storm surge hazard frequency curve at a particular site
- Treats tides probabilistically
- Accounts for correlation of storm parameters



External Flooding PRA Walkdown Guidance

- External flooding walkdowns for deterministic flood analyses (such as for answering the 50.54(f) letter) may not be sufficient for an external flooding PRA
- EPRI will develop a guidance document for conducting a walkdown to support an external flooding PRA
- This guidance will help utilities use the results of a PFHA to assess the impact on the site from the external flooding hazards

EPRI Technology Innovation Research

- Technology Innovation (TI) Projects at EPRI are long-term, high-risk, high-payoff research investigations
- EPRI has a TI project looking at smooth particle hydrodynamics (SPH) for flooding simulations
  - Initial project is focused on an internal flooding scenario
  - Results will be compared to existing flooding assessments
- Goal of the project is to determine if any new risk insights are obtained with this approach
- SPH may be useful for simulating external flooding scenarios
  - Note: Idaho National Labs is investigating the use of SPH for use in dynamic PRA models

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Seiche and Tsunami Frequency Estimation

- Seiche and Tsunami are not a large driver for plants in the United States
- Focus of this research will be international utilities

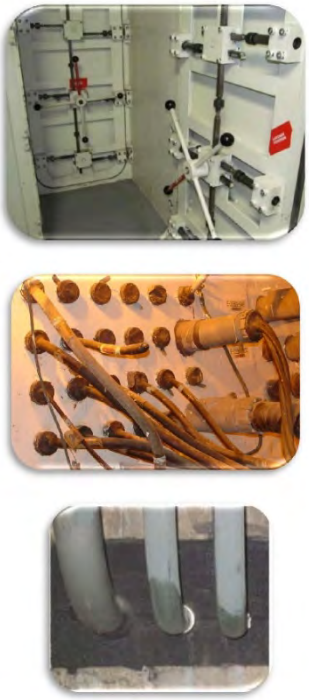
Dam Failure

- Difficulty exists in getting data from dam regulators for risk assessment
- Best approach seems to be working through the NRC to get needed data
- This approach has generally produced more of a deterministic result and not a flood hazard frequency curve
- Best research approach may be to work with a dam regulator to come up with a methodology they can use to produce the hazard frequency curve the utilities need

Correlated Hazards

- External flooding may often be correlated with high winds
- A complete analysis of the hazard of the event will require consideration of both flooding and wind effects
- Further research is required to assess the best way to integrate separate PRA models correctly when the hazards are correlated

Flood Barrier Fragility



- Once the hazard is known, it is important to assess the probability of success of the flood barriers
- Typically, this is done deterministically
  - Assume a door fails with a certain height of water on one side
  - Assume a levee is successful until overtopping and then assume complete failure
- Evaluating a fragility for some barriers may make the analysis more realistic
  - Flood barrier seals
  - Doors
- Idaho State University is building a testing facility that can evaluate flood barriers

---

Together…Shaping the Future of Electricity

John E. Weglian
Senior Technical Leader
jweglian@epri.com
704-595-2763

2.3.12.1.2 Questions and Answers

Question:

How are you planning to model the storm surges for the Monte Carlo simulations?

Response:

We will use probability density functions for the storm surge parameters that will be used. The actual hydrologic model (developed by the contractor) has not been chosen yet.

Question:

What EPRI exists for NPP sites located on the Great Lakes?

Response:

If the meteorological parameters can be successfully estimated, then this modeling may be applicable to both coastal and Great Lakes sites.

2.3.12.2 Future Work in PFHA at NRC, Joseph Kanney, Ph.D., Meredith Carr*, Ph.D., P.E., Thomas Aird, Elena Yegorova, Ph.D., and Mark Fuhrmann, Ph.D., Fire and External Hazards Analysis Branch, Division of Risk Analysis; and Jacob Philip, P.E., Division of Engineering, Structural, Geotechnical and Seismic Engineering Branch, Office of Nuclear Regulatory Research, U.S. NRC (Session 3E-2; ADAMS Accession No. ML17054C494)

2.3.12.2.1 Presentation

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

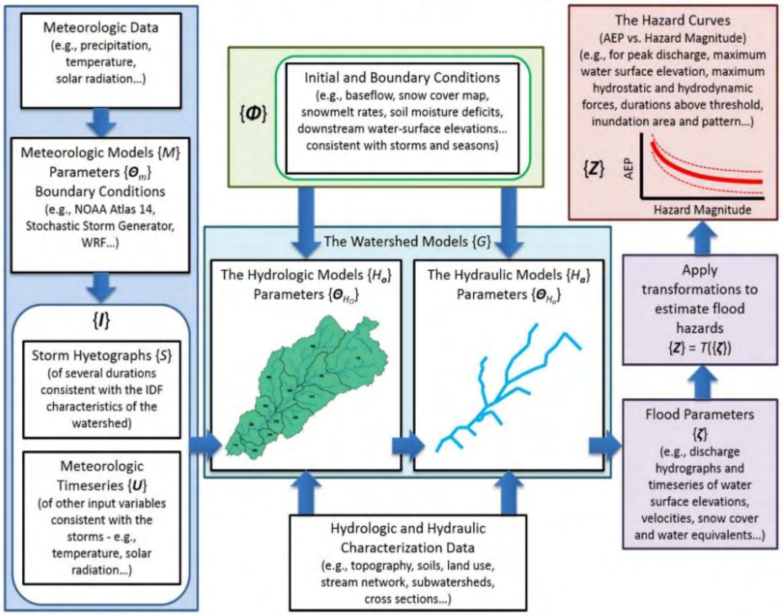
Future PFHA Research at NRC

Meredith Carr, Ph.D., PE
Mark Fuhrman, Ph.D.
Joseph Kanney, Ph.D.
Jacob Philip, PE
Elena Yegorova, Ph.D.
Fire and External Hazards Analysis Branch, Division of Risk Analysis
Office of Nuclear Regulatory Research

2nd Annual PFHA Research Workshop
NRC HQ, Rockville, MD
January 23-25, 2017

Expected Project Completions in FY17

- **PFHA Technical Basis – Riverine (PNNL)**
  - Project competed in FY16
  - NUREG/CR publication expected in FY17-Q3



Meteorologic Data (e.g., precipitation, temperature, solar radiation...)

Meteorologic Models $\{M\}$ Parameters $\{\Theta_m\}$ Boundary Conditions (e.g., NOAA Atlas 14, Stochastic Storm Generator, WRF...)

$\{I\}$

Storm Hyetographs $\{S\}$ (of several durations consistent with the IDF characteristics of the watershed)

Meteorologic Timeseries $\{U\}$ (of other input variables consistent with the storms - e.g., temperature, solar radiation...)

$\{\Phi\}$

Initial and Boundary Conditions (e.g., baseflow, snow cover map, snowmelt rates, soil moisture deficits, downstream water-surface elevations... consistent with storms and seasons)

The Watershed Models $\{G\}$

The Hydrologic Models $\{H_o\}$ Parameters $\{\Theta_{H_o}\}$

The Hydraulic Models $\{H_a\}$ Parameters $\{\Theta_{H_a}\}$

Hydrologic and Hydraulic Characterization Data (e.g., topography, soils, land use, stream network, subwatersheds, cross sections...)

The Hazard Curves (AEP vs. Hazard Magnitude) (e.g., for peak discharge, maximum water surface elevation, maximum hydrostatic and hydrodynamic forces, durations above threshold, inundation area and pattern...)

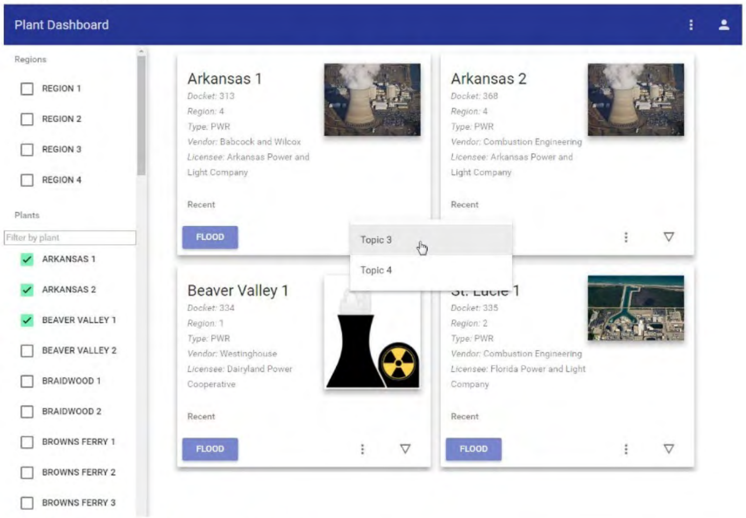
Apply transformations to estimate flood hazards $\{Z\} = T(\{\zeta\})$

Flood Parameters $\{\zeta\}$ (e.g., discharge hydrographs and timeseries of water surface elevations, velocities, snow cover and water equivalents...)

* Subject to availability of funding

Expected Project Completions in FY17

- **Flood Hazard Information Digest (INL)**
  - Complete population of the database and Finalize User Guide (FY17-Q4)



Plant Dashboard

Regions

☐ REGION 1
☐ REGION 2
☐ REGION 3
☐ REGION 4

Plants

Filter by plant

☑ ARKANSAS 1
☑ ARKANSAS 2
☑ BEAVER VALLEY 1
☐ BEAVER VALLEY 2
☐ BRAIDWOOD 1
☐ BRAIDWOOD 2
☐ BROWNS FERRY 1
☐ BROWNS FERRY 2
☐ BROWNS FERRY 3

Arkansas 1
Docket: 313
Region: 4
Type: PWR
Vendor: Babcock and Wilcox
Licensee: Arkansas Power and Light Company
Recent

Arkansas 2
Docket: 368
Region: 4
Type: PWR
Vendor: Combustion Engineering
Licensee: Arkansas Power and Light Company
Recent

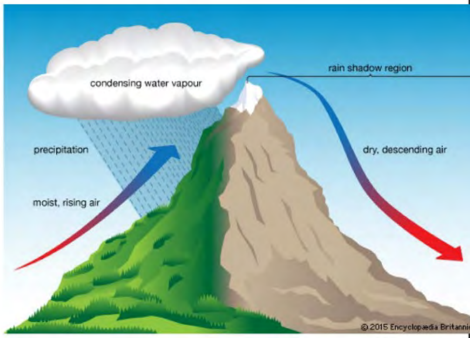
Beaver Valley 1
Docket: 334
Region: 1
Type: PWR
Vendor: Westinghouse
Licensee: Dairyland Power Cooperative
Recent

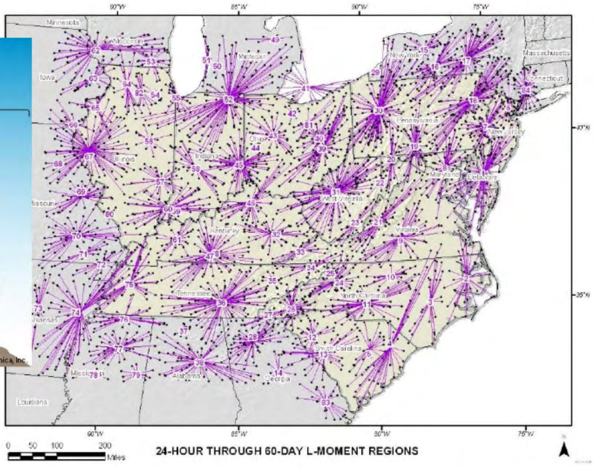
St. Lucie 1
Docket: 335
Region: 2
Type: PWR
Vendor: Combustion Engineering
Licensee: Florida Power and Light Company
Recent

* Subject to availability of funding

Expected Project Completions in FY17

- **Precipitation Frequency Estimates in Orographic Regions (USBR)**
  - Expected completion in FY17-Q4 (NUREG/CR and Seminar)





*** Subject to availability of funding**

Expected Project Completions in FY17

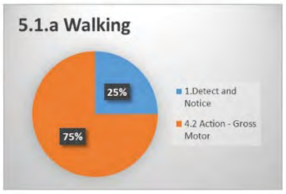
- **Effects of Environmental Factors on Manual Actions for Flood Protection and Mitigation at NPPs (PNNL)**
  - Expected completion in FY17-Q3 (NUREG/CR)

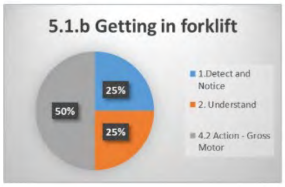
5.1.1 Position Forklift

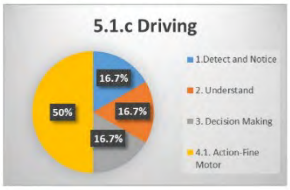
5.1.a Walking	
1.Detect and Notice	4.2 Action – Gross Motor
0.25	0.75

5.1.b. Getting in forklift		
1. Detect and Notice	2. Understand	4.2 Action - Gross Motor
0.25	0.25	0.5

5.1.c. Driving			
1. Detect and Notice	2. Understand	3. Decision Making	4.1. Action-Fine Motor
0.167	0.167	0.167	0.5



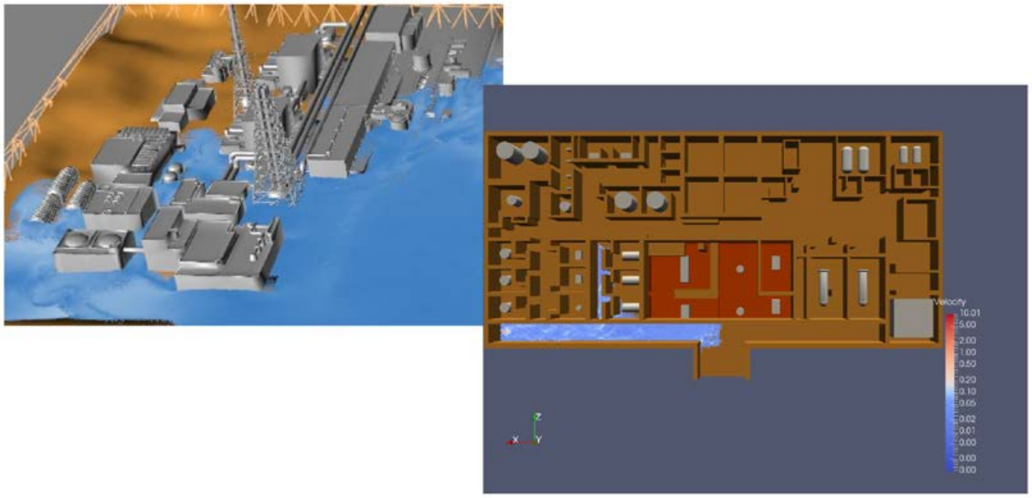




*** Subject to availability of funding**

Expected Project Completions in FY17

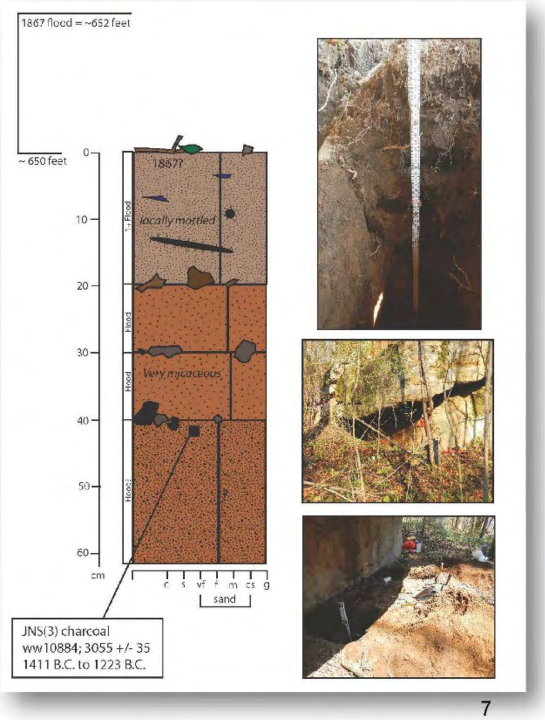
- **Modeling Total Plant Response to Flooding Events (INL)**
  - Expected completion in FY17-Q3 (NUREG/CR)



*** Subject to availability of funding**

FY17 – Initiatives*

- **Detailed TN River Flood Geomorphology Study in Gorge below Chattanooga**
  - *Contractor: USGS*
  - *NRC PM: Mark Fuhrmann*



*** Subject to availability of funding**

FY17 – Initiatives*

- **Critical Review of the State of Practice in Probabilistic Risk Assessment for Dams**
  - *Contractor: TBD*
  - *NRC PM: TBD*
    - System modeling
    - Operation and human actions
    - Failure modes and fragility
  - Coordinate with partner federal agencies (public workshop?)

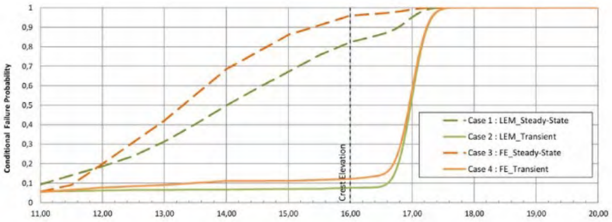


Figure 5: Reference Fragility Curves of the embankment structural behavior

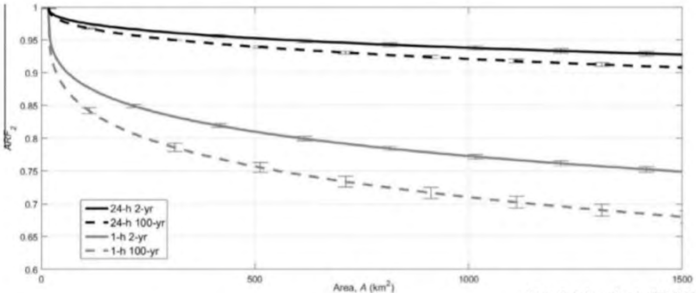
Mouyeaux et al, 2015

U.S. Bureau of Reclamation

*** Subject to availability of funding**

FY17 – Initiatives*

- **Application of precipitation frequency estimates to watersheds**
  - *Contactor: Under discussion with NOAA/NWS*
  - *NRC PM: Yegorova*
    - Leverage point precipitation estimates (e.g., NOAA Atlas 14)
    - Areal reduction factors
    - Temporal and spatial patterns
    - Uncertainty



Pavlovic et al, 2016

*** Subject to availability of funding**

FY17 – Initiatives*

- **Interfacing Flood Hazard Modeling Outputs with Plant PRA Models**
  - Internal effort (collaboration between FXHAB and PRAB)
  - Focus on incorporating flooding hazard in SPAR Models

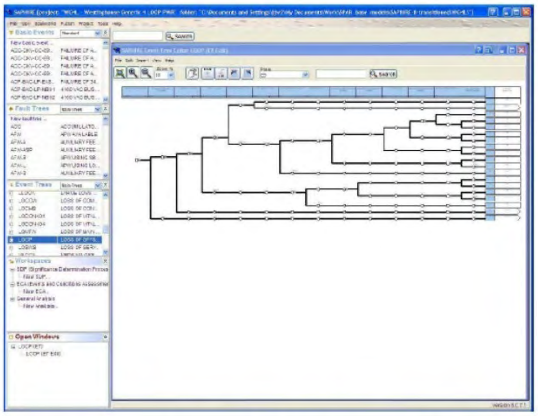


Figure 5.9 Example Loss of Offsite Power SPAR Model Event Tree Display with SAPHIRE Version 8

FY17 – Initiatives*

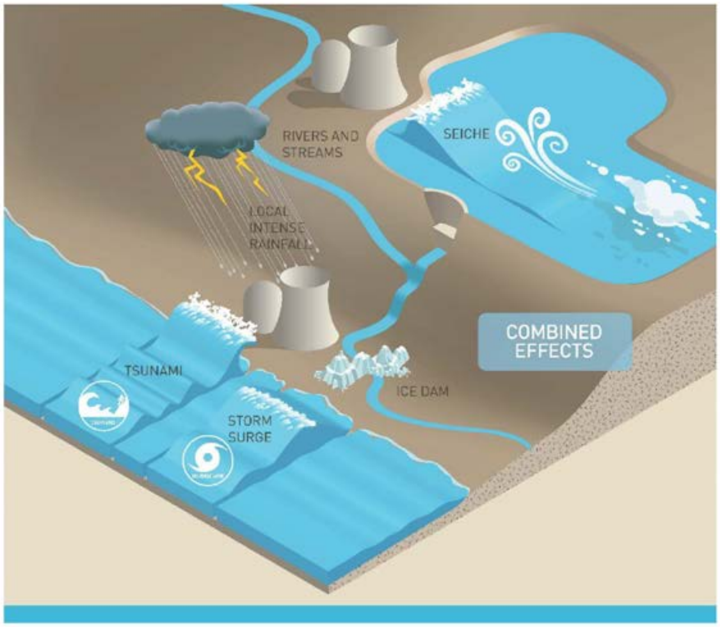
IRSN
INSTITUT
DE RADIOPROTECTION
ET DE SÛRETÉ NUCLÉAIRE

- **Formalize collaboration with IRSN**
- **Potential areas under discussion**
  - **Comparison of storm surge modeling**
  - **Riverine flooding uncertainty**
  - **Probabilistic flood hazard assessment: development and application including Plant Response**

*** Subject to availability of funding**

Projected FY18-19 Work*

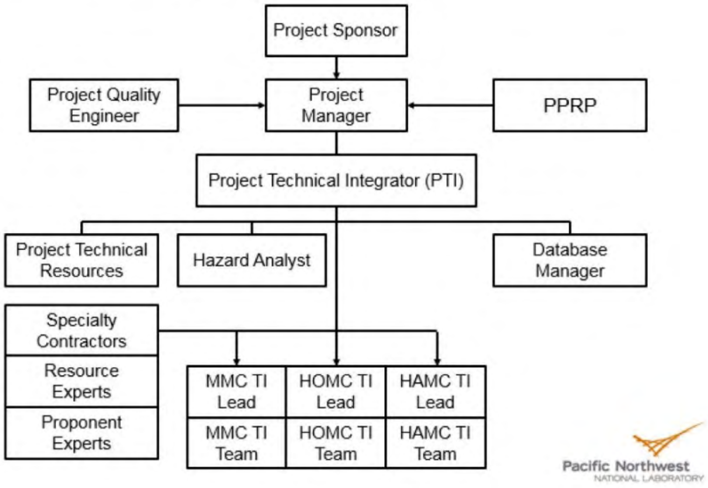
- Develop Pilot Tests
  - *Work with Industry, other Agencies*
  - *Inland location, coastal location*



*** Subject to availability of funding**

Projected FY18-19 Work*

- Further Development of SHAC-F
  - *Coastal flooding mechanisms*


Project Sponsor

Project Quality Engineer

Project Manager

PPRP

Project Technical Integrator (PTI)

Project Technical Resources

Hazard Analyst

Database Manager

Specialty Contractors

Resource Experts

Proponent Experts

MMC TI Lead

HOMC TI Lead

HAMC TI Lead

MMC TI Team

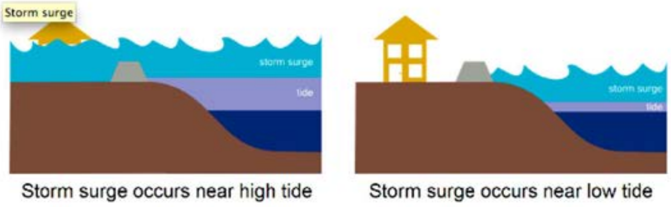
HOMC TI Team

HAMC TI Team

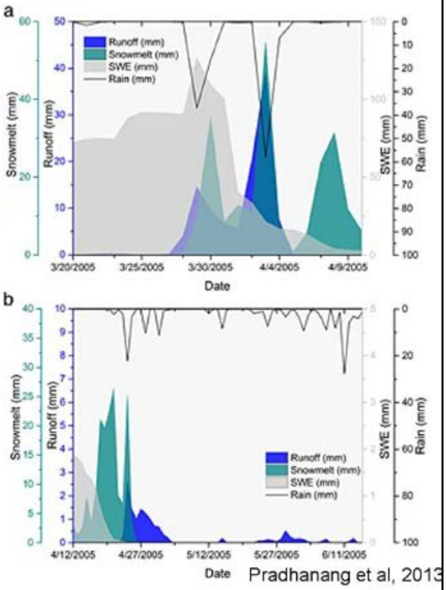
*** Subject to availability of funding**

Projected FY18-19 Work*

- Probabilistic treatment of combined processes/events



Storm surge occurs near high tide   Storm surge occurs near low tide

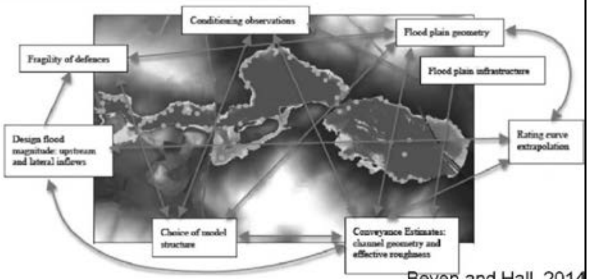


Pradhanang et al, 2013

*** Subject to availability of funding**

Projected FY18-19 Work*

- Quantifying Uncertainties in Probabilistic Riverine Flood Models



Beven and Hall 2014

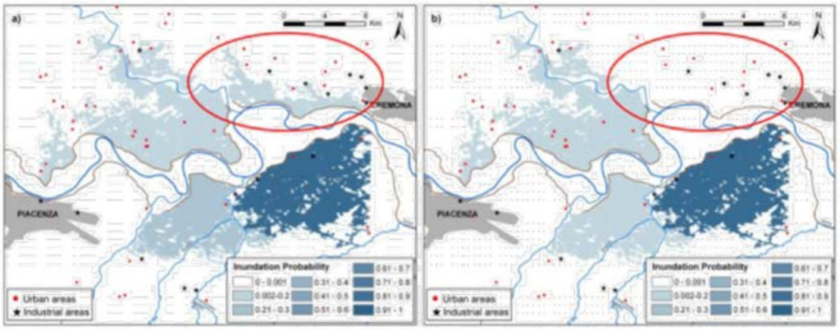


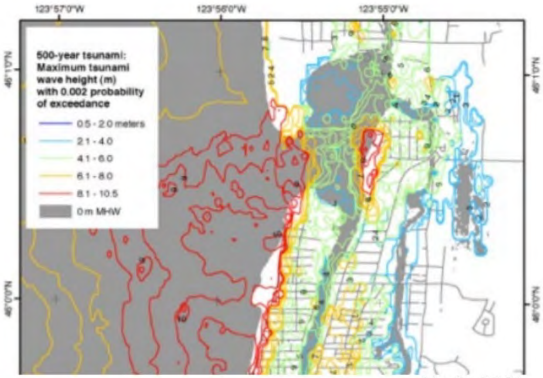
Fig. 9. Probabilistic flood hazard maps for the Tr200 event obtained with variable Traditional (**a**: RandomT subset) and Constrained (**b**: RandomC subset) rating curves.

Domeneghetti et al, 2013

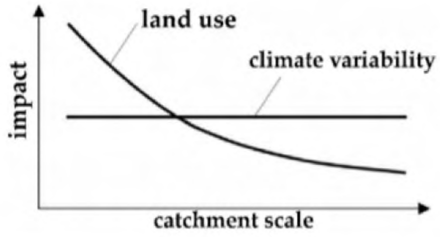
*** Subject to availability of funding**

Projected FY18-19 Work*

- Assess probabilistic tsunami modeling methods
  - Assess current state of practice (low priority)
- Application of Land Use/Land Cover Change Models for Assessing Potential Changes in Watershed Flooding Risks
  - Assess current state of practice (low priority)



Vasily, 2011



Bloschl et al, 2007

* Subject to availability of funding

Projected FY18-19 Work*

- Develop Draft Regulatory Guide

U.S. NUCLEAR REGULATORY COMMISSION
OFFICE OF NUCLEAR REGULATORY RESEARCH
DRAFT REGULATORY GUIDE

December 2011
Division 4

DRAFT REGULATORY GUIDE
(Proposed Revision 3 to Regulatory Guide 4.7, dated April 1998)

* Subject to availability of funding

2.3.12.2.2 Questions and Answers

Question:

You alluded to combining different flood mechanisms in a single hazard curve. I would think of treating them differently in building the PRA and considering the importance of other factors besides the water level. Note that the hazard curve may be discontinuous (including step changes).

Response:

Realistically, different portions of the hazard curves will come from different places. Contributions to the total hazard may come from different processes.

Question:

What is the peer review process for your model and its application/performance demands?

Response:

The model will be reviewed internally at the NRC. This report can be shared with other Federal agencies as well.

Comment:

Validation should reflect the predictive power of the model.

Question:

With respect to the utility of the models, how would you use surrogate models?

Response:

With local intense precipitation, for example, we will use anecdotal data to deal with the limited data case. These data can be used to constrain the model in certain situations. Other situations include ungauged catchment areas.

2.4 Summary

This report documents the 2nd Annual NRC Probabilistic Flood Hazard Assessment Research Workshop held at NRC Headquarters in Rockville, MD, on January 23–25, 2017. These proceedings included the following:

- Section 3.2: Workshop Agenda (in the program (ADAMS Accession No. ML17054C495)
- Section 3.3: Proceedings (abstracts in the program at ADAMS Accession No. ML17054C495 and complete workshop presentation package including slides and questions and answers at ADAMS Accession No. ML17040A626)
- Section 3.4: Summary
- Section 3.5 Workshop Participants

2.5 Participants

** indicates speaker, ^ indicates remote participant*

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5 SUMMARY AND CONCLUSIONS

5.1 Summary

This report has presented agendas, presentations and discussion summaries for the first four NRC Annual PFHA Research Workshops (2015-2019). These proceedings include presentation abstracts and slides and a summary of the question and answer sessions. The first workshop was limited to NRC technical staff and management, NRC contractors, and staff from other Federal agencies. The three workshops that followed were meetings attended by members of the public; NRC technical staff, management, and contractors; and staff from other Federal agencies. Public attendees over the course of the workshops included industry groups, industry members, consultants, independent laboratories, academic institutions, and the press. Members of the public were invited to speak at the workshops. The fourth workshop included more invited speakers from the public than from the NRC and the NRC's contractors.

The proceedings for the second through fourth workshops include all presentation abstracts and slides and submitted posters and panelists' slides. Workshop organizers took notes and audio recorded the question and answer sessions following each talk, during group panels, and during end of day question and answer session. Responses are not reproduced here verbatim and were generally from the presenter or co authors. Descriptions of the panel discussions identify the speaker when possible. Questions were taken orally from attendees, on question cards, and over the telephone.

5.2 Conclusions

As reflected in these proceedings PFHA is a very active area of research at NRC and its international counterparts, as well as other Federal agencies, industry and academia. Readers of this report will have been exposed to current technical issues, research efforts, and accomplishments in this area within the NRC and the wider research community.

The NRC projects discussed in these proceedings represent the main efforts in the first phase (technical-basis phase) of NRC's PFHA Research Program. This technical-basis phase is nearly complete, and the NRC has initiated a second phase (pilot project phase) that is a syntheses of various technical basis results and lessons learned to demonstrate development of realistic flood hazard curves for several key flooding phenomena scenarios (site-scale, riverine and coastal flooding). The third phase (development of selected guidance documents) is an area of active discussion between RES and NRC User Offices. NRC staff looks forward to further public engagement regarding the second and third phases of the PFHA research program in future PFHA Research Workshops.

ACKNOWLEDGEMENTS

These workshops were planned and executed by an organizing committee in the U.S. Nuclear Regulatory Commission’s (NRC’s) Office of Nuclear Regulatory Research (RES), Division of Risk Analysis, Fire and External Hazards Analysis Branch, and with the assistance of many NRC staff.

Organizing Committees

1st Workshop, October 14–15, 2015: Joseph Kanney and William Ott.

2nd Workshop, January 23–25, 2017: *Co-Chairs*: Meredith Carr, Joseph Kanney; *Members:* Thomas Aird, Thomas Nicholson, MarkHenry Salley; *Workshop Facilitator:* Kenneth Hamburger

3rd Workshop, December 4–5, 2017: *Chair:* Joseph Kanney, *Members:* Thomas Aird, Meredith Carr, Thomas Nicholson, MarkHenry Salley; *Workshop Facilitator*: Kenneth Hamburger

4th Workshop, April 30–May 2, 2019: *Co-Chairs:* Meredith Carr, Elena Yegorova; *Members:* Joseph Kanney, Thomas Aird, Mark Fuhrmann, MarkHenry Salley; *Workshop Facilitator:* Kenneth Hamburger

Many NRC support offices contributed to all of the workshops and these proceedings. The organizing committee would like to highlight the efforts of the RES administrative staff; the RES Program Management, Policy Development and Analysis Branch; and the audiovisual, security, print shop, and editorial staff. The organizers appreciated office and division direction and support from Jennene Littlejohn, William Ott, MarkHenry Salley, Mark Thaggard, Michael Cheok, Richard Correia, Mike Weber, and Ray Furstenau. Michelle Bensi, Mehdi Reisi-Fard, Christopher Cook, and Andrew Campbell provided guidance and support from the NRC Office of New Reactors and the Office of Nuclear Reactor Regulation. The organizers thank the Electric Power Research Institute (EPRI) for assisting with planning, contributions, and organizing several speakers. EPRI personnel who participated in the organization of the workshops include John Weglian, Hasan Charkas, and Marko Randelovic.

During the workshops, Tammie Rivera assisted with planning and organized the registration area during the conference. David Stroup and Don Algama assisted with room organization. Notes were studiously scribed by Mark Fuhrmann, David Stroup, Nebiyu Tiruneh, Michelle Bensi, Hosung Ahn, Gabriel Taylor, Brad Harvey, Kevin Quinlan, Steve Breithaupt, Mike Lee, Jeff Wood, and organizing committee members. The organizers appreciate the assistance during the conference of audiovisual, security, and other support staff. The organizers thank the panelists, the technical presenters, and poster presenters for their contributions; Thomas Aird and Mark Fuhrmann for performing a colleague review of this document; and the Probabilistic Flood Hazard Assessment Research Group for transcript reviews.

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APPENDIX A: SUBJECT INDEX

APPENDIX B: INDEX OF CONTRIBUTORS

This index includes authors, co-authors, panelists, poster authors and self-identified participants from the audience who spoke in question and answer or panel discussions.

APPENDIX C: INDEX OF PARTICIPATING AGENCIES AND ORGANIZATIONS