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Protecting People and the Environment

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

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Part 4: *Forth 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).

4 FOURTH ANNUAL NRC PROBABILISTIC FLOOD HAZARD ASSESSMENT RESEARCH WORKSHOP

4.1 Introduction

This chapter details the 4th Annual NRC Probabilistic Flood Hazard Assessment (PFHA) Research Workshop held at the U.S. Nuclear Regulatory Commission (NRC) Headquarters in Rockville, MD, on April 30–May 2, 2019. These proceedings include presentation abstracts and slides, selected posters, and a summary of question and answers and panel discussions. The workshop was a public meeting attended by members of the public; NRC technical staff, management, and contractors; and staff from other Federal agencies.

The workshop began with an introduction from Ray Furstenau, Director, NRC Office of Nuclear Regulatory Research (RES). Following the introduction, RES and Electric Power Research Institute (EPRI) staff described their flooding research programs. Additionally, John Nakoski, RES, provided an overview of internal flood hazard efforts underway by the Nuclear Energy Agency, Committee on the Safety of Nuclear Installations (CSNI), Working Group on External Events (WGEV) Flooding.

Technical sessions followed the introduction session. Most sessions began with an invited keynote speaker, followed by several technical presentations, and concluded with a panel of all speakers, who discussed the session topic in general. At the end of each day, participants provided feedback and asked generic questions about research related to PFHA for nuclear facilities.

4.1.1 Organization of Conference Proceedings

Section 4.2 provides the agenda for this workshop. The agenda is also available in the NRC's Agencywide Documents Access and Management System (ADAMS) at Accession No. ML19156A448.

Section 4.3 presents the proceedings from the workshop, including abstracts, presentation slides, selected posters, and summaries of the question and answer sessions and panel discussions for each technical session.

The summary document of session abstracts for the technical presentations is available at ADAMS Accession No. ML19156A447. The complete workshop presentation package is available at ADAMS Accession No. ML19156A446.

Section 0summarizes the workshop, and Section 0lists the workshop attendees, including remote participants.

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4.2 Workshop Agenda

4th Annual NRC Probabilistic Flood Hazard Assessment Research Workshop at NRC Headquarters in Rockville, Maryland

AGENDA: TUESDAY, APRIL 29, 2019

09:00–09:10	Welcome & Logistics	

Session 1A - Introduction
Session Chair: *Meredith Carr, NRC/RES*

09:10–09:25	Introduction *Raymond Furstenau*, Director, Office of Nuclear Regulatory Research*	1A-1
09:25–09:45	NRC Flooding Research Program Overview *Joseph Kanney*, Meredith Carr, Tom Aird, Elena Yegorova, Mark Fuhrmann and Jacob Philip, NRC/RES*	1A-2
09:45–10:05	EPRI External Flooding Research Program Overview *Marko Randelovic*, EPRI*	1A-3
10:05–10:20	Nuclear Energy Agency: Committee on the Safety of Nuclear Installations (CSNI): Working Group on External Events (WGEV) Flooding Overview *John Nakoski*, NRC/RES*	1A-4
10:20–10:35	**BREAK**	

Session 1B - Coastal Flooding
Session Chair: *Joseph Kanney, NRC/RES*

10:35–11:05	KEYNOTE: National Weather Service Storm Surge Ensemble Guidance *Arthur Taylor*, National Weather Service/Office of Science and Technology Integration/Meteorological Development Laboratory*	1B-1
11:05–11:30	Advancements in Probabilistic Storm Surge Models and Uncertainty Quantification Using Gaussian Process Metamodeling *Norberto C. Nadal-Caraballo*, Victor M. Gonzalez and Alexandros Taflanidis, USACE R&D Center, Coastal and Hydraulics Laboratory*	1B-2
11:30–11:55	Probabilistic Flood Hazard Assessment Using the Joint Probability Method for Hurricane Storm Surge *Michael Salisbury^, Atkins North America, Inc.;* *Marko Randelovic*, EPRI*	1B-3

**** denotes presenter, ^ denotes remote presenter***

continued…

Session 1B - Coastal Flooding

Session Chair: *Joseph Kanney, NRC/RES*

11:55–12:20	Assessment of Epistemic Uncertainty for Probabilistic Storm Surge Hazard Assessment Using a Logic Tree Approach *Bin Wang*, Daniel C. Stapleton and David M. Leone, GZA GeoEnvironmental, Inc.*	1B-4
12:20–13:00	Coastal Flooding Panel *Arthur Taylor, National Weather Service* *Victor Gonzalez, USACE Coastal and Hydraulics Laboratory* *Michael Salisbury, Atkins North America, Inc.* *Bin Wang, GZA GeoEnvironmental, Inc.* *Guest Panelist: Chris Bender, Taylor Engineering*	1B-5
13:00–14:00	**LUNCH**	

Session 1C - Precipitation

Session Chair: *Elena Yegorova, NRC/RES*

14:00–14:30	KEYNOTE: Satellite Precipitation Estimates, GPM, and Extremes *George J. Huffman*, National Aeronautics and Space Administration/Goddard Space Flight Center (NASA/GSFC)*	1C-1
14:30–14:55	Hurricane Harvey Highlights: Need to Assess the Adequacy of Probable Maximum Precipitation Estimation Methods *Shih-Chieh Kao, Scott T. DeNeale and David B. Watson, ORNL*	1C-2
14:55–15:20	Reanalysis Datasets in Hydrologic Hazards Analysis *Jason Caldwell, USACE, Galveston District. Presented by John England, USACE/RMC*	1C-3
15:20–15:35	**BREAK**	
15:35–16:00	Current Capabilities for Developing Watershed Precipitation-Frequency Relationships and Storm-Related Inputs for Stochastic Flood Modeling for Use in Risk-Informed Decisionmaking *Mel Schaefer*, MGS Engineering Consultants, Inc.*	1C-4
16:00–16:25	Factors Affecting the Development of Precipitation Areal Reduction Factors *Shih-Chieh Kao* and Scott DeNeale, ORNL*	1C-5
16:25–17:05	Precipitation Panel Discussion *George J. Huffman, NASA/GSFC* *Shih-Chieh Kao, ORNL* *John England, USACE, Risk Management Center* *Mel Schaefer, MGS Engineering Consultants* *Guest Panelist: Kevin Quinlan, NRC/NRO/DLSE/EXHB*	1C-6
17:05–17:20	**Daily Wrap-up**	

08:20–08:30	Day 2 Welcome	

Session 2A - Riverine Flooding

Session Chairs: *Meredith Carr and Mark Fuhrmann, NRC/RES*

08:30–9:00	KEYNOTE: Watershed level Risk Analysis with HEC-WAT *Will Lehmann*, Lea Adams and Chris Dunn, USACE, Institute for Water Resources, Hydrologic Engineering Center (IWR/HEC)*	2A-1
09:00–09:25	Global Sensitivity Analyses Applied to Riverine Flood Modeling *Claire-Marie Duluc*, Vincent Rebour, Vito Bacchi, Lucie Pheulpin & Nathalie Bertrand, Institut de radioprotection et de sûreté nucléaire Radioprotection and Nuclear Safety Institute*	2A-2
09:25–09:50	Detection and Attribution of Flood Change Across the United States *Stacey A. Archfield*, Water Mission Area, U.S. Geological Survey – Presentation Cancelled*	2A-3
09:50–10:15	Bulletin 17C: Flood Frequency and Extrapolations for Dams and Nuclear Facilities *John F. England* and Haden Smith, USACE, Risk Management Center; Brian Skahill, USACE R&D Center, Coastal and Hydraulics Laboratory*	2A-4
10:15–10:35	**BREAK**	

Session 2A - Riverine Flooding, *continued…*

Session Chairs: *Meredith Carr and Mark Fuhrmann, NRC/RES*

10:35–11:00	Riverine Paleoflood Analyses in Risk-Informed Decisionmaking: Improving Hydrologic Loading Input for USACE Dam Safety Evaluations *Keith Kelson*, USACE, Sacramento Dam Safety Production Center; Justin Pearce, USACE, Risk Management Center; and Brian Hall, Dam Safety Modification Mandatory Center of Expertise*	2A-5
11:00–11:25	Improving Flood Frequency Analysis with a Multi-Millennial Record of Extreme Floods on the Tennessee River near Chattanooga, TN *Tess Harden*, Jim O'Connor and Mackenzie Keith, USGS*	2A-6
11:25–12:05	Riverine Flooding Panel Discussion *Will Lehmann, USACE/IWR Hydrologic Engineering Center* *Claire-Marie DuLuc, IRSN* *John F. England, USACE, Risk Management Center* *Keith Kelson, USACE, Sacramento Dam Safety Protection Center* *Tess Harden, U.S. Geological Survey*	
12:05–13:25	**LUNCH**	

Session 2B - Modeling Frameworks

Session Chair: *Thomas Nicholson, NRC/RES*

13:25–13:50	Structured Hazard Assessment Committee Process for Flooding (SHAC-F) *Rajiv Prasad^ and Philip Meyer, Pacific Northwest National Laboratory; Kevin Coppersmith, Coppersmith Consulting*	2B-1
13:50–14:15	Overview of the Tennessee Valley Authority (TVA) PFHA Calculation System *Shaun Carney*, RTI International, Water Resource Management Division; Curt Jawdy, Tennessee Valley Authority*	2B-2
14:15–14:40	Development of Risk-Informed Safety Margin Characterization Framework for Flooding of Nuclear Power Plants *M.A. Andre, George Washington University; E. Ryan, Idaho State University, Idaho National Laboratory; Steven Prescott, Idaho National Laboratory; N. Montanari and R. Sampath, Centroid Lab; L. Lin, A. Gupta and N. Dinh, North Carolina State University; and Philippe M. Bardet*, George Washington University*	2B-3
14:40–15:20	Modeling Frameworks Panel Discussion *Rajiv Prasad, Pacific Northwest National Laboratory* *Shaun Carney, RTI International* *Philippe M. Bardet, George Washington University* *Will Lehmann, USACE/IWR, HEC* *Guest Panelist: Joseph Kanney, NRC/RES*	2B-4
15:20–15:35	Daily Wrap-up	

15:35–16:50 **<u>Session 2C - Poster Session</u>**

Session Chair: *Meredith Carr, NRC/RES*

2C-1 Coastal Storm Surge Assessment using Surrogate Modeling Methods

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

2C-2 Methods for Estimating Joint Probabilities of Coincident and Correlated Flooding Mechanisms for Nuclear Power Plant Flood Hazard Assessments

Michelle (Shelby) Bensi and Somayeh Mohammadi, Center for Disaster Resilience, University of Maryland; Scott DeNeale and Shih-Chieh Kao, Environmental Sciences Division, Oak Ridge National Laboratory

2C-3 Modelling Dependence and Coincidence of Flooding Phenomena: Methodology and Simplified Case Study in Le Havre in France

A. Ben Daoued, Sorbonne University—Université de Technologie de Compiègne; Y. Hamdi, Institut de Radioprotection et de Sûreté Nucléaire; Mouhous-Voyneau, Sorbonne University—Université de Technologie de Compiègne; and P. Sergent, Cerema

2C-4 Current State-of-Practice in Dam Risk Assessment

Scott DeNeale, Environmental Sciences Division, Oak Ridge National Laboratory; Greg Baecher, Center for Disaster Resilience, University of Maryland; and Kevin Stewart, Environmental Sciences Division, Oak Ridge National Laboratory

2C-5 Hurricane Harvey Highlights the Challenge of Estimating Probable Maximum Precipitation

Shih-Chieh Kao, Scott T. DeNeale and David B. Watson, Environmental Sciences Division, Oak Ridge National Laboratory

2C-6 Uncertainty and Sensitivity Analysis for Hydraulic Models with Dependent Inputs

Lucie Pheulpin, Vito Bacchi and Nathalie Bertrand, Institut de Radioprotection et de Sûreté Nucléaire, Fontenay-aux-Roses, France

2C-7 Development of Hydrologic Hazard Curves using SEFM for Assessing Hydrologic Risks at Rhinedollar Dam, CA

Bruce Barker, MGS Engineering Consultants, Inc.; Nicole Novembre, Brava Engineering, Inc.; Matthew Muto and John Dong, Southern California Edison; Blake Allen and Katie Ward, MetStat, Inc.; Jason Caldwell, Weather & Water, Inc.

2C-8 Probabilistic Flood Hazard Analysis of Nuclear Power Plant in Korea

Beomjin Kim, Ph.D. Candidate, Kyungpook National University, Korea; Kun-Yeun Han, Professor, Department of Civil Engineering, Kyungpook National University; Minkyu Kim, Principal Researcher, Korea Atomic Energy Institute, Korea

18:00 **<u>Group Dinner</u>**

AGENDA: THURSDAY, MAY 2, 2019

08:20–08:30	Day 3 Welcome	

Session 3A - Climate and Non-stationarity
Session Chair: *Joseph Kanney, NRC/RES*

08:30–09:00	KEYNOTE: Hydroclimatic Extremes Trends and Projections: A View from the Fourth National Climate Assessment *Kenneth Kunkel*, North Carolina State University*	3A-1
09:00–09:25	Regional Climate Change Projections: Potential Impacts to Nuclear Facilities *L. Ruby Leung*, Rajiv Prasad, Pacific Northwest National Laboratory*	3A-2
09:25–09:50	Role of Climate Change/Variability in the 2017 Atlantic Hurricane Season *Young-Kwon Lim*; NASA/GSFC, Global Modeling and Assimilation Office, Goddard Earth Sciences, Technology, and Research/I.M. Systems Group; Siegfried Schubert and Robin Kovach; NASA/GSFC, Global Modeling and Assimilation Office and Science Systems and Applications, Inc.; Andrea Molod and Steven Pawson, NASA/GSFC, Global Modeling and Assimilation Office*	3A-3
9:50–10:30	Climate Panel Discussion *Kenneth Kunkel, North Carolina State University* *L. Ruby Leung, Pacific Northwest National Laboratory* *Young-Kwon Lim, NASA/GSFC* *Guest Panelist: Kevin Quinlan, NRC/NRO/DLSE/EXHB*	3A-4
10:30–10:50	**BREAK**	

Session 3B - Flood Protection and Plant Response
Session Chair: *Thomas Aird, NRC/RES*

10:50–11:15	External Flood Seal Risk-Ranking Process *Ray Schneider*, Westinghouse; and Marko Randelovic*, EPRI*	3B-1
11:15–11:40	Results of Performance of Flood-Rated Penetration Seals Tests *William (Mark) Cummings, Fisher Engineering, Inc.*	3B-2
11:40–1205	Modeling Overtopping Erosion Tests of Zoned Rockfill Embankments *Tony Wahl^, U.S. Bureau of Reclamation*	3B-3
12:05–12:45	Flood Protection and Plant Response Panel Discussion *Ray Schneider, Westinghouse* *William (Mark) Cummings, Fisher Engineering, Inc.* *Tony Wahl^, U.S. Bureau of Reclamation* *Guest Panelist: Jacob Philip, NRC/RES/DRA/DE*	3B-4

12:45–13:45	**LUNCH**		

Session 3C - Towards External Flooding PRA

Session Chair: *Joseph Kanney, NRC/RES*

13:45–14:10	External Flooding PRA Walkdown Guidance *Andrew Miller*, Jensen Hughes; and Marko Randelovic*, EPRI*	3C-1
14:10–14:35	Updates on the Revision and Expansion of the External Flooding PRA Standard *Michelle (Shelby) Bensi*, University of Maryland*	3C-2
14:35–15:00	Update on ANS 2.8: Probabilistic Evaluation of External Flood Hazards for Nuclear Facilities Working Group Status *Ray Schneider, Westinghouse*	3C-3
15:00–15:25	Qualitative PRA Insights from Operational Events of External Floods and Other Storm-Related Hazards *Nathan Siu, Ian Gifford*, Zeechung (Gary) Wang, Meredith Carr and Joseph Kanney, NRC/RES*	3C-4
15:25–16:05	Towards External Flooding PRA Discussion Panel *Andrew Miller, Jensen Hughes* *Michelle (Shelby) Bensi, University of Maryland* *Ray Schneider, Westinghouse* *Ian Gifford, NRC/RES* *Guest Panelist: Suzanne Denis, NRC/RES* *Guest Panelist: Jeremy Gaudron, EDF*	3C-5
16:05–16:25	Wrap-up Discussion	

4.3 <u>Proceedings</u>

4.3.1 Day 1: Session 1A - Introduction

Session Chair: Meredith Carr, NRC/RES/DRA/FXHAB

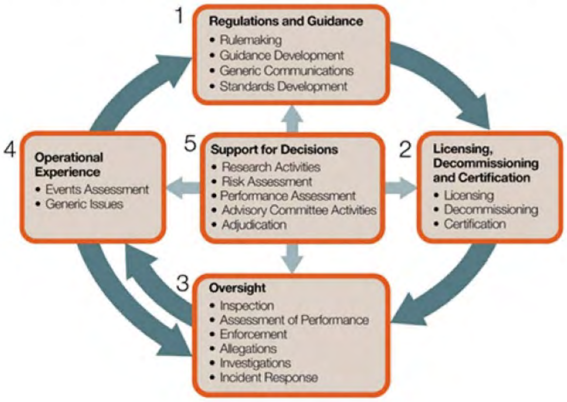
There are no abstracts for this introductory session.

4.3.1.1 Introduction. Raymond Furstenau*, Director, Office of Nuclear Regulatory Research (Session 1A-1)

4.3.1.1.1 Presentation

Programmatic Need for PFHA Research

- NRC Risk-Informed Regulatory Policy
- Policy translated into practice in many areas
- Gap with respect to flooding
- PFHA research is aimed at filling this gap



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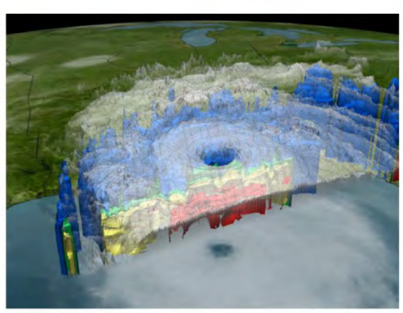
Practical Need for PFHA Research

- Recent experience has highlighted importance of risk-informing flood hazard assessments
  - Flooding events at or near NPPs in U.S. and abroad
  - Post-Fukushima flood hazard reevaluations and integrated assessments
- Ongoing and new risk-informed initiatives



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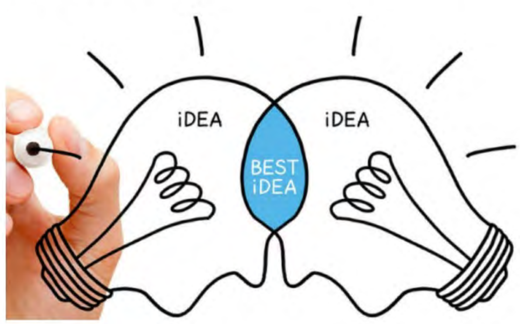
Progress

- Phased Approach
  - Technical basis
  - Pilot Studies
  - Guidance
- Bulk of technical basis research completed
  - Climate
  - Precipitation
  - Riverine flooding
  - Storm surge
  - Reliability of flood protection and mitigation
  - Modeling frameworks

4

Next Steps

- Turn focus towards pilot studies
  - Needed to inform guidance
    - Fine-tune scenario-specific issues
    - Hazard curves for spectrum of flood impacts
    - Interface between flood hazard assessment and plant risk assessment models
- Seeking collaboration



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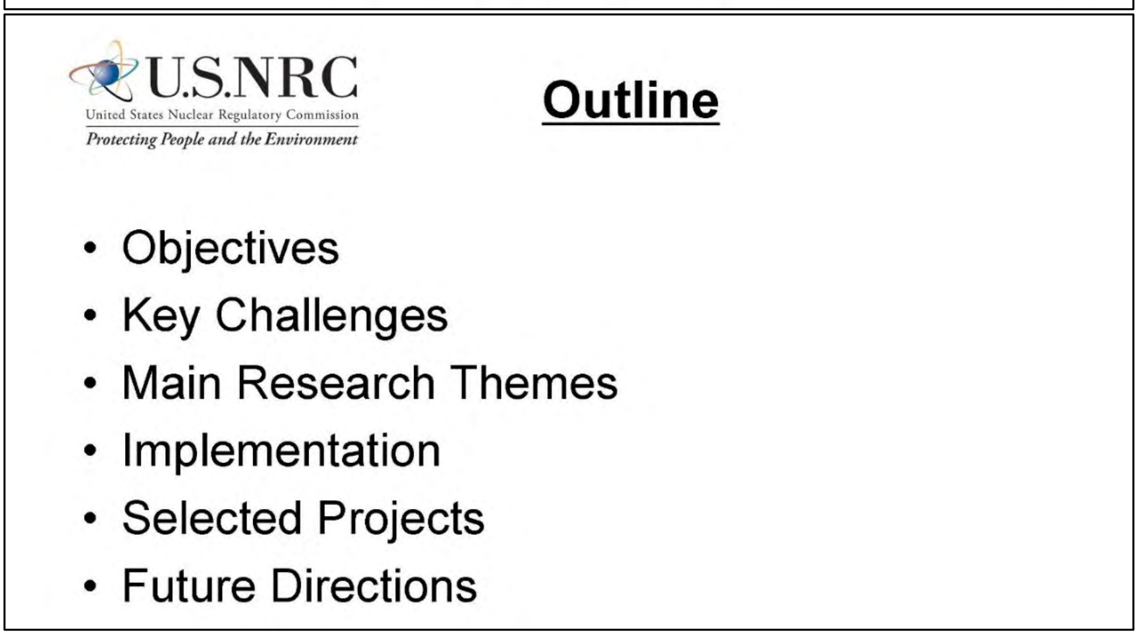
4.3.1.2 NRC Flooding Research Program Overview. Joseph Kanney*, Meredith Carr, Thomas Aird, Elena Yegorova, Mark Fuhrmann and Jacob Philip, NRC/RES (Session 1A-2; ADAMS Accession No. ML19156A449)

4.3.1.2.1 Presentation



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PFHA Research Objectives

- Address significant gap in technical basis for guidance for probabilistic assessment of external hazards
  - Probabilistic: seismic, high winds
  - Deterministic: flooding
- Develop resources, tools and selected guidance
  - Support risk-informed licensing and oversight activities associated with flooding hazards and consequences
    - Licensing and oversight in operating reactor program
    - Design basis flood hazard assessments for new facilities

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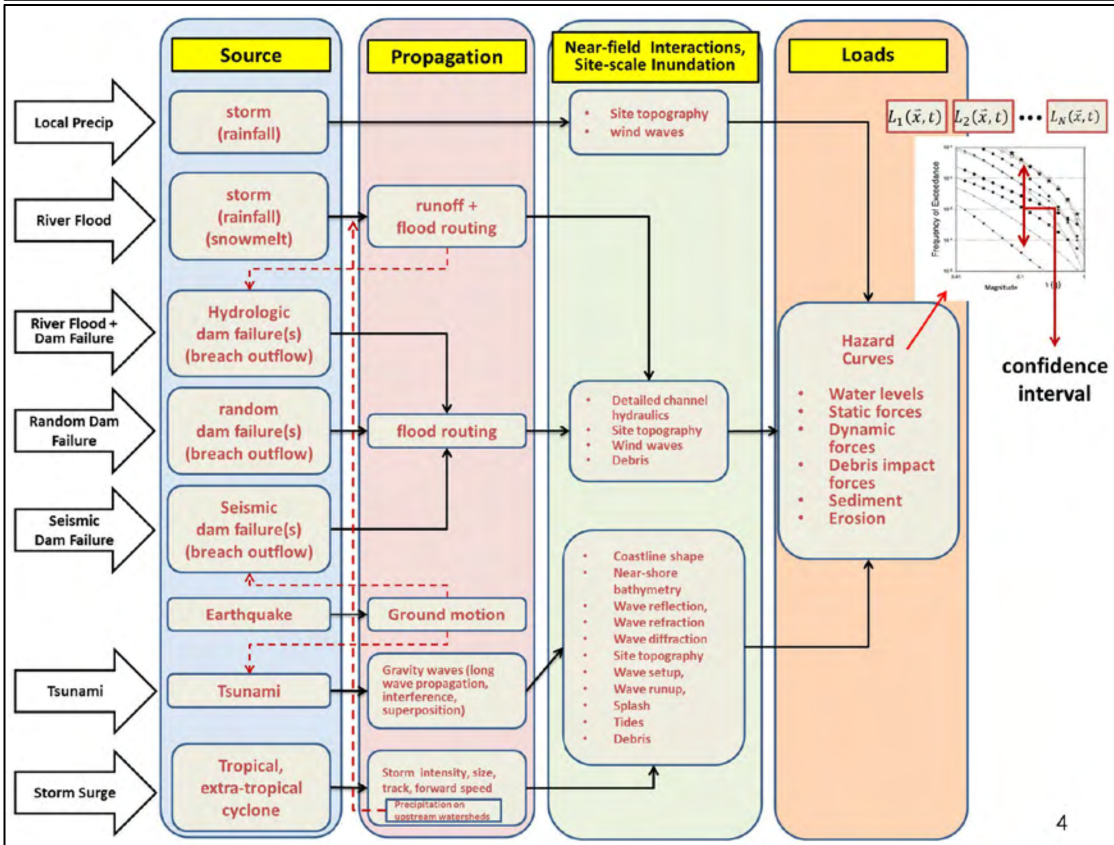

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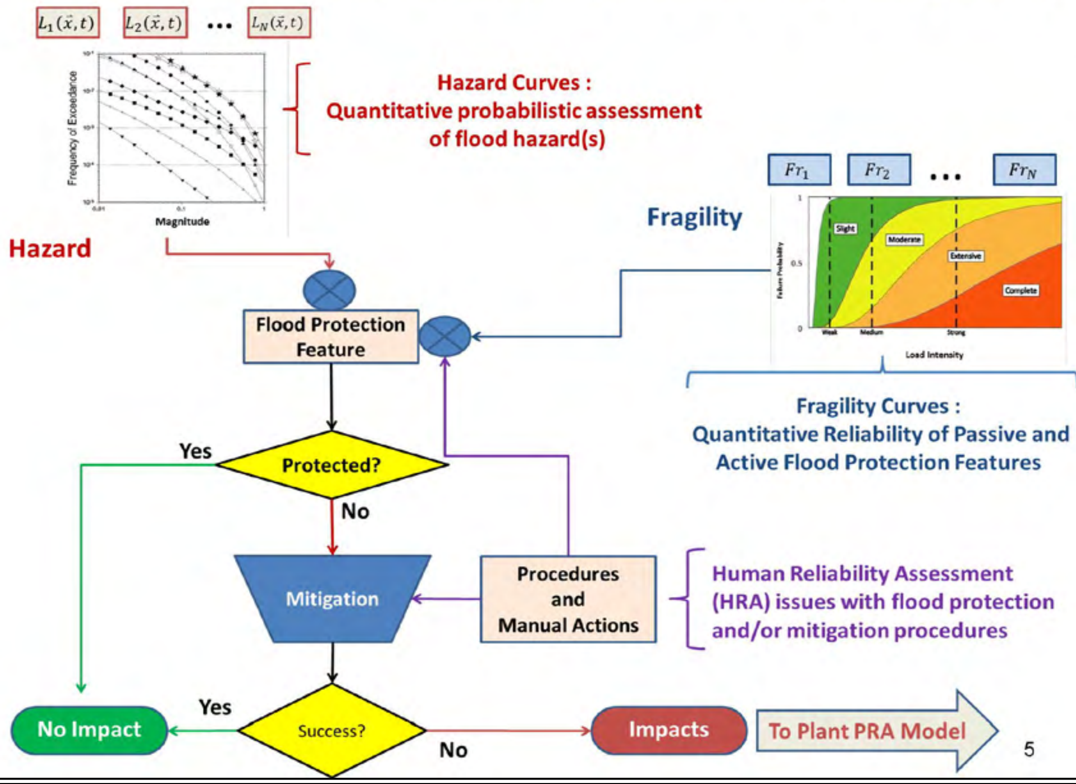
Risk-informed Assessment of Flooding Hazards and Consequences



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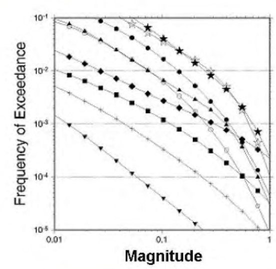
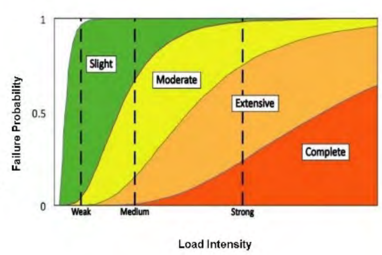
Key Challenges

- Hazard Curve Development
  - Range of annual exceedance probabilities (AEPs)
    - Moderately rare to extreme floods
  - Multiple flooding mechanisms
    - Coincident and correlated mechanisms
  - Uncertainty characterization and estimation
    - Aleatory (e.g. storm recurrence rates)
    - Epistemic (e.g. model structure, parameters)
- Fragility Curve Development
  - Information on reliability of flood protection features and procedures is sparse
  - Cliff-edge effects





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Main Research Themes

- Leverage available flood hazard information
- Develop PFHA modeling 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

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Phased Approach

- Phase 1 (FY15-FY19)
  - Technical basis research
- Phase 2 & 3 (FY20-FY22)
  - Selected draft guidance documents
  - Perform pilot studies
  - Finalize guidance

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Implementation

- Internal Collaborations
  - User offices
  - Other RES divisions/branches
- External Contract technical support
  - Interagency Agreements
  - Commercial contracts
- External Collaborations
  - MOUs
    - EPRI
    - France Institute for Radiological Protection and Nuclear Safety (IRSN)
  - Federal interagency working groups
  - International working groups

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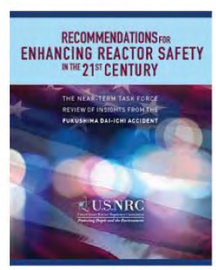
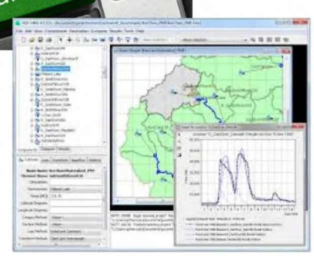
Additional Activities



- Support Agency Post-Fukushima Activities
- Collaboration with other RES and Agency Initiatives
- Training Seminars & Workshops
- Technical Exchanges



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Phase 1 (Technical Basis) Projects

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Leverage Available Flooding Information

- **Development of Natural Hazard Information Digests for Operating NPP Sites (INL)**
  - *In progress (completion expected FY19)*
- **Application of State-of-Practice Flood Frequency Analysis Methods and Tools (USGS)**
  - *https://pubs.er.usgs.gov/publication/sir20175038*
  - *2nd USGS SIR in publication (expected in FY19)*
- **Extreme Precipitation Estimates in Orographic Regions (USBR)**
  - *NUREG/CR report in publication*
- **Technical Basis for Extending Frequency Analysis Beyond Current Consensus Limits (USBR)**
  - *In progress (expected completion in CY19)*

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Leverage Available Frequency Information (Cont.)

- **Eastern US Riverine Flood Geomorphology Feasibility Study (USGS)**
  - *Completed (https://doi.org/10.3133/sir20175052)*
- **Eastern US Riverine Flood Geomorphology Comprehensive Study (USGS)**
  - *In progress (completion expected FY19)*
- **Framework for Technical Review of Paleoflood Information (USGS)**
  - *New start (expected completion FY20)*
- **Application of Point Precipitation Estimates to Watersheds (ORNL)**
  - *In progress (completion expected FY19)*

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PFHA Modeling Frameworks

- **Probabilistic Flood Hazard Assessment Framework Development (USACE)**
  - *In progress (completion expected FY19)*
- **Structured Hazard Assessment Committee Process for Flooding (SHAC-F) for LIP & Riverine Flooding (PNNL)**
  - *In progress (completion expected FY19)*
- **Development of SHAC-F for Coastal Flooding (PNNL & USACE)**
  - *New start (completion expected CY19)*

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Improved Modeling

- **Numerical Modeling of Local Intense Precipitation Processes (USGS/UC Davis)**
  - *NUREG-CR report in publication*
  - *Mure-Ravaud, et al. (2019a,b) https://www.sciencedirect.com/science/article/pii/S0048969719306734*
  - *https://www.sciencedirect.com/science/article/pii/S0048969719306291*
- **Quantifying Uncertainties in Probabilistic Storm Surge Models (USACE)**
  - *In progress (completion expected CY19)*
  - *ERDC/CHL SR-19-1 (Literature Review)*
    - *https://erdc-library.erdc.dren.mil/xmlui/handle/11681/32293*
- **Erosion Processes in Embankment Dams (USBR)**
  - *NUREG-CR report in publication*
- **Methods for Estimating Joint Probabilities of Coincident and Correlated Flooding Mechanisms for Nuclear Power Plant Flood Hazard Assessments (ORNL)**
  - *New start (completion expected FY20)*

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Reliability of Flood Protection

- **Modeling Plant Response to Flooding Events (INL)**
  - *NUREG/CR report in publishing*
- **Effects of Environmental Factors on Manual Actions for Flood Protection and Mitigation at Nuclear Power Plants (PNNL)**
  - *In Progress (completion expected FY19)*
- **Critical Review of the State of Practice in Probabilistic Risk Assessment for Dams (ORNL, UMD)**
  - *In Progress (completion expected FY19)*
- **Performance of Flood Penetration Seals at NPPs (Fire Risk Management)**
  - *NUREG report in preparation*

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Dynamic and Nonstationary Processes

- **Regional Climate Change Projections: Potential Impacts to Nuclear Facilities (PNNL)**
  - *YR1 (CONUS) - published as a PNNL report (PNNL-24868)*
  - *YR2 (Southeast US) - published as a PNNL report (PNNL-26226)*
  - *YR3 (Midwest US) - report in review*
  - *YR4 (Northeast US) in progress*

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Future Directions

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Phase 1 Completion

- FY19-20
  - Follow-on Flood Protection Performance Research
    - In discussions w/ ERPI, DOE/INL
  - Identify Selected Draft Guidance Documents
    - White papers
    - Reg Guides

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Phase 2 Pilot Studies

- FY20-21
  - LIP flooding scenario(s)
  - Inland (riverine) flooding scenario(s)
  - Coastal flooding scenario(s)
- *Seeking collaboration*
  - *Industry/EPRI*
  - *Other agencies*
  - *International*

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Phase 3 (FY22-?)

- Revise guidance documents based on pilots
- Stakeholder & Public Interactions
- Finalize guidance

Questions?
Contact: joseph.kanney@nrc.gov

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Mark Your Calendar!

5th Annual NRC PFHA Research Workshop
Feb 18-20, 2020
NRC HQ, Rockville, MD

Contact: Tom Aird Thomas.Aird@nrc.gov

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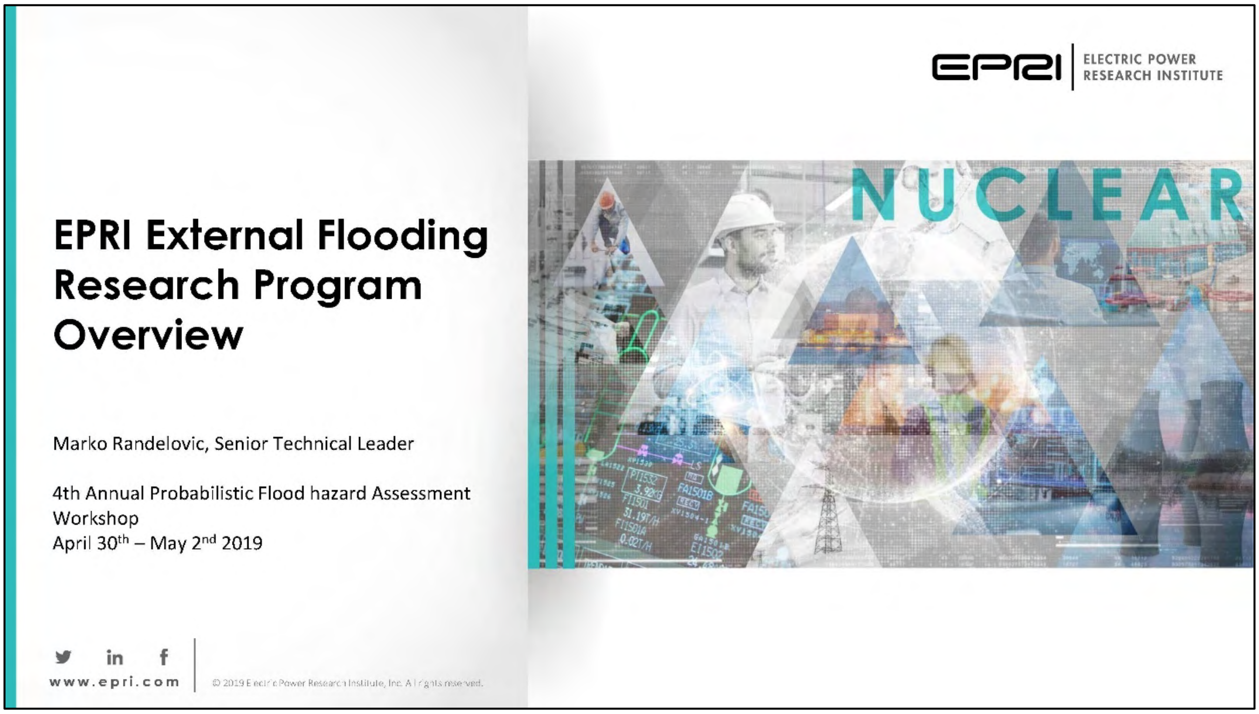
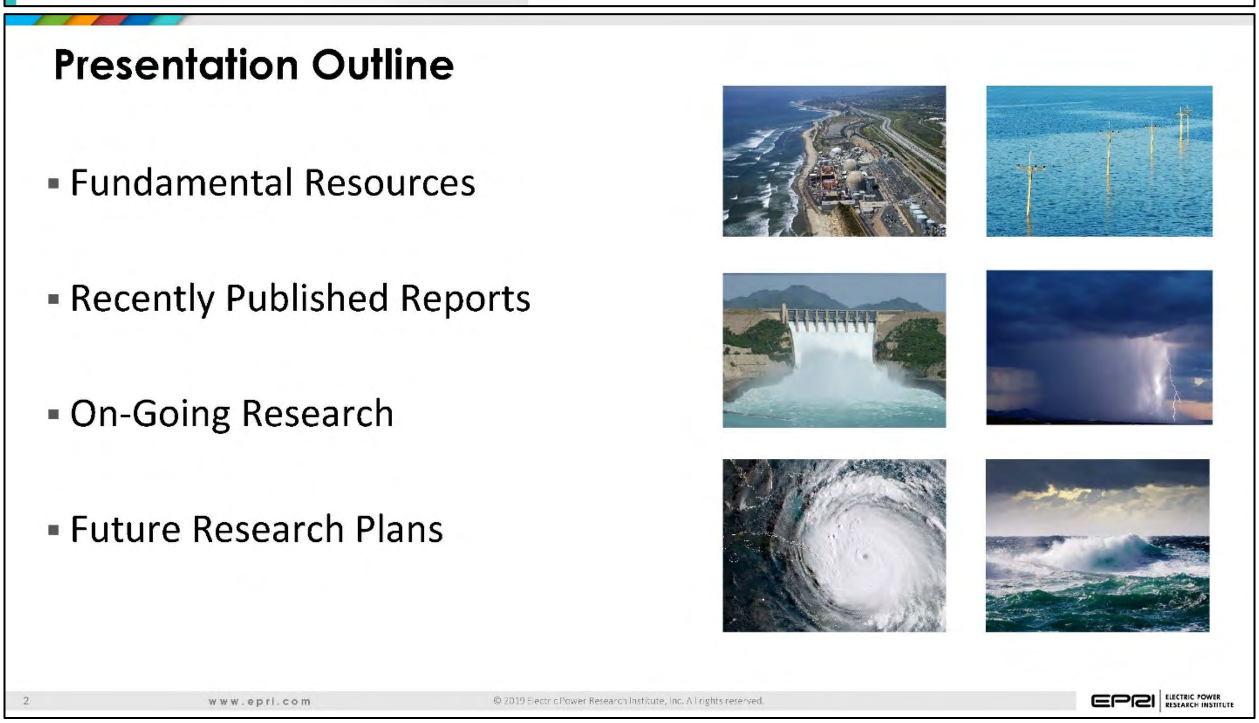
4.3.1.3 EPRI External Flooding Research Program Overview. Marko Randelovic*, EPRI (Session 1A-3; ADAMS Accession No. ML19156A450)

4.3.1.3.1 Presentation





EPRI Fundamental Resources

- Hazard Assessment
  - State of knowledge of external flooding analysis – 3002005292 (Freely available to public)
  - Riverine flooding – 3002003013
  - Local intense precipitation – 3002004400 (Freely available to public)
  - Probabilistic Flooding Hazard Assessment for Storm Surge – 3002008111
  - Evaluation of Deterministic Approaches to Characterizing Flood Hazards– 3002008113 (Freely available to public)
- Analysis Techniques
  - Use of 3-D modeling techniques for Int. flooding – 3002010673 (Freely available to public)
- Managing existing design and licensing bases for flood protection barriers
  - Flood Protection Systems Guide – 3002005423
  - External Flood Protection Design/License Basis Management Best Practices Guide – 3002010620

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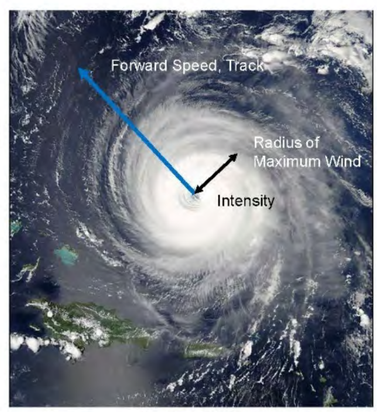
Recently Published - Storm Surge (Hazard)-JPM

- 3002012996 - EPRI conducted research into the use of joint probability method (JPM) to simulate hurricanes and establish flood hazard curve
- Hurricanes are simulated using stochastic model of storm parameters
  - Proximity of the landfall
  - Track angle of the storm
  - Storm intensity (central pressure)
  - Storm size
  - Storm forward speed

Storm Meteorological Parameters



Source: NASA Earth Observatory Image

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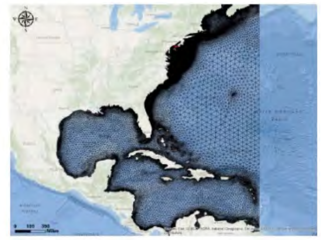
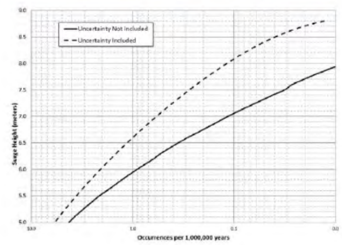
Storm Surge (Hazard)-JPM

- Report provides step-by-step guidance for utilities to use for scoping and performing the analysis
  - Storm Surge Model Development
    - Recommendations on model selection
    - How to build a model mesh
    - Model calibration
    - Model Validation
  - Detailed discussions on tropical storm parameter attributes
  - Treatment of uncertainties
- Example of real application





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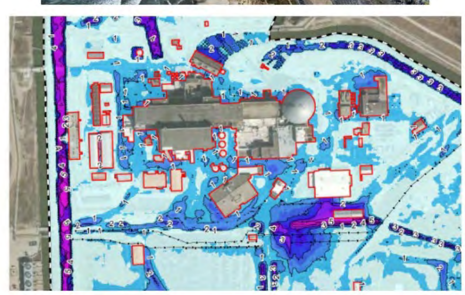
EPRI On-Going Research – Walkdown Guidance

- EPRI is developing guidance for performing an external flooding PRA walkdown in support of developing an external flooding PRA model
  - External flooding equipment list
    - List of components that could be required to mitigate the event
  - External flood operator actions list
    - Actions personnel take to provide flood protection prior to the arrival of the flood
    - Actions the personnel take after the flood arrives to mitigate the event that may be impacted by the flood
  - External flood protection features
    - Barriers to prevent flood waters from affecting plant equipment
    - Sumps or basements that may provide water retention
    - Drainage systems



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Walkdown Process Flowchart

1 **Flood Mechanism Review**
Define Key Flood Characteristics for Understanding During Walkdowns

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2 **Pre-Walkdown Preparation**
Develop XF Equipment, Operator Actions & Protection Features Lists

↓

3 **Initial XF Walkdown**
Confirm Assumptions of Walkdown Preparation and Gather Data

↓

4 **Refined Assessments or Additional Walkdowns**
Determine the Need for Refinements Based on Initial PRA Results

↓

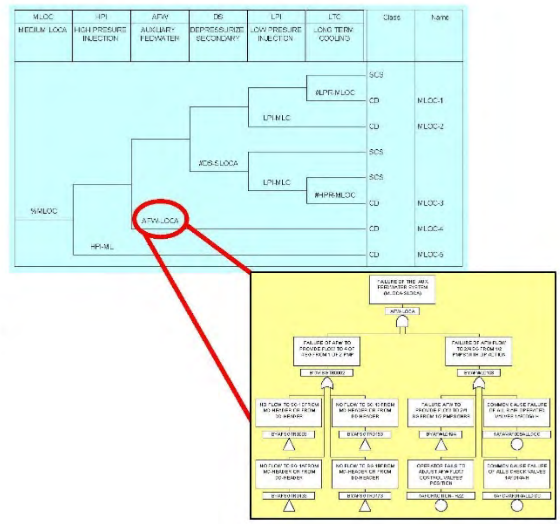
5 **Documentation**
Prepare a Practical XF Walkdown Notebook

EPRI On-Going Research – Flood Protection

- Flood barrier seals protect plant areas from external and internal flooding
- EPRI is currently developing a qualitative process for risk ranking plant flood seals based on:
  - Seal design and installation,
  - Maintenance,
  - Age,
  - Failure characteristics, and
  - Consequence to overall plant risk
- Process will explore means to assess risk to plant features due to potential water intrusions
- Work being done in coordination with deterministic maintenance EPRI guidance and existing industry testing
  - EPRI 3002005423 – Flood Protection Systems Guide

EPRI Future Research – External Flooding PRA guidance

- EPRI is initiating a research project on guidelines for building a complete External Flooding PRA
- Capitalize on the lessons learned from domestic and international members
- The guidelines will assist utilities to perform External Flooding PRA if needed



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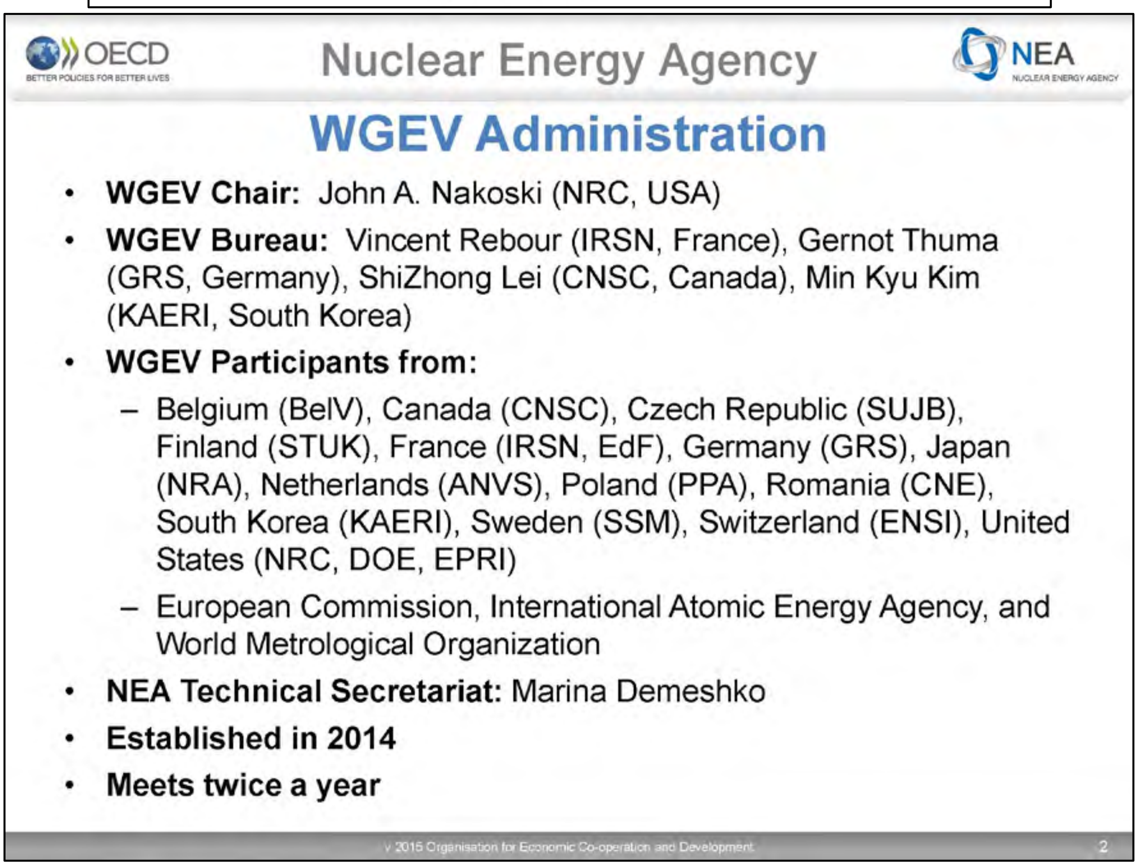
4.3.1.4 Nuclear Energy Agency, Committee on the Safety of Nuclear Installations (CSNI): Working Group on External Events (WGEV). John Nakoski*, NRC/RES (Session 1A-4; ADAMS Accession No. ML19156A451)

4.3.1.4.1 Presentation



Severe Weather and Storm Surge

Proceedings published – NEA/CSNI/R(2017)13

Key Messages:

- There is a need to improve reliability of information and understanding of boundary conditions for hazard analysis
- Data is sparse
  - Use simulation (needs to be validated)
  - Other data sources to extend available data
- Paleodata and historical data is important, but challenging to use
- Uncertainties need to be better understood and quantified
  - Be aware of the uncertainties and take them into account
- Fragility information for infrastructure is a key knowledge gap
  - Interface between insights gained from hazards assessment and application of those insights in a PRA
- Climate change is introducing new challenges that require new approaches and models

Approaches for Screening External Hazards

Technical Report in publication – NEA/CSNI/R(2018)7

– Effective screening of hazards promotes an efficient modelling practice for risk assessment

Key Messages:

- There is a need to screen and group hazards
- Develop and use lists of generic hazards and initiating events
- Group considering facility type, hazard frequency, facility impacts, and consequences
- Potential Issues with existing screening approaches
  - Varying definitions
  - Reliance on deterministic technical bases
  - Lack of consideration of uncertainty
  - Absence of physic-based information integrated into statistical models
  - Lack of supporting rational behind screening criteria

Riverine Flooding (1 of 4)

Proceedings in publication – NEA/SEN/SIN/WGEV(2018)1

Workshop Highlights:

- Challenging to bridge the gap between hydrologists and regulatory decision-makers
- Need correct and reliable weather forecasting for flooding
- Historic information, paleodata, and simulations can supplement the instrumental data
  - Difficult to incorporate into the existing hazard assessment framework
- Challenging to treat uncertainties
- Assessment of impact should consider more that flood level (associated effects)

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NEA NUCLEAR ENERGY AGENCY

Riverine Flooding (2 of 4)

Proceedings in publication – NEA/SEN/SIN/WGEV(2018)1

Workshop Highlights:

- Need rigorous understanding for fragility of facilities to strengthen protective measures technical bases
- Nature of flooding hazards and associated plant impacts challenge PSA methods
- Time consuming calculations, characterization of probability distributions, and dependent input parameters challenge PFHA methodology
- Need to balance consideration of the spectrum of associated effects from flooding and the information necessary to support decision-making
- The concept of a “dry site” needs to be reconsidered

v 2015 Organisation for Economic Co-operation and Development

Riverine Flooding (3 of 4)

Proceedings in publication – NEA/SEN/SIN/WGEV(2018)1

Workshop Conclusions and Recommendations:

- Share information between nuclear and non-nuclear organizations as well as with neighboring countries
- Augment temporally and spatially sparse historical data with simulations and other information
- Further work is needed to understand how metrics, such as a selected value for annual exceedance frequency, can be used in regulatory decision making

Riverine Flooding (4 of 4)

Proceedings in publication – NEA/SEN/SIN/WGEV(2018)1

Workshop Conclusions and Recommendations:

- Uncertainties with data and modelling need to be better understood and quantified
  - Decision makers should be aware of the uncertainties and take them appropriately into account
- Develop new approaches and models to identify and address the challenges introduced by climate change
- The workshop demonstrated that:
  - It is important for the nuclear and meteorological communities to work together
  - Subject matter expert co-operation, including non-nuclear experts, is important as well as regional co-operation to share experience and data

Ongoing Activities

- **Concepts and Definitions for Protective Measures in Response to External Flooding Hazards**
  - Survey responses provided to WGEV writing group (January 2019)
  - Guidance for writing group and assessment of survey responses (March 2019)
  - Preparation of initial draft report - June 2019,
  - Final report – June 2020
- **Benchmark on Hazard Frequency and Magnitude Model Validation for External Events**
  - Finalization of the benchmark specification – November 2018
  - Gather input from benchmark participants – July 2019
  - Final Report – December 2020
  - For more information contact Curtis Smith (Curtis.Smith@inl.gov) or Vincent Rebour (Vincent.Rebour@irsn.fr)

OECD BETTER POLICIES FOR BETTER LIVES Nuclear Energy Agency NEA NUCLEAR ENERGY AGENCY

Potential Future Activities

- **High winds and tornadoes –** to CSNI for approval
- **Integrated hazards assessment –** under development
  - Sequential and correlated hazards (i.e., seismically induced tsunamis, high winds and local intense precipitation, etc.)
  - Associated affects (i.e., flooding hydrodynamic loads and debris impacts, wind loads and missile impacts, etc.)
- **Improving understanding and application of uncertainty in hazards assessment and decision-making –** under development
- **Topical discussions – next WGEV meeting topics**
  - Space weather
  - Improving data sources for hazards assessment

v 2015 Organisation for Economic Co-operation and Development

4.3.2 Day 1: Session 1B - Coastal Flooding

Session Chair: Joseph Kanney, NRC/RES/DRA/FXHAB

4.3.2.1 KEYNOTE: National Weather Service Storm Surge Ensemble Guidance.

Arthur Taylor*, National Weather Service/Office of Science and Technology Integration/Meteorological Development Laboratory (Session 1B-1; ADAMS Accession No. ML19156A452)

4.3.2.1.1 Abstract

The National Weather Service (NWS) Meteorological Development Laboratory (MDL) is tasked with developing storm surge guidance to help protect life and property from disastrous storms. After developing the Sea Lake and Overland Surges from Hurricanes (SLOSH) storm surge model in the 1980s, we recognized that storm surge is highly dependent on the location of the winds with regard to the underlying bathymetry, so one of the largest errors in storm surge guidance was the quality of the wind forecasts. Thus, to save lives, we had to account for wind uncertainty in a timely manner, even if that meant erring on the side of caution in regard to the storm surge guidance.

Initially, our approach was to develop Maximum Envelopes of Water (MEOWs) and Maximum of MEOWs (MOMs). MEOWs and MOMs are the maximum storm surge attained in each grid cell from a set of hypothetical hurricanes. As such, they approximate the potential inundation for an area from a specific type of hurricane. MEOWs and MOMs form the basis of the hurricane evacuation plans in the United States[7]. The National Storm Surge Hazard map, developed by the

[7] Shaffer WA, Jelesnianski CP, Chen J (1989) Hurricane storm surge forecasting. Preprints, *11th Conf on Probability and Statistics in Atmospheric Sciences*, Monterey, CA, Amer Meteor Soc 53–58.

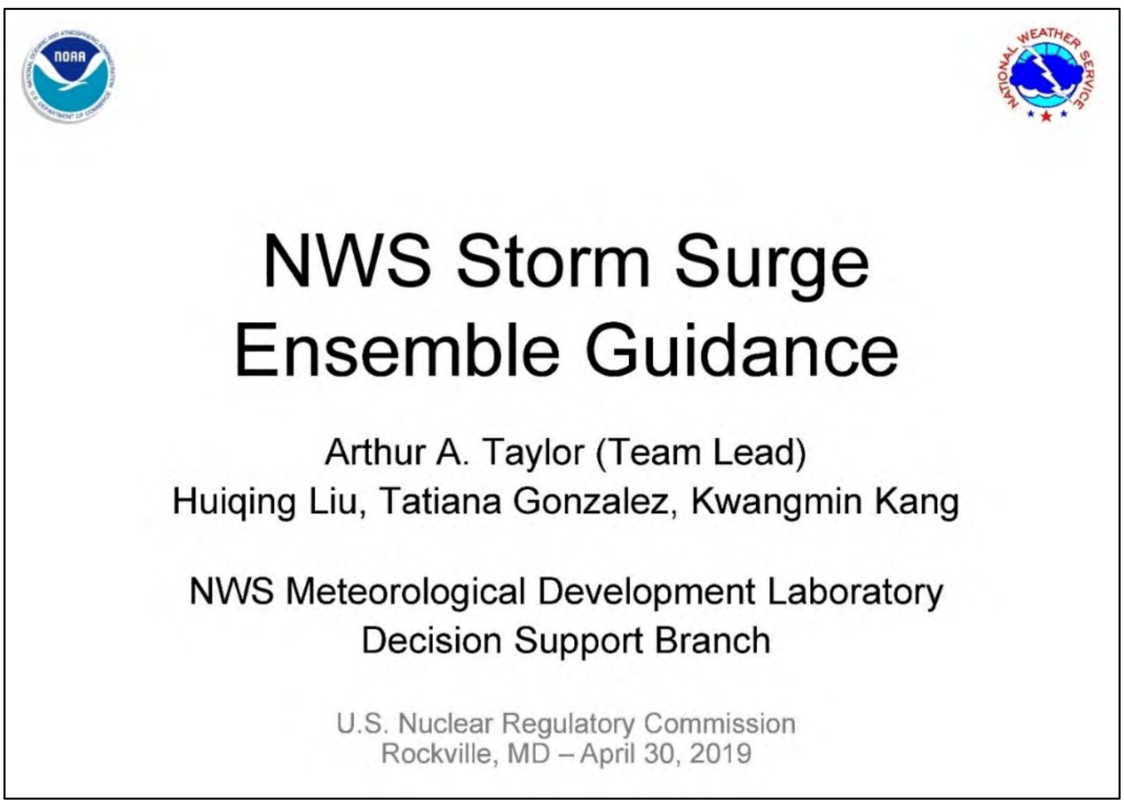
National Hurricane Center (NHC), was created by merging the MEOWs and MOMs from each computational domain onto a uniform grid.

In the 2000s, we addressed the issue via the Probabilistic Tropical Cyclone Storm Surge model (P-Surge)[8]. P-Surge is a real-time ensemble based on parameterizing an active storm and permuting it via NHC's 5-year average forecasting errors. MEOWs and MOMs are based on an undefined error space, hypothetical storms, and an unknown time and tide, whereas P-Surge is based on a defined error space, an active storm, and the current time and tide. NWS's storm surge watch and warning is primarily based on P-Surge.

More recently, in the 2010s, we treated wind uncertainty for extratropical and post-tropical storms via the Probabilistic Extra-Tropical Storm Surge model (P-ETSS). Extratropical storms do not lend themselves to parameterization, so instead of permuting through an error space, P-ETSS is based on running a storm surge model with each of the 21 members of the Global Ensemble Forecasting System (GEFS). P-ETSS is intended for storms that are not well represented by a parametric hurricane wind model, such as broader extratropical storms, weaker tropical storms, or post-tropical depressions.

This talk will briefly describe the SLOSH model and then focus on the details of P-Surge and P-ETSS and future plans for development. The audience should learn why NWS uses P-Surge and P-ETSS for the forecasting problem (as opposed to design).

4.3.2.1.2 Presentation



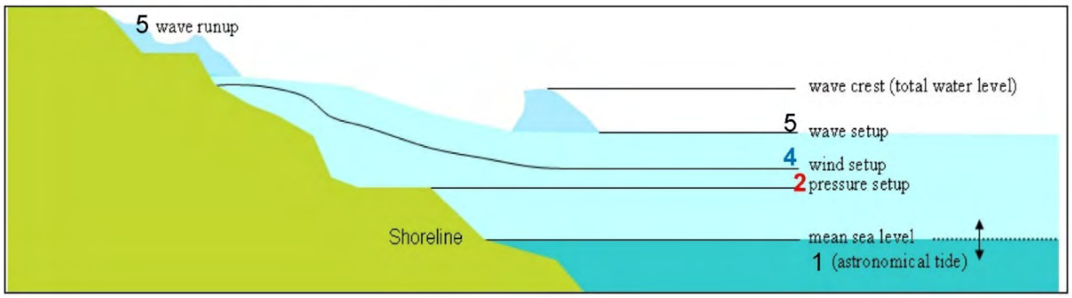
[8] Taylor, AA, & Glahn, B (2008). Probabilistic guidance for hurricane storm surge. *In 19th Conference on probability and statistics:* Vol. 74.

What is Storm Surge?

A rising of the sea as a result of atmos. pressure changes and winds associated with a storm.

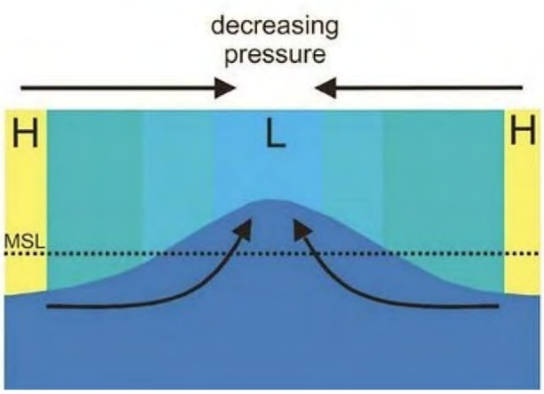
1. **Astronomical Tide**
2. **Pressure setup** – water level change due to lower atmos. pressure
3. **Geostrophic adjustment** – adjustment due to longshore current
4. **Wind setup** – water level change due to the force of the wind
5. **Wave setup** – water level change due to wave setup and run-up
6. **Nonlinear Advection**

Dissipation terms; Steric setup

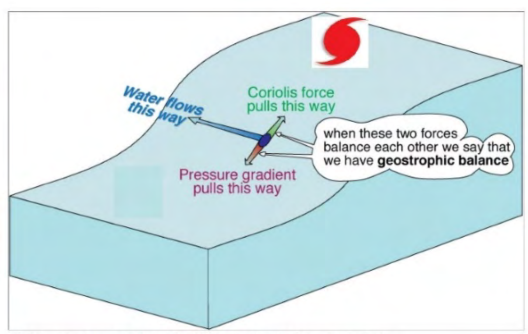


Pressure Terms

Pressure Setup



Geostrophic Adjustment

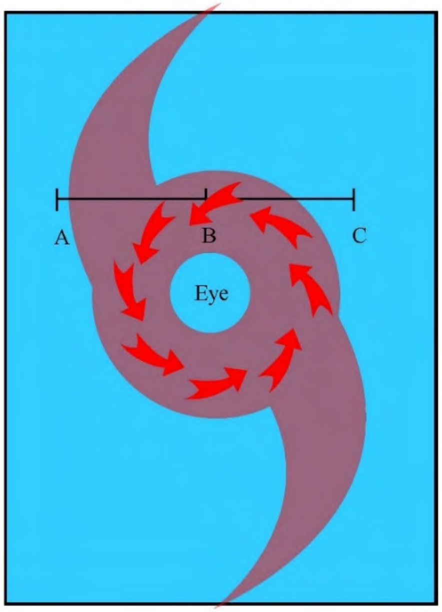


The balance between pressure gradient forces and Coriolis forces on a parcel of water is what we call geostrophic balance.

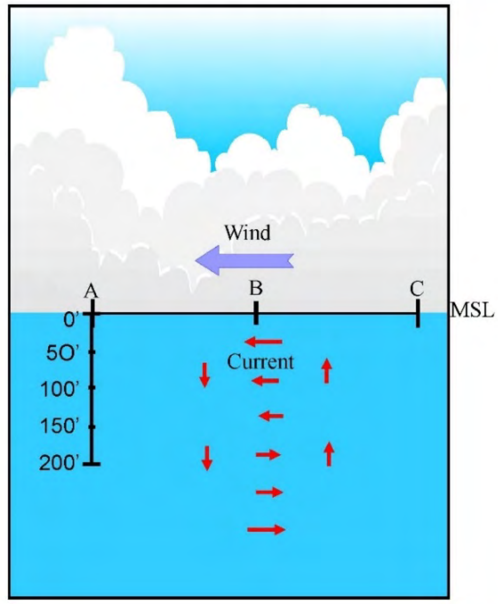
Slower and/or **Larger** storms increase the geostrophic adjustment's impact on storm surge.

Wind Setup

a. Top view of Sea Surface



b. Side view of Cross Section "ABC"



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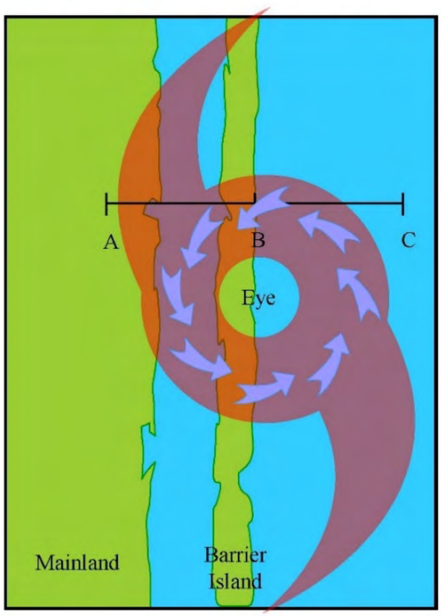
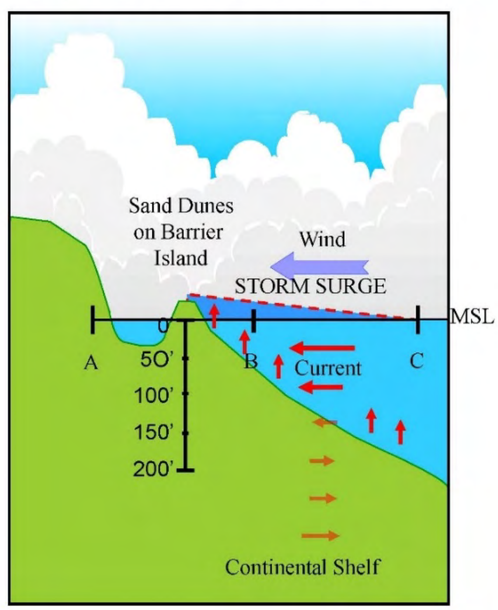
Wind Setup

a. Top view of Sea Surface and Land



b. Side view of Cross Section "ABC"



5

What is the SLOSH model?

(Sea Lake and Overland Surges from Hurricanes)

Wind

- Pressure
- Radius of Max Winds
- Differential Equations
- Location
- Forward Speed

Basin

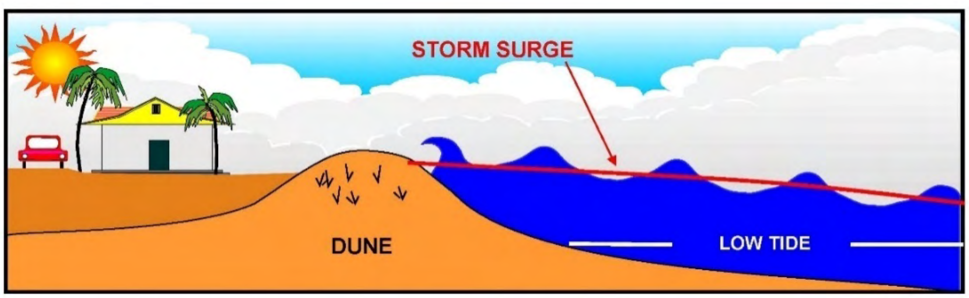
- Grid Definition
- Topography
- Tidal Database
- Bathymetry

SLOSH Model

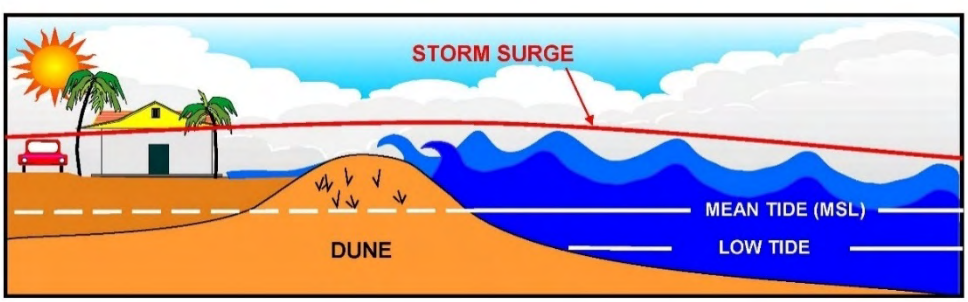
- Parametric Wind Model
- Tide Model
- Momentum Equations
- Continuity Equation
- Smoothing

Heights of Storm Surge + Tide

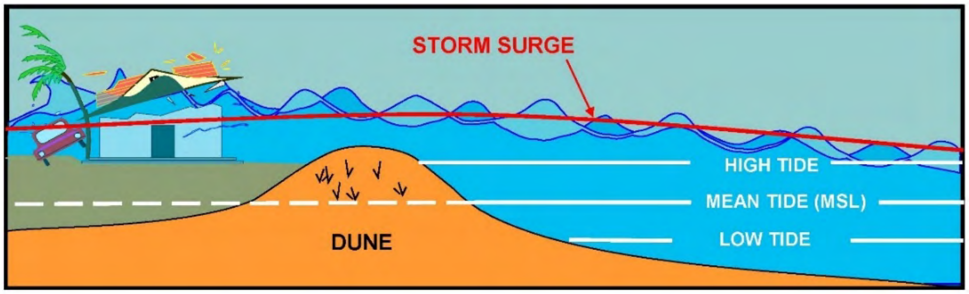
SLOSH Tide Model



SLOSH Tide Model



SLOSH Tide Model



Extract harmonic constituents at every SLOSH grid cell from a tidal model

V1 – Add after model run (*Tide not considered during inundation step*)

V2 – Add/Subtract tidal field at each time step (*Wetting / Drying complication*)

$$H(t_0) = Tide(t_0)$$
$$H(t_n) = SLOSH\left(H(t_{n-1})\right) - Tide(t_{n-1}) + Tide(t_n)$$

V3 – Tide as a boundary condition (*Spin-up to initialize transport variables; narrow estuary mouths obstruct the tide*)

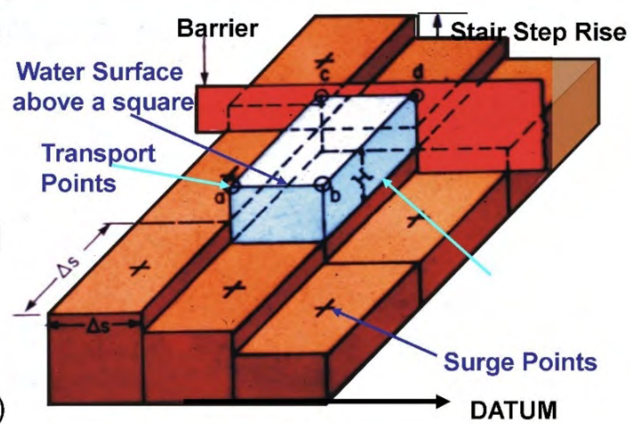
9

SLOSH Basin

Tropical basins maintained by the National Hurricane Program (update cycle approximately 6 years)

Structured, Arakawa B-Grid

- Heights at the center and transports on the corners
- Finer resolution (~**100 m**) overland, and coarser (~**2 km**) offshore
- Locally orthogonal



Sub-grid elements:

- 1 dimensional flow for rivers and streams
- Barriers
- Cuts between barriers
- Channel flow with chokes and expansions
- Increased friction for trees and mangroves

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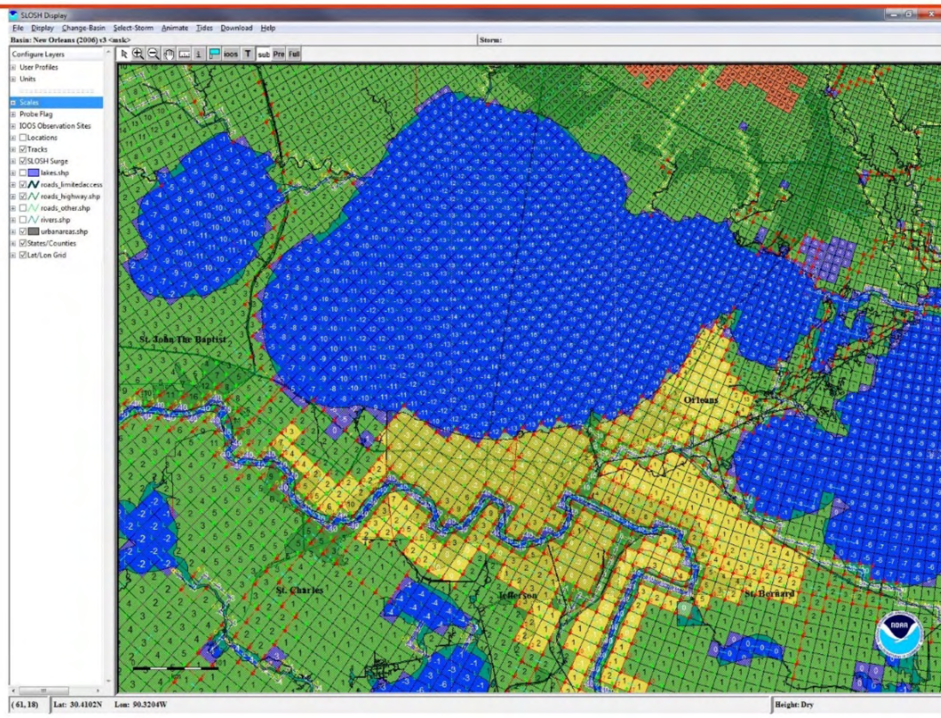
SLOSH Basin - Example



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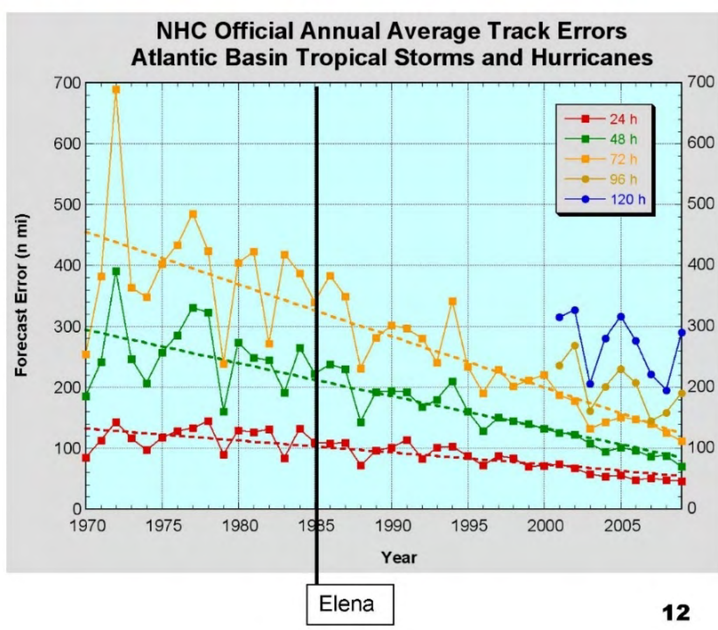
Why ensembles of model runs?

Wind input is the Largest Storm Surge Error

In 1986, due to the uncertainty in the forecast of 1985-Elena

- 100 n mi at 24-h
- 220 n mi at 48-h
- 340 n mi at 72-h

MEOW and MOM products created to represent "potential" Storm Surge risk



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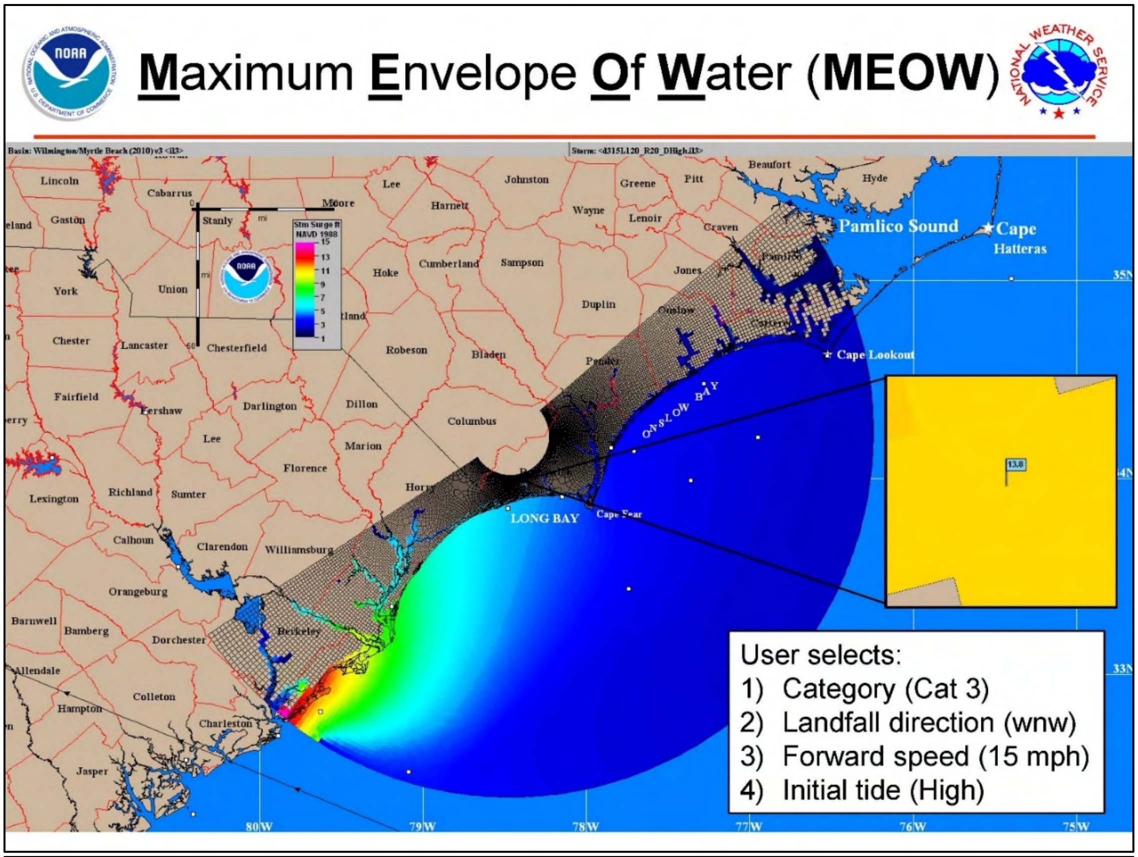
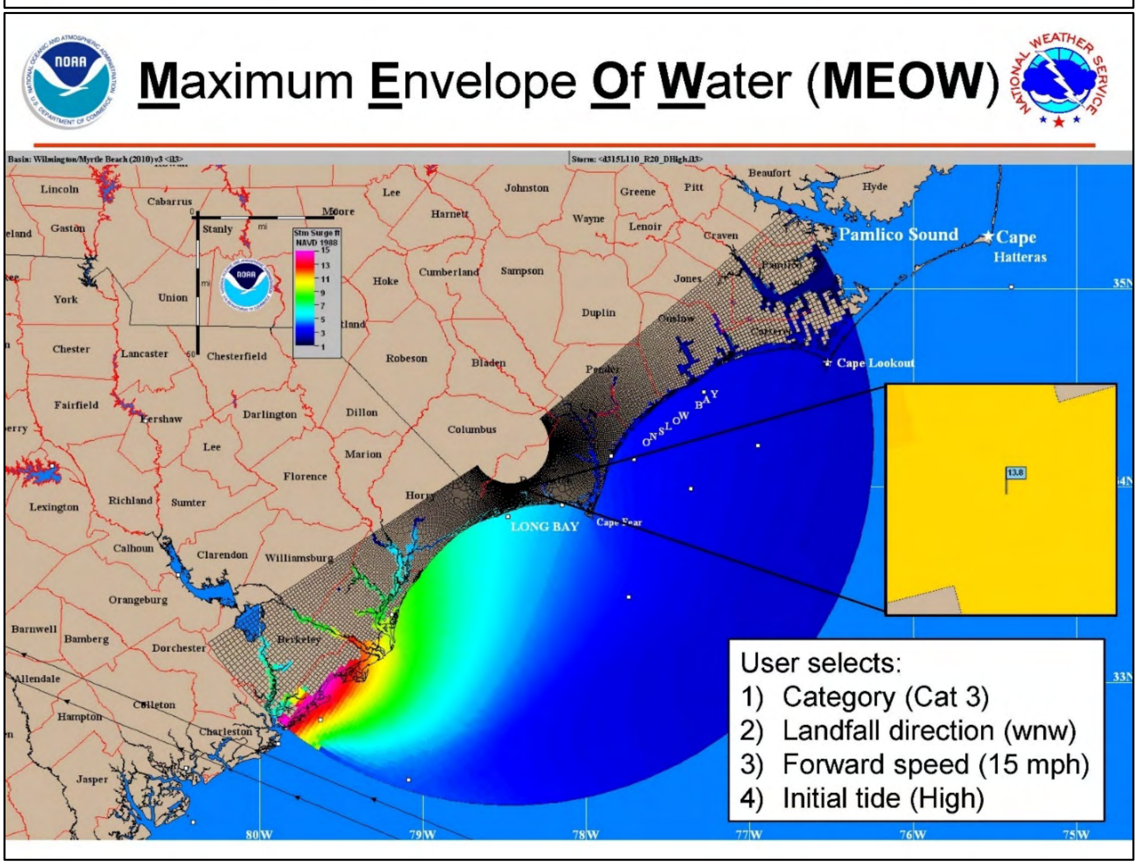

Maximum Envelope Of Water (MEOW)
Pamlico Sound
Cape Hatteras
Cape Lookout
LONG BAY
Cape Fear
User selects:
1) Category (Cat 3)
2) Landfall direction (wnw)
3) Forward speed (15 mph)
4) Initial tide (High)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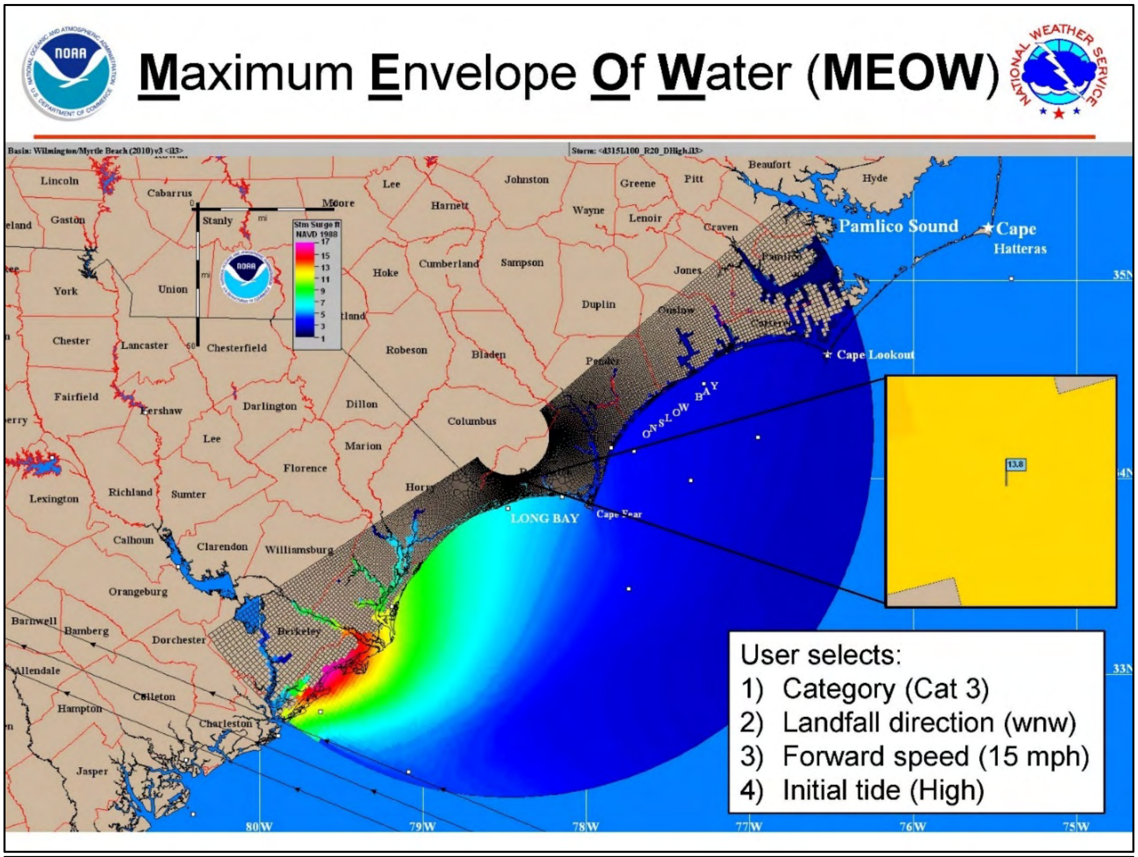
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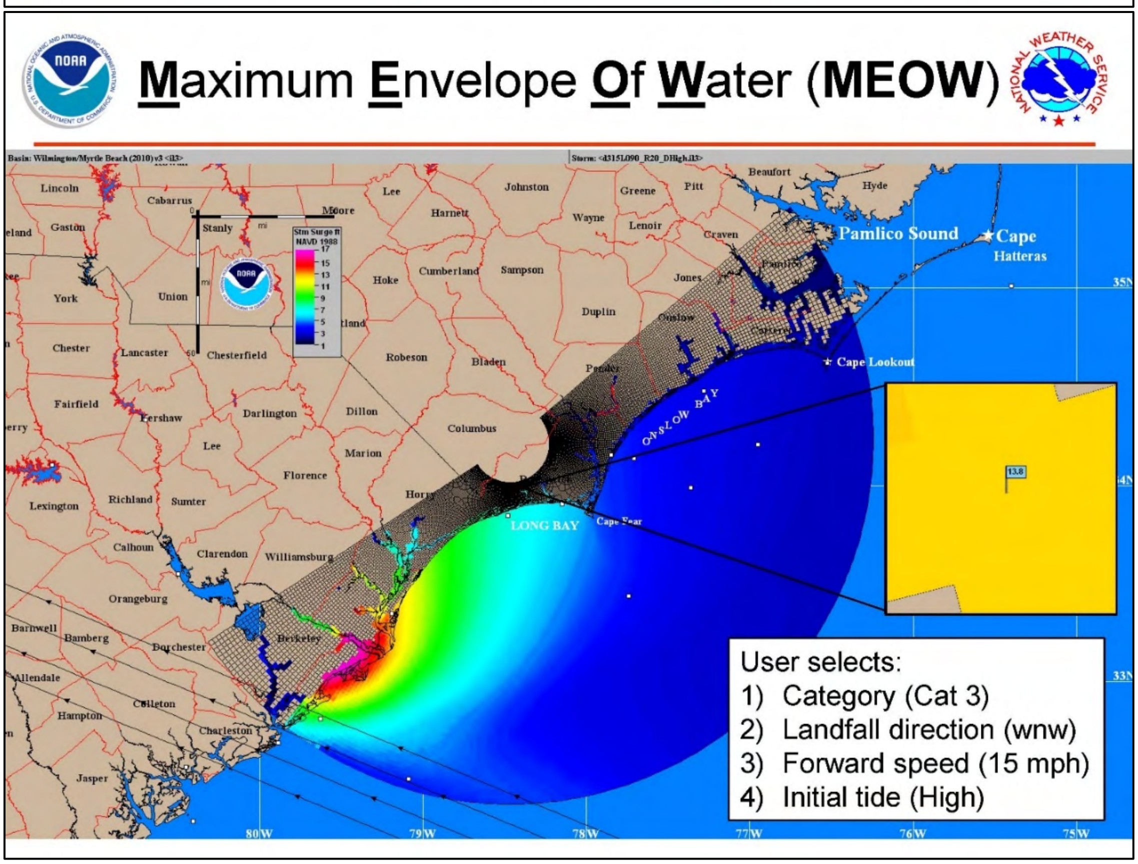
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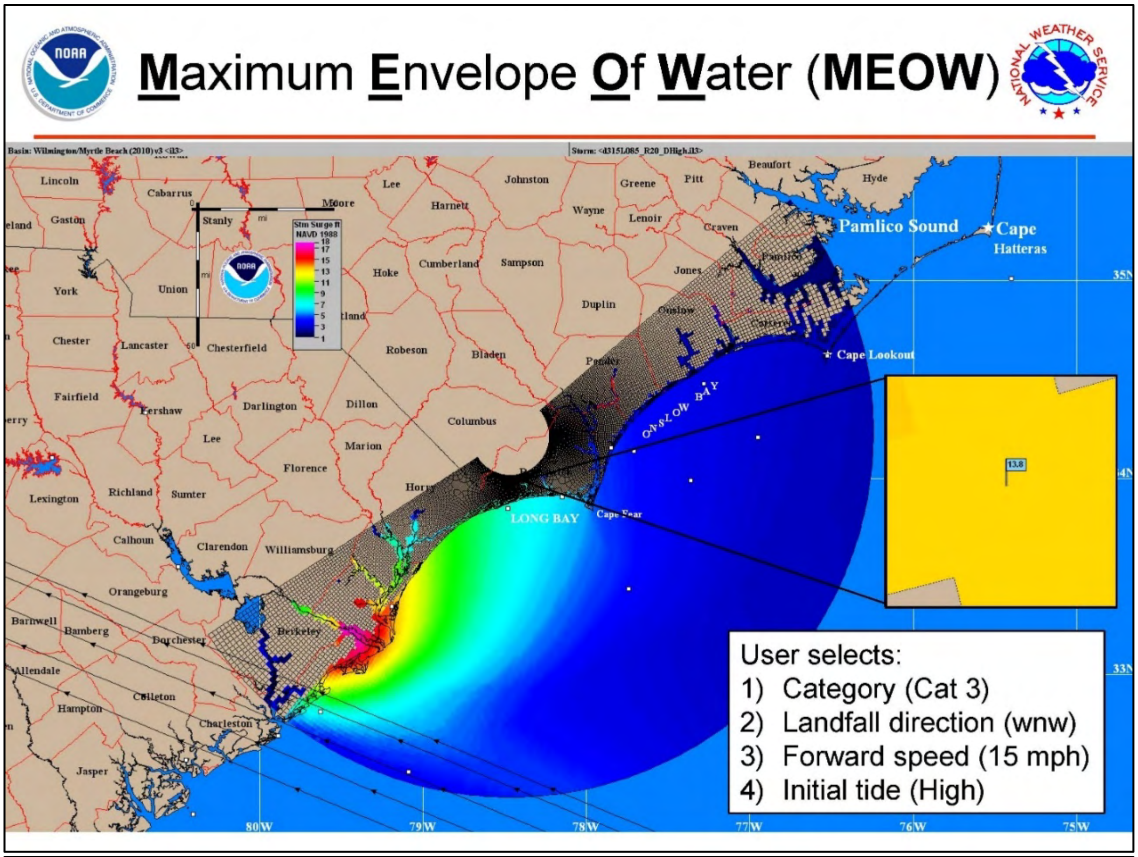
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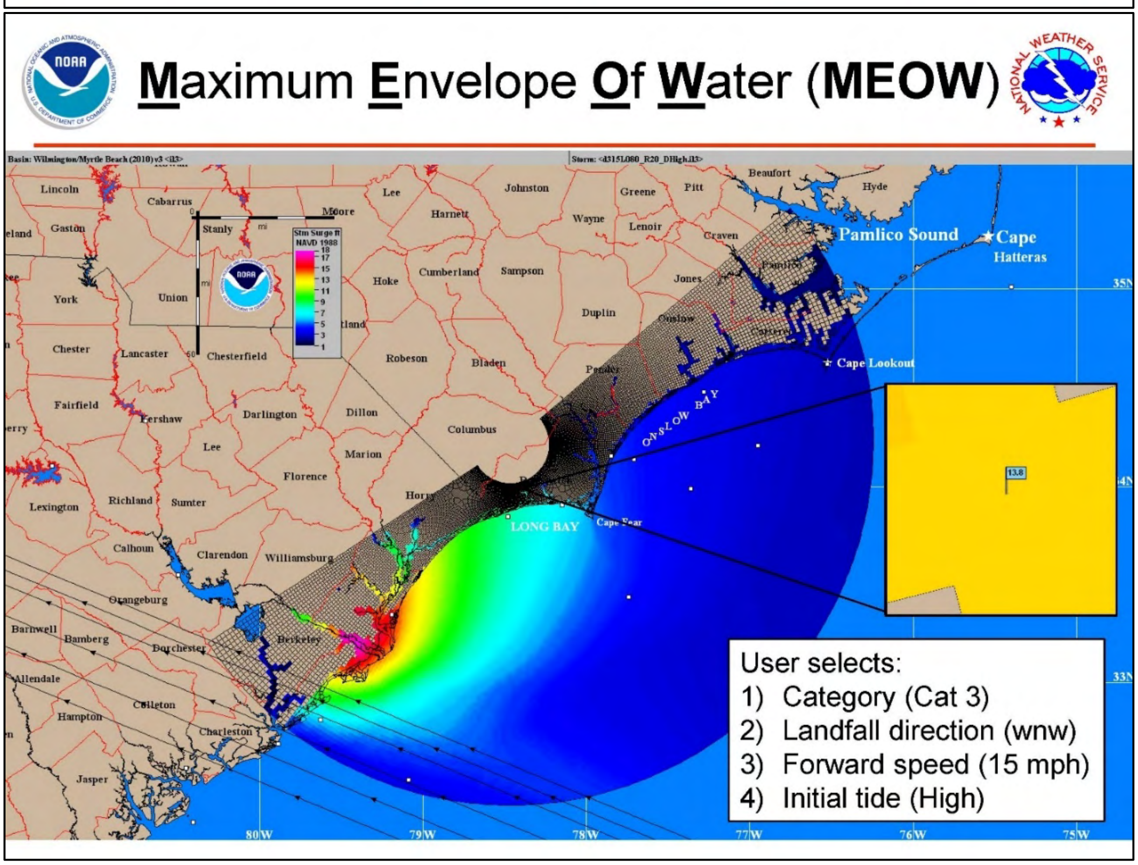
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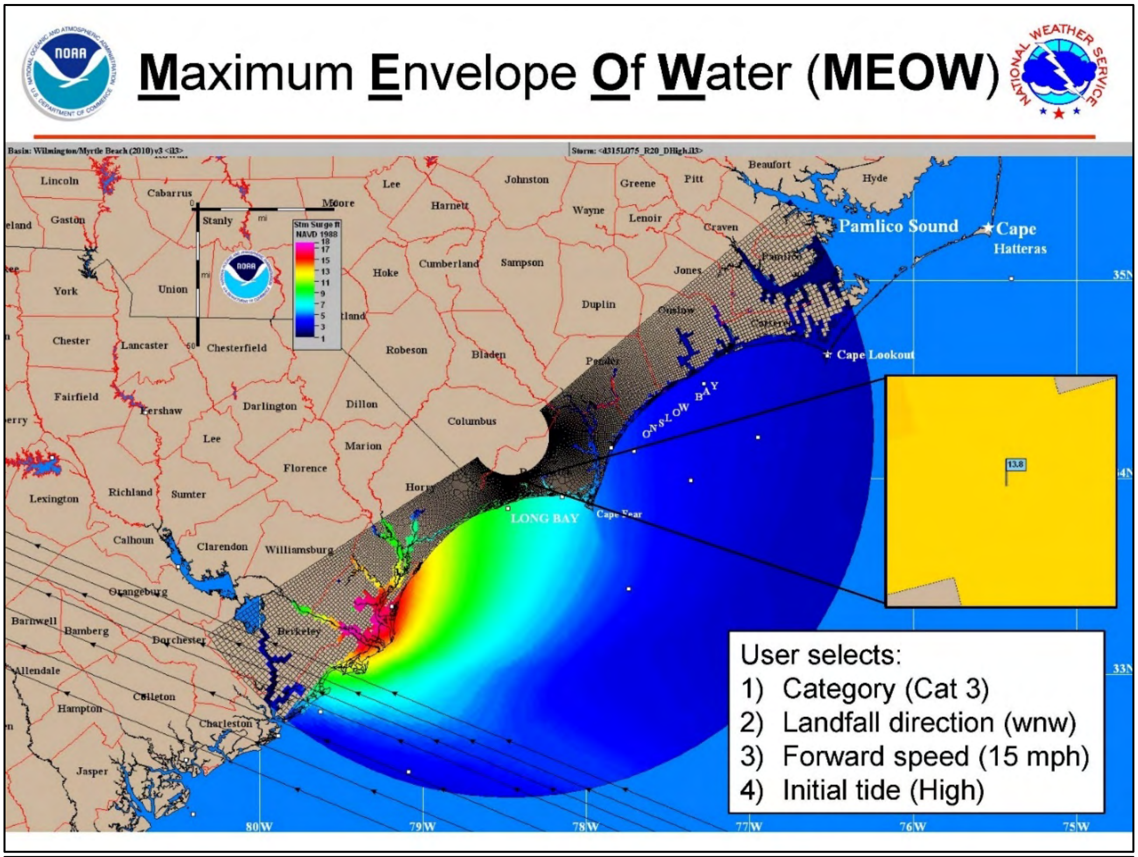
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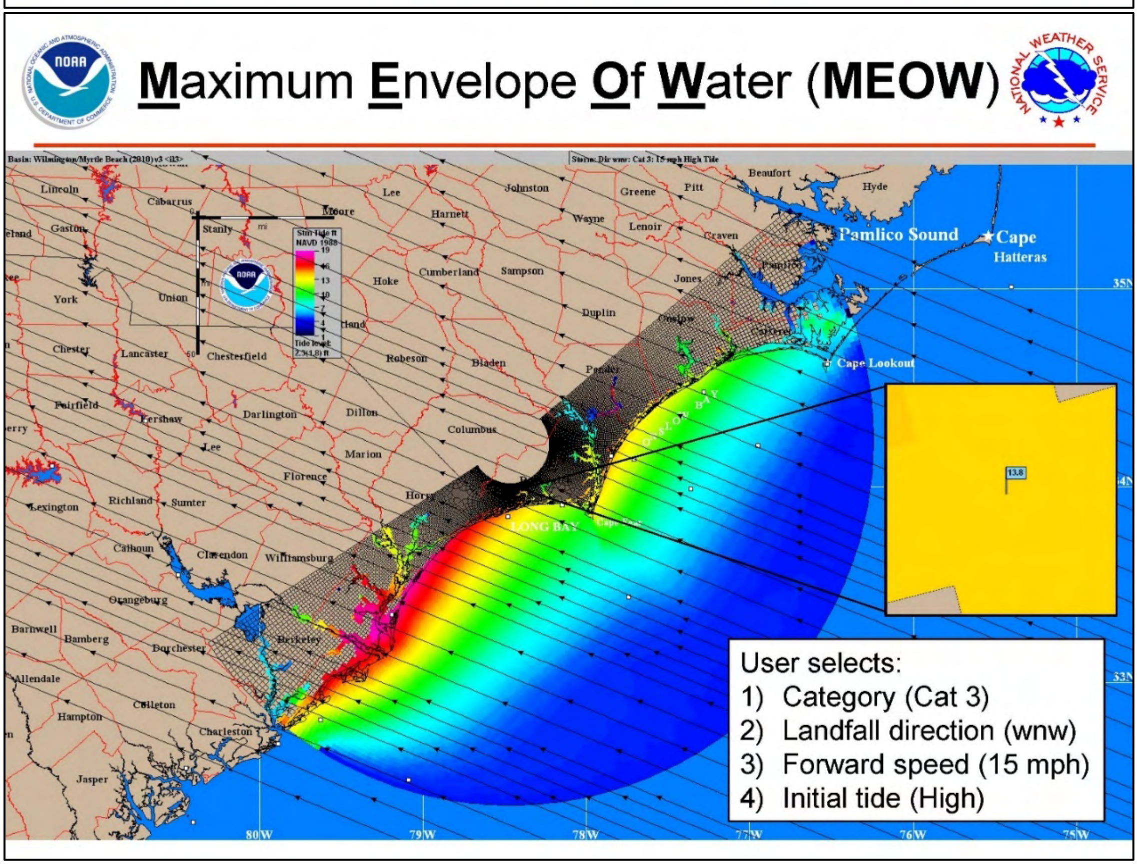
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Cape Hatteras
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User selects:
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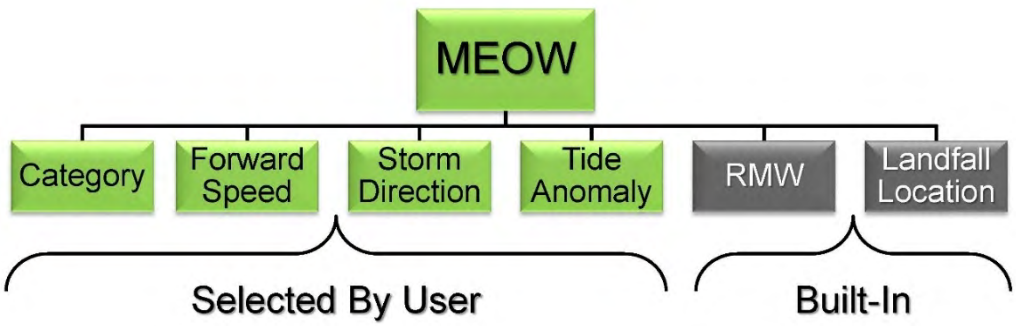
3) Forward speed (15 mph)
4) Initial tide (High)

Maximum Envelope Of Water (MEOW)

Composite of the maximum storm surge for all surge simulations for a given set of parameters (by basin)

Used as guidance for planning and operations



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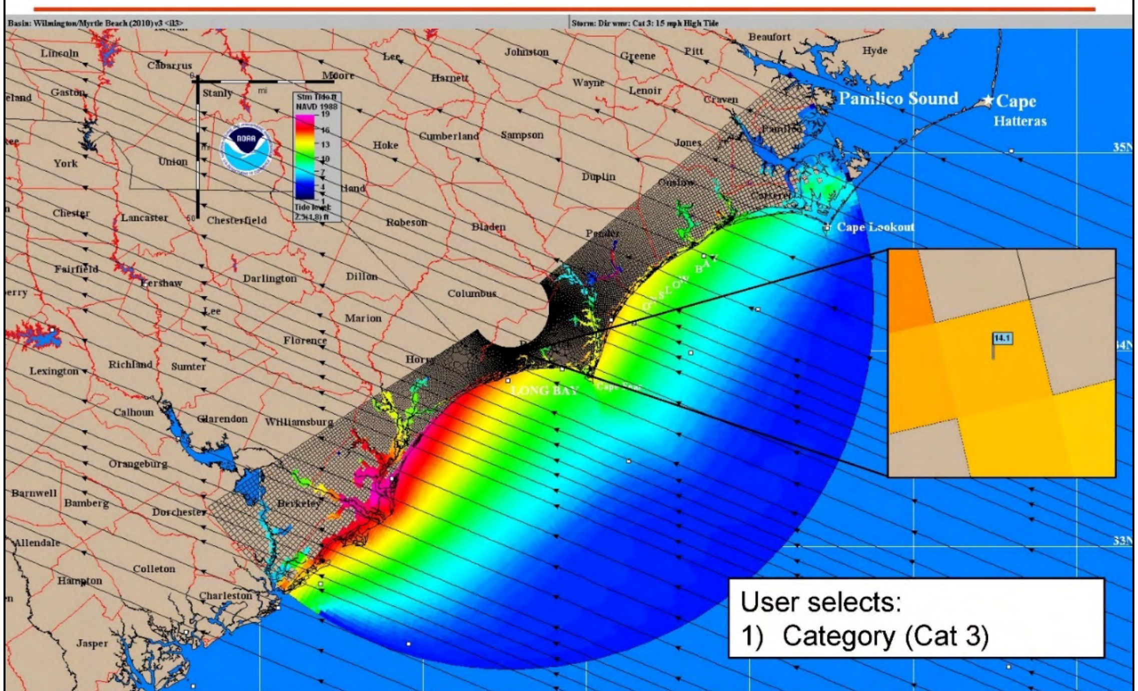
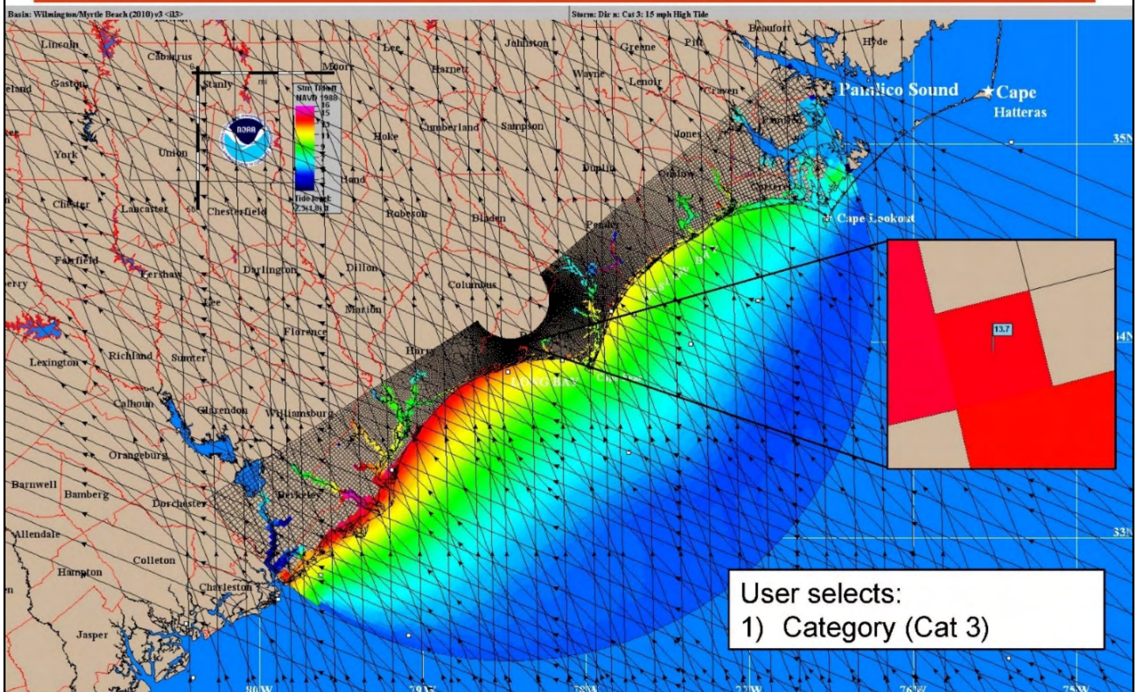
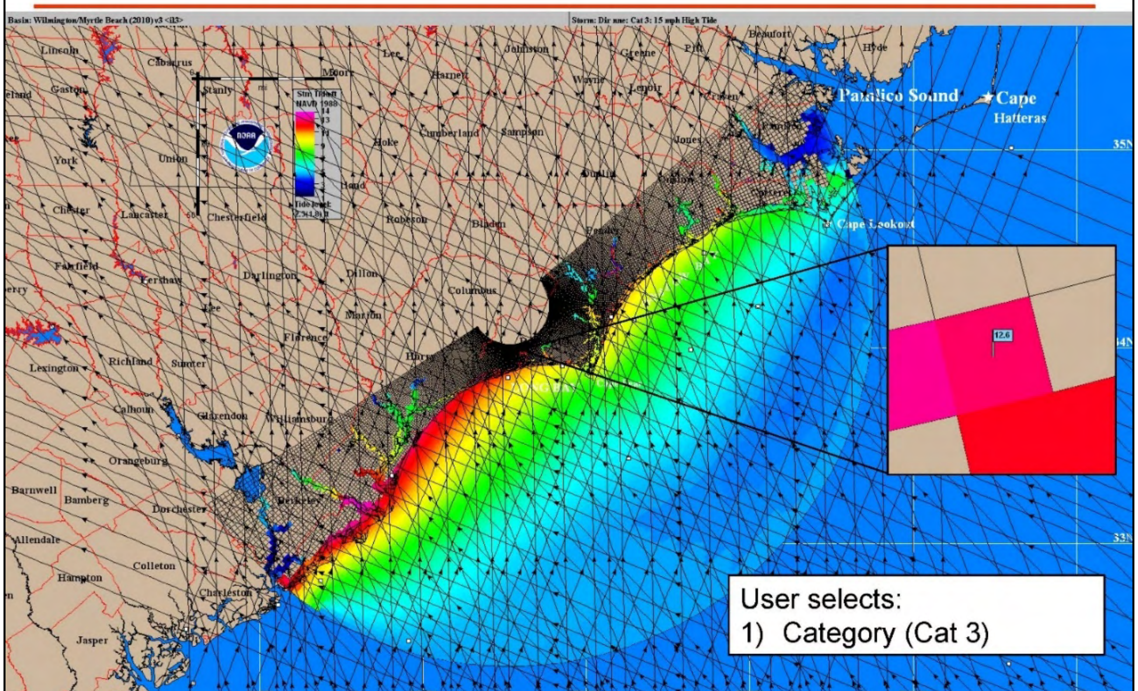
Maximum Of MEOWs (MOM)

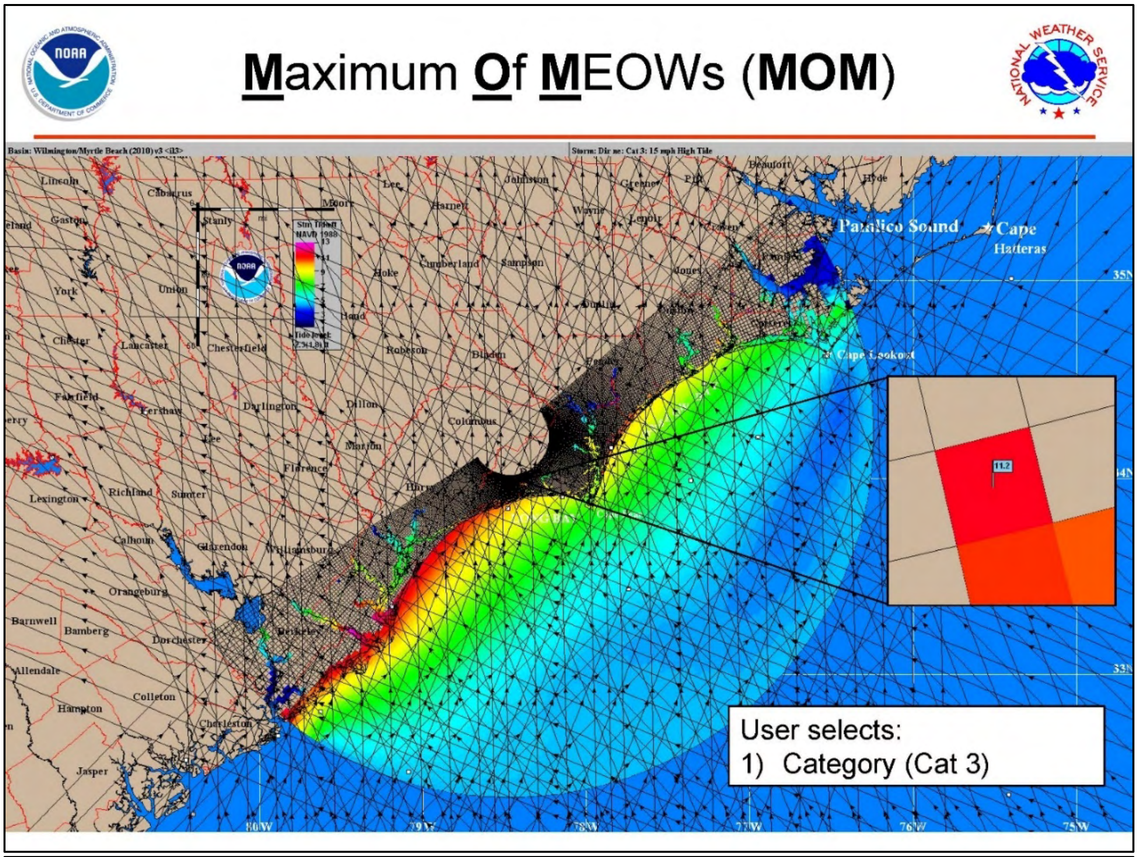


Maximum Of MEOWs (MOM)



Maximum Of MEOWs (MOM)

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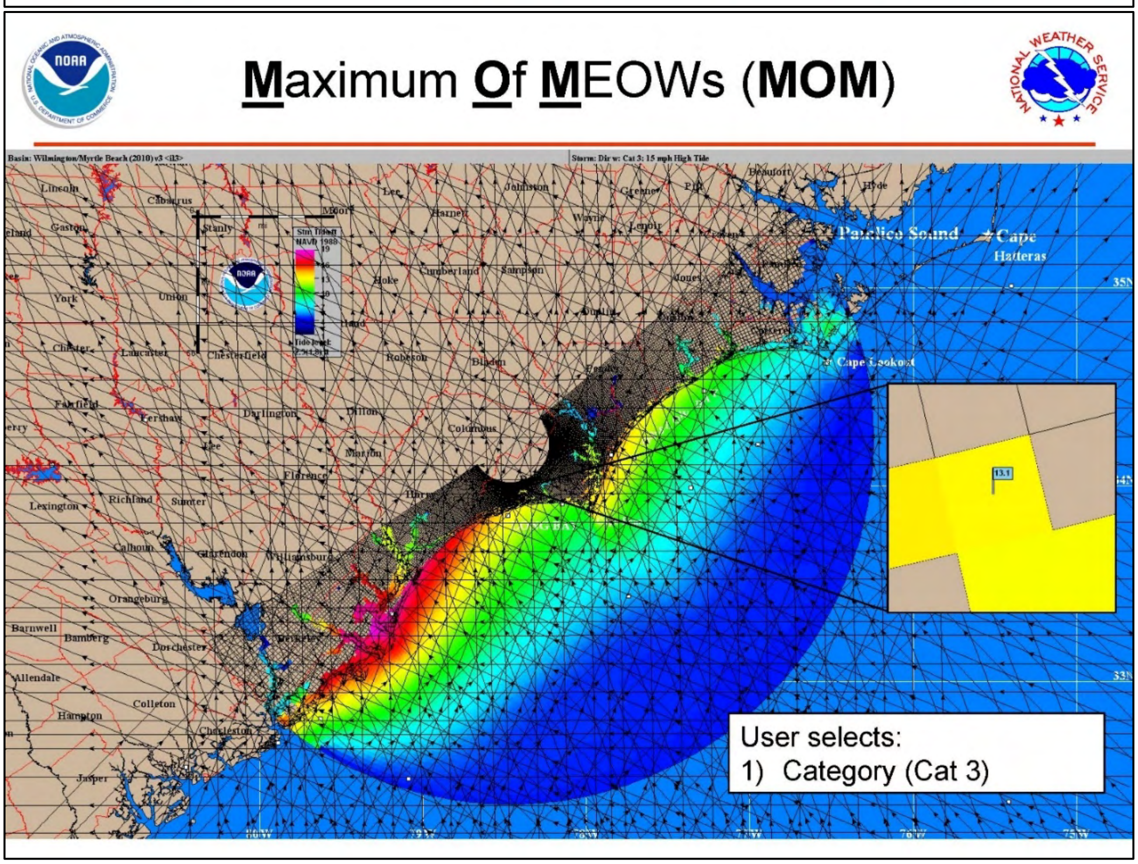
Maximum Of MEOWs (MOM)
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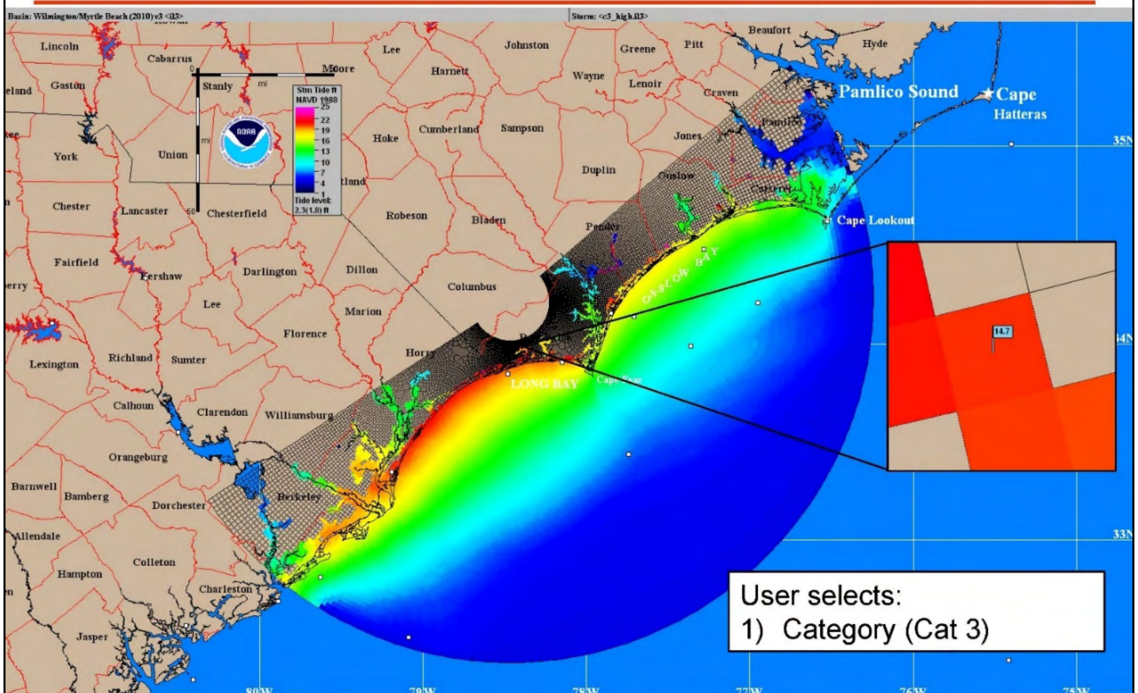
Cape Hatteras
Cape Lookout
User selects:
1) Category (Cat 3)

Maximum **O**f **M**EOWs (**MOM**)



U.S. National Hurricane Program

Step 1	Step 2	Step 3	Step 4	Step 5
Basin Build: Basin grid and data are modified to reflect recent changes NWS (MDL/NHC)	**Stability Test:** Basin undergoes extensive QA/QC process NWS (NHC)	**Simulation Runs:** MEOWs and MOMs are created NWS (NHC)	**Evacuation Plans:** MEOWs and MOMs are combined with infrastructure US Army Corp of Engineers	**Evacuation Decisions:** Plans are triggered based on real-time information Emergency Management

Run from the water, Hide from the wind

SLOSH MOMs and MEOW's form the basis of the water hazard within U.S. evacuation plans

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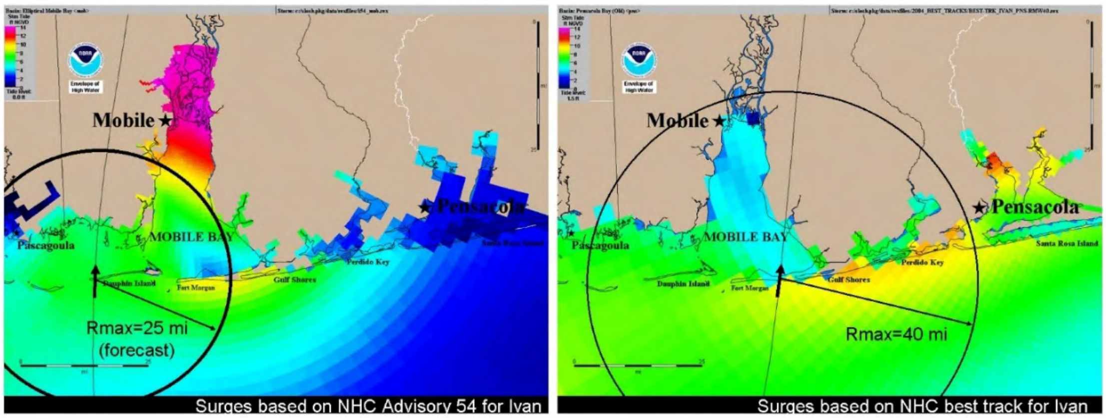
Why Real-Time Ensembles?

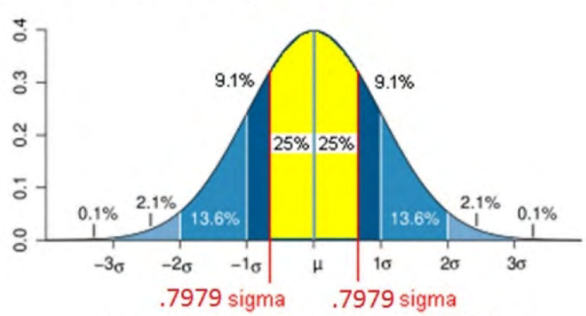
- Short term forecast has considerable uncertainty to it
- Climatological ensemble isn't tailored to the active storm and conditions (tide, initial water anomalies, etc.)



Example: Ivan 2004 – Advisory 54
12-hr before landfall.

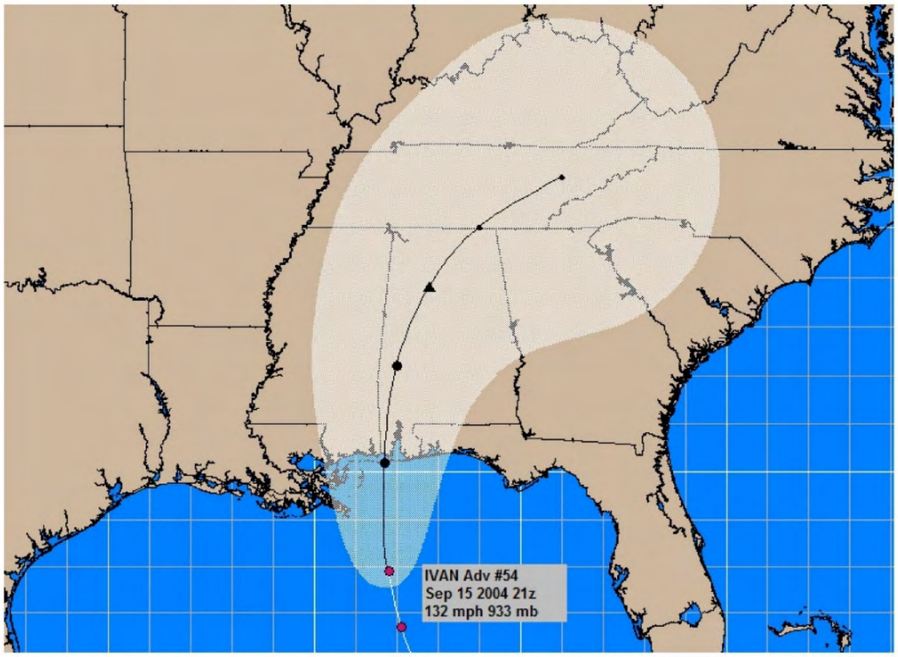
Probabilistic Tropical Storm Surge (P-Surge) Error Distributions

- Error distributions are computed for cross track, along track and intensity by:
  - Assuming a normal distribution
  - Using a 5-year "mean absolute error" and getting the standard deviation (sigma) from:

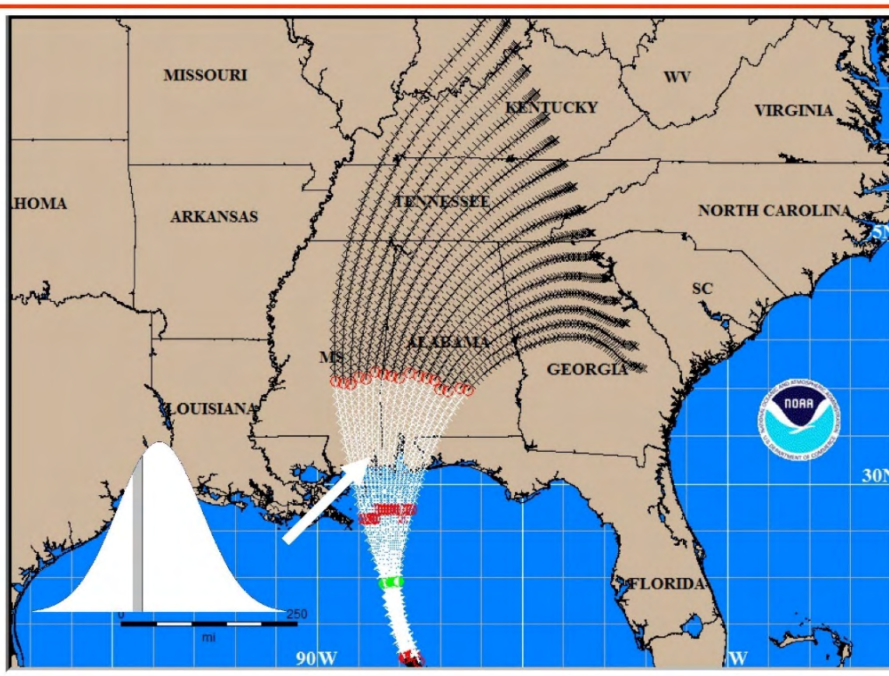


Mean absolute error occurs at.7979sigma

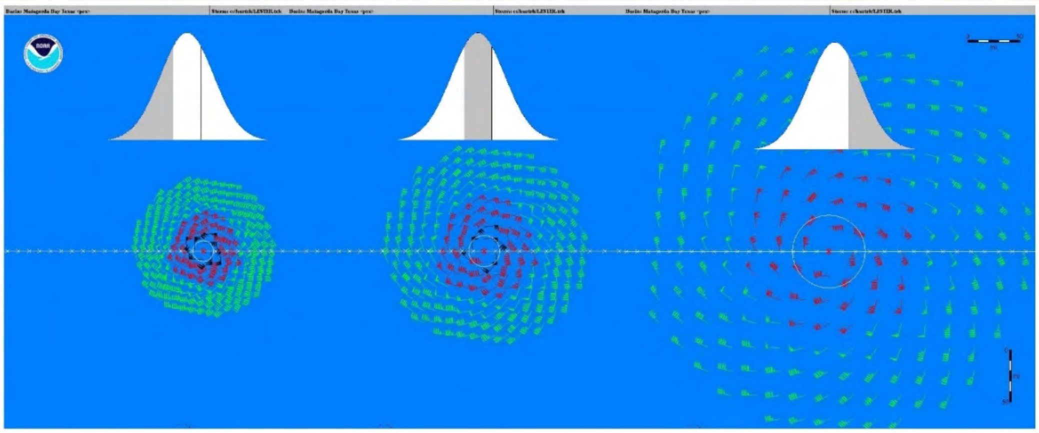
2004-Ivan - Advisory 54



P-Surge - Vary Cross Track



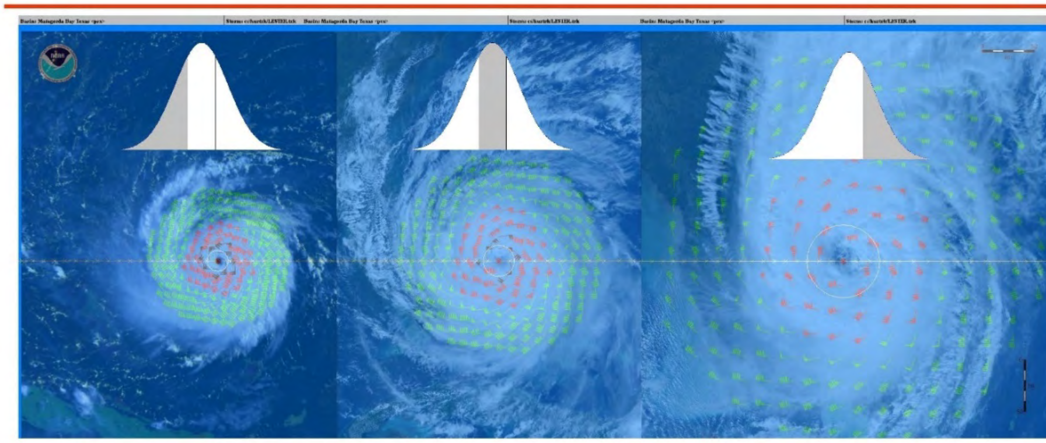
P-Surge – Vary Other Variables



- Size: Small (30%), Medium (40%), Large (30%)
- Forward Speed (*): Fast (30%), Medium (40%), Slow (30%)
- Intensity: Strong (30%), Medium (40%), Weak (30%)

(*) Changed in 2014 to 7 forward speed samples (14% each)

P-Surge – Vary Other Variables



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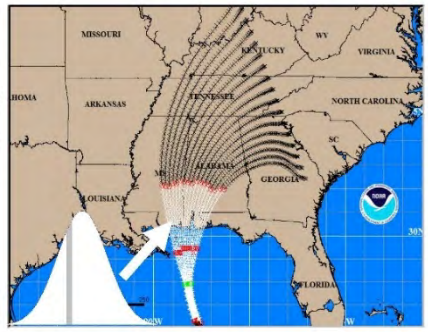
- Intensity: Strong (30%), Medium (40%), Weak (30%)

(*) Changed in 2014 to 7 forward speed samples (14% each)

Probabilistic Tropical Cyclone Storm Surge (P-Surge) - Summary

Requirements

- Consistent: Based on the official advisory
- Parametric Wind: Needed for permutations
- Fast: Results 1-hour after forecast release
- 4-day Forecast: Required evacuation time
- Overland: Inundation to 50-foot contour
- Total Water: (surge + tide + wave + river)
- Efficient: Limited resources to run ~630 ensemble members in 5 to 10 basins



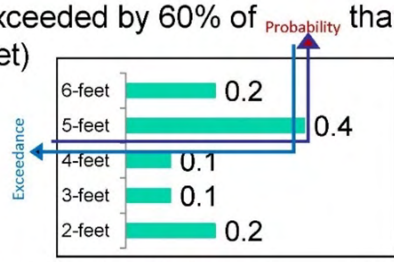
Solution: Suite of products derived from an ensemble of SLOSH runs

- Ensemble centered on NHC's official advisory
- Error spaces defined by a normal distribution with 5-yr MAE = 0.8 sigma
- Error spaces sampled via representative storms with dense cross-track sampling

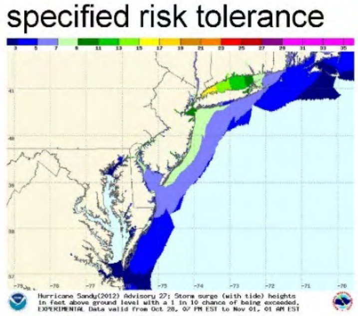
P-Surge Product Creation

Exceedance Height: The surge value which is exceeded by Y% (e.g. height exceeded by 60% of storms is 4 feet)

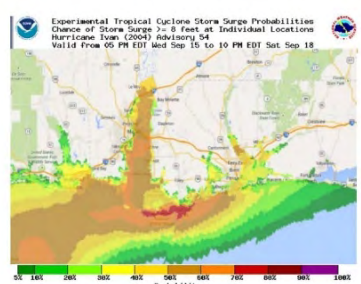
Probability of Surge: The probability of storm surge greater than X feet (e.g. probability of > 4 feet is 60%)



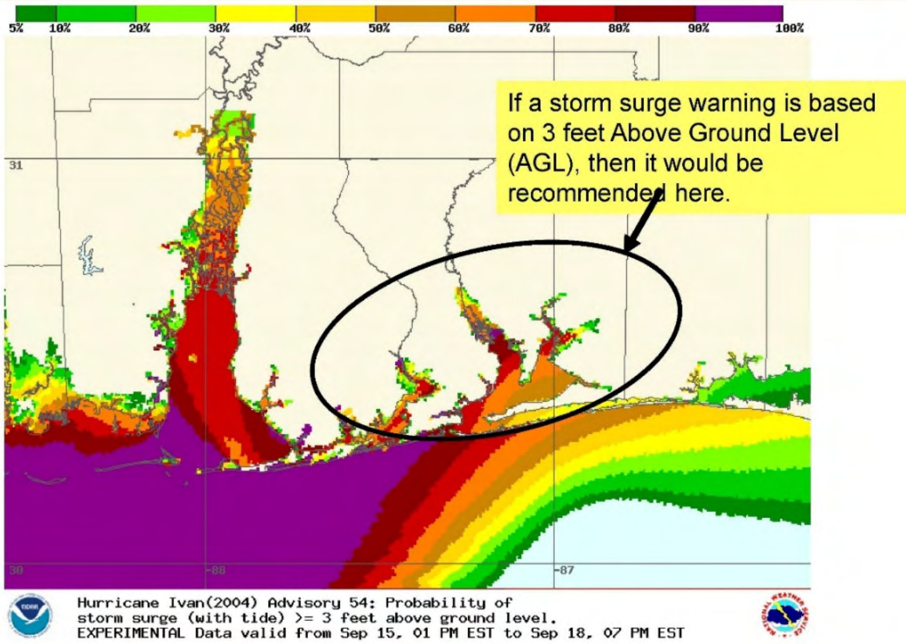
Use: Estimate water levels based on a specified risk tolerance



Use: Estimate risk at a specific site



Storm Surge Warning Guidance
Probability of Surge + Tide > 3 feet AGL



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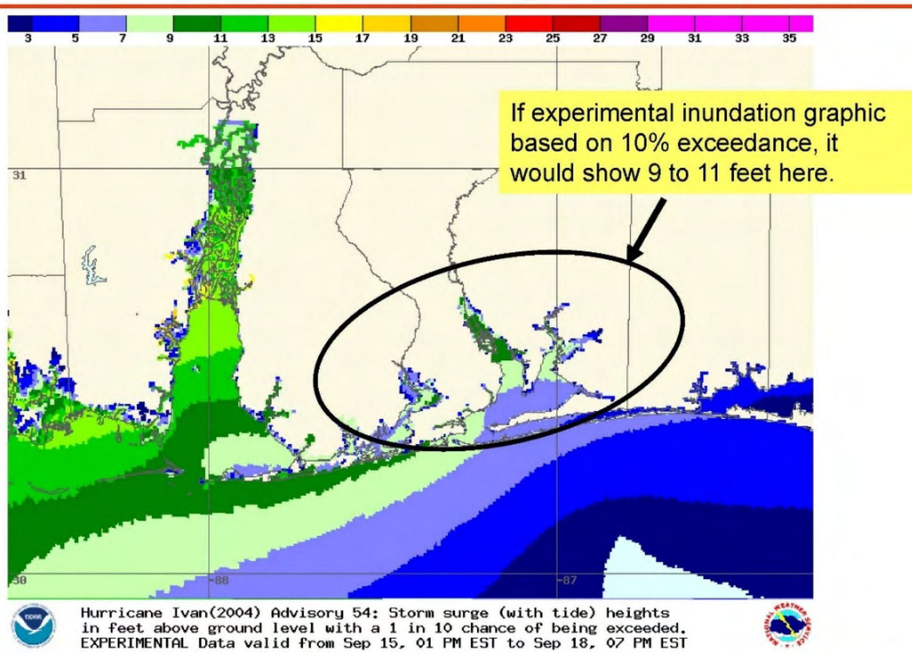
Inundation Graphic Guidance
10% Exceedance of Surge + Tide AGL



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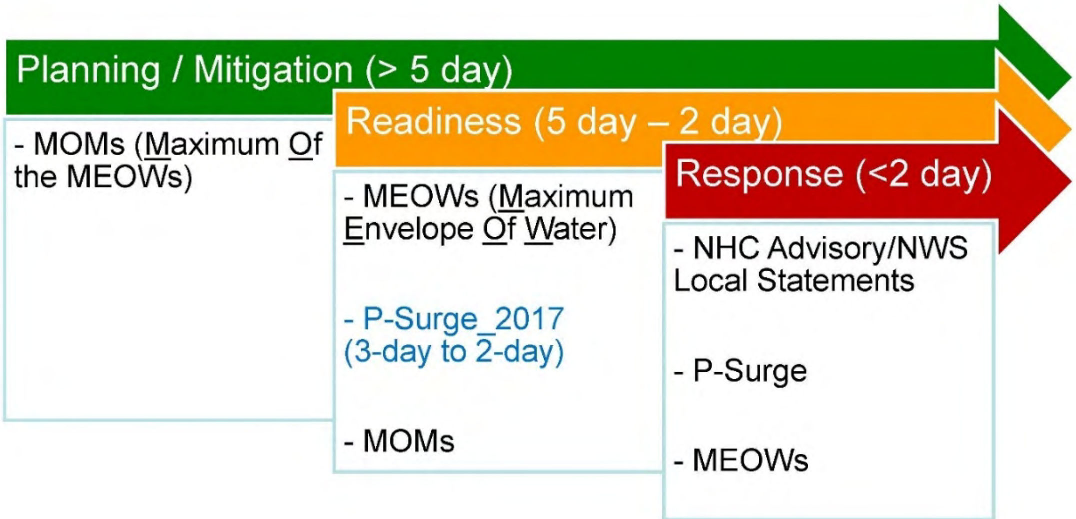
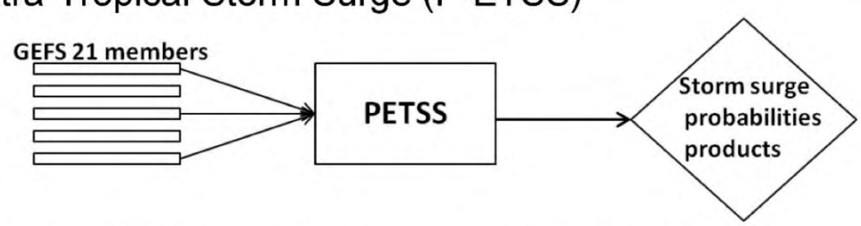
Tropical Guidance Timeline



(*) These are in days before landfall

What about Non-Tropical Storms?

- Problem: Extra-Tropical (Nor' Easters) and Post-Tropical (Sandy 2012) storms are not easily parameterized
- Solution: Use atmospheric ensemble models: Probabilistic Extra-Tropical Storm Surge (P-ETSS)



❖ 1.0 – Equally weight the ensemble members

❖ 1.0 – Use the 21 member Global Ensemble Forecast System (GEFS) as wind forcing

❑ Goal – Use the 42 member North American Ensemble Forecast System (NAEFS) as wind forcing

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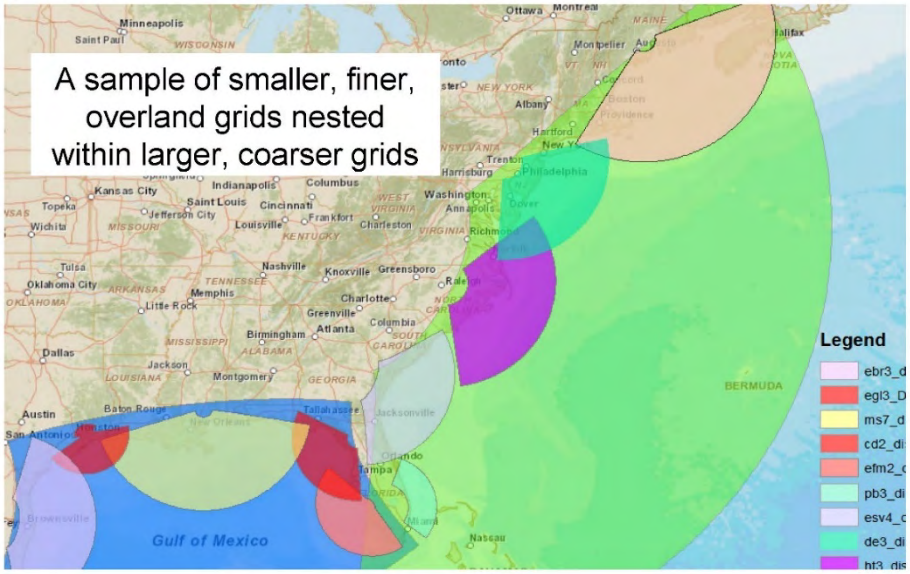
Non-Tropical Computational Challenge

Problem: Larger (typically Non-Tropical) storms require larger basins to capture the extent of the winds which results in longer run-times
Solution: Nest smaller fine scale grids within the larger coarse grids



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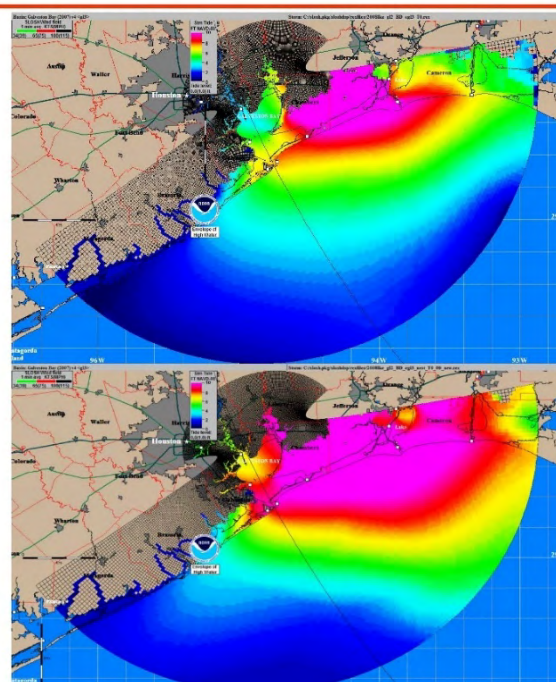
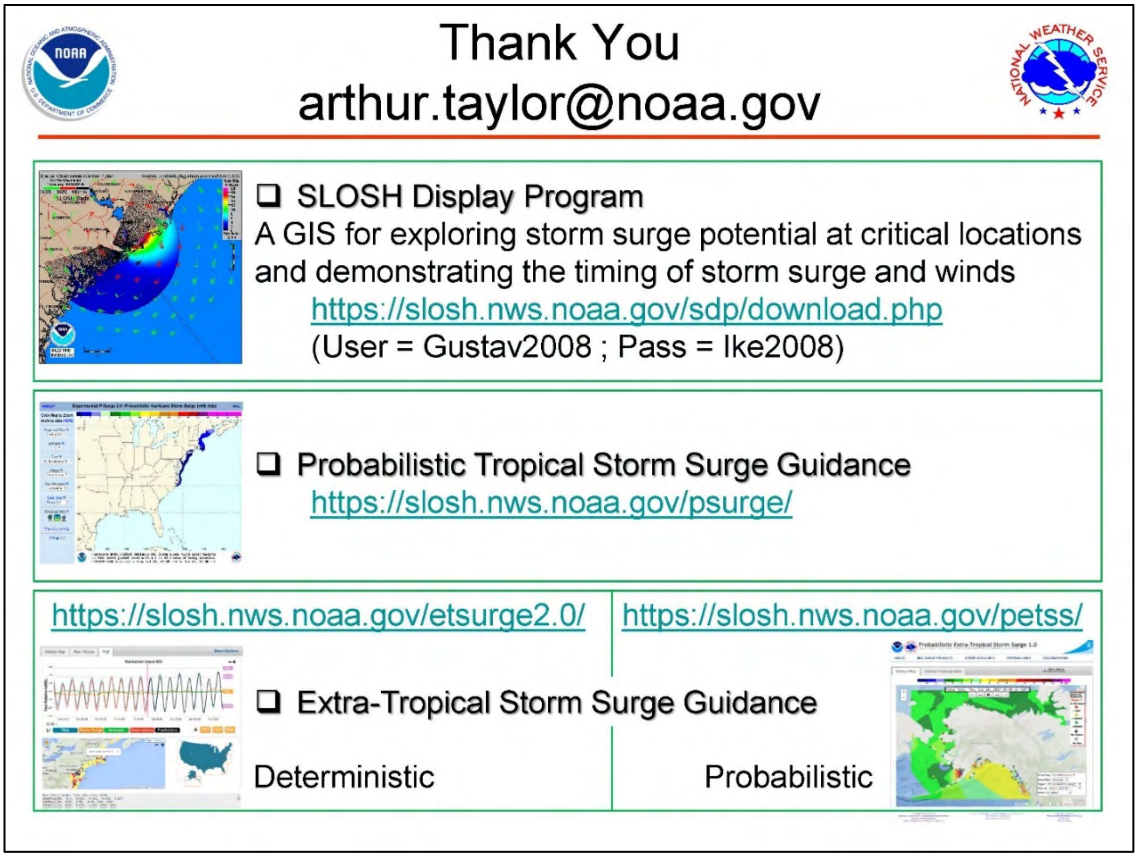
The Benefit of Nesting

Hurricane Ike 2008

- Top panel: Modeled in the Galveston basin
- Bottom panel: Modeled by nesting the Galveston basin within the Gulf of Mexico basin
- Better captures fore-runner phenomena





4.3.2.1.3 Questions and Answers

Question:

I'm interested in how you would apply this to the Great Lakes. How would you use this approach for nuclear power plants (NPPs) on Lake Ontario?

Answer:

Unfortunately, we haven't done basins in the Great Lakes. The Great Lakes have a different model. We've done basins for Lake Okeechobee and so we have an Okeechobee result. You would do something very similar for the Great Lakes. You would first need to build a computational basin. With P-Surge, you are not ending up with a hurricane in the Great Lakes region, so it wouldn't be applicable for P-Surge. However, for an extratropical event, you could easily do the P-ETSS runs in the Great Lakes area. The only piece missing is having a basin. We would need funding to build a basin in that area, just as we need to have funding to build some higher resolution basins in the Bering Sea. We are also working with P-ETSS on ensemble models from the GEFS to provide quantitative precipitation forecasts (QPFs). At some point, I want to take the river input from the 21 different GEFS ensemble member QPFs) as river inputs. I think that would be very important for the Great Lakes to complete the river ensembles. I plan to go first to the West Coast for the river work, but the Great Lakes would be very interesting.

4.3.2.2 Advancements in Probabilistic Storm Surge Models and Uncertainty Quantification Using Gaussian Process Metamodeling. Norberto C. Nadal-Caraballo*, Victor M. Gonzalez*, Alexandros Taflanidis, USACE R&D Center, Coastal and Hydraulics Laboratory (Session 1B-2; ADAMS Accession No. ML19156A453)

4.3.2.2.1 Abstract

The application of probabilistic storm surge models for the PFHA of critical infrastructure in coastal zones requires a comprehensive uncertainty quantification framework. The new approach for treating uncertainty in probabilistic storm surge studies consists of quantifying aleatory and epistemic uncertainties associated with the application of data, methods, and models in each step of the analysis. The U.S. Army Engineer Research and Development Center, Coastal and Hydraulics Laboratory (ERDC-CHL), 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 for NPPs.

In the case of the joint probability method (JPM), which is the standard probabilistic model used to assess coastal storm hazard in hurricane-prone coastal regions of the United States, the error is incorporated in the integration of the hazard curve. Recent advancements by ERDC-CHL include the computation of spatially varying hydrodynamic modeling errors and the development of Gaussian process metamodels (GPMs) based on existing JPM storm suites. The GPMs emulate the response of hydrodynamic numerical models, such as the Advanced CIRCulation model (ADCIRC), and enable the development of augmented storm suites consisting of tens of thousands to millions of tropical cyclones without introducing significant error. This, in turn, facilitates the evaluation of JPM and Monte Carlo methods and other probabilistic models and approaches for the integration of uncertainty that would otherwise be unfeasible due to computational burden constraints.

The treatment of epistemic uncertainty in the present study expands upon the traditional JPM approach of considering this uncertainty as an error term in the JPM integral by estimating the epistemic uncertainty that arises from the selection and application of alternate technically defensible data, methods, and models at each step of the probabilistic storm surge modeling. The approach followed is based on NRC guidance on probabilistic seismic hazard assessments (PSHAs), where the uncertainty is propagated through the use of logic trees. The epistemic uncertainty is then quantified through the development of a family of hazard curves, with individual curves corresponding to evaluated data sources and methods associated with the different applications of probabilistic storm surge models. The range of the epistemic uncertainty is conveyed through the fractiles of the family of storm hazard curves, which are equivalent to nonexceedance confidence limits (e.g., 0.05, 0.16, 0.5 (median), 0.84, and 0.95).

4.3.2.2.2 Presentation

4th Annual Probabilistic Flood Hazard Assessment Workshop
Rockville, MD – April 30-May 2, 2019

ERDC
ENGINEER RESEARCH & DEVELOPMENT CENTER

Advancements in Probabilistic Storm Surge Models and Uncertainty Quantification using Gaussian Process Metamodeling

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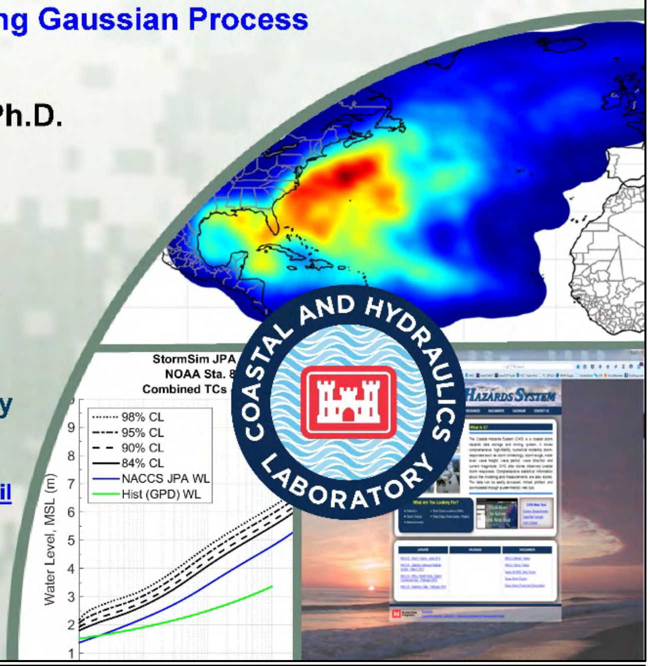

Outline

- Introduction.
- Quantification of uncertainty in probabilistic storm surge models.
- Gaussian process metamodeling (GPM): definition and error quantification.
- GPM Applications in probabilistic storm surge modeling:
  - Reference set
  - Monte Carlo simulation
  - Meta-Gaussian distribution (multivariate Gaussian copula)
- Epistemic uncertainty/Logic tree approach.

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Introduction

- Study objectives:
  - Identification of technically defensible data sources, models, and methods for the computation of storm surge.
  - Assessment for carrying forward for evaluation of epistemic uncertainty.
  - Epistemic uncertainty is quantified and propagated through logic tree approach (PSHA approach).
- Gaussian process metamodeling.
  - Augmented storm suite for:
    - Reference set
    - Monte Carlo simulation
    - Meta-Gaussian distribution (multivariate Gaussian copula)
  - Error quantification.

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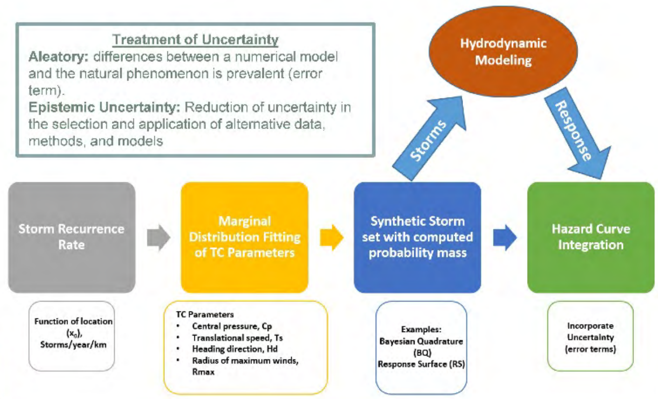
Quantification of Uncertainty in Probabilistic Storm Surge Models

- Characterize, quantify, and propagate both aleatory and epistemic uncertainties through the probabilistic framework of storm surge assessment.



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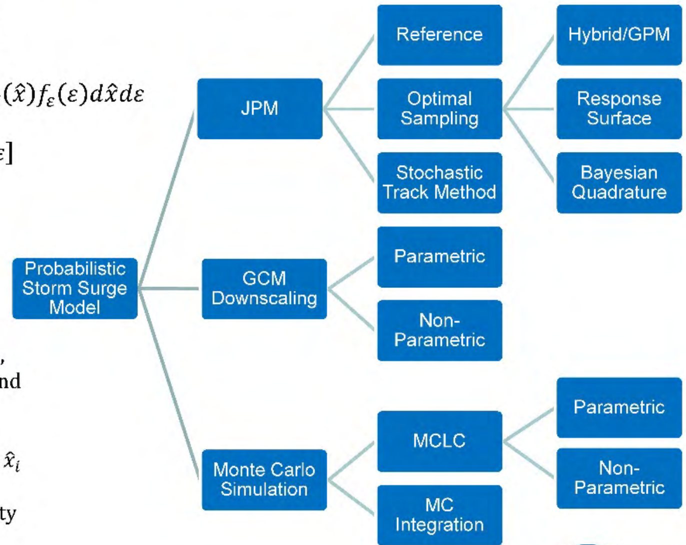
Logic Tree Approach

JPM Integral

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

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

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)
$\hat{\lambda}_i$ = probability mass (storms/yr) or λp_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 or aleatory uncertainty of r



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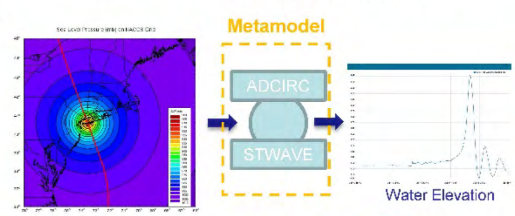
Metamodeling

- Mathematical approximation for the **input/output** (x/z) relationship of complex numerical models.
- "State-of-practice" in coastal hydrodynamic modeling for coastal hazard studies:

  Computationally-intensive coupled ocean circulation models and spectral wave models over large domains
- Metamodel is designed (trained) using parameterized TC inputs and hydrodynamic model outputs.

$$\text{Response} = f(\hat{x}) = f(x_0, \Delta p, R_{\max}, V_f, \theta)$$



Synthetic Storm 445, NACCS

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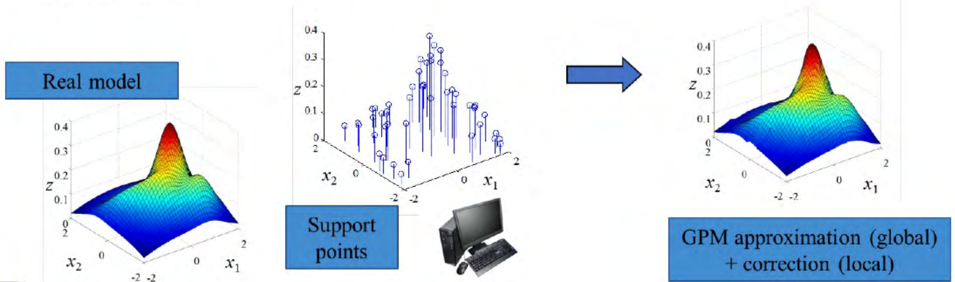
Gaussian Process Metamodeling

- GPM formulation has 2 parts:
  - Global regression model
  - Gaussian process or local correction
- GPM advantages:
  - Computational efficient
  - Handles complex models
  - Uncertainty of predictions



Gaussian Process Metamodeling

- Fundamental GPM formulation:
  - Regression: de-trend data.
  - GP: interpolates within the residuals of the regression.
- The predictive mean combines both the regression and GP.
- Regression is not optimized irrespective of GP.
- Validation metrics.
  - Example Types: average, per save point, per storm.

e.g. R^2, Mean Absolute Error, Correlation Coefficient, RMS.

$$h(\boldsymbol{x}) = \underbrace{\boldsymbol{f}_k(\boldsymbol{x})^T \beta_k}_{\text{Global regression}} + \underbrace{z_k(\boldsymbol{x})}_{\text{Gaussian process (GP)}} \quad (1)$$

$$\bar{h}(\boldsymbol{x}|M_k) = \boldsymbol{f}_k(\boldsymbol{x})^T \beta_k^{MLE} + \boldsymbol{r}_{\theta_k^{MLE}}(\boldsymbol{x})^T \boldsymbol{R}^{-1}_{\theta_k^{MLE}}(\boldsymbol{H} - \boldsymbol{F}_k \beta_k^{MLE}) \quad (2)$$

$$\beta_k^{MLE} = \left(\boldsymbol{F}_k^T \boldsymbol{R}^{-1}_{\theta_k^{MLE}} \boldsymbol{F}_k\right)^{-1} \boldsymbol{F}_k^T \boldsymbol{R}^{-1}_{\theta_k^{MLE}} \boldsymbol{H} \quad (3)$$

Where:
β_k: regression coefficient
$\boldsymbol{f}_k$: basis functions (regression models)
$h(\boldsymbol{x})$: output
$\boldsymbol{R}_{\theta_k}$: Gaussian correlation function
θ_k: vector of parameters for correlation

GPM Training – NACCS

- The GPM used in this study was trained using the 1050 synthetic TCs developed as part of the NACCS (Nadal-Caraballo et al. 2015).
- Trained on WL peaks (time series training also possible).
- Validation of landfalling TCs.

Coastal Reference Location	NACCS Save Point	R^2	Mean Absolute Error	Correlation Coefficient	RMS
Virginia Beach, VA	6488	0.988	0.071	0.994	0.064
Chesapeake Bay, MD	5951	0.974	0.072	0.988	0.082
The Battery, NY	7672	0.989	0.066	0.994	0.090
Newport, RI	1082	0.985	0.077	0.993	0.068
Boston, MA	1884	0.982	0.069	0.992	0.057

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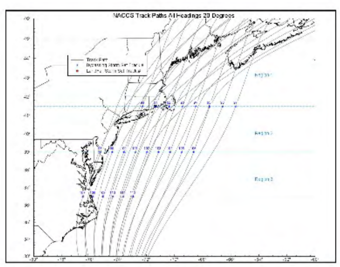
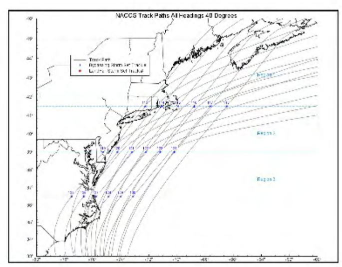
GPM Training – NACCS

- Validation of bypassing TCs.





Coastal Reference Location	NACCS Save Point	R^2	Mean Absolute Error	Correlation Coefficient	RMS
Virginia Beach, VA	6488	0.970	0.091	0.986	0.089
Chesapeake Bay, MD	5951	0.963	0.075	0.983	0.060
The Battery, NY	7672	0.974	0.086	0.988	0.100
Newport, RI	1082	0.952	0.111	0.979	0.121
Boston, MA	1884	0.946	0.093	0.977	0.070

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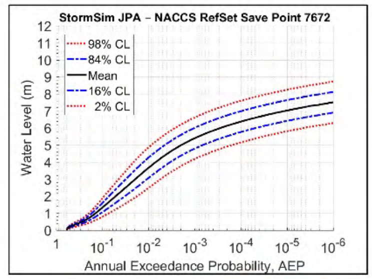
GPM Applications: Reference Set

- Developed a reference set that considers all parameter combinations.
- The reference set was developed for five coastal reference locations located within the NACCS project area.

Region	Number of tracks	Number of Δp, R_{max} and V_t unique combinations	Number of tropical cyclones
Bypassing			
1	14	495	6,930
2	15	585	8,775
3	12	675	8,100
Landfalling			
1	40	495	19,800
2	25	585	14,625
3	24	675	16,200
Total			74,430



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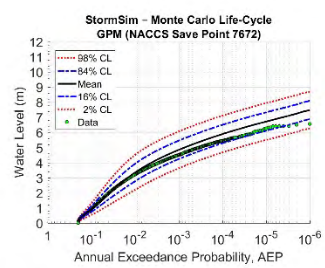
GPM Applications: Monte Carlo Simulation

- Monte Carlo Life-Cycle.
  - ► Univariate distributions of TC parameters were sampled for a 1,000,000-yr period, which resulted in 211,997 TCs.
  - ► No probability masses required.
    - TC's sampled based on their likelihood of occurrence and parameters joint probability.
    - Storm surge hazard curve from **empirical distribution** (Weibull plotting position).
  - ► Mean hazard curve and confidence levels calculated through bootstrap resampling using replicated storm surge values with added discretized uncertainty.



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GPM Applications: Meta-Gaussian Distribution

Joint Probability: TC Parameter Dependence

Typical approaches in previous studies:

- Assumed independence.

$$P(x_0, \Delta p, R_{\max}, V_f, \theta) = P(x_0) \cdot P(\Delta p) \cdot P(R_{\max}) \cdot P(V_f) \cdot P(\theta)$$

- Correlation tree (1:1 dependence).

$$P(x_0, \Delta p, R_{\max}, V_f, \theta) = P(x_0)$$

$P(x_0) \rightarrow P(\Delta p \mid x_0) \rightarrow P(R_{\max} \mid \Delta p)$

$P(x_0) \rightarrow P(\theta \mid x_0) \rightarrow P(V_f \mid \theta)$

GPM Applications: Meta-Gaussian Distribution

Previous approaches for TC parameter dependence:

Study	Δp	R_{max}	θ	V_f
LA/TX	$P(\Delta p \mid x_0)$	$P(R_{max} \mid \Delta p)$	$P(\theta \mid x_0)$	$P(V_f \mid \theta)$
Mississippi	$f(x_0)$	$f(\Delta p)$	Δp *slices*	Δp *slices*
FEMA R2	$f(x_0)$	$f(\Delta p)$	$f(x_0)$	$f(\Delta p)$
SFL	$f(x_0)$	$f(\Delta p)$	$f(x_0)$	*independent*
SWFL	$f(x_0)$	$f(\Delta p)$	$f(x_0)$	*independent*
WFL	$f(x_0)$	$f(\Delta p)$	$f(x_0)$	*independent*
Big Bend	$f(x_0)$	$f(\Delta p)$	$f(x_0)$	*independent*

Meta-Gaussian Distribution (MGD)

- **MGD** refers to a set of marginal (univariate) probability distributions with a multivariate Gaussian copula as dependence structure.

- Sklar's theorem (1959):
  - ► Any joint (multivariate) distribution, H, can be deconstructed into marginal distributions, $F_1, \dots, F_n$, and a copula, C.

$$H(x_1, \dots, x_n) = C\big(F_1(x_1), \dots, F_n(x_n)\big)$$

$$F_1(x_1), \dots, F_n(x_n) \rightarrow \Delta p, R_{max}, V_f, \theta$$

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Meta-Gaussian Distribution (MGD)

- **Copula** – dependence function that "links" a set of marginal distributions to form a joint distribution.
  - ► Must be expressed in terms of

    u_n = uniform margins defined on [0,1]

$$C(u_1, \dots, u_n) = H\left(F_1^{-1}(x_1), \dots, F_d^{-1}(x_d)\right)$$

- **Gaussian Copula** – "elliptical" copula.

$$C_R^{Gauss}(u) = \Phi_R\big(\Phi^{-1}(u_1), \dots, \Phi^{-1}(u_d)\big)$$

Φ_R = CDF of a multivariate standard normal distribution, $\mathcal{N}(0,1)$

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Meta-Gaussian Distribution (MGD)

Limitations of Gaussian Copula

- “A recipe for disaster”
  - Tail dependence is 0, regardless of the correlation matrix

$$\lambda_l = \lambda_u = 2 \lim_{x \to \infty} \Phi\left(x \frac{\sqrt{1-\rho}}{\sqrt{1+\rho}} \right) = 0$$

- Correlation ρ (X, Y) is static and symmetrical along [0,1] range
  - Slices (e.g., Δp)
- Pearson’s ρ – measures linear correlation; affected by outliers
  - Spearman’s ρ (rank correlation coefficient)
  - Kendall’s τ

Gaussian Copula

- Correlation matrix, R

$$R = \begin{pmatrix} 1 & \rho_{1,2} & \cdots & \rho_{1,d} \\ \rho_{2,1} & 1 & \cdots & \rho_{2,d} \\ \vdots & \vdots & \ddots & \vdots \\ \rho_{d,1} & \rho_{d,2} & \cdots & 1 \end{pmatrix}$$

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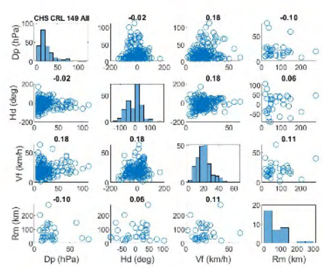
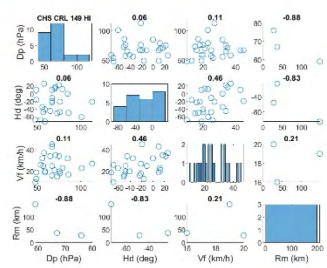
Meta-Gaussian Distribution (MGD) (Mississippi Example)

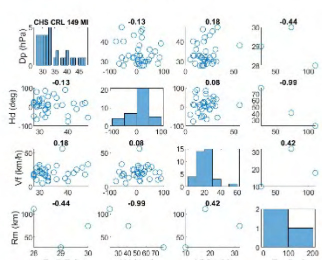
Correlation Plots



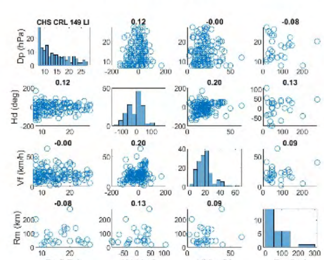
All TCs



High Intensity TCs



Medium Intensity TCs



Low Intensity TCs

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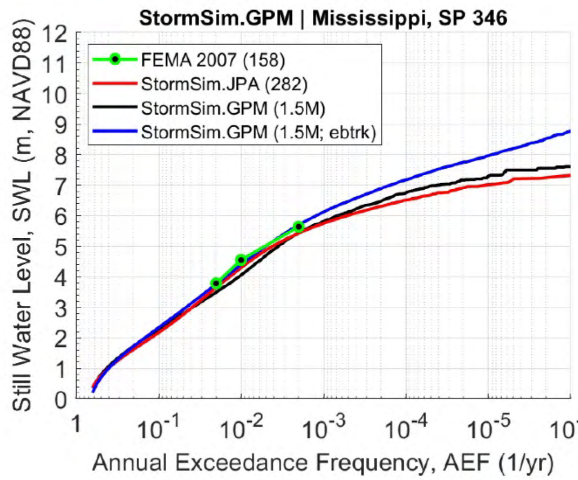
Meta-Gaussian Distribution (MGD)
(Mississippi Example)

- **MGD**
  - Marginal distributions are defined for each JPM parameter.
  - A unique copula can be fitted per Δp "slice" to maintain parameter dependencies for different TC intensity ranges.
  - The correlation between Δp and R_{max} can be updated.



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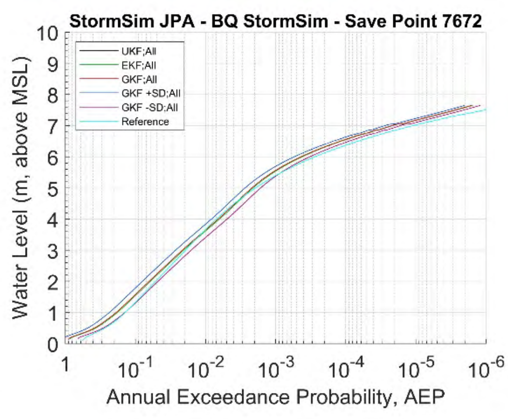
Epistemic Uncertainty in SRR Models

- Models for Calculating SRR.
  - Uniform kernel function (UKF) or capture zone.
  - Gaussian kernel function (GKF).
  - Epanechnikov kernel function (EKF).
- Incorporated +/- 1 standard deviation (SD).
  - SRR uncertainty contribution (Δp ≥ 28 hPa):
    - Sampling uncertainty – 65%
    - Selected period of record – 19%
    - Gaussian kernel size – 15%
    - Observational data – 1%



$$\lambda = \frac{1}{T}\sum_{i}^{n} w(d_i)$$

$$w(d_i) = \frac{1}{h_d}\begin{cases} 0.5, & if \left|\frac{d_i}{h_d}\right| < 1 \\ 0, & otherwise \end{cases}$$

UKF

$$w(d_i) = \frac{1}{\sqrt{2\pi}h_d} exp\left[-\frac{1}{2}\left(\frac{d_i}{h_d}\right)^2\right]$$

GKF

$$w(d_i) = \frac{1}{h_d}\begin{cases} \frac{3}{4}\left[1-\left(\frac{d_i}{h_d}\right)^2\right], & if \left|\frac{d_i}{h_d}\right| < 1 \\ 0, & otherwise \end{cases}$$

EKF

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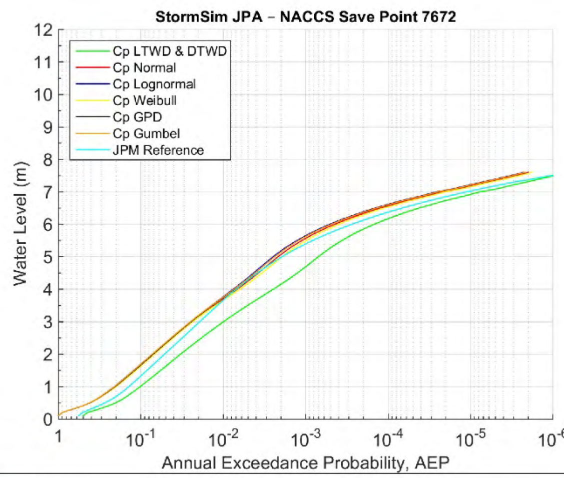
Defining Joint Probability of Storm Parameters

- Effect of selection of Δp distribution on hazard curve.



LTWD & DTWD curve considers the discretization of TCs into high and low intensity.

The effect is to lower the hazard curve.

Choice of Δp distribution showed limited impact

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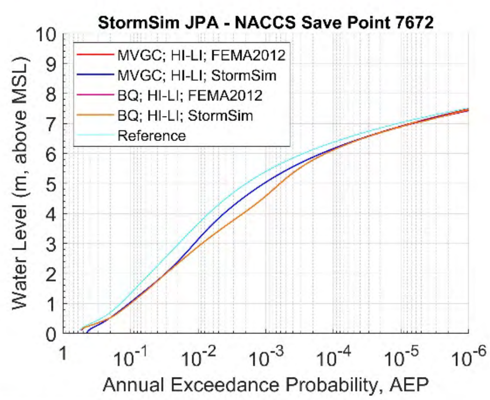
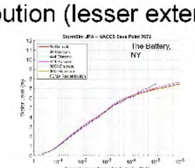
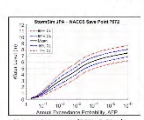
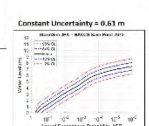
Computation probability masses/integration

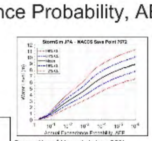
- MGD vs BQ.
- Hazard curve integration method did not have an effect.
- Elements of integration process that affect curve:
  - Characterization method:
    - Constant
    - Proportional
    - Constrained [min(20%, 0.61m)]
  - Discretization of normal distribution (lesser extent).











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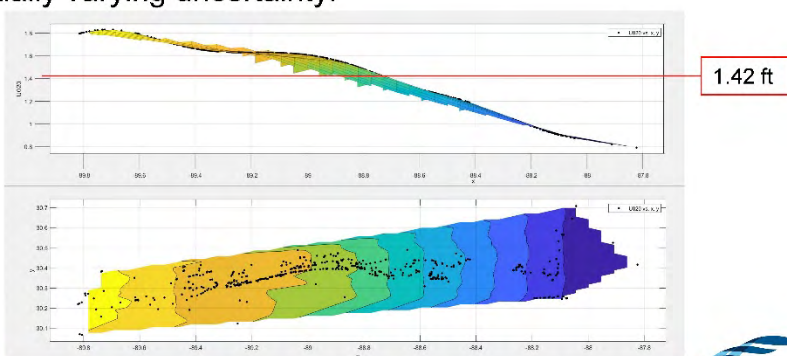
Spatially Varying Modeling Error
(Mississippi Example)

- Modeling error: has a direct effect on hazard curve shape and confidence limits.
  - ► Global uncertainty: **1.42 ft.**
  - ► Spatially varying uncertainty:



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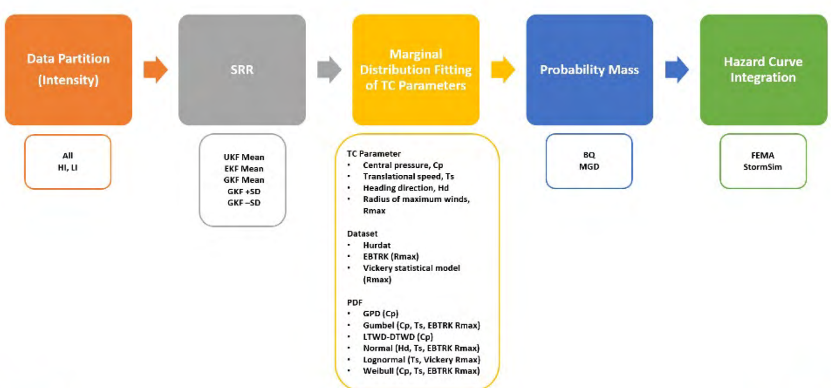
Quantification and Propagation of Epistemic Uncertainty

- Evaluated alternate data, models, and methods (logic tree branches).



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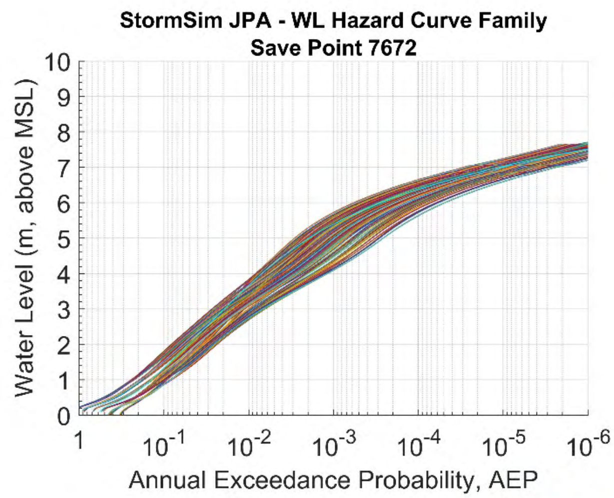
Quantification of Epistemic Uncertainty

- Family of hazard curves representing alternate data, model and methods.
- Number of curves: 1,261.
- About 5 ft spread at 100 years.



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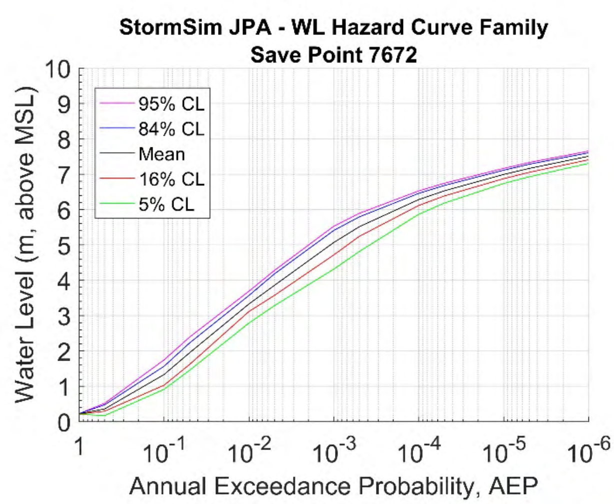
Quantification of Epistemic Uncertainty

- Demonstration: all curves assigned same weight.
- Logic tree branches have been trimmed.
- Mean hazard curve with confidence limits.



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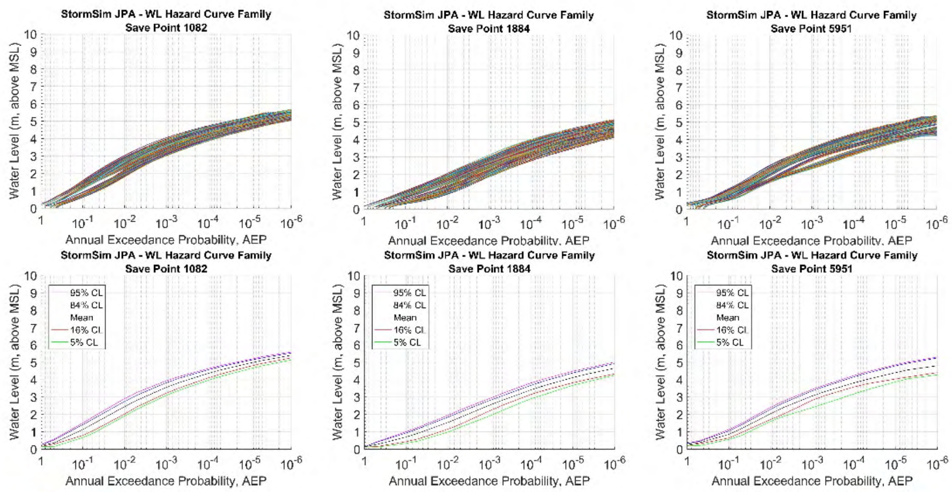
Quantification of Epistemic Uncertainty



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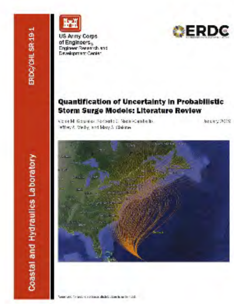
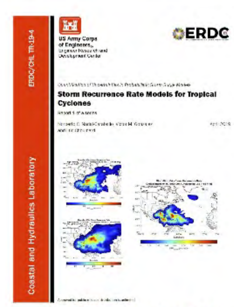
Reports

- Gonzalez V.M., N.C. Nadal-Caraballo, J.A. Melby, and M.A. Cialone. 2019. *Quantification of Uncertainty in Probabilistic Storm Surge Models: Literature Review*. ERDC/CHL SR-19-1.



- Nadal-Caraballo, N.C., V.M. Gonzalez, and Chouinard, L. 2019. *Quantification of Uncertainties in Probabilistic Storm Surge Models: Storm Recurrence Rate Models for Tropical Cyclones*, ERDC-CHL TR-19-4. Vicksburg, MS: U.S. Army Engineer Research and Development Center.



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4.3.2.2.3 Questions and Answers

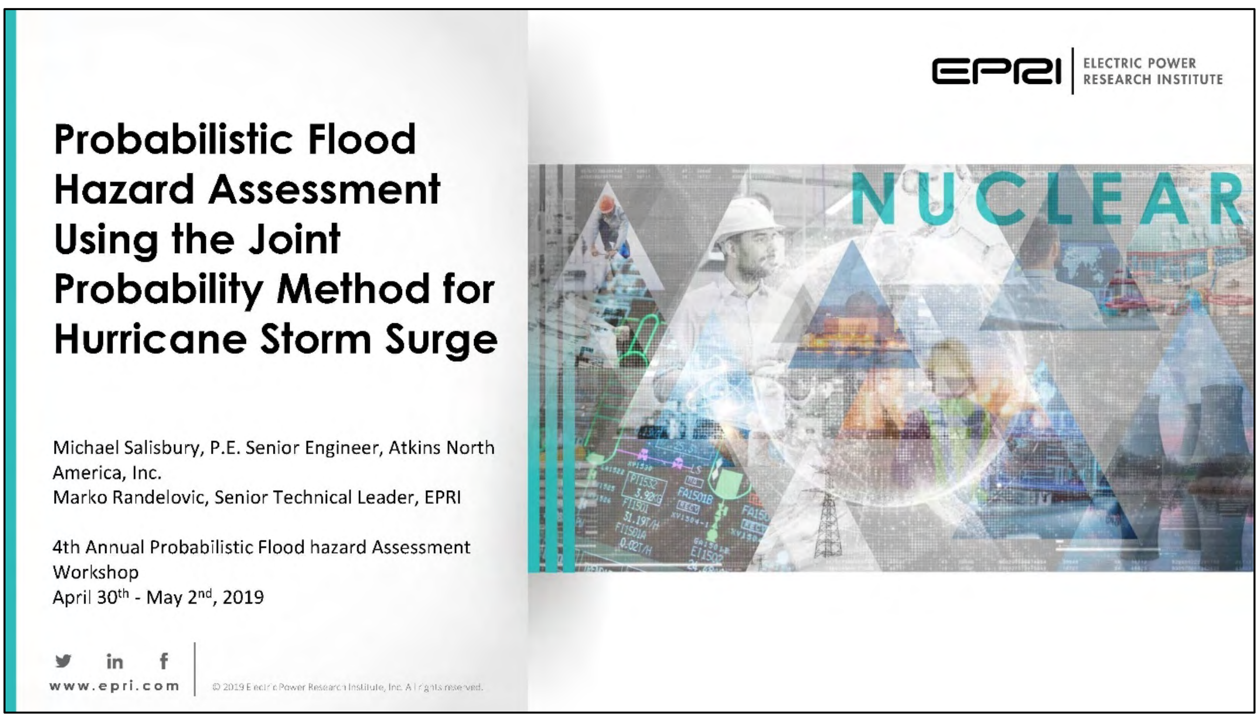
No time was available for questions.

4.3.2.3 Probabilistic Flood Hazard Assessment Using the Joint Probability Method for Hurricane Storm Surge. Michael Salisbury^, Atkins North America, Inc.; and Marko Randelovic*, EPRI (Session 1B-3; ADAMS Accession No. ML19156A454)

4.3.2.3.1 Abstract

Hurricane-induced storm surge can be significant, depending on the circumstances. For nuclear plants to adequately assess the risk posed by storm surge, we need to better understand the expected frequencies of storms that would produce a storm surge that could affect a site. A PFHA can be used to determine the frequency of a storm surge that would be expected to exceed a particular flood height. This report explains how to use the JPM and numerical simulations to obtain an estimate of annual exceedance probabilities as a function of surge height. This method can be used to determine the appropriate design basis and develop the flood hazard curve—the relationship between surge level and frequency—for a probabilistic risk assessment. The report includes discussions on developing and validating storm surge models for project sites, determining storms to be simulated, and identifying storm surge parameters and their associated probabilistic uncertainties. The methodology presented in the report is applicable to any coastal NPP that could be impacted by tropical cyclones (hurricanes). A practical example is presented to help demonstrate the method.

4.3.2.3.2 Presentation



Objective

- To provide guidance on the estimation of annual exceedance probability (AEP) surge levels generated by tropical cyclones
- Support both a probabilistic flood hazard assessment for a coastal site as well as the siting and design of nuclear power plants in coastal environments
- Example AEP range: 10^{-5} to 10^{-7} (100,000- to 10,000,000-yr return period)

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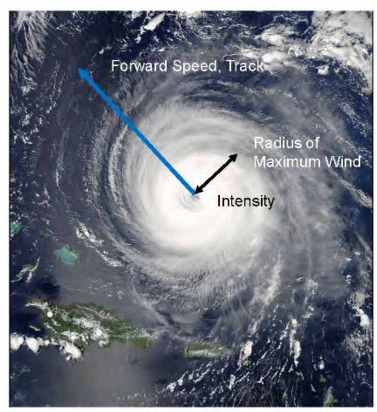
Storm Surge (Hazard)-JPM

- EPRI conducted research into the use of the joint probability method (JPM) to simulate hurricanes and establish flood hazard curve
- Hurricanes are simulated using stochastic model of storm parameters
  - Proximity of the landfall
  - Track angle of the storm
  - Storm intensity (central pressure)
  - Storm size (radius of maximum wind)
  - Storm forward speed

Storm Meteorological Parameters



Source: NASA Earth Observatory Image

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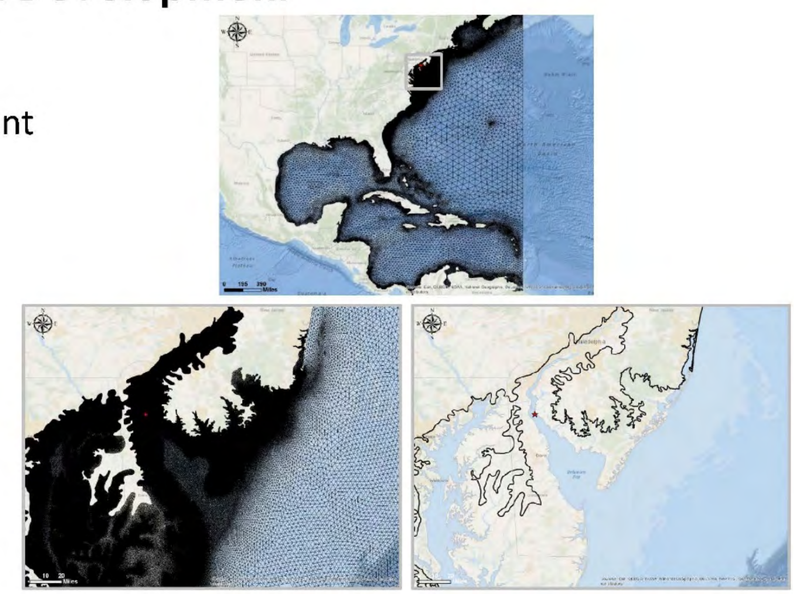
JPM Steps

1. Develop/validate storm surge model
2. Determine range of storm parameters
3. Develop wind fields for hypothetical storm events
4. Simulate surge and wave fields for each storm event
5. Estimate surge response functions
6. Estimate storm parameter and uncertainty distributions
7. Estimate surge cumulative distribution function including effects of uncertainty

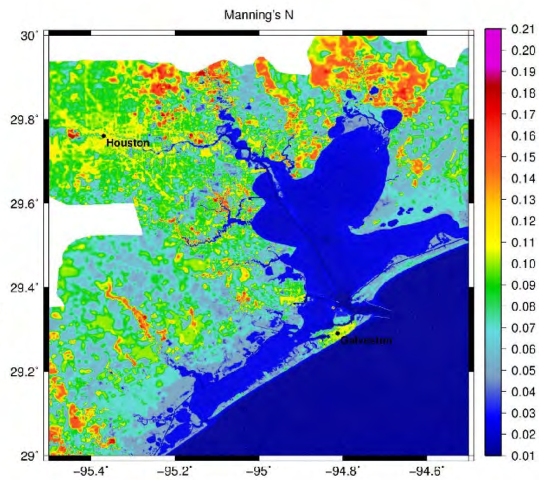
Storm Surge Model Development

- Model selection
- Mesh/grid development
- Calibration
- Validation
- Application



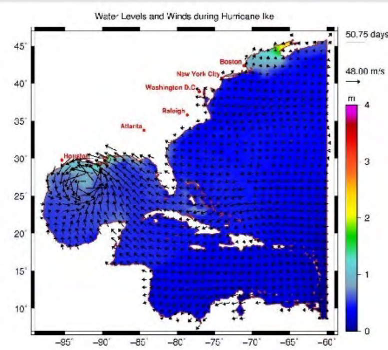
Model Parameterization and Calibration

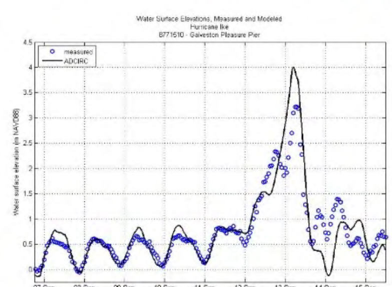
- Establishes important model parameters
- Examples:
  - Bottom friction
  - Wind Stress Formulation
  - Time step
  - Wave coupling parameters
- Sensitivities in results due to changes in parameter values need to be tested to verify model produces reasonable results within the standard of practice



Model Validation

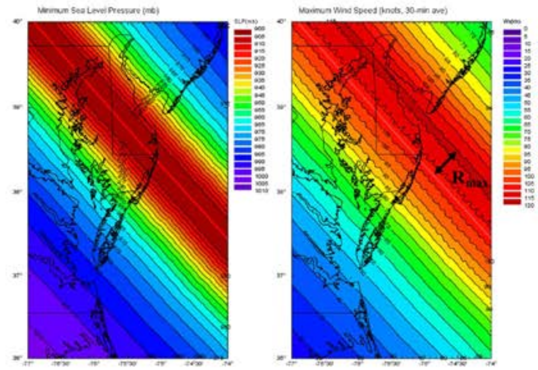
- Develop wind field data for each relevant historical storm event
  - Note that wind field data is often obtained from marine meteorological models, which have their own development and validation process
- Simulate each storm event using the storm surge model and wind field data
- Validate model results to measured data and compute error metrics





JPM - Storm Parameters

- Proximity of the landfall (x_0)
- Track angle of the storm (ϑ_f)
- Storm intensity (Δp)
- Storm size (R_{max})
- Storm forward speed (v_f)
- Other parameters (tides, etc.)



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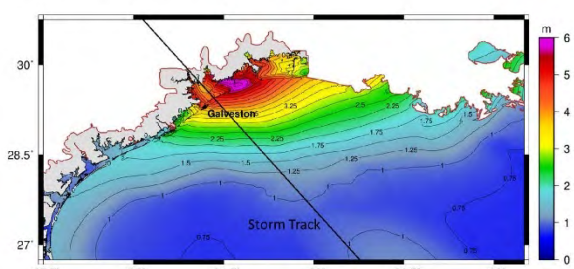
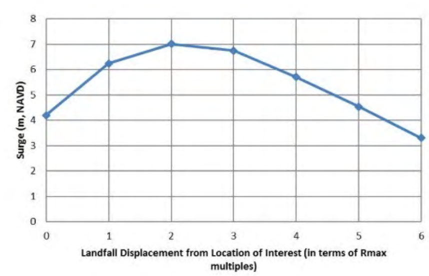
JPM – Range of Storm Parameter Values

- Determine relevant range of parameter values
  - Sensitivity of each storm parameter varies by location
- Perform simulations and compare results for each parameter
- Some parameters (e.g., storm intensity) have physical limitations based on location





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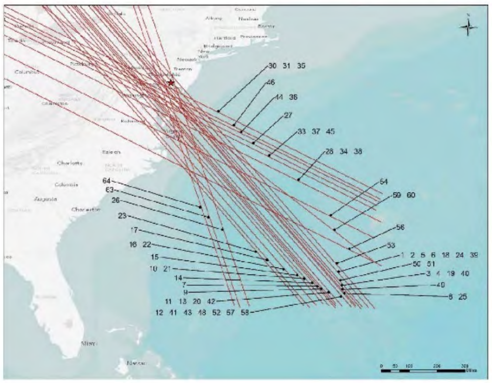
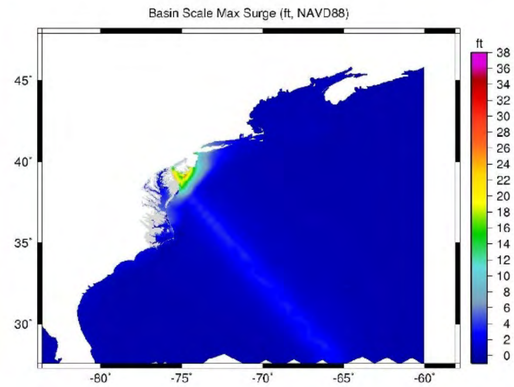
JPM – Simulate Synthetic Storm Events

- Create set of synthetic storm events with unique combinations of parameter values
- Simulate with the validated storm surge and wave model





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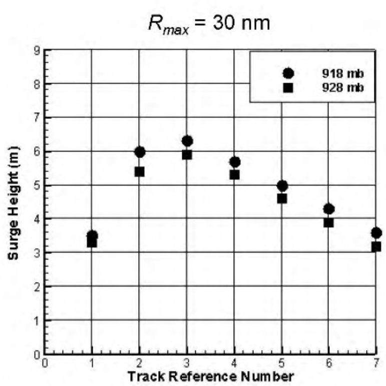
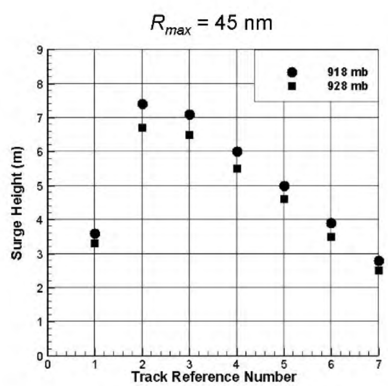
JPM – Develop Surge Response Functions

- Isolate influence of each individual storm parameter
- Results used to numerically evaluate JPM equation





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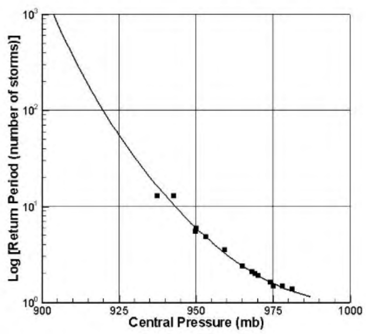
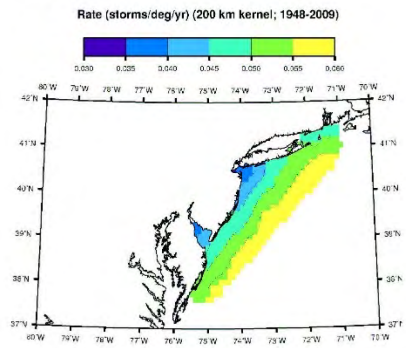
JPM – Estimate Storm Parameter Distributions

- Relies on best available data and previous statistical analyses to estimate probability distributions for each storm parameter
- Obtained from literature (journal articles, technical reports, etc.) and historical databases (HURDAT, IBTrACS, etc.)

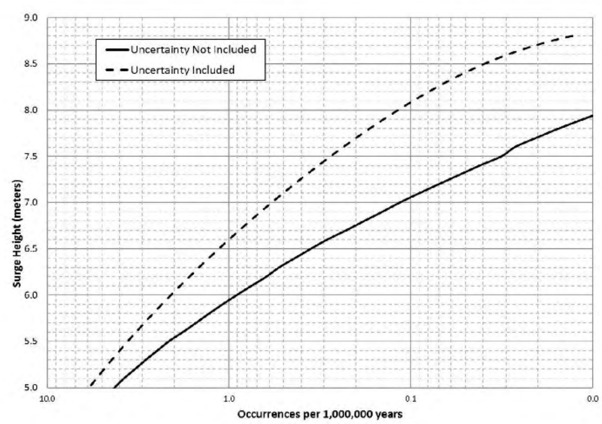




JPM – Estimate Flood Hazard Curve

$$F(\eta) = \sum_{i,j,k,l,m,n} p\left(\Delta p_i, R_{max_j}, v_{f_k}, \theta_{f_l}, x_{0_m}\right) p(\varepsilon|\eta) \text{ for } \left[\eta_*\left(\Delta p_i, R_{max_j}, v_{f_k}, \theta_{f_l}, x_{0_m}\right) + \varepsilon_n < \eta\right]$$

- Include uncertainty
  - Epistemic (modeling error)
  - Aleatory (sample size error)
- Storm surge vs. AEP relationship creates the storm surge flood hazard curve for use in a PRA



JPM Key Findings

- Robust framework that covers a range of scenarios.
- Can be used to support both design basis evaluations and PRA.
- Can be used to assess the frequency of a storm surge that would be expected to exceed a flood height.
- An iterative process with the storm surge model simulations informing the JPM analysis and vice versa. Therefore, it is important to have a close coordination between numerical modelers and statistical analysts to support JPM analysis.
- Full report available on EPRI website: Product ID 3002012996

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4.3.2.3.3 Questions and Answers

Question:

One of the big issues with this topic is you are in a part of the parameter space that we have not really encountered. As you mentioned, there are a lot of details about setting up the model, like picking friction values and the wind drag model. Did you recommend how to deal with the fact that those issues, and others like erosion, are things we have not really observed at the scale of storms, such as what we are probably looking at here. It is hard to know how one might extrapolate those sorts of things to calibrate the model, as we do not have representative events.

Answer:

That's a good point. Adding to that point, you often have topographic or bathymetric data that represent recent conditions and you are trying to simulate a storm from 1950 or 1960 as one of your validation storms, where obviously coastal landscapes could have looked different, land use looks different, and the data available to develop the wind field are certainly sparse and limited. That is certainly built into it when you are quantifying the uncertainty in the model. If you have measured data, you are able to quantify the uncertainty. But certainly, it is somewhat of a limitation when you are factoring in erosion and similar considerations dynamically for this type of event. Because when you are looking at a million-year return interval storm event, or types of storms that contribute to that risk level, there are no historical data. At some level, you are taking a leap of faith that the available historical data represent that million-year event. There are some limitations with the abilities of the model, even though there has been a lot of progress in advancements of the best state of the art.

4.3.2.4 Assessment of Epistemic Uncertainty for Probabilistic Storm Surge Hazard Assessment Using a Logic Tree Approach. Bin Wang*, Daniel C. Stapleton and David M. Leone, GZA (Session 1B-4; ADAMS Accession No. ML19156A455)

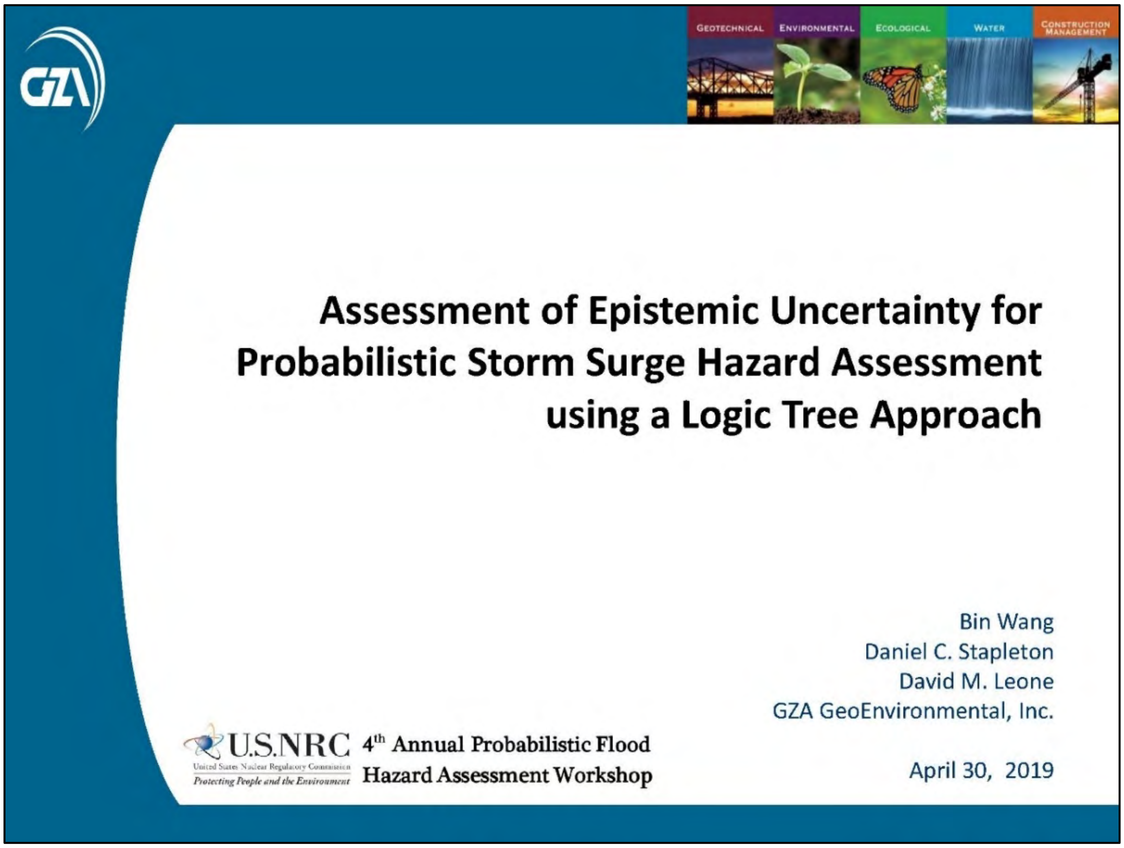
4.3.2.4.1 Abstract

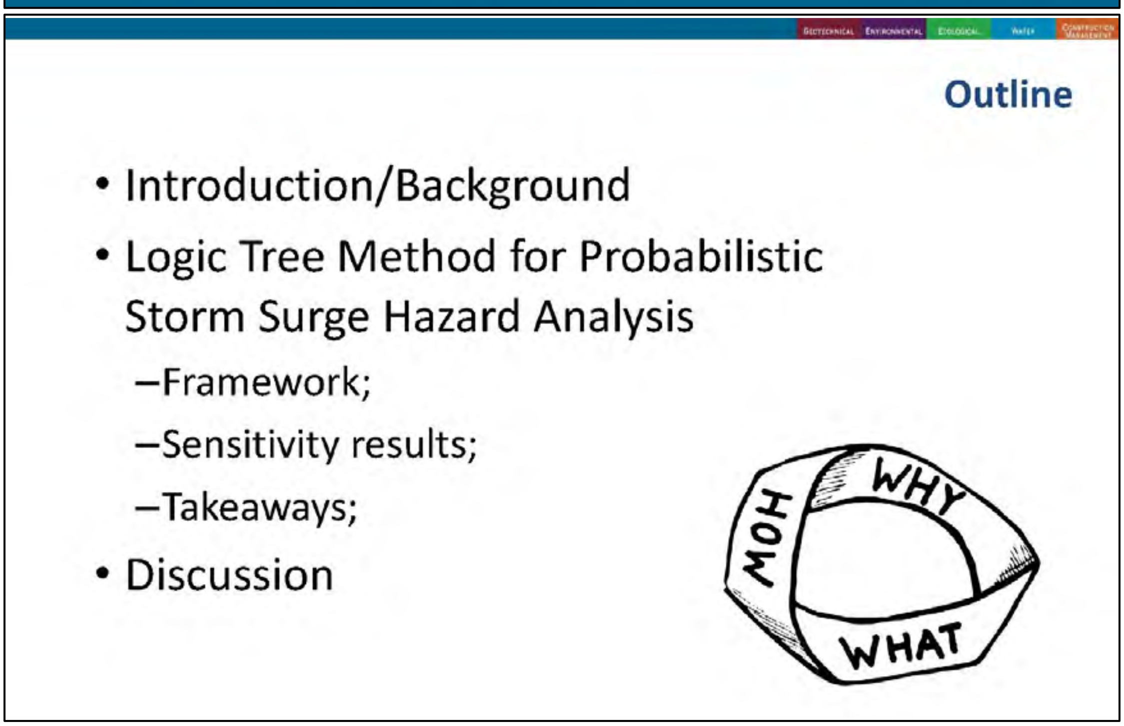
Probabilistic storm surge hazard assessment (PSSHA) requires the characterization of the mean storm surge frequency, inclusive of consideration of epistemic uncertainty. The PSSHA often involves inevitably significant uncertainty, especially at the low-frequency range that is often applicable for hazard evaluations at critical infrastructures and facilities. Epistemic uncertainty arises due to the use of models to characterize the hazard input such as data source, probability distribution, storm rate, and storm surge modeling. A logic tree approach uses alternatives at various input nodes and generates a family of hazard curves from which a mean hazard curve can be derived. Branch weights are assigned based on the analyst's confidence that the selected alternatives are the best representation of the hazard input. The logic tree provides a transparent, structured framework for systematic characterization and quantification of potential epistemic uncertainties. The final product is a weighted mean flood hazard curve with confidence intervals (CIs) based on the family of flood hazard curves from the logic tree.

This presentation provides an overview of the logic tree methodology and key engineering considerations including the role of engineering judgment. In the presented examples, each hazard curve was developed using the JPM with Optimal Sampling and Response Surface method (JPM-OS-RS), which allows a full coverage of the hurricane parameter space with minimum modeling effort and surge interpolation with reasonable accuracy. However, alternative methods (e.g., empirical track method) can also be used for the logic tree. Multiple data sources

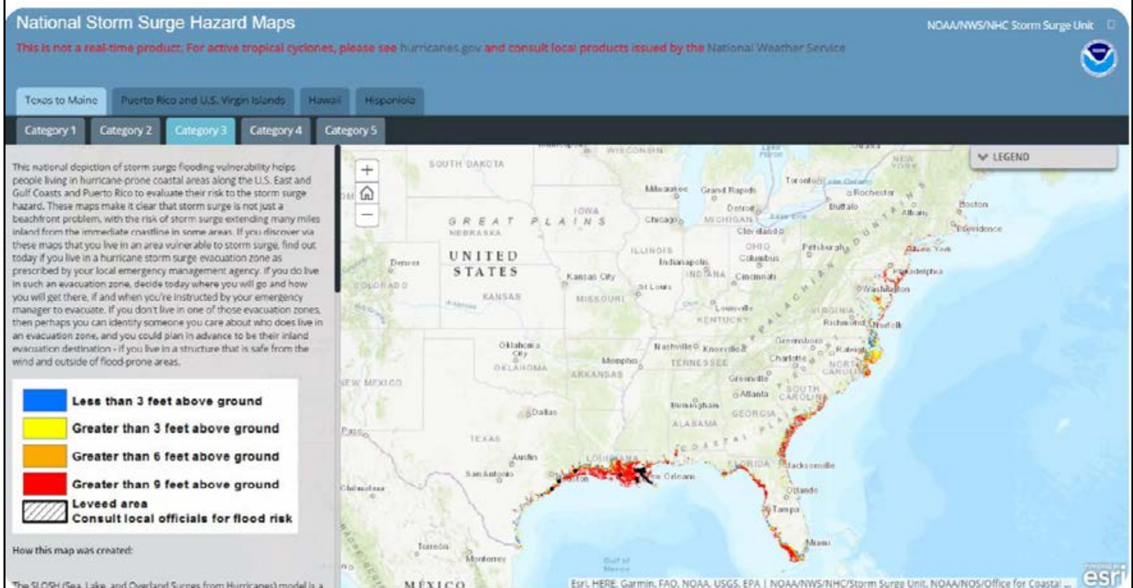
are discussed, including historical and synthetic hurricane tracks. The presentation also discusses sensitivity of various nodes and engineering decisions.

4.3.2.4.2 Presentation



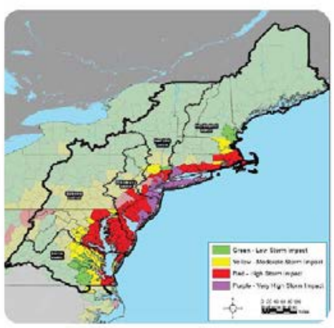


Storm Surge Hazard

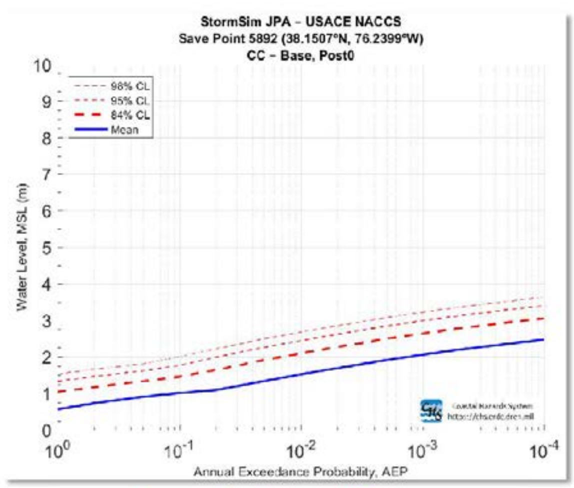


Storm Surge Hazard

FEMA – Hurricane Sandy Impact



USACE NACCS



Example Hazard Curves (Chesapeake Bay)

General Methodology / Example Analysis

- Deterministic analysis;
- Probabilistic analysis:
  - Empirical simulation technique (e.g., TR CHL-99-21, Scheffner, et al., 1999);
  - Empirical track method (e.g., Vickery et al., 2009);
  - Synthetic track method (e.g., Lin et al., 2010);
  - Joint probability method (e.g., FEMA, 2008 & 2014 and USACE TR-15-5, 2015);

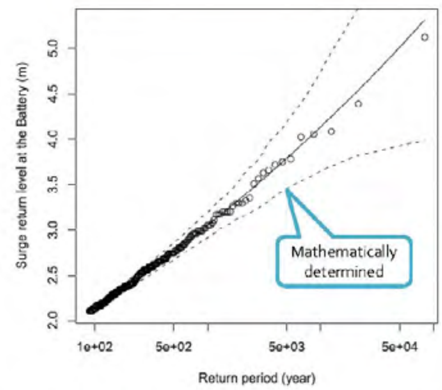


Figure 14. Return level plot for extreme storm surge heights for New York City. The solid curve is the mean return level. The dashed curves are the 95% confidence limits. The open circles are the empirically estimated return levels.

→ **"Best Estimate"**

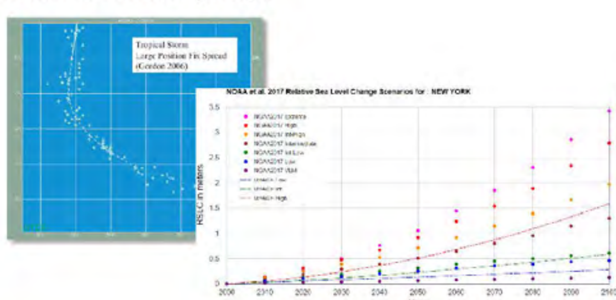
Sources of Epistemic Uncertainty

- Uncertainty = **Knowledge Uncertainty** + **Natural Variability**

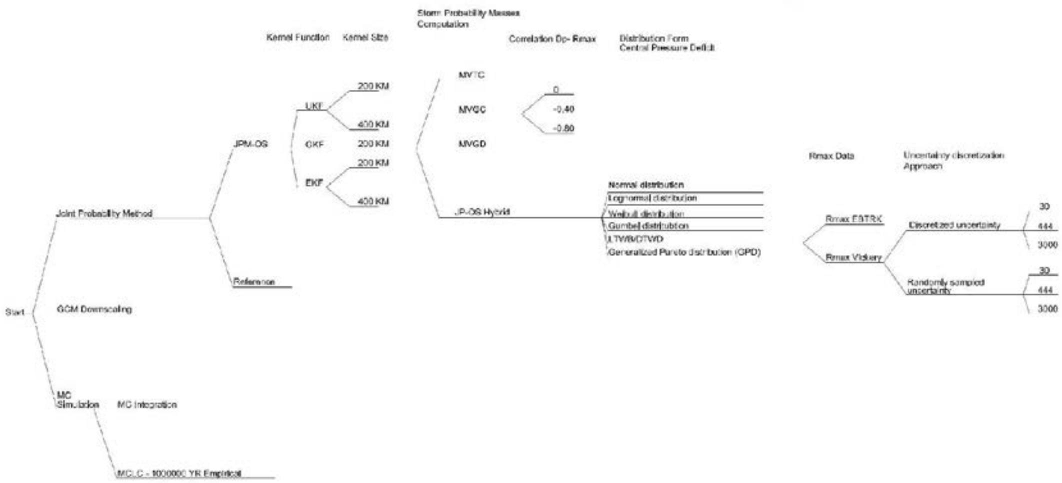
Knowledge Uncertainty	Natural Variability
Facts that can be known with uncertainty, but are not currently known by the observer. Obtaining more information can reduce this type of uncertainty.	Inherent variability in the physical world that cannot be known for certain. Cannot be reduced, however, our estimation can be improved with more information.

*** Storm surge hazard analysis – epistemic uncertainty, e.g.,**

- Limited historical record;
- Limitations in physical models;
- Storm recurrence rate;
- Coincident astronomical tides;
- Meteorological parameters;
- Hydrodynamic modeling;
- Projected sea level rise scenarios;
- …



Logic Tree Method



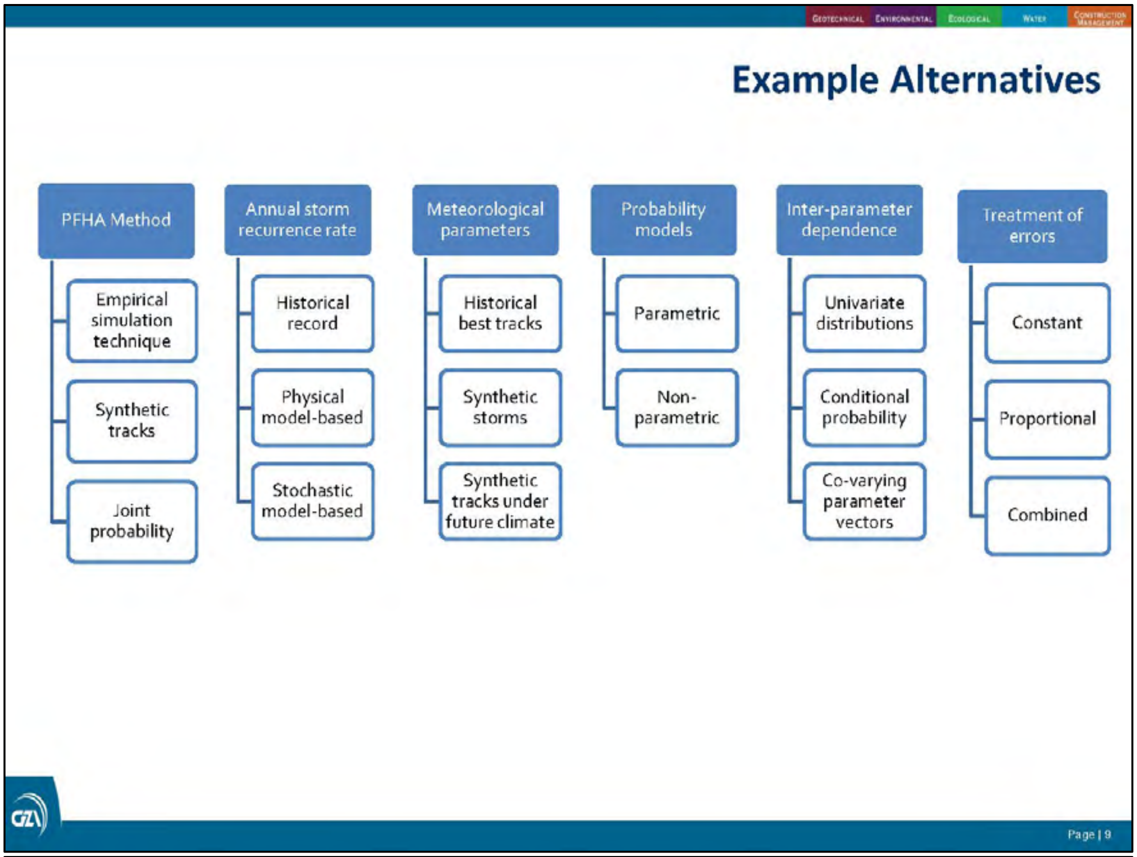
- Alternative models;
- Alternative parameter values;
- Weights;

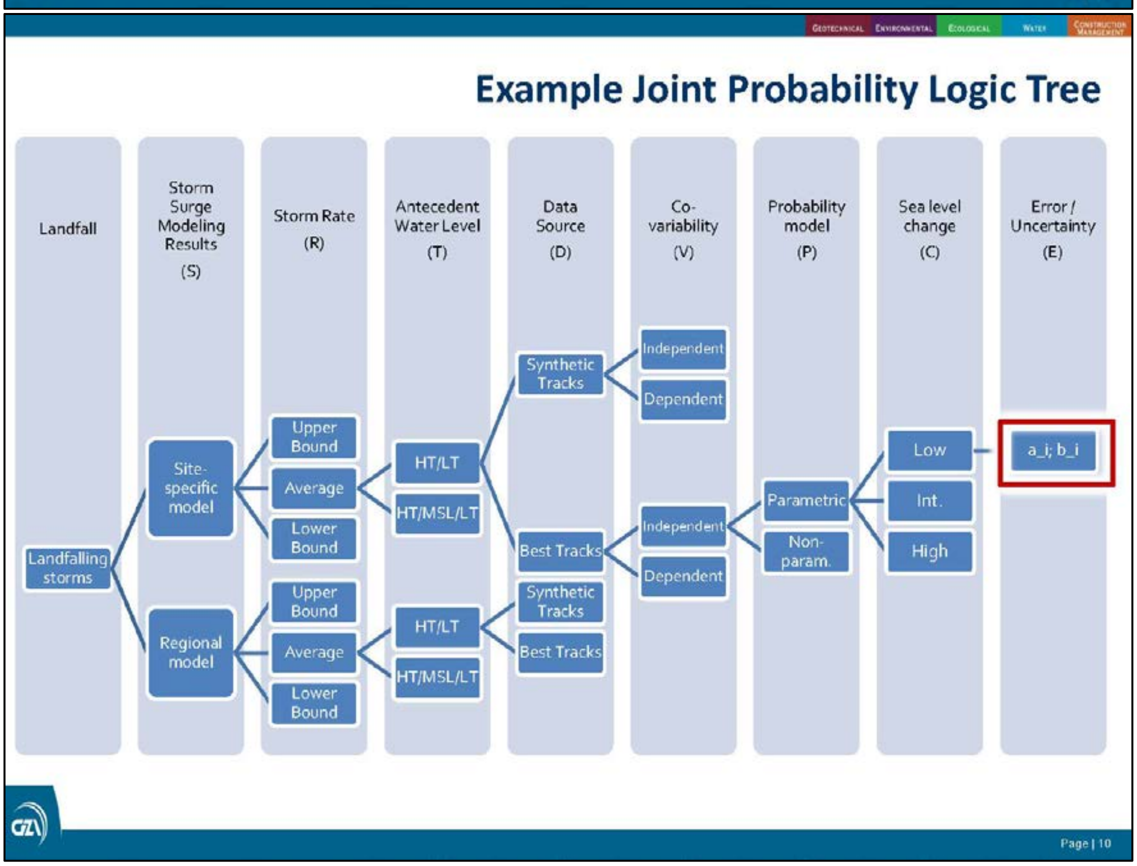
➡ Comprehensive & systematic treatment of uncertainty

➡ Mean hazard + confidence interval

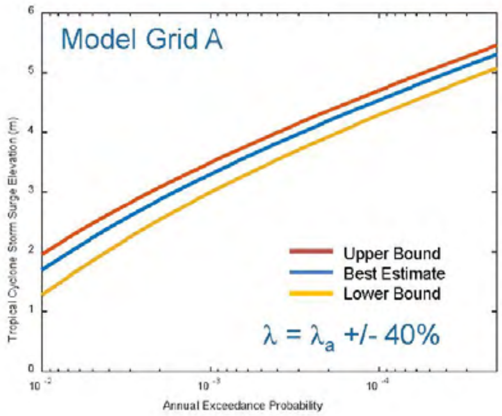
Sources: Gonzalez, et al., 2017, 3rd PFHA Workshop; Bensi and Kanney, 2015.

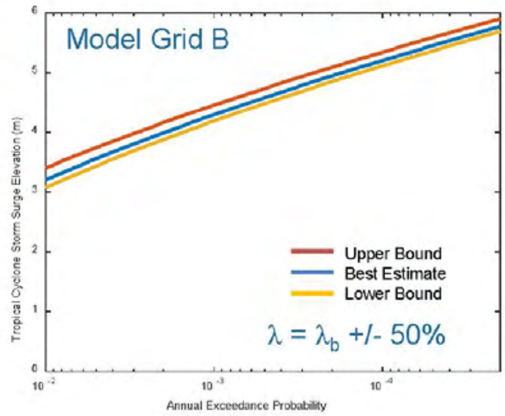
Logic Tree Example for Probabilistic Storm Surge Analysis


Example Alternatives
PFHA Method
Empirical simulation technique
Synthetic tracks
Joint probability
Annual storm recurrence rate
Historical record
Physical model-based
Stochastic model-based
Meteorological parameters
Historical best tracks
Synthetic storms
Synthetic tracks under future climate
Probability models
Parametric
Non-parametric
Inter-parameter dependence
Univariate distributions
Conditional probability
Co-varying parameter vectors
Treatment of errors
Constant
Proportional
Combined
Page | 9

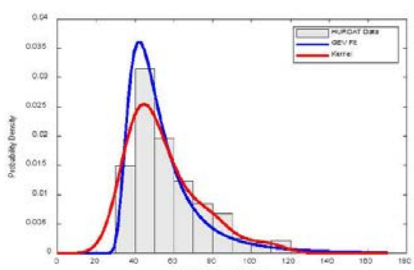

Example Joint Probability Logic Tree
Landfall
Storm Surge Modeling Results (S)
Storm Rate (R)
Antecedent Water Level (T)
Data Source (D)
Co-variability (V)
Probability model (P)
Sea level change (C)
Error / Uncertainty (E)
Landfalling storms
Site-specific model
Regional model
Upper Bound
Average
Lower Bound
Upper Bound
Average
Lower Bound
HT/LT
HT/MSL/LT
HT/LT
HT/MSL/LT
Synthetic Tracks
Best Tracks
Synthetic Tracks
Best Tracks
Independent
Dependent
Independent
Dependent
Parametric
Non-param.
Low
Int.
High
a_i; b_i
Page | 10

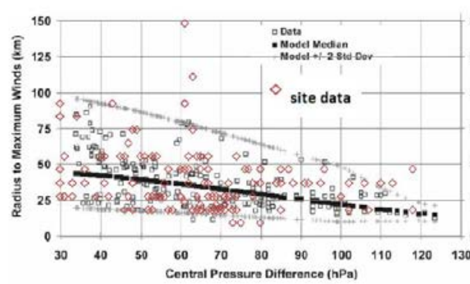
Sensitivity Analysis – Storm Recurrence Rate

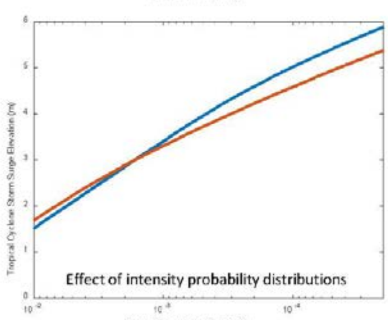


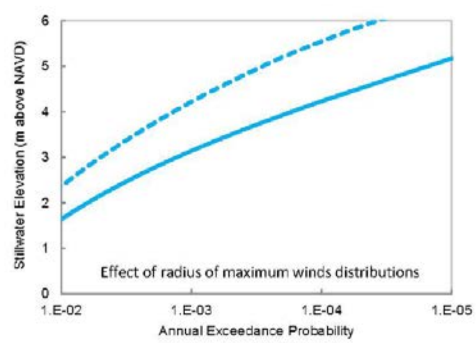


Sensitivity Analysis – Probability Distributions

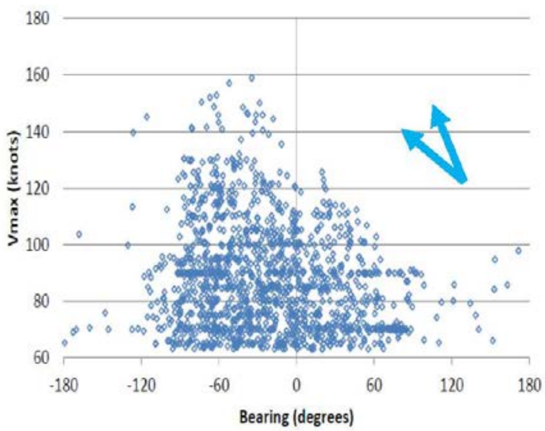


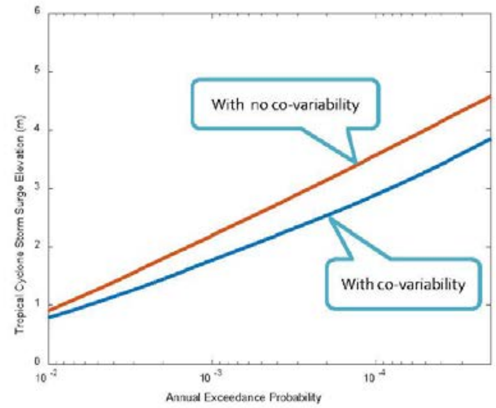






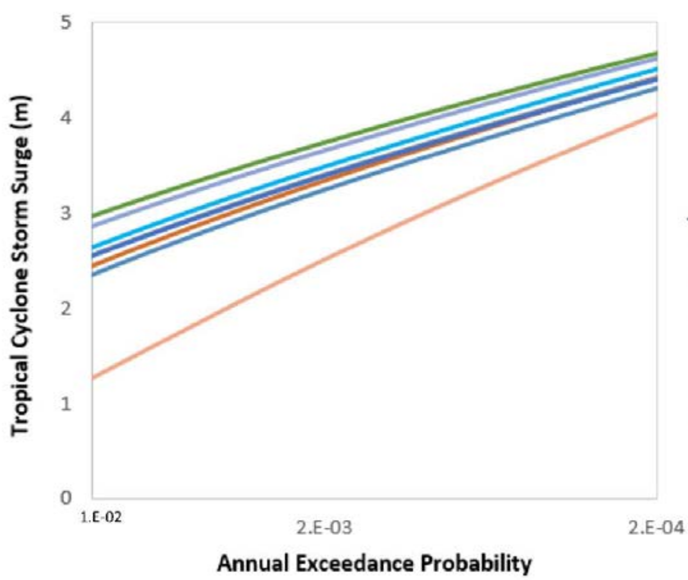
Sensitivity Analysis – Parameter Co-variability





Example: heading vs. wind intensity (Gulf of Mexico)

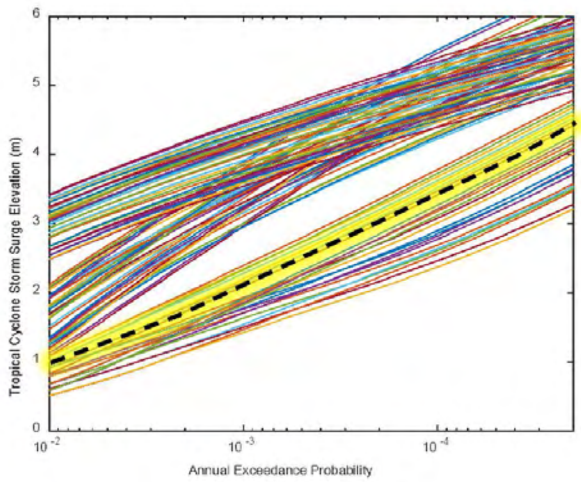
Effects of Different Input



Tested:

- Parameter co-variability;
- Parametric vs non-parametric;
- Storm surge modeling results;

Example Hazard Curves with Error/Uncertainty



$$P[\eta_{\max(1yr)} > \eta] \approx \sum_{i=1}^{n} \lambda_i P[\eta(\underline{x}_i) + \varepsilon > \eta]$$

$$\sigma = \sqrt{a_i^2 + (b_i \cdot \eta)^2}$$

where

$a_i = \sqrt{\varepsilon_1^{\,2} + \varepsilon_2^{\,2}}$ $\quad b_i = F(\varepsilon_3, \varepsilon_4)$

i = branch number

ε_1 = uncertainty representing tide coincident with storm surge

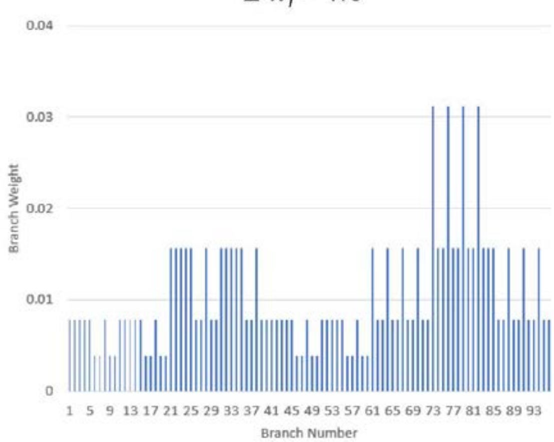
ε_2 = uncertainty in numerical surge modeling

ε_3 = uncertainty due to sampling (intensity variability)

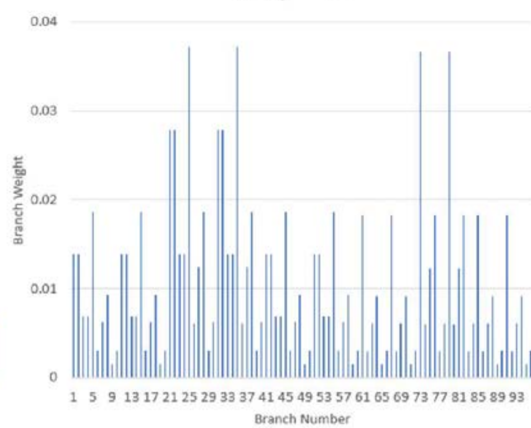
ε_4 = correction factor (project specific)

Example Branch Weights

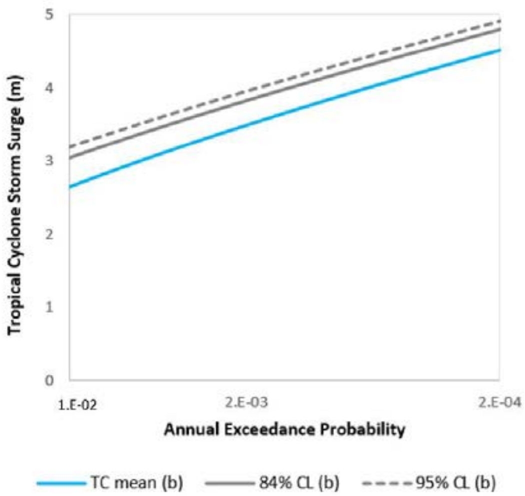
$\Sigma\, w_i = 1.0$

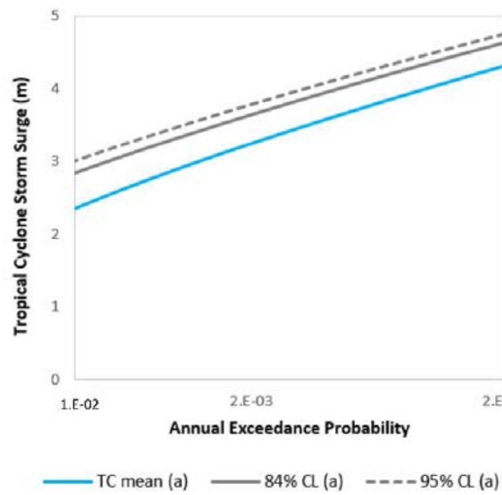


$\Sigma\, w_i = 1.0$

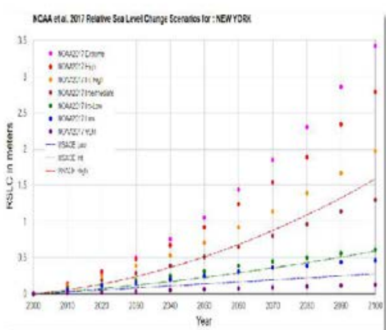


Effect of Weights on Mean Hazard Curves





Effect of Sea Level Change Scenarios



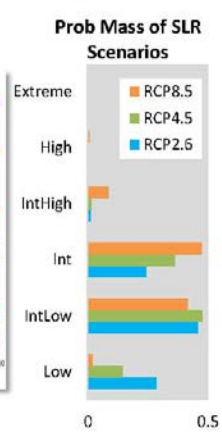
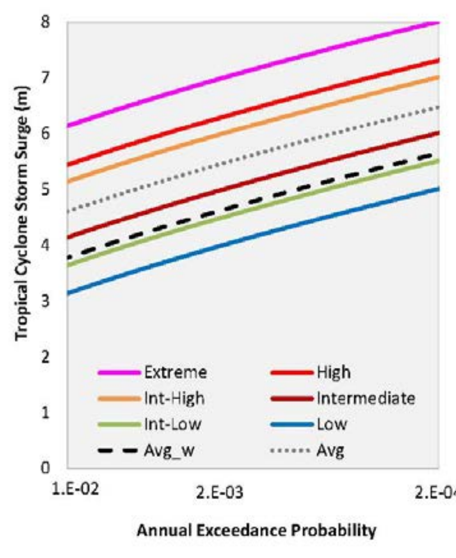


Table 4. Probability of exceeding GMSL (median value) scenarios in 2100 based upon Kopp et al. (2014).

GMSL rise Scenario	RCP2.6	RCP4.5	RCP8.5
Low (0.3 m)	94%	98%	100%
Intermediate-Low (0.5 m)	49%	73%	96%
Intermediate (1.0 m)	2%	3%	17%
Intermediate-High (1.5 m)	0.4%	0.5%	1.3%
High (2.0 m)	0.1%	0.1%	0.3%
Extreme (2.5 m)	0.05%	0.05%	0.1%



Note: SLC adjusted by linear superposition. Assumed RCP4.5

Sources: NOAA, 2017. USACE, 2017.

Takeaways

- Comprehensive and systematic approach for epistemic uncertainty assessment;
- Flexibility for sensitivity evaluation;
- Transparency for risk assessment and communication;
- Diverse applications for complex multi-component system;
- ...

USACE Risk Analysis Gateway

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4.3.2.4.3 Questions and Answers

There were no questions.

4.3.2.5 Coastal Flooding Panel. (Session 1B-5)

Moderator: Joseph Kanney, NRC/RES/DRA/FXHAB

Arthur Taylor, National Weather Service/Office of Science and Technology Integration/Meteorological Development Laboratory
Victor Gonzalez, U.S. Army Corps of Engineers (USACE) Research and Development (R&D) Center, Coastal and Hydraulics Laboratory
Norberto Nadal-Caraballo, USACE R&D Center, Coastal and Hydraulics Laboratory
Michael Salisbury, Atkins North America, Inc.
Bin Wang, GZA GeoEnvironmental, Inc.
Guest Panelist: Chris Bender, Taylor Engineering

Moderator:

For the purposes of the panel discussion, we have invited Chris Bender, a senior engineer at Taylor Engineering, to participate. Chris Bender and Taylor Engineering have supported the NRC on several reviews of storm surge hazard assessment submittals over the years.

Moderator Question:

I'd like to start off with a question for the entire panel related to Bin Wang's presentation. Bin did a good job talking about all the different epistemic uncertainties, presenting the logic tree approach. One of the places where the logic tree approach has been used extensively is in probabilistic seismic hazard analysis. One of the other tools that's used in probabilistic seismic hazard analysis is the so-called SSHAC approach (the Senior Seismic Hazard Assessment Committee process), where essentially you try to represent in your analysis not just your individual judgment as an analyst, but the center body and range of the technically defensible data models and methods. One way of sketching that out is using the logic tree approach. But a lot of questions or issues remain. For example, how extensive does that logic tree have to be? Who decides on the weights? How do we decide on the weights? So, I would ask any one of the panelists who is familiar with the SSHAC process whether it has a role in something like storm surge hazard analysis?

Norberto Nadal-Caraballo:

I think SSHAC definitely needs to be part of the overall approach. We have seen that, just as discussed in the previous presentation, every path ends sometimes with very different results. So it is not just using one path as we typically do in USACE and FEMA studies (and sometimes there is justification to a single path approach). If you want to expand the methodologies and to innovate on some of the approaches, including an additional path, then we need to determine how to assign weights, or there has to be a consensus on how to assign either credibility or weights, some formal way to do that. I think that's clearly most important.

Question:

This question is for Chris Bender and follows up on Joe's approach of asking about SSHAC if you are developing a full range of scenarios. We heard from Arthur Taylor, who emphasized on P-SURGE as being real time. He puts in the time component because of tides and currents, but another perspective is evolution of the flooding. If the storm is approaching, which causes inundation, the wind fetch may increase dramatically because areas that were not inundated become inundated, especially for a slow-moving hurricane. How important is it to put this into some real-time perspective?

Chris Bender:

One thing that I think was brought up by all the different presentations today is that each study needs to first define its purpose. As Arthur Taylor mentioned, NWS has an hour to develop its estimates, given the latest advisory. Many decisions follow, related to model resolution, number of runs, and the goal of the NWS objective. Other analyses are looking at a probable maximum hazard for design application. Analysts are considering a completely different set of constraints in terms of how many model runs they are going to make, how long it can take, and the resolution that's needed. For the North Atlantic Coast Comprehensive Study (NACCS), USACE had to consider that the model grid went from Virginia all the way up to Maine. Hundreds of miles of coast then required a huge storm set (a thousand storms). One takeaway from all these talks, the work that we have done for the NRC, and other studies is that each study is unique.

When it comes to the real-time component, the individual storm simulation that is conducted in the NACCS study or in Bin Wang's study or in other NRC independent studies is a full, 5-day storm surge simulation for a tropical storm. You can obtain the individual time history of the surge, the duration of the surge, and how the waves are influenced based on the fetch increasing as areas are inundated. The state of the practice in modeling can get that time evolution. To be "real time," the models need to run quickly, based on fresh information such as the latest update on the on the winds, for the purposes of Arthur Taylor's studies.

It is clear that there are a lot of little decisions along the way that can have some major implications on the storm surge. It would be great to move towards a SSHAC approach so then it is not just Bin Wang's solution or GZA's solution, for example. If there was a consensus of experts, then there would be maybe more of a "community of practice" estimate. But the challenge I see is that each site and each area is going to have different decisions and values that are required. You would need to bring those experts together and have a set of decisions for each specific site. Also, sometimes the hazard level influences the amount of uncertainty. As was mentioned, for a 100-year record, you may have enough data to reduce certain aspects of the uncertainty. But then if you are looking at an annual exceedance probability level of 10^{-5}, there is a lot more uncertainty just because there is not enough storm history. I think the effort going into having a kind of national comprehensive SSHAC approach would need to involve determining how to divide up all the decisions that are necessary to create kind of that consensus.

Moderator Question:

With respect to Arthur Taylor's emphasis on real time, one of the things that we have observed over the years is that NWS uses SLOSH for forecasting, but it has also made the model available broadly. Consultants and other researchers can use the SLOSH model in ways other than forecasting. In fact, people have used SLOSH to perform many runs fast and then refine those with a higher resolution or higher fidelity model like ADCIRC. Sometimes they were not aware of some of the simplifications that are built into SLOSH to make it run fast. Could you speak to some of those simplifications, for people who are trying to use SLOSH for some of these other applications, like design calculations? What are some of the key simplifications that are built into SLOSH that someone using it should really be aware of and make sure that it's consistent with their application?

Arthur Taylor:

This is going to be a hard one to answer because I'm not entirely sure of all the different things others have done. One of the primary things is bottom stress. For example, the bottom stress in SLOSH is one value instead of a spatially varying one. We are starting to work on modifying that. There are assumptions made about how you define the grid and create the grid. But if someone is building their own grid, then they are going to introduce those types of errors. SLOSH deals with the first-order terms and does not go into the second-order differentials. That missing component would need to be taken into consideration when running with a higher fidelity model. The tides were more recently added. Historically, the model had only used a high-tide component. With regard to the issue of real time, I have been trying to determine, long term, whether it is better to use a database of runs and come up with a surface or whether there was a need for real-time runs. I think it comes down to the second-order interactions, the combinations of the tide and the surge. Linear addition is something that you could do without having real-time information, but to get the second-order interactions with a tide, you have to be concerned about exactly when you ran it. You can simulate that with enough runs at a spring tide, but that is something that needs to be strongly considered. The other aspects would be the initial water conditions that surround you. A storm like Hurricane Harvey, with a lot of rain, will have a lot of impact on the rivers. In addition, although SLOSH does not do this yet, if you start getting into the spatially varying bottom frictions, you have to worry about whether the land has been saturated already. That saturation caused by a very large rain event will have impacts. The different choices of models are mainly affected by identifying the problem you are trying to solve. In my case, I had MEOW and a MOM, which would be a first-order path through the logic tree. I came up with a maximum of all those answers rather than assigning a weight or uncertainty to it. That gave sort of an annual assessment, the worst case that you can plan for. That challenge is different than the challenge of initial real-time response. For a case scenario to determine where to place a power plant, you can just run the model at a high tide. But if you are trying to get more precise about how you want to respond to a particular event that is occurring right now, you need to have the real-time information. It depends on which problem you are dealing with. In the NPP realm, siting decisions can be done years in advance. When the storm is here, and you need to respond to it, you need to shut down the power plant and worry about whether to involve responders and whether you need to build a bridge to get to the power plant. Those are different problems.

Question:

With the notion of logic trees being an inevitable action to really get at all the layers of complexity in a PFHA, it seems to me that it also means that the use of surrogate models is going to become inevitably necessary just because of the number of simulations that would otherwise need to be run. What are the panel members' thoughts on the following question: There's everything that occurs after simulations and doesn't depend on your choice of simulation structure. But everything that comes before, like changes in drag terms or changes in tides, add in all sorts of layers of complexity. Do you envision there being much more complicated surrogate models constructed, using a much larger parameter space, or building multiple discrete ones with different model setups?

Norberto Nadal-Caraballo:

Right now, we are employing Gaussian process metamodels, and the short answer is that we take what comes out ADCIRC or other models, the weight models, as the right answer, or at least the best answer. I think there needs to be additional research, additional processes evaluating the different set of surrogate models. We also need to look at the different components and parameters in the methodological models, even different wind models that generate the wind and pressure fields. Hopefully, there will be new developments in terms of the metamodels or the sorts of models that can take into account those variations because that is something that is certainly lacking. I think we have made several improvements in terms of how to compute the probabilities of the storms, but we need better acknowledgment of the uncertainties arising from the hydrodynamic models and better validation, in many cases. We also need better ways to propagate that uncertainty and integrate the uncertainty into the logic tree approach. A lot of work is still needed in those areas.

Question (Bin Wang):

I just wanted to point out that this session is called coastal flooding, not storm surge flooding. I understand that my talk and most of the presentations that we see in this session are about storm surge. I just wanted to ask the other panelists for your thoughts on how we carry the logic tree process forward. My logic tree basically ended at the storm still water level. However, coastal flooding usually has other components, such as wave runup, loading due to wave actions, and sometimes even overtopping or erosion if it's a beach or dune. Do you think that the Gaussian process modeling, maybe the stochastic part of the method, could actually carry forward from the storm surge into the so-called combined effect flooding world?

Chris Bender:

I do agree. I see the opportunity for an extension of the logic tree approach, just adding more boxes at the end because now you do have different estimates of the still water level. Then, similarly, to the branches before that, there are different options for runup equations and runup coefficients and uncertainty with those and overtopping equations and methods and approaches. If you have a suite of water levels for which you've defined the mean and range of values, then that can provide input into moving to the right with additional boxes. For example, we might have three different runup equations. Similar to the storm surge calculation, it depends on how complicated you want to get. You can do runup with a Boussinesq model or you can do runup with a simple Excel toolkit. There would be different options for what you need. You could end up with a range of runups and associated probabilities. Once again, decisions are required for how much you believe each one of those boxes, but I do see the potential for that.

Follow-up/Elaboration (Bin Wang):

Thanks, Chris. We were aware that we could do additional paths or build additional small logic trees after we ended up with that gigantic storm surge logic tree. However, then we realized that one still water elevation is often associated with numerous storm tracks. The combined effects are very sensitive to these storm tracks. For example, a smaller, slow-moving storm may produce very different wave characteristics versus a large, slower moving storm (or a faster moving storm). We found that the duration and the wave characteristics often depend on storm tracks, not just the still water elevation that we just defined. So that becomes a challenge.

Arthur Taylor:

With P-SURGE, we are starting to introduce waves. Initially, waves had been included by using the still water elevation and just estimating the waves on top of that. The Great Lakes wave model is a second-generation wave model, which is faster than the normal third-generation wave models. We are coupling SLOSH with that second-generation wave model, which will allow us to do an ensemble of SLOSH and wave model runs with tides and coupled surge, wave, and tide simulations that we would then run through an ensemble and each would have a probability associated with it. ADCIRC has been taking a similar approach with the SWAN wave model (ADCIRC-SWAN). The challenge there has been that the sample set is not very large, posing sensitivity problems with regard to direction (not having enough samples). Maybe it would help to use the second-generation wave model coupled with SLOSH, once we finish it. Or you can do a second-generation wave model coupled with ADCIRC. We are doing waves because we want to move to Puerto Rico and Hawaii, which are wave-dominated areas and so we need to have a probabilistic surge and wave model.

Victor Gonzalez:

I want to circle back to the issue of runup and overtopping, in terms of the complexity. The logic tree for the family of hazard curves in our presentation had already been culled. Some branches were already taken out. It was a reduced number of combinations, and it still resulted in a family of 1,261 hazard curves. Each additional layer that we add after that, in terms of runup or overtopping, gets multiplied by that number. More research is needed to really hone in on what is really driving variation to get to a simplified approach.

Question (from Phone Line):

Norberto Nadal-Caraballo made a good point about correlations being different if you bin your data rather than grouping them all together. However, in his plots, some of the correlations were based on very small number of points. How do you keep that balance?

Norberto Nadal-Caraballo:

In the plots shown, we just wanted to illustrate an example. We were using data from the (International Best Track Archive for Climate Stewardship (IBTrACS) database. The advantage of that dataset is that it has estimates of R_{max} (radius to maximum winds), but it is very limited and goes back only to 1988 or 1990. Once the partitioning was done, we had approximately 40 values for the high-intensity bin in those plots. We just wanted to illustrate the effect of having different correlations based on different bins of intensity. There are other datasets that we can explore, for example, Applied Research Associates (ARA) or Ocean Wind, Inc. (OWI) hurricane wind speed maps. Some other estimates of R_{max} have been documented in the literature. For implementing these, we need to explore additional sets that provide a more robust estimate of the correlation between the parameters, specifically the correlation between R_{max} and the other parameters.

Moderator Question:

I have two questions for Michael Salisbury. The first is just a scope question. In the report that you talked about in your presentation, did you look at methods for total water level analysis, runup, and things like that?

The second question is, in your report, do you focus strictly on tropical cyclones? Or did you also look at methods for extratropical cyclone storm surge analysis?

Michael Salisbury:

With respect to the first question, we looked just at storm surge. We did make mention of additional steps that would be required, particularly for possible design applications such as calculating wave runup and converting to total water level. We have done that for a site using an extension of the reported methodology, but the report mentioned in our talk focused just on the storm surge swell values.

With respect to the second question, we focused just on tropical cyclones. The parameterized storm event, using combinations of discretized storm parameters, is a tropical storm system. Extratropical storms are not defined by parameters like that.

Moderator Question:

One quick question for Norberto Nadal-Caraballo or Victor Gonzalez: Do you think that the copula method might be useful for combining extratropicals and tropicals?

Norberto Nadal-Caraballo:

It could probably be a solution. Typically, we assume that there is zero correlation between tropical and extratropical events. But the copula method can be used to incorporate the effects of multiple events occurring at the same time. We know it is unlikely that it happens, but if we can establish or estimate the correlation, then we can use a joint probability model to account for it, similar to accounting for the joint probability between storm surge and river flow due to the occurrence of tropical cyclone rainfall.

Question:

As you move north in the Gulf of Mexico, you can use all the data from all the hurricanes because there seems to be some regional commonality. However, as you go north up the Atlantic coast, if you have a shortage of data for both tropical and extratropical storms, would it be wrong to take information from, for example, North Carolina and extended to New Jersey or up into New England? If you believe that there is climatic variability or climate change, would it be wrong to take data from that area and project it north?

Arthur Taylor:

My take is that it would be problematic. The map that Bin Wang showed (which was done by the National Hurricane Center) basically combined all the MEOWs and MOMs and stopped showing Category 5 storms above a certain latitude. This is because, climatologically, it is highly unlikely that a Category 5 storm will occur that far north. Perhaps with climate change, that will change. But currently, that would be problematic. The characteristics of storms that are in the North Carolina area are not going to be the same characteristics of storms in Maine. Storms in Maine will be faster and bigger. They will not be as tight because they have been hit either by landfall or various interactions with the atmosphere. However, North Carolina will experience nice, tight storms coming right off Puerto Rico. There will be completely different characteristics of the storms.

Chris Bender:

The sea surface temperature provides the energy for those tropical systems. If there was a climate model that showed increases in sea surface temperature up in the New England area in the future, whether that's 50 years, 100 years, or 150 years in the future, that increase in temperature could allow for changes to the amount of energy that those tropical systems can receive from the water. Other meteorological aspects could also have an impact, such as winds and the Gulf Stream. Future sea level change estimates have a huge uncertainty band. I think the climate change effect on future storminess, storm intensity, and storm frequency has an even broader uncertainty range. There is a lot of uncertainty associated with that.

Arthur Taylor:

Additionally, Maine has larger tide ranges than North Carolina. The sea surface temperature would impact how well you would be able to get energy into the storm. I think the tide would also have an impact on how that energy gets transferred from the surface. In a hypothetical situation where you had higher temperatures in Maine, you would still have problems getting that energy because of the churning of the tide.

Victor Gonzalez:

For the NACCS, the North Atlantic was divided into three regions specifically to account for the variation in parameters as you go north. That was appropriate for NACCS, as we had enough data to produce good hazard curves and quantify the variation. But it would matter, and we did not have enough data, if we partitioned the hurricanes into low, high, and extreme intensity (instead of low and high intensity). Then, as you go north, you stop getting hurricanes that belong to that extreme intensity population. In that case, we would rather scale back to just using low and high intensity rather than try to transport some additional data from farther south.

Question (Bin Wang):

To account for spatial variability in the storm recurrence rate, USACE used a Gaussian kernel to weight different tracks for each specific location differently. Do you think there is also a systematic way to weight an intensity parameter spatially rather than dividing the data source into three distinctive regions? In other words, rather than treat the whole dataset as one cohesive set, could we weight them using different kernel functions?

Norberto Nadal-Caraballo:

We are currently using a similar approach but based on a Gaussian kernel function. To account for the limited data at some of the locations, we are, at least as a statistical correction, expanding the radius of the capture zone to add storms. We compute statistics based on that sampling set, but we do corrections based on the distance from our location. For example, if we are doing a study in New York, we can expand the radius of where we are capturing the storms. But by using the Gaussian kernel function, we can adjust the statistics. We can adjust, for example, the mean based on the Gaussian kernel. It's a way of carrying that same approach beyond the simple calculation of the storm recurrence rate and incorporating some of that knowledge into the computation of the marginal distributions.

4.3.3 Day 1: Session 1C - Precipitation

Session Chair: Elena Yegorova, NRC/RES/DRA/FXHAB

4.3.3.1 KEYNOTE: Satellite Precipitation Estimates, GPM, and Extremes.

George J. Huffman*, NASA/GSFC (Session 1C-1; ADAMS Accession No. ML19156A456)

4.3.3.1.1 Abstract

The satellite precipitation retrievals considered “high quality” come from passive microwave sensors, and they have been available in sufficient quantity to construct fairly high-resolution time sequences of maps for about 20 years. The resulting publicly available, quasi-global, long-term datasets are listed in the tables at http://www.isac.cnr.it/~ipwg/data/datasets.html. In particular, the GPM mission, a joint project of the National Aeronautics and Space Administration (NASA) and the Japanese Aerospace Exploration Agency, is working to create a long-term (1998–present) data record that is relatively homogeneous across the many individual precipitation-related satellites that have flown during that time. From the U.S. Science Team, the Integrated Multi-satellitE Retrievals for GPM (IMERG) algorithm intercompares and merges these satellite data together with other inputs to create a “best” map of global precipitation every half hour with a resolution of 0.1°x 0.1 of latitude/longitude. IMERG processing back to June 2000 should take place in the first 4 months of 2019. The ongoing IMERG processing occurs three times to serve different needs: an Early Run 4 hours after observation time (rapid analysis of flood, landslide, and other high-impact events), a Late Run 14 hours after (a better estimate for crop, drought, and water resource analysis), and a Final Run 3.5 months later (the research-grade product that incorporates the most data, including monthly precipitation gauge information).

One key issue in defining extreme precipitation events is the strong interdecadal variability in “extreme” for any reasonable index of the term (Fu et al. 2010).[9] The intermittent occurrence and non-Gaussian statistics that characterize precipitation make the analysis much more challenging than for temperature. Nonetheless, a recent study (Demirdjian et al. 2018)[10] demonstrates reasonable skill at computing average recurrence interval (ARI) maps from 15 years of a predecessor of IMERG (the Tropical Rainfall Measuring Mission (TRMM) Multi-satellite Precipitation Analysis, or TMPA) that are comparable to ARI (up to about 20 years) computed with 65 years of gauge data over the continental United States. The advantage of the satellite datasets is that they cover much of the globe, providing information that is not otherwise obtainable from surface data in remote, developing, and oceanic regions.

[9] Fu, G., N.R. Viney, S.P. Charles, J. Liu, 2010, “Long-Term Temporal Variation of Extreme Rainfall Events in Australia: 1910–2006.” *J. Hydrometeor.*, 11, 950–965. doi:10.1175/2010JHM1204.1.

[10] Demirdjian, L., Y. Zhou, G.J. Huffman, 2018, “Statistical Modeling of Extreme Precipitation with TRMM Data.” *J. Appl. Meteor. Climatol.*, 57(1), 15-30. doi:10.1175/JAMC-D-17-0023.1.

4.3.3.1.2 Presentation

Satellite Precipitation Estimates, GPM, and Extremes

George J. Huffman
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1. Introduction
2. From Data to Estimates
3. IMERG
4. Schedule
5. Application
6. Concluding Remarks

1. INTRODUCTION – Rain is easy to measure, hard to analyze

The physical process is hard to represent:

- rain is generated on the microscale
- the decorrelation distance/time is short
- point values only represent a small area & snapshots only represent a short time
- a finite number of samples causes problems

Image courtesy of the University Corporation for Atmospheric Research 2

1. INTRODUCTION – Instrumentation strong points

Knowledge of precipitation is key to a wide range of users

Data sources have recognized strengths:

- microwave imagers — good instantaneous results
- geo-IR — good sampling
- satellite soundings — some information in cold-surface conditions
- precipitation gauge — near-zero bias
- model — complete coverage and "physics"

Different data sources are best in different regions

All have bigger errors in

- mountains
- snowy/icy regions

3

1. INTRODUCTION – But ...

Instruments have characteristic errors:

- raingauge
  - wind losses
  - splashing
  - evaporation
  - side-wetting
  - interpolation
- radar
  - raindrop population changes
  - anomalous propagation
  - beam blockage by surface features
  - sidelobes
- satellite
  - physical retrieval errors
  - beam-filling errors
  - time-sampling
- numerical prediction models
  - computational approximations
  - initialization errors
  - errors in other parts of the computation

Sensor-specific strengths and limitations

	infrared	microwave
latency	15-60 min	3-4 hr
footprint	4-8 km	5-30+ km
interval	15-30 min (up to 3 hr)	12-24 hr (~3 hr)
"physics"	cloud top weak	hydrometeors strong

- additional PMW issues over land include
  - scattering channels only
  - issues with orographic precip
  - estimates not currently useful over snow and sea ice

4

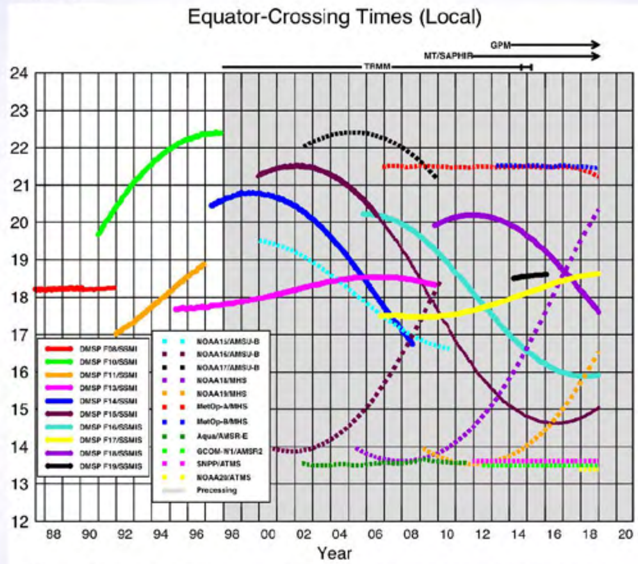
2. FROM DATA TO ESTIMATES – The constellation (1/2)

We want 3-hourly observations, globally

- sampling the diurnal cycle
- morphed microwave loses skill outside ±90 min

The current international constellation includes:

- 5 polar-orbit passive microwave imagers
  - 3 SSMIS, AMSR-2, GMI
- 6 polar-orbit passive microwave sounders
  - 3 MHS, 2 ATMS, SAPHIR
- input **precip** estimates
  - GPROF (LEO PMW) & PRPS (SAPHIR)
  - PERSIANN-CCS (GEO IR)
  - 2BCMB (combined PMW-radar)
  - GPCP SG (monthly satellite-gauge)

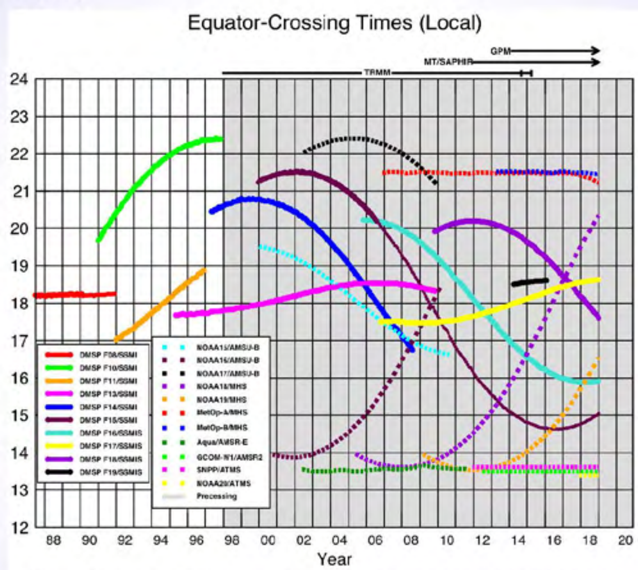


Ascending passes (F08 descending); satellites depicted above graph process throughout the day.
Image by Eric Nelkin (SSAI), 30 January 2019, NASA/Goddard Space Flight Center, Greenbelt, MD.

2. FROM DATA TO ESTIMATES – The constellation (2/2)

The constellation is evolving

- legacy satellites are allowed to drift
  - exact coverage is a complicated function of time
  - duplicate orbits aren't very useful for getting 3-hourly observations
- launch manifests tend to show fewer satellites in the next decade



Ascending passes (F08 descending); satellites depicted above graph process throughout the day.
Image by Eric Nelkin (SSAI), 30 January 2019, NASA/Goddard Space Flight Center, Greenbelt, MD.

2. FROM DATA TO ESTIMATES – Single-satellite estimates

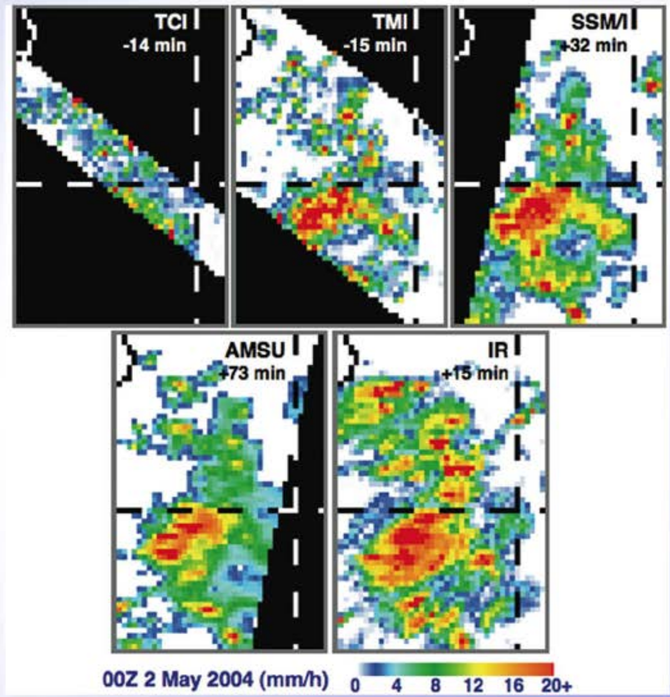
Nearly coincident views by 5 sensors southeast of Sri Lanka

The offset times from 00Z are below the "sensor" name

The estimates are related, but differ due to

- time of observation
- resolution
- sensor/algorithm limitations

Combination schemes try to work with all of these data to create a uniformly gridded product



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2. FROM DATA TO ESTIMATES – There are numerous choices out in public

The International Precipitation Working Group (IPWG) web site

- http://www.isac.cnr.it/~ipwg/
- a concerted effort in the next biennium to beef up user-oriented information
  - "fitness for use"
  - http://www.isac.cnr.it/~ipwg/data.html
- tables listing publicly available, long-term, quasi-global precipitation data sets
  - http://www.isac.cnr.it/~ipwg/data/datasets.html
  - combinations with gauge data
  - satellite-only combinations
  - single-satellite
  - gauge analysis

And I have a dog in this show …

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3. IMERG – Quick description (1/2)

IMERG is a unified U.S. algorithm based on

- Kalman Filter CMORPH – NOAA/CPC
- PERSIANN CCS – U.C. Irvine
- TMPA – GSFC
- PPS (GSFC) processing environment

IMERG is a single integrated code system for near-real and post-real time

- multiple runs for different user requirements for latency and accuracy
  - "Early" – 4 hr (flash flooding)
  - "Late" – 14 hr (crop forecasting)
  - "Final" – 3 months (research)
- time intervals are half-hourly and monthly (Final only)
- 0.1° global CED grid
  - morphed precip, 60° N-S in V05, 90° N-S in V06
  - IR covers 60° N-S

	Half-hourly data file (Early, Late, Final)
1	*[multi-sat.] precipitationCal*
2	[multi-sat.] precipitationUncal
3	*[multi-sat. precip] randomError*
4	[PMW] HQprecipitation
5	[PMW] HQprecipSource [identifier]
6	[PMW] HQobservationTime
7	IRprecipitation
8	IRkalmanFilterWeight
9	*[phase] probabilityLiquidPrecipitation*
10	*precipitationQualityIndex*
	Monthly data file (Final)
1	*[sat.-gauge] precipitation*
2	*[sat.-gauge precip] randomError*
3	GaugeRelativeWeighting
4	*probabilityLiquidPrecipitation [phase]*
5	*precipitationQualityIndex*

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3. IMERG – Quick description (2/2)

IMERG is adjusted to GPCP monthly climatology zonally to achieve a bias profile that we consider reasonable

- Over Versions 04 to 06 the GPM core products have similar zonal profiles (by design)
  - these profiles are systematically low in the extratropical oceans compared to
    - GPCP monthly Satellite-Gauge product is a community standard climate product
    - Behrangi Multi-satellite CloudSat, TRMM, Aqua (MCTA) product
- over land this provides a first cut at the adjustment to gauges that the final calibration in IMERG enforces
- similar bias concerns apply during TRMM era

	Half-hourly data file (Early, Late, Final)
1	*[multi-sat.] precipitationCal*
2	[multi-sat.] precipitationUncal
3	*[multi-sat. precip] randomError*
4	[PMW] HQprecipitation
5	[PMW] HQprecipSource [identifier]
6	[PMW] HQobservationTime
7	IRprecipitation
8	IRkalmanFilterWeight
9	*[phase] probabilityLiquidPrecipitation*
10	*precipitationQualityIndex*
	Monthly data file (Final)
1	*[sat.-gauge] precipitation*
2	*[sat.-gauge precip] randomError*
3	GaugeRelativeWeighting
4	*probabilityLiquidPrecipitation [phase]*
5	*precipitationQualityIndex*

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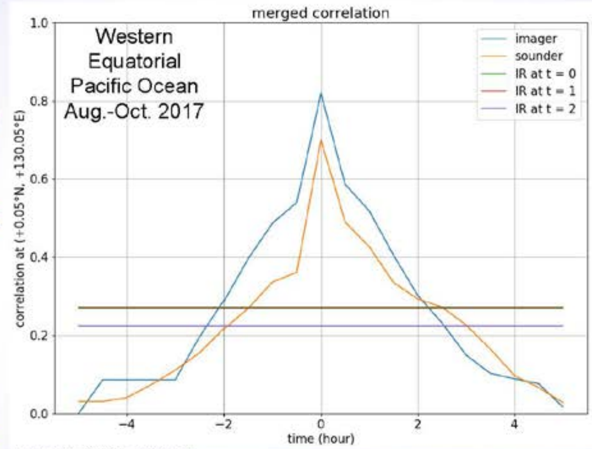
3. IMERG – Key points in morphing (1/2)

Following the CMORPH approach

- for a given time offset from a microwave overpass
- compute the (smoothed) average correlation between
  - morphed microwave overpasses and microwave overpasses at that time offset, and
  - IR precip estimates and microwave overpasses at that time offset and IR at 1 and 2 half hours after that time offset
  - for conical-scan (imager) and cross-track-scan (sounder) instruments separately
  - by season and regional blocks
- the microwave correlations drop below the IR correlation within a few hours (2 hours in the Western Equatorial Pacific)



D.Bolvin (SSAI; GSFC)

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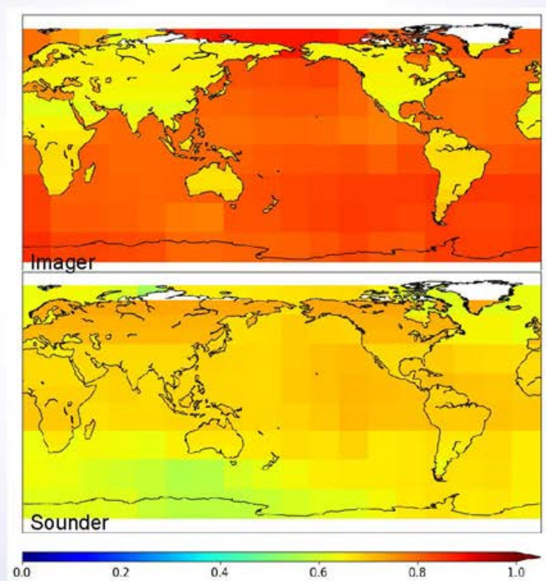
3. IMERG – Key points in morphing (2/2)

Following the CMORPH approach

- for a given time offset from a microwave overpass
- compute the (smoothed) average correlation between
  - morphed microwave overpasses and microwave overpasses at that time offset, and
  - IR precip estimates and microwave overpasses at that time offset and IR at 1 and 2 half hours after that time offset
  - for conical-scan (imager) and cross-track-scan (sounder) instruments separately
  - by season and regional blocks
- the microwave correlations drop below the IR correlation within a few hours (2 hours in the Western Equatorial Pacific)
- at t=0 (no offset), imagers are better over oceans, sounders are better or competitive over land



L2 correlation at t=0 Aug.-Oct. 2017

D.Bolvin (SSAI; GSFC)

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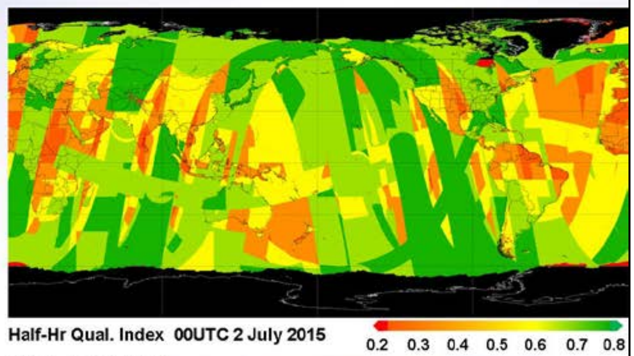
3. IMERG – Quality Index (1/2)

Half-hourly QI (revised)

- approx. Kalman Filter correlation
  - based on
    - times to 2 nearest PMWs (only 1 for Early)
    - IR at time (when used)

$$QI_h = tanh\left(\sqrt{\sum arctanh^2(r_i)}\right)$$

  - where *r* is correlation, and the *i*'s are for forward propagation, backward propagation, and IR
  - approximate *r* when a PMW overpass is used
- revised to 0.1° grid (0.25° in V05)
- thin strips due to inter-swath gaps
- blocks due to regional variations
- snow/ice masking will drop out microwave values



Half-Hr Qual. Index 00UTC 2 July 2015

D.Bolvin (SSAI; GSFC)

The goal is a simple "stoplight" index

- ranges of QI are considered to be:
  - > 0.6 good
  - 0.4–0.6 use with caution
  - < 0.4 questionable
- is this a useful parameter?

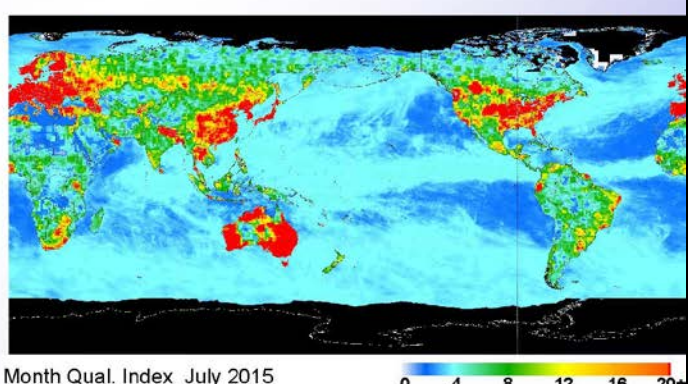
3. IMERG – Quality Index (2/2)

Monthly QI (unchanged from V05)

- Equivalent Gauge (Huffman et al. 1997) in gauges / 2.5°x2.5°

$$QI_m = (S + r) * H * (1 + 10 * r^2)/e^2$$

  - where r is precip rate, e is random error, and H and S are source-specific error constants
- invert random error equation
- largely tames the non-linearity in random error due to rain amount
- some residual issues at high values
- doesn't account for bias
- $QI_m \geq 4$ is "good"
- $2 \leq QI_m < 4$ is "use with caution"
- $QI_m < 2$ is "questionable"



Month Qual. Index July 2015

D.Bolvin (SSAI; GSFC)

4. SCHEDULE – Version 06 in the GPM era

Early March 2019: began Version 06 IMERG Retrospective Processing

- the GPM era was launched first, Final Run first
  done
- the TRMM era Final Run reprocessing is underway
  underway
  - complete data will take about a month
  - 4 km merged global IR data files continue to be delayed for January 1998-January 2000
    - the run will build up the requisite 3 months of calibration data starting from February 2000
    - the first month of data will be for June 2000
    - the initial 29 months of data will be incorporated when feasible
- Early and Late Run Retrospective Processing uses Final intermediate files, so they come after Final
  - Final is always ~3.5 months behind, so the Early and Late retrospective processing have to wait on Final Initial Processing to fill in the last 3 months before May 2019 (i.e., until mid-August)
- Early and Late Run Initial Processing will start ~1 May
  coming

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4. SCHEDULE – Development work for V07

Multi-satellite issues

- improve error estimation
  - field seems to be headed toward posting quantile values
- develop additional data sets based on observation-model combinations
- work toward a cloud system development component in the morphing system

General precipitation algorithmic issues

- introduce alternative/additional satellites at high latitudes (TOVS, AIRS, AVHRR, etc.)
- evaluate ancillary data sources and algorithm for Prob. of Liq. Precip. Phase
- work toward using PMW retrievals over snow/ice
- work toward improved wind-loss correction to gauge data

Version 07 release should be in about 2 years (late 2021?)

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4. SCHEDULE – Version 06 summary

The product structure remains the same

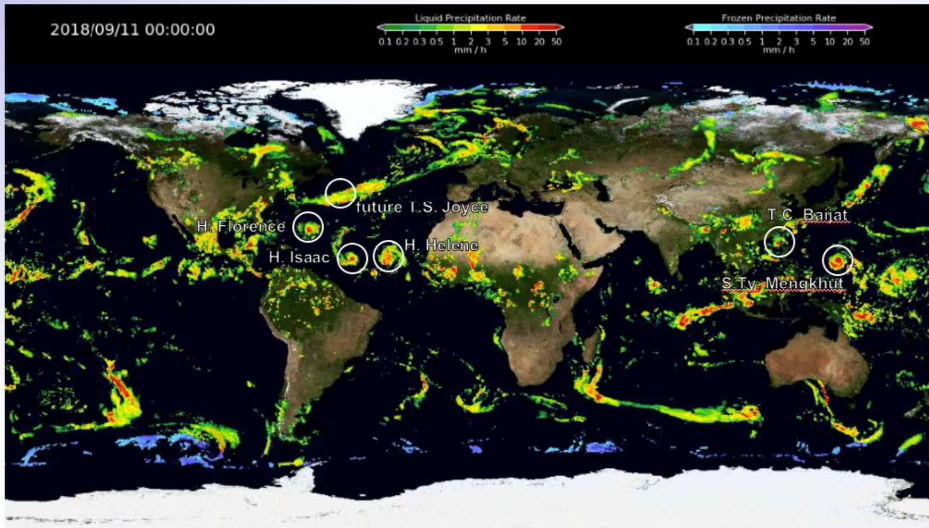
- Early, Late, Final
- 0.1°x0.1° half-hourly (and monthly in Final)

New source for morphing vectors

Higher-latitude coverage

Extension back to 2000 (and eventually 1998)

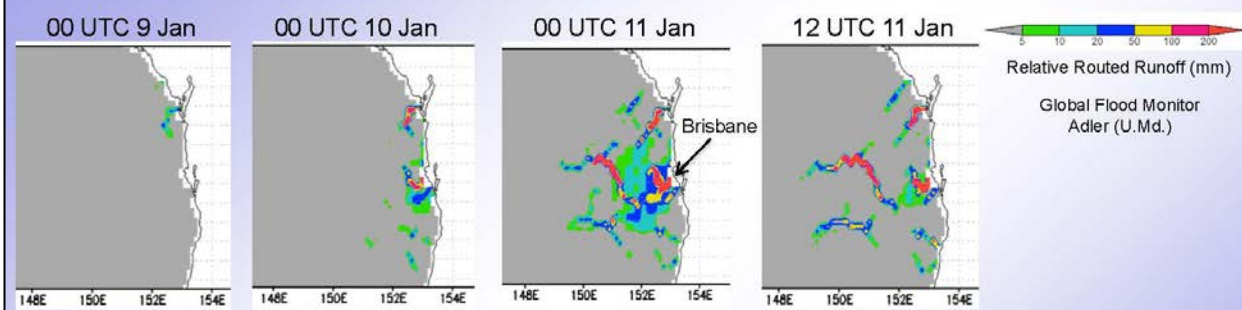
Improved Quality Index

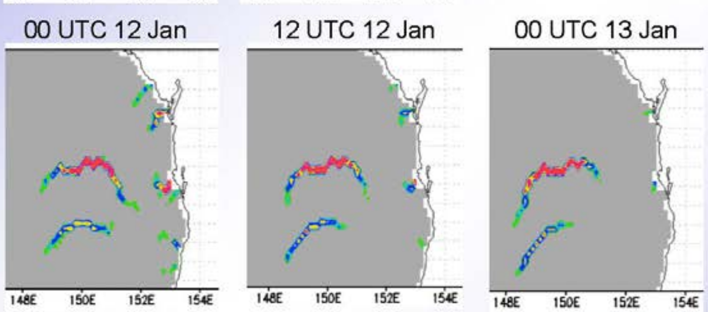


see 1C-1-Huffman_NASA_SatPrecipslides_Video.mp4

J. Tan (USRA; GSFC)

5. APPLICATION – Estimated flood evolution for 9-13 January 2011, Australia



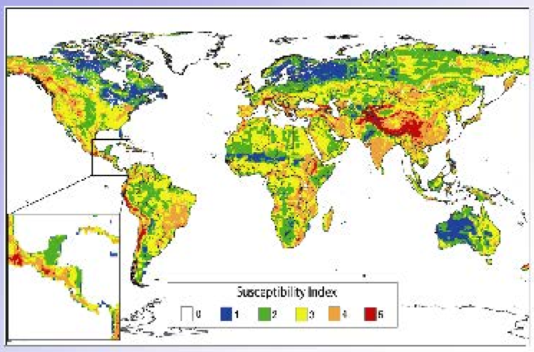


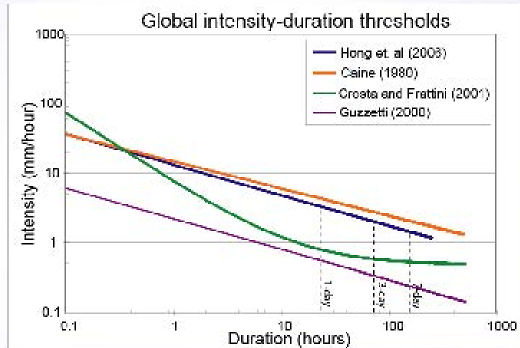
Individual events happen quickly; heavy localized rain events captured by satellite data

Flood models estimate flood evolution

- Brisbane area floods peak on 11 Jan. then subside
- To the west another flood area develops from the same rain system
- high water levels move downstream into relatively unpopulated areas

5. APPLICATION – Global landslide occurrence algorithm





Surface Data:

- topographic variables
- land cover
- soil type and texture
- drainage density

Rainfall Data:

- TMPA
- 0.25°, 3-hourly resolution

Circles enclose small areas of estimated landslide locations

D. Kirschbaum (GSFC)

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5. APPLICATION – Extreme precipitation

Fu et al. (2010) examined long-term behavior of "extreme" precip in Australian gauge data

- computed 7 measures of "extreme"
- all measures roughly tracked together
- all measures of "extreme" showed strong multi-time-scale variability
    - a strong interdecadal component is present over the entire record
- provides a strong cautionary statement about reliability of fitting to a few decades of data

Adler et al. (2010) show only modest trends in global mean precip over 1979-2014

- but regional trends are substantially larger
- the global change seems to mostly manifest as wetter/drier in wet/dry areas

Adler, R.F., G. Gu, M. Sapiano, J.-J. Wang, G.J. Huffman, 2017: Global Precipitation: Means, Variations and Trends during the Satellite Era (1979-2014). *Surv. Geophys.*, 21 pp. *doi:10.1007/s10712-017-9416-4*

Fu, G., N.R. Viney, S.P. Charles, J. Liu, 2010: Long-Term Temporal Variation of Extreme Rainfall Events in Australia: 1910-2006. *J. Hydrometeor.*, **11**, 950-965. *doi:10.1175/2010JHM1204.1*

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5. **APPLICATION –** Estimate Average Recurrence Interval for precipitation (1/2)

Tropical Rainfall Measuring Mission (TRMM) Multi-satellite Precipitation Analysis (TMPA) dataset

- predecessor to IMERG
- 15 years, 50ºN-S

Approach builds on a previous avg. recurrence study

- domain partitioned into ~28,000 non-overlapping clusters using recursive k-means clustering
- peak-over-threshold classification as extreme if gridbox day value exceeds a (regional, seasonally varying) 99% threshold
- only the maximum day's value is retained in a run of over-threshold days
- analysis is a generalized extreme value (GEV) fitted with maximum likelihood estimation (MLE)

Demirdjian, L., Y. Zhou, G.J. Huffman, 2018: Statistical Modeling of Extreme Precipitation with TRMM Data. *J. Appl. Meteor. Climatol.*, **57**, 15-30. *doi:10.1175/JAMC-D-17-0023.1*

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5. **APPLICATION –** Estimate Average Recurrence Interval for precipitation (2/2)

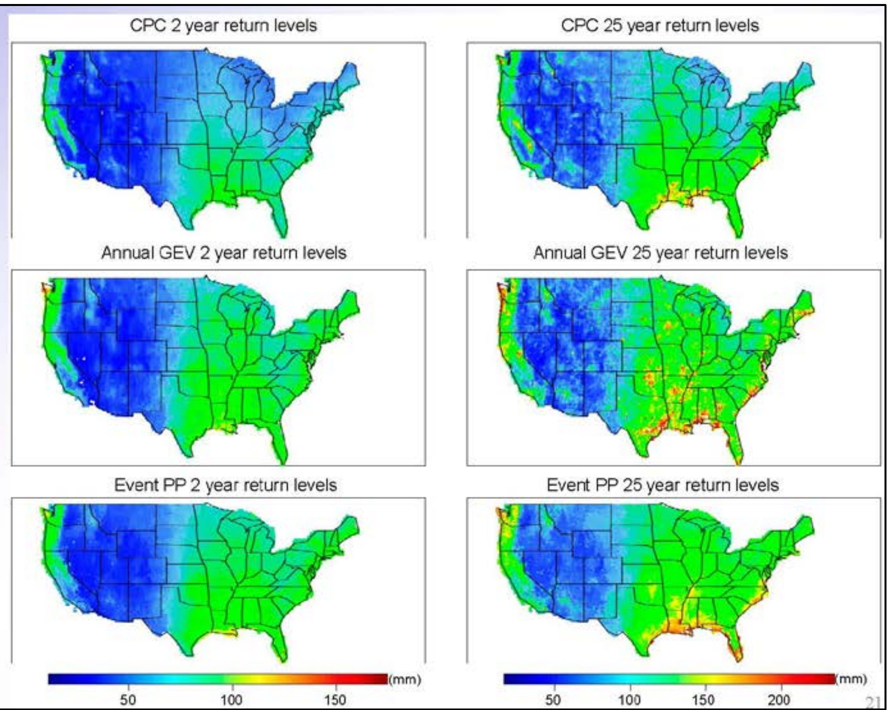
Compare Event PP to

- GEV of annual maximum data for 65 years of CPC gauge
- previous GEV using annual maximum data for 14 years of TMPA

Satellite schemes match each other for short interval

- and generally resemble CPC
- systematically high to the north

Event PP is closer to CPC at 25 years



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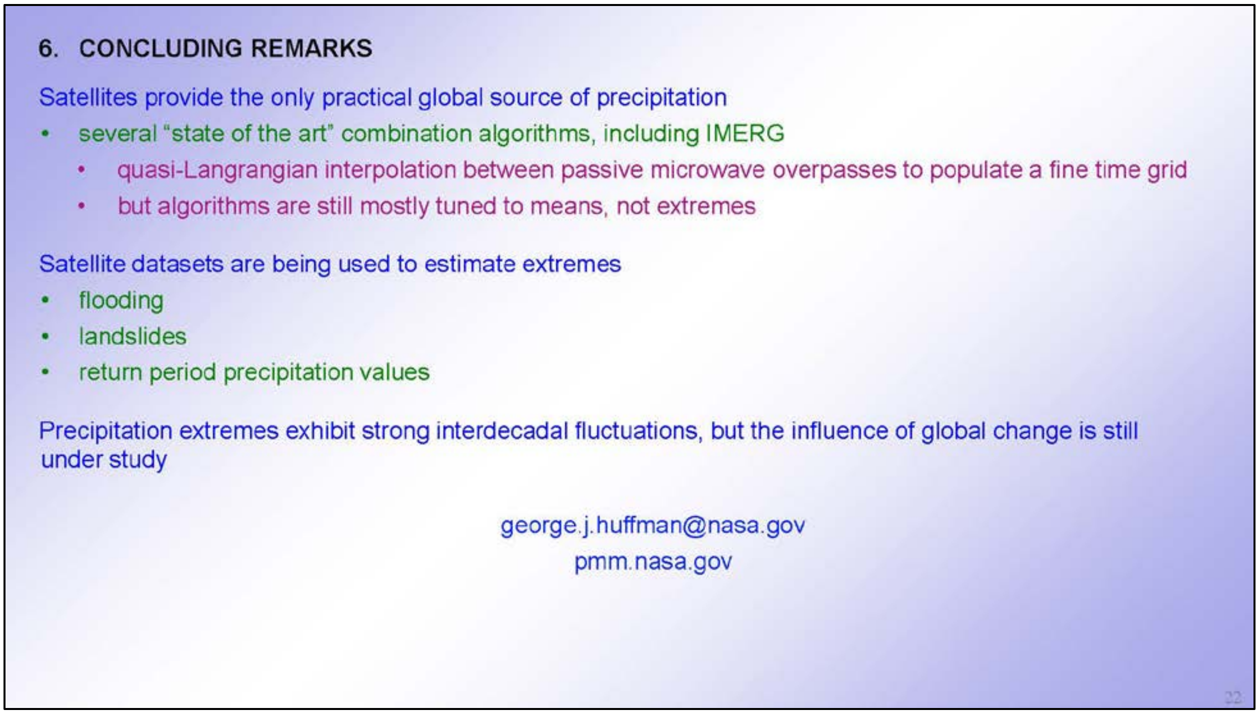


4.3.3.1.3 Questions and Answers

Question:

You mentioned that you have subhourly data and then monthly data. When you refer to monthly data, do you mean monthly maximum intensity, or do you mean the monthly means—a total depth?

Answer:

We add up the processing that we do for half-hourly satellite estimates for the entire calendar month, then we do a combination of the monthly satellite with the monthly gauge. We think of that as being the best estimate of the month. Then we basically just aggregate that into the half hourly values as just a ratio. So, the monthly is the average for the calendar month and is used in the final product; it is used to adjust every half hour, so they approximately add up to the monthly number.

Question:

How does the Climate Prediction Center (CPC) Morphing Technique (CMORPH) work? Are you just advecting the field based upon some other dataset that you have access to?

Answer:

By chance, the IMERG uses CMORPH technology, so I know how it works together. The original CMORPH simply took the overpass and advected it along and then took the next overpass and advected it backwards in just a linear average from one time to the next following; I call it Lagrangian time interpolation. Since then, it has become more complicated, something Ping-Ping Shi calls a Kalman filter, where you have the backward advected and the forward advected and then you have the infrared. Each has a correlation structure. You conduct an optimal interpolation among the three, but you do not use the infrared if you are within a half hour of overpass time. It is no longer strictly a Lagrangian time interpolation because now there is a background infrared field that is keeping the correlations up some. In the original scheme, with just backward and forward, if you are 10 hours apart, you have 5 hours of interpolation one way and 5 hours of interpolation the other way. Using the infrared keeps you closer to reality. A geo-spatial map uses only a forward morphing. In my case, the early run is a forward only because we do not have time to get the next overpass into a backward. But all the rest are our full common filter.

Question:

What is the spatial resolution for the pixel size or grid shell size?

Answer:

The grid cells are a 10th of a degree.

4.3.3.2 Hurricane Harvey Highlights: Need to Assess the Adequacy of Probable Maximum Precipitation Estimation Methods. Shih-Chieh Kao, Scott T. DeNeale and David B. Watson, ORNL (Session 1C-2)

This presentation was based on Kao, S.-C., S.T. DeNeale, and D.B. Watson (2019), "Hurricane Harvey Highlights: Need to Assess the Adequacy of Probable Maximum **Error! Bookmark not defined.**Estimation Methods," *J. Hydrol. Eng*., 24(4), 05019005, doi:10.1061/(ASCE)HE.1943-5584.0001768.

4.3.3.2.1 Questions and Answers

Question:

Thank you for your presentation. With regard to the slide with the trend as a perceptible water, I think that period of record is quite short because, as the previous speaker mentioned, there was the issue of multidecadal variability or persistence. This has a strong role, I think, to play in that. I look at long-term precipitation records on the West Coast, for example, and I see exactly that same trend. But if I back it up 50 years to 1900–1950, I see the exact opposite. You have basically relatively high rainfall in the late 1900s; midcentury, relatively low, now relatively high again. The question is, was this just a one-time situation? If you look at the paleo records, you can see that we have had that periodic signal change—from wet to dry, wet to dry, wet to dry—over and over again for a thousand years. The periods tend to be random; there is no significant signal in the data. It is suggested that our climate, certainly regionally, remains in a dry regime for a long period of time, multiple decades, and remains in a wet period for a long period of time. When looking at the model performance, I think that the global climate models (GCMs) do not handle that multidecadal persistence very well yet. I am reluctant to rely too much on trends that come out of modeling efforts, in particular, to make long-term extrapolations.

Answer:

Thank you for your good comment. But first, I need to clarify that so far, in these two analyses, none of them is related to GCM. One is purely based on observation, and the other is reanalysis data. This model has a basic calculation, but we all know reanalysis and how we usually use that as a proxy.

Follow-up Comment:

That still gets to my point about the timeframe. Your timeframe of 60 years is still relatively short, when you look at the multidecadal persistent signal that seems to be in our climate signal.

Answer:

I agree with that. That actually brings up two questions, assuming that we do believe that the data are not over a long enough period, that there is some uncertainty about your calculation of the value. As a civil engineer, when we have something that we believe is more uncertain, we ensure the risk or ensure the safety and we will use a safety factor. We will use different ways to account for that. That's basically one aspect: if we do not have good data, what should we do? Second, the current method does not actually account for any of the trends. If right now the methods actually have a way to remove the trend and incorporate analysis and try to bring a better precipitable water (PW) estimate, that's fine. But right now, if we have data input to our analysis where there is a trend, that is against the prerequisite we have for statistical analysis. It may be independent and identically distributed, but there is a trend here. So, what should we do?

4.3.3.3 Reanalysis Datasets in Hydrologic Hazards Analysis. Jason Caldwell, USACE, Galveston District. Presented by John England*, USACE/RMC (Session 1C-3; ADAMS Accession No. ML19156A458)

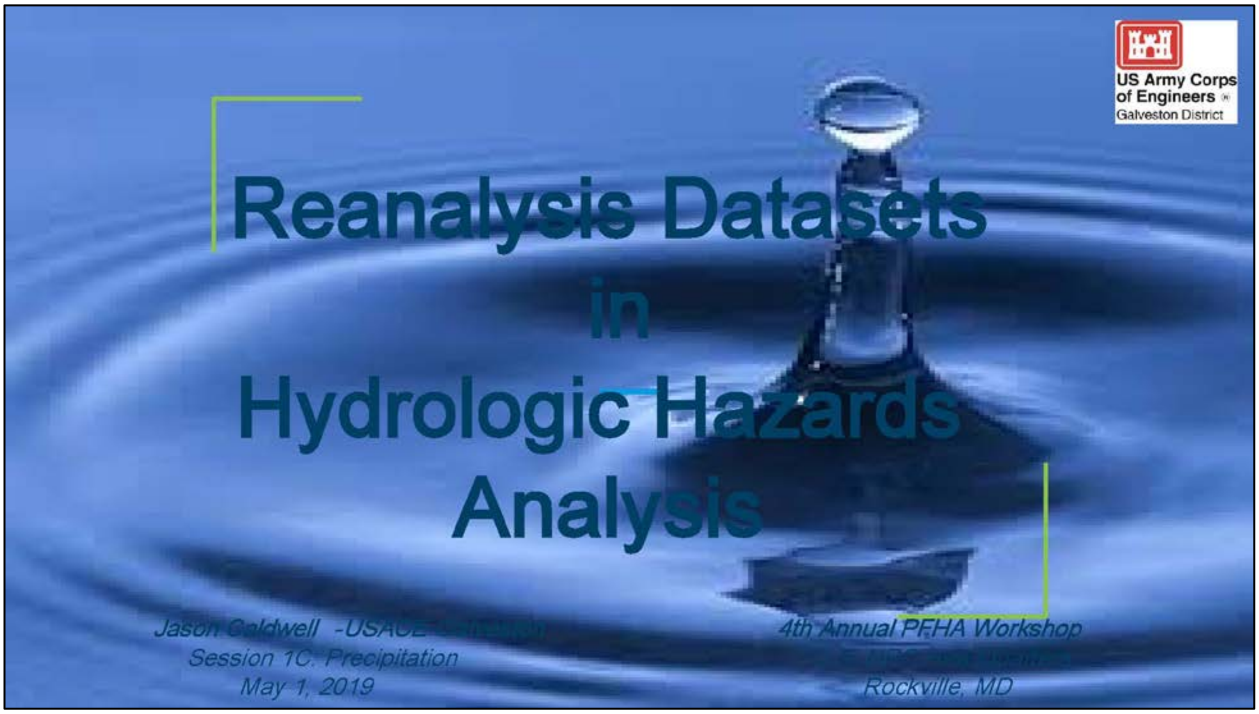
4.3.3.3.1 Abstract

As spatio-temporal resolution of reanalysis products and the quality of numerical weather prediction models continue to improve, the utility of these data may serve to supplement historical storm analyses. There is great potential to enrich the sample set of temporal and spatial distributions of precipitation for stochastic modeling approaches (e.g., those rooted in extreme value theory/frequency analyses and probable maximum precipitation (PMP).

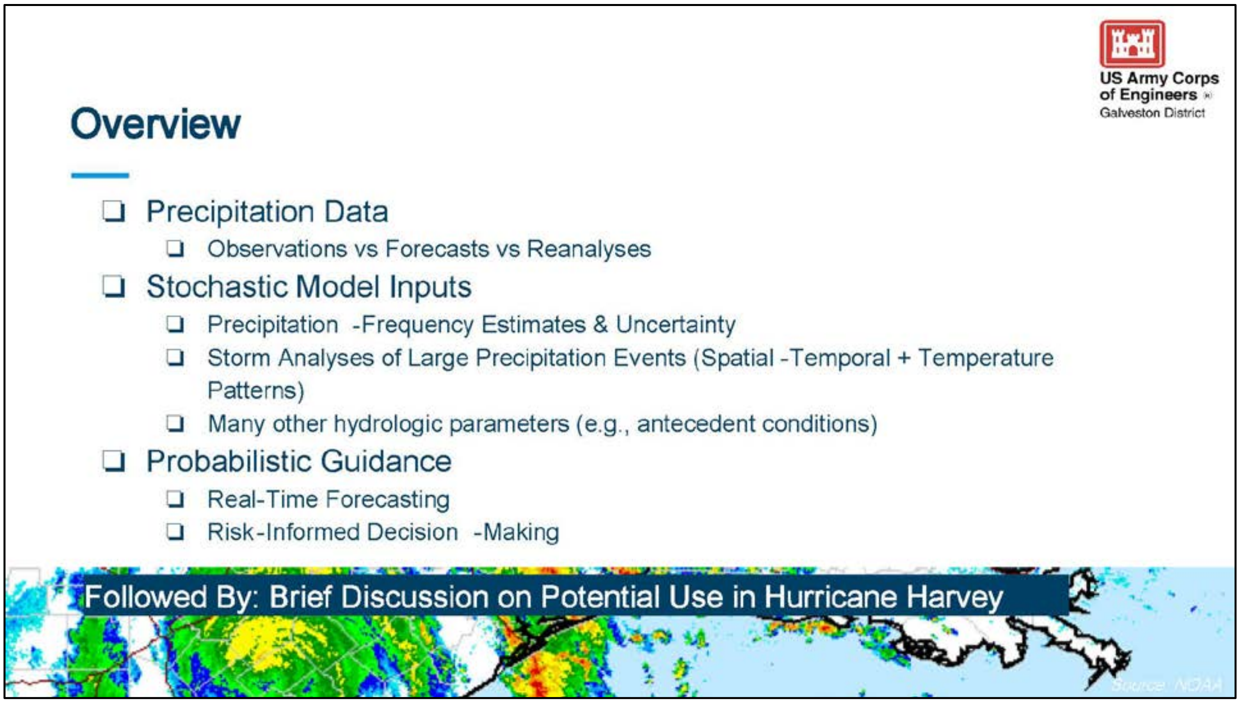
In situ measurements of precipitation are now assimilated into some numerical weather models for initialization; therefore, the future may hold opportunity to use model-generated data as a surrogate in low- and mid-level hydrologic hazard analysis (HHA) studies. Comparison of model forecast and reanalysis representations of Hurricane Harvey to quantitative precipitation estimates (QPE) are provided, focusing on the perspective of dam safety HHA, including (1) evaluation of depth-area statistics, (2) spatial/temporal evolution, and (3) ensemble-based probabilistic measures of confidence. Additional potential applications of these products will be summarized.

4.3.3.3.2 Presentation

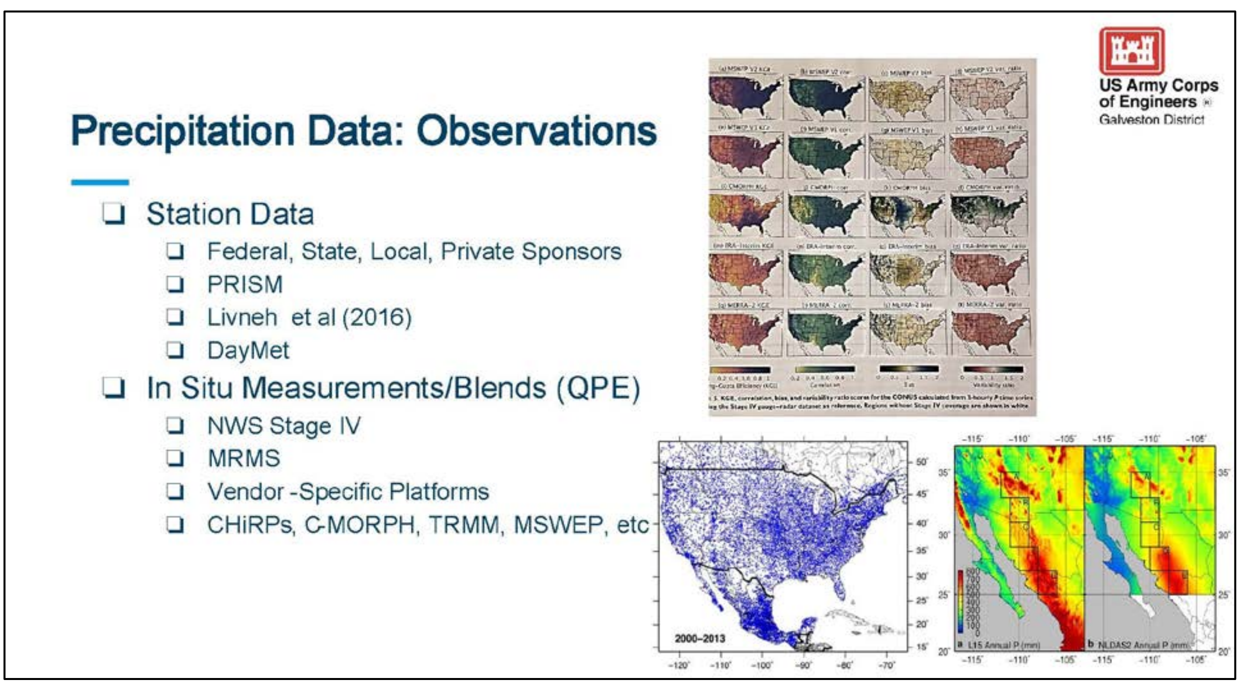
This presentation was given by John England, USACE/RMC using the notes included here with the presentation slides.



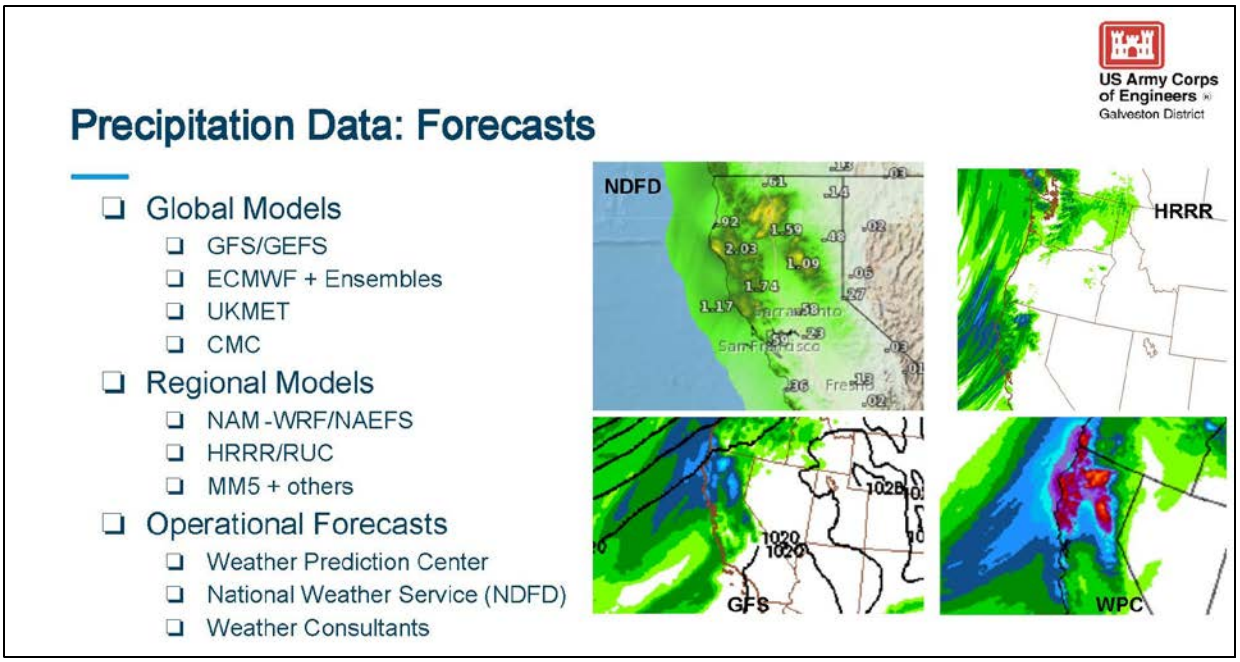
This talk is focused on the use of readily available reanalysis products, primarily meteorological in nature that are available to support hydrologic hazards analyses through model inputs for hydraulics and hydrology (H&H) models and hydrometeorological design criteria. The goal of the presentation is to describe ongoing and potential applications of reanalysis data and to spur the vision toward the future use of these data in on-the-ground application. While recently employed at USACE, the presentation's perspective is from Jason Caldwell's background across State and Federal agencies and private industry.



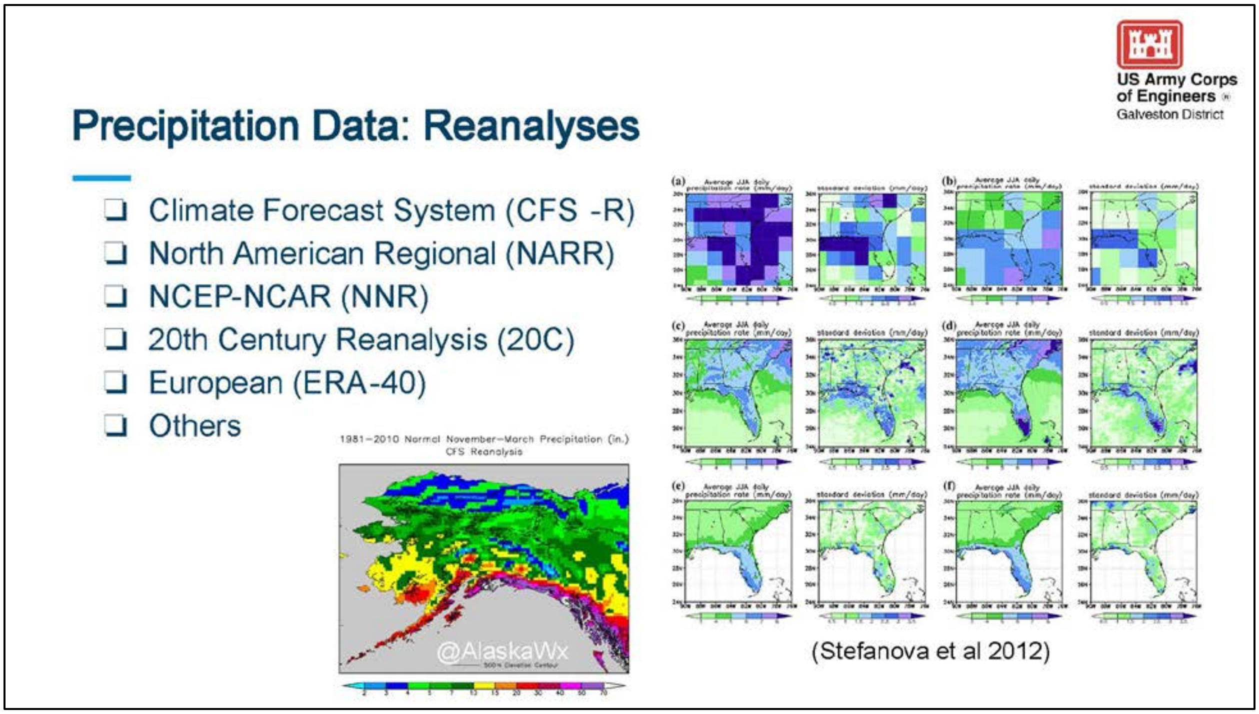
Today, we will discuss primarily precipitation and precipitation-related datasets—either raw or postprocessed—and how these are used in stochastic approaches and probabilistic hazard assessments, primarily from the presenter's time at the U.S. Bureau of Reclamation (USBR). Mel Schaefer's talk later today will elaborate on some of these items. Historically, engineers have been limited to point precipitation data and, for about 15 years, multisensor precipitation estimates (MPEs); however, as time continues to march on with technological advances, so do the confidence, resolution, and availability of atmospheric data and reanalyses representative of those data.



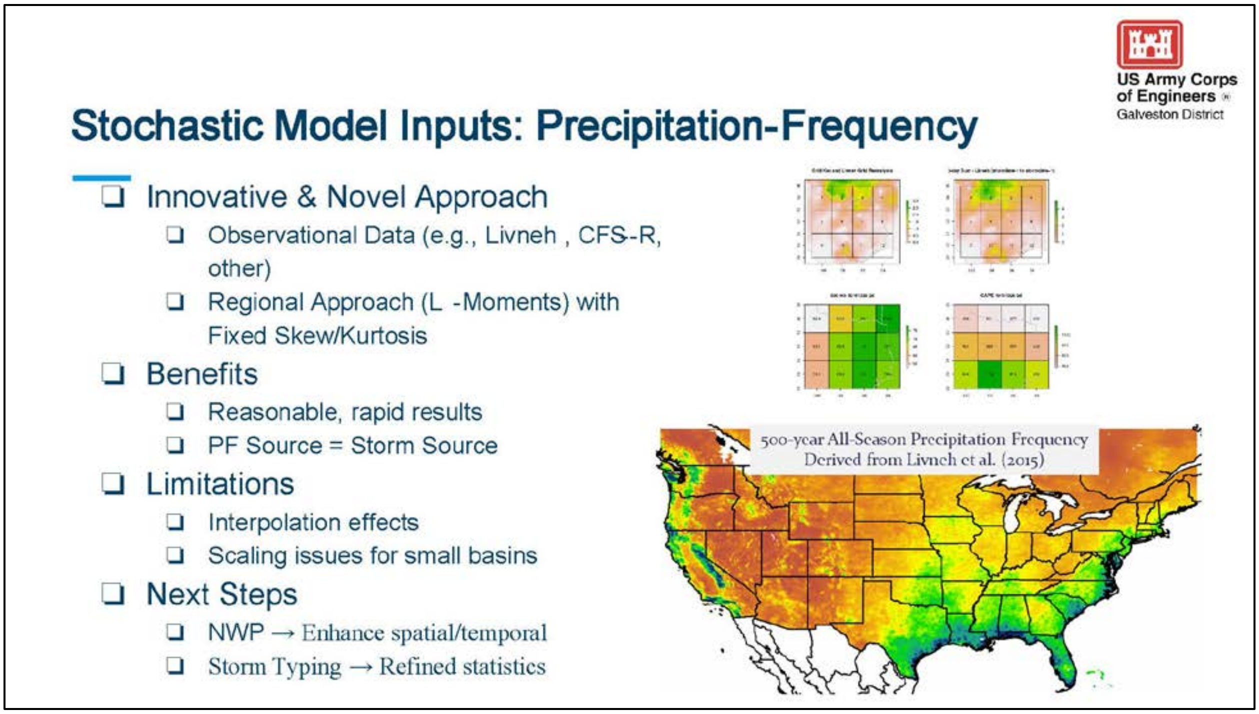
Observational data (gauges) come from a variety of sources and have been interpolated using PRISM-based technologies into historical and real-time versions of storm analysis systems. Reanalyses using these observations can also include numerical weather prediction model output constrained to these observations, which provides an opportunity to harvest additional variables of interest in the hydrometeorological community such as moisture availability and temperatures. Most recently (top image), satellite-derived 3-hour precipitation estimates have been produced globally and published in the most recent Bulletin of the American Meteorological Society journal. The growth in meteorological data is expected to continue to be refined and improve.



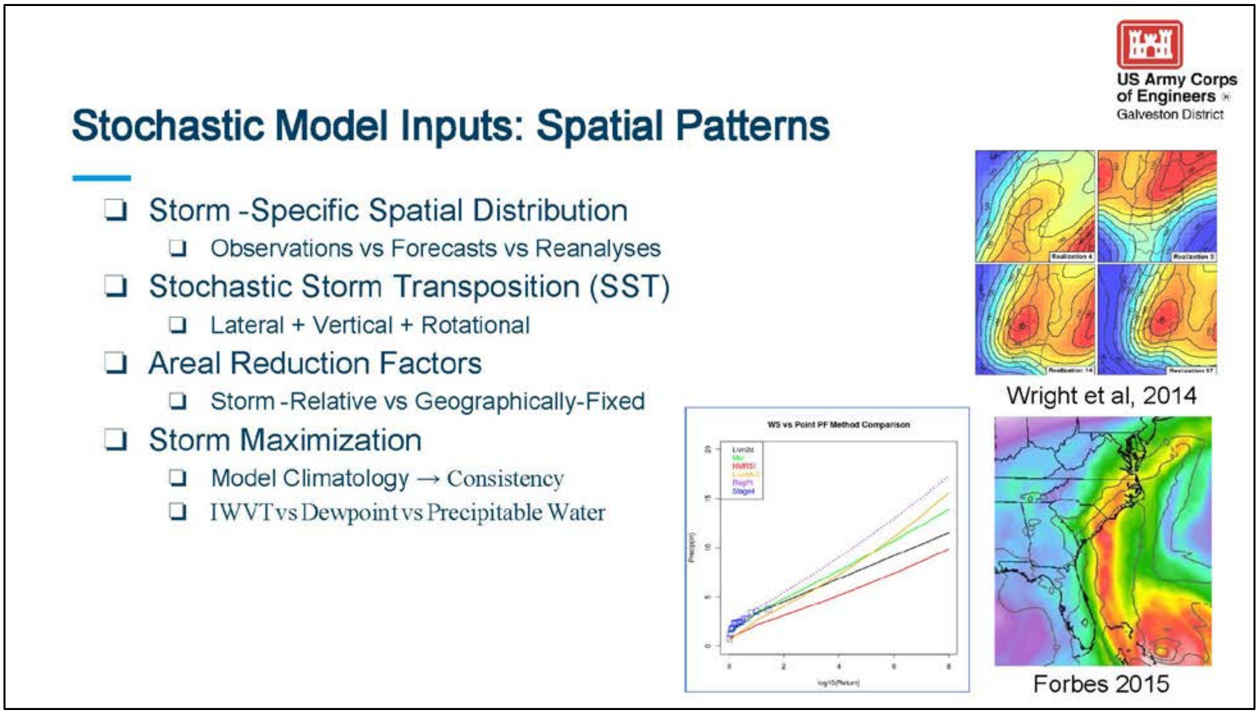
In addition to the historical data shown, forecast data are produced several times daily by weather models. The harvest of this data is, I would consider, at its infancy, but 1-kilometer (km), subhourly precipitation forecasts are at hand. While not the focus, necessarily, of this conference, the spatial-temporal information available can be archived to represent large events of PMP and stochastic modeling interest (i.e., annual maxima) or used for identification of areas of concern in operational decisionmaking processes. Private industry and now the Weather Prediction Center offer these products for flood monitoring.



As before, the reanalyses data continue to improve with the Climate Forecast System Reanalysis (CFSR) data providing 1979–2014 hourly forecast fields for the entire period at approximately 12-km resolution. Others also offer 3- and 6-hour outputs, particularly useful for larger watershed or longer duration events, or for analyzing frequency patterns of multiple events and quasistationary patterns—see central Texas in 2019 or the Midwest floods in the mid-1990s.

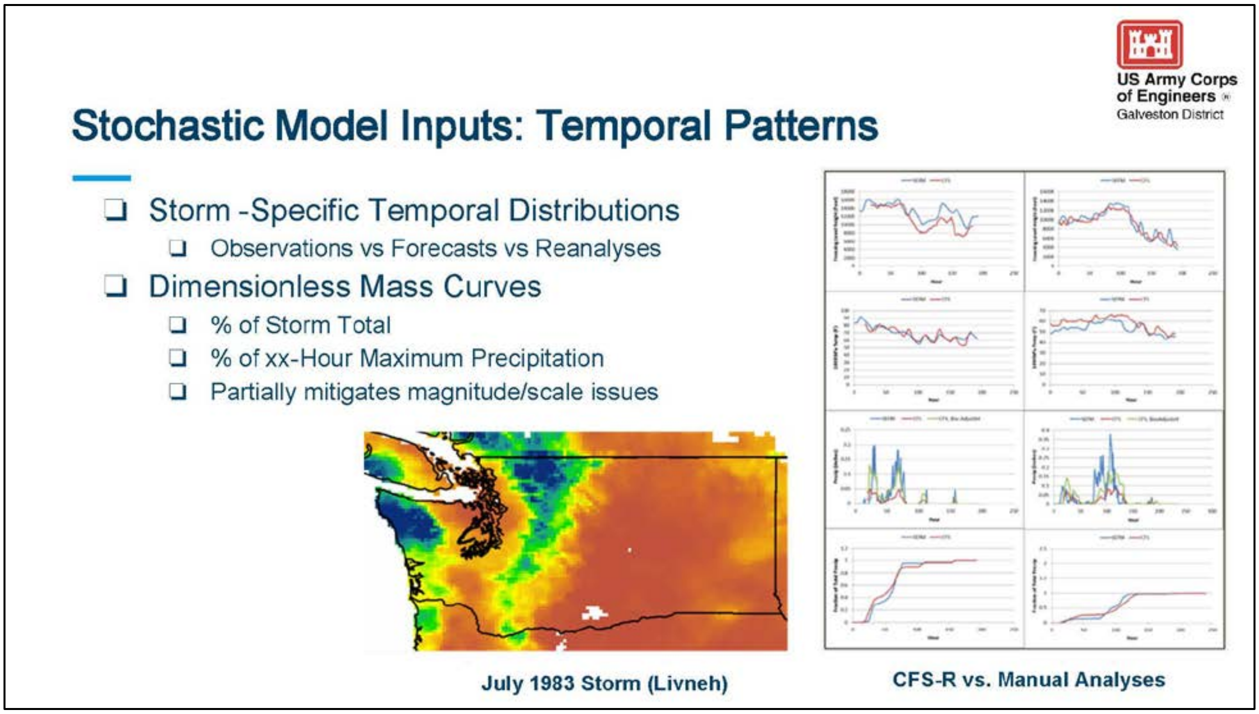


At USBR, I initiated the use of Livneh data for creating a Continental United States-wide precipitation-frequency analyses and continued into the private sector at MetStat. For perspective, Livneh data are daily data used for the Variable Infiltration Capacity (VIC) models under historical and future climate scenarios. I believe the information from high-resolution weather models can inform the subdaily time steps for short-duration weather events. Furthermore, as Mel Schaefer will describe later, storm typing is the largest advancement in many years in precipitation frequency analysis and can be applied with this coincident time series data to construct reasonable estimates quickly compared to the massive data quality procedures for more refined precipitation frequency analysis such as NOAA Atlas 14 or site-specific analyses. This method is limited, however, in use for the interpolation methods because of issues at the tails and in parameter selection or for small basins or short durations. With storm typing and generalized extreme value (GEV)-convergence (see Mel Schaefer's presentation), better understanding of the tail behavior is underway and will soon allow this process to be further refined.

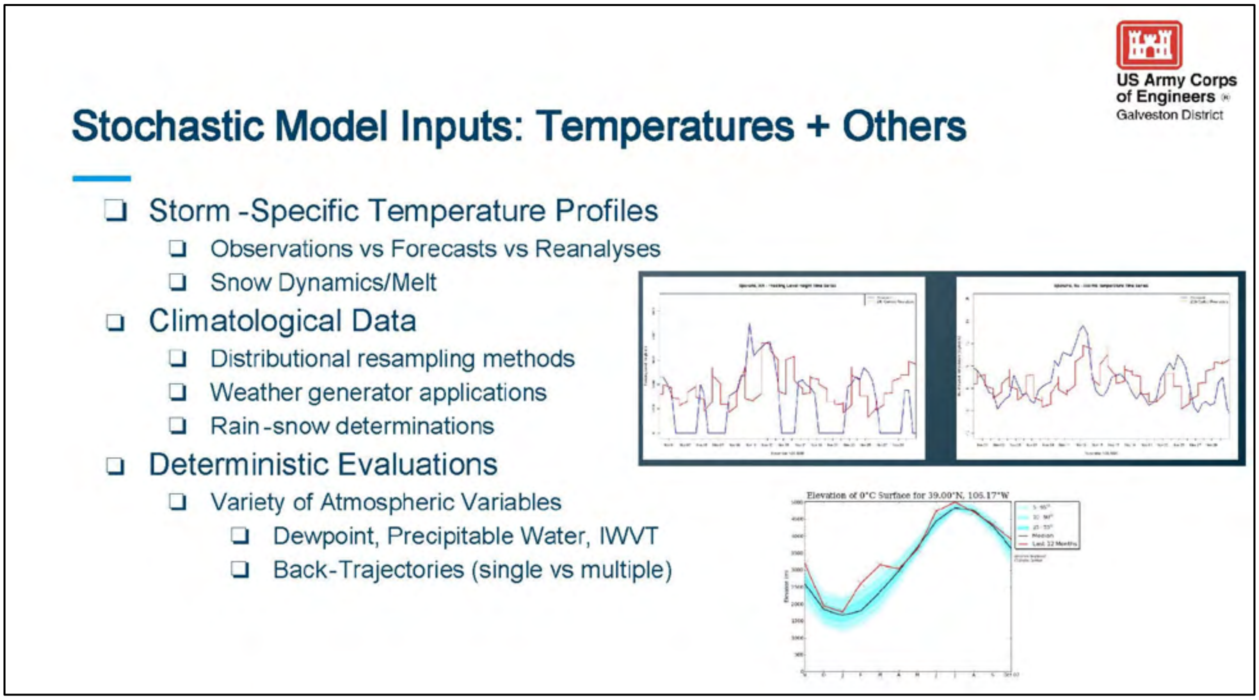


The days of the smooth isohyetal pattern are gone. Now we have access to MPE and models that show the spatial and temporal variability of storm precipitation.

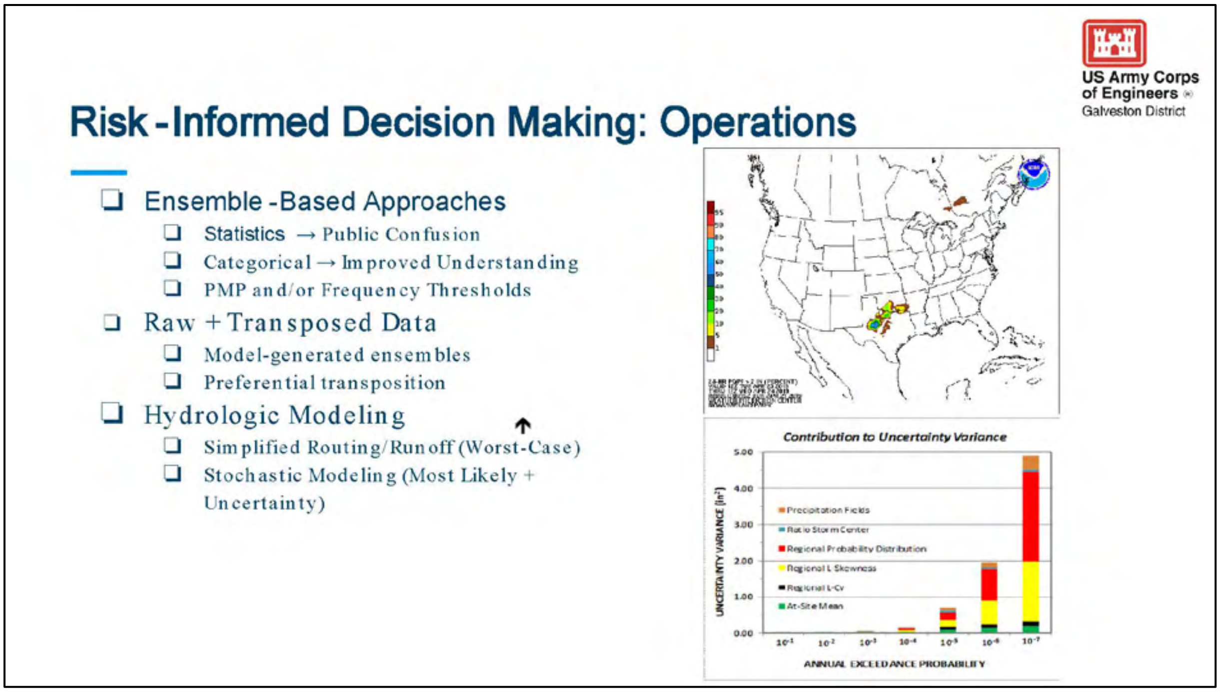
Discoveries in areal reduction factor (ARF) variability came from these and other studies showing how different thunderstorm ARF is for example relative to a large mid-latitude cyclone or relative to the basin orientation with respect to the general storm motion. We have a lot to learn, but the quality of meteorological data provides the ability to investigate the simplicity of elliptical storm patterns and dictated temporal patterns and their effects on hydrology and specifically annual exceedance probabilities (AEPs). Lastly, from the PMP world, we continue to move toward understanding the moisture maximization problem—is surface dewpoint sufficient? Are we missing important considerations? Is having consistency for computation important (e.g., gauge dewpoint temperature, old map stochastic storm transposition/precipitable water)? These are industrywide research questions we should be asking.



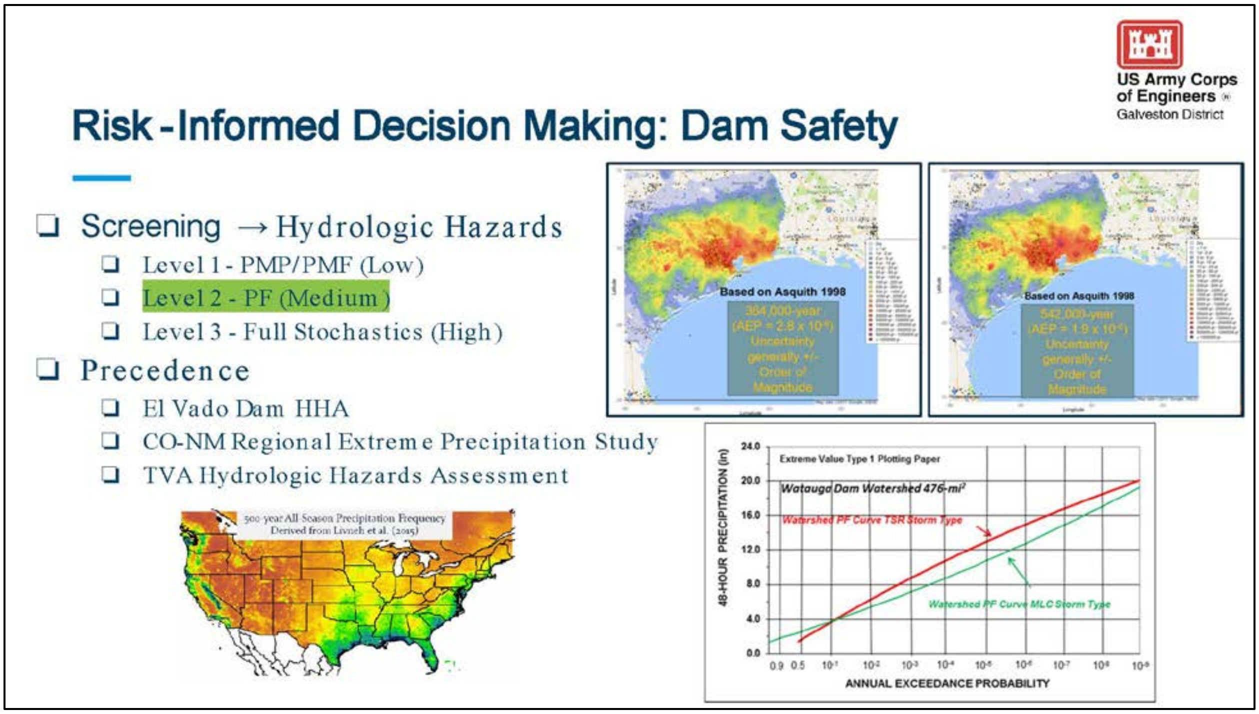
Hourly observations even in today's world continue to be sparse; subhourly, even more so. But past studies have shown that the disaggregation of observed data manually in a quite time-consuming process of painful spreadsheets is reasonably reconstructed in normalized time series from numerical models and reanalyses.



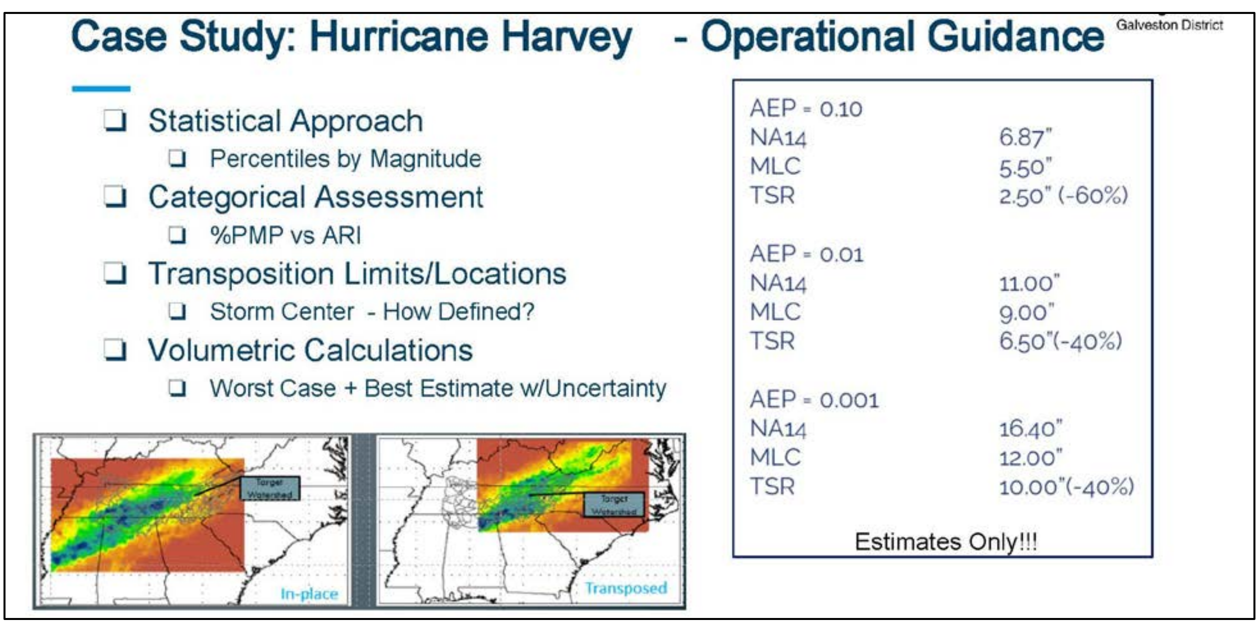
As we've walked through, I'm trying to focus on the items needed for hydrologic models—precipitation spatial and temporal—now on to temperatures. In southern locations, the snowmelt component is trivial and in transition areas perhaps the most difficult due to rain on snow, where hydrologic risk is a mixed bag from event-driven to seasonal pack and anomalously warm spring seasons. Shown here are a few examples of seasonal variability in freezing level and times series that could be normalized to an average value for the period for scaling using these distributional properties. In the future, perhaps the categorical snow, freezing rain, sleet, and liquid fields from numerical weather prediction reanalyses might be useful to eliminate the need for lapse rates in modeling efforts or to establish the correct criteria for a watershed rather than assumed from location-specific literature. We should not constrain ourselves to single-trajectory answers for things but rather to explore the understanding of moisture for storms and what is truly the best criterion—maybe it is dewpoint, though doubted.



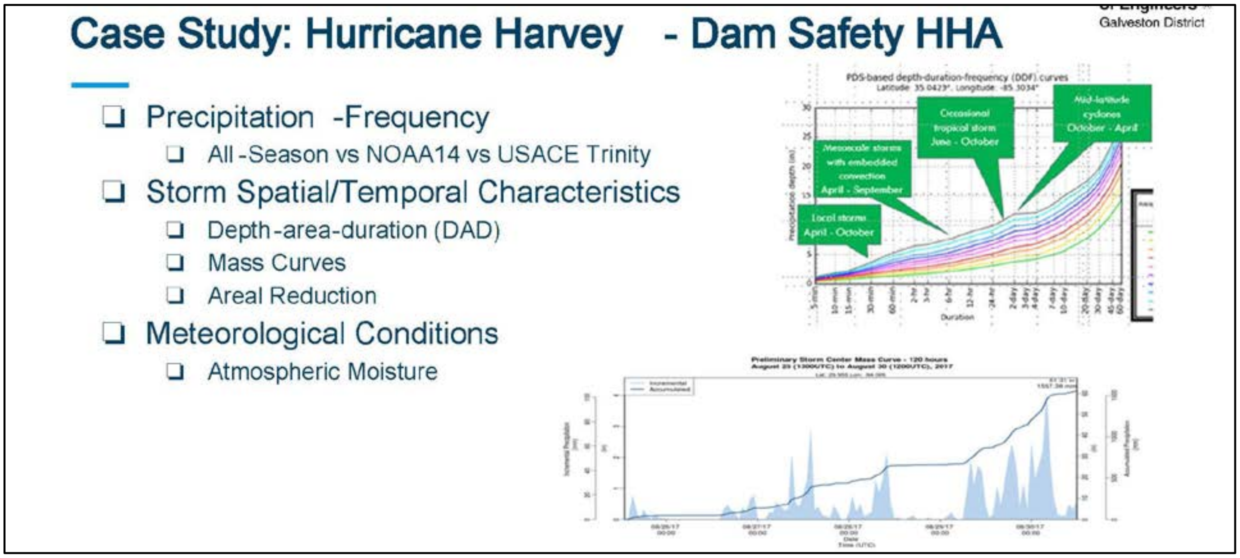
I hope by now it is clear that many components can be accessed from these data. Important strides are being made to include these into tools and formats for ease of access to the larger community. Past studies for the NRC, TVA, and others elucidate this fact, and the onus/responsibility lies with this group to forge a path forward. The next few slides will discuss the potential applications, some already in practice in industry and government. How do we turn these data into meaningful products? Statistics are useful from the government and operator perspectives, but for public communication they continue to be a struggle point. Placing these into categorical perspective (minor, moderate, major) or some relative amount of PMP or AEP may help. Probabilistic products from the Weather Prediction Center provide a focus for where the largest precipitation amounts should occur based on ensembles—can we use this prestorm to inform SST for H&H models? Will simple ones suffice and where and why or why not? How can this be coupled with national efforts like the National Water Model? Literally, the options are limitless, and social scientists will need to be involved to describe impacts. Frameworks are needed for everything from one dimensional (1-D) to three dimensional (3-D) coastal compound flood issues. Where might this feed in? This is a presentation on questions—motivating thought and future goals.



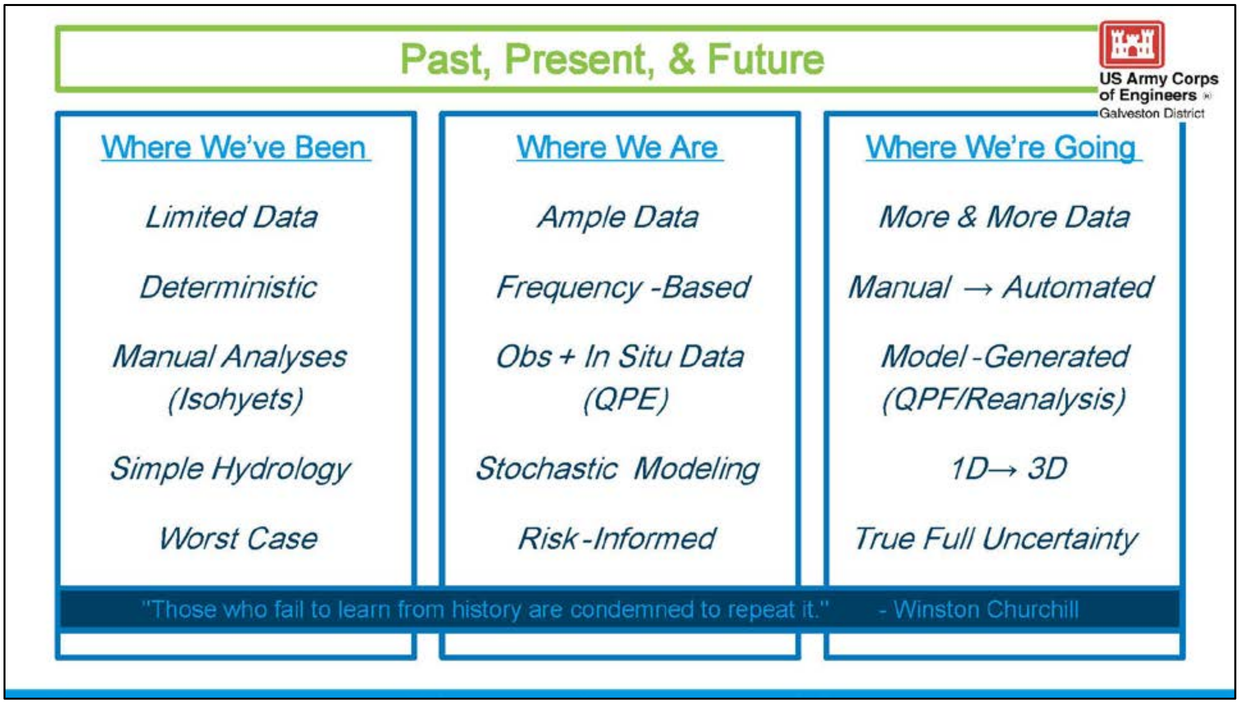
Dam safety is discussed from the perspective of USBR. Discuss how dam safety analyses were conducted before. Now, improvements include the Centre for Energy Advancement through Technological Innovation (CEATO)-sponsored work in private industry (MetStat) for Federal Energy Regulatory Commission (FERC) Level 2 support. MetStat images and credit to MGS Engineering.



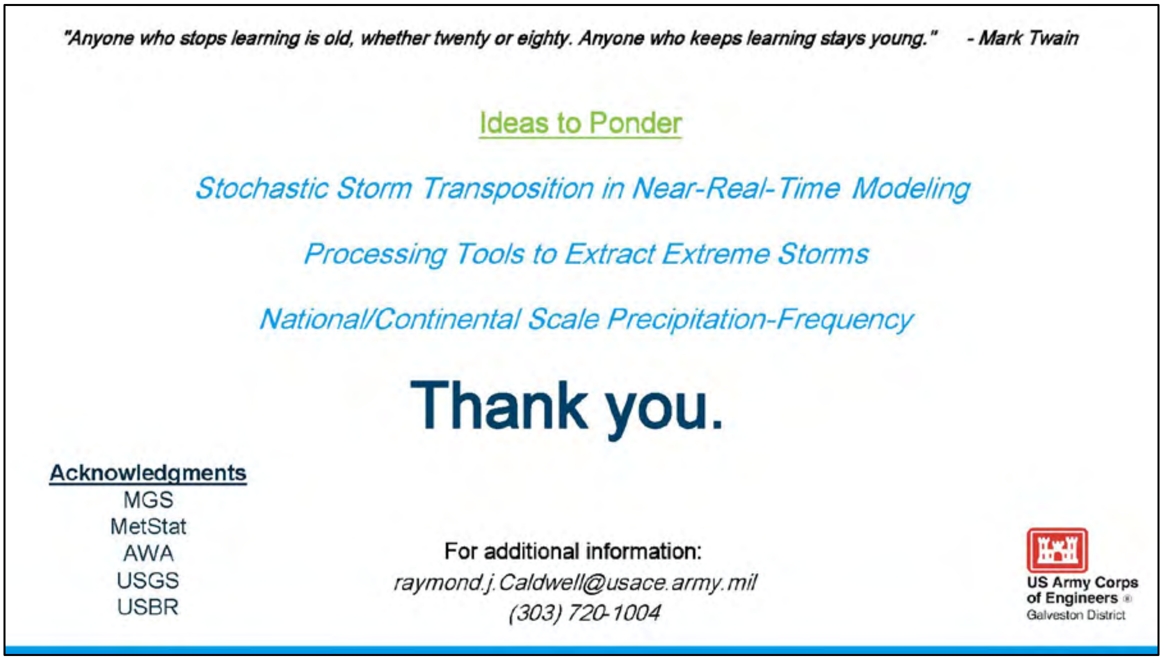
These two slides are estimates based on plots from the Trinity River study, and the net reduction may be overestimated due to gradients in at-site means near the coast between river basins. The goal is the same—to highlight the differences that may exist and show the importance of storm typing for assessing hazards. The relative AEP of tropical cyclone (TC) occurrence is small (0.30 or so every third year), which affects a much more gentle tail relative to other types. This will be important in scaling storms for stochastic models or the relative magnitude in frequency or PMP space.



Again, just to emphasize the mixed distribution issue and describe here how you might get the plot at bottom from reanalysis—that it is likely a similar time series has occurred albeit at a different magnitude in the historical past. Can we answer whether this is unique for a tropical storm or could a more general storm produce the same dimensionless answer? Talk about moisture source and PMP and how close Hurricane Harvey was, and do we really know the climate of SST and moisture when using a single value?



How to get where we are going. Where we are, where we were? Do we want to stay there? Other presentations today I believe show the movement toward the right column. I am personally pleased to be here and be part of that discussion.



Finally, a few ideas to ponder in operational and storm archival (i.e., the USACE effort mentioned here and the Extreme Storm Events Work Group). And, thank those at left and the NRC for their contributions.

4.3.3.3.3 Questions and Answers

Question:

I'm curious that you look at the NOAA Atlas; basically look at all types and do frequency analysis and it will give you the highest amount. But when you just look at the tropical-storm remnant (TSR) or other specific storm type, it will give you a much smaller value. What is the reason for that?

Answer:

The reason for that is the splitting out specifically by type. In NOAA Atlas 14, the trouble is that when you use all seasons, it is combining everything into one, which inflates the value. In terms of mixtures of populations, you essentially get a maximum rather than a mixed population probability. The numbers are lower, in some cases, because of the relationship between the higher order L-moments. In L-skewness and L-kurtosis, you sometimes get a flatter curve, and then the tail picks up at the very end. These are comparisons at about 10^{-3}, so Jason Caldwell did not do this and got to the problems of interest. Those estimates will pick up. By splitting out by type, you can do the same thing; sometimes a season, and you may, in some cases, get some lower estimates. Now these are estimates and I do not know if Jason Caldwell has actually included Hurricane Harvey or not.

4.3.3.4 Current Capabilities for Developing Watershed Precipitation-Frequency Relationships and Storm-Related Inputs for Stochastic Flood Modeling for Use in Risk-Informed Decisionmaking. Mel Schaefer*, MGS Engineering Consultants, Inc. (Session 1C-4; ADAMS Accession No. ML19156A460)

4.3.3.4.1 Abstract

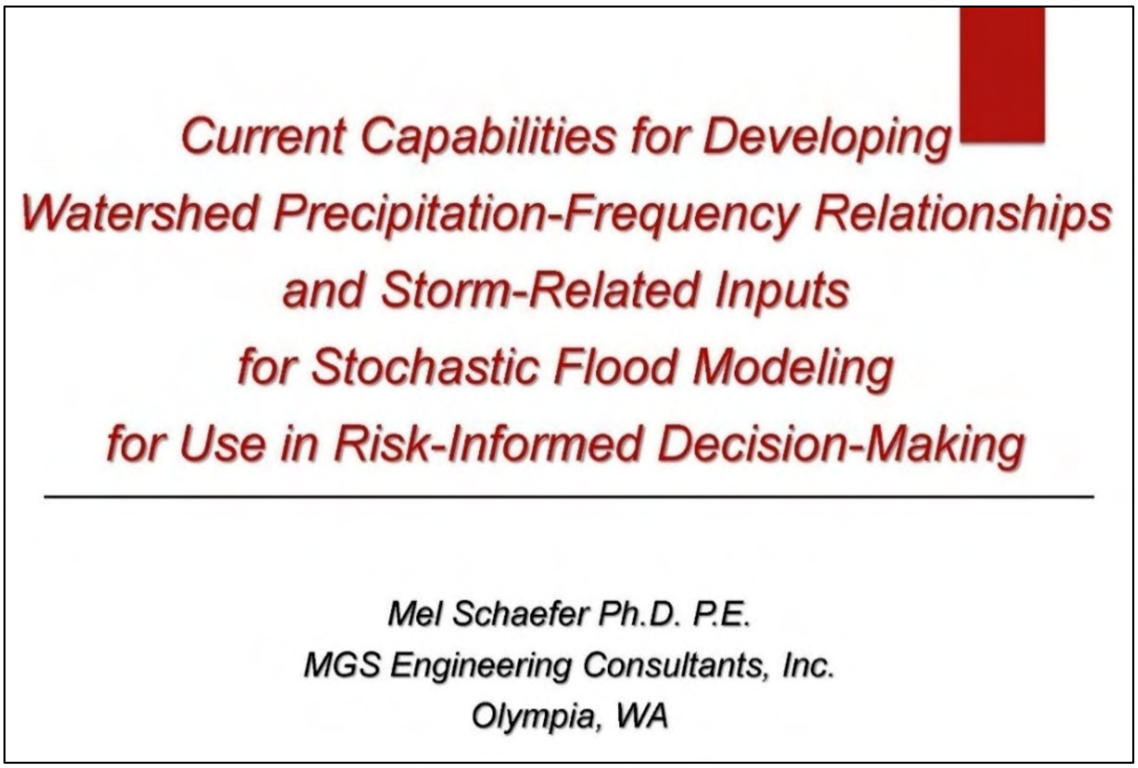
Several advancements in watershed precipitation frequency analysis over the past 5 years have increased the practicality and reduced uncertainties in using stochastic flood modeling for estimating the hydrologic characteristics of extreme floods with AEPs of 10^{-5} and rarer. Stochastic flood modeling is now the preferred method for PFHA for high-consequence dams owned by Federal agencies (e.g., TVA, USACE, USBR), where information and decisions are required about the hydrologic performance of large capital projects under extreme flood-loading conditions.

The introduction of storm typing in 2014 for assembling precipitation maxima datasets for a given storm type for use in regional precipitation-frequency (PF) analysis was a major advancement that provides increased data homogeneity and reduction of uncertainties for estimation of extreme precipitation. This approach allows separate point and watershed PF relationships to be developed for each storm type. This is important because different storm types have different spatial and temporal patterns and storm seasonality that must be matched with the appropriate watershed PF relationship for proper hydrologic modeling. For watersheds subjected to snowmelt and rain-on-snow floods, compatibility of storm-related inputs must also extend to air temperature and freezing level time series and associated temperature lapse rates. The storm-typing approach allows development of separate stochastic flood models and separate hydrologic hazard curves for each storm or flood type and addresses the problem of mixed populations of flood types common to many watersheds and climatic environments.

Stochastic storm generation methods have been developed for synoptic scale mid-latitude cyclone (MLC) and TSR storm types. Stochastic storm transposition methods with resampling of historical convective spatial patterns have been developed for the Mesoscale Storm with Embedded Convection (MEC) storm type. These stochastic storm generation methods, in combination with the Schaefer-Wallis-Taylor (SWT) method of regional PF analysis, provide for the development of the watershed PF relationship for a given storm type.

The current capabilities and practices for development of watershed PF relationships will be presented along with the associated topics of storm typing, SWT method of regional PF analysis, storm seasonality, storm spatial and temporal patterns, stochastic storm generation methods, and characterization of uncertainties.

4.3.3.4.2 Presentation



Acknowledgements

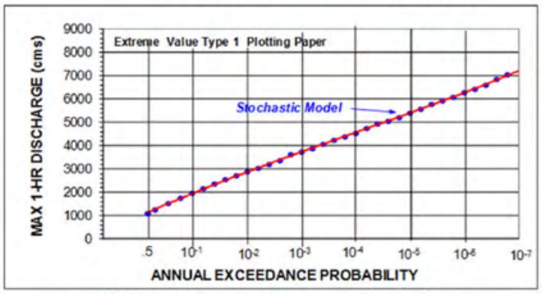
Many of the Advancements in Watershed Precipitation-Frequency and Storm-Related Inputs Were Accomplished in Assisting the Tennessee Valley Authority in Conducting Hydrologic Hazard Assessments for Dams in the Tennessee Valley

This was a Team Effort by:
MGS Engineering Consultants, Inc.
Meteorologists from MetStat Inc.
Hydrologists at RTI International
and Engineers at the Tennessee Valley Authority

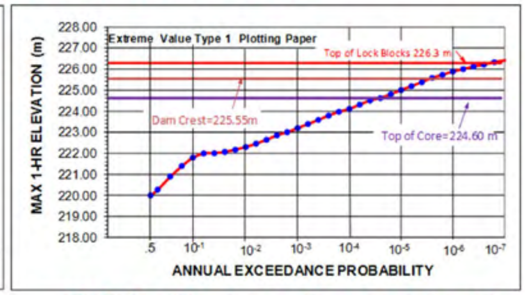
PFHA Application: Stochastic Flood Modeling

After Nearly 30-Years of Debate in the Dam Safety Community, Probabilistic Methods are Now an Accepted Alternative to Deterministic Methods for Assessing Hydrologic Performance at Dams

Flood Loading Condition - Hydrologic Hazard Curves



HHC for Peak Reservoir Inflow



HHC for Maximum Reservoir Level

Depth of Overtopping

Duration Above an Elevation of Interest

Reservoir Outflow

HHC for Any Flood Characteristic Generated in Flood Modeling for a Failure Mode of Interest

PFHA Application: Stochastic Flood Modeling

Detailed Stochastic Flood Modeling is the Preferred Method for Assessing Hydrologic Risk at Federally Owned Dams in the U.S. where Large Capital Expenditures are being Considered

Tennessee Valley Authority
U.S. Bureau of Reclamation
U.S. Army Corps of Engineers

Detailed Stochastic Flood Modeling is also Being Conducted by:
BCHydro in British Columbia
Southern California Edison
Large Water Utilities in Australia

Why are Watershed PF Relationships Important?

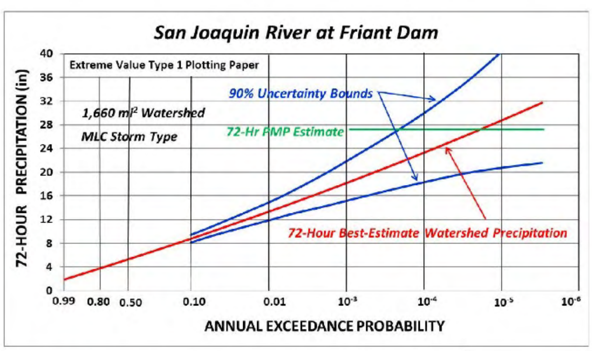
Watershed Precipitation-Frequency Relationship
is a Key Component in Stochastic Flood Modeling
for Assessing Hydrologic Risk

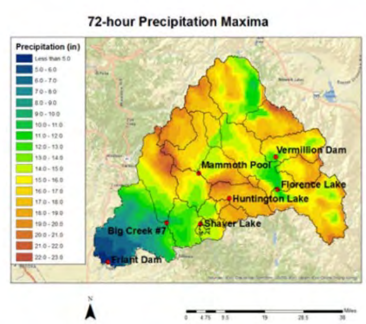
Decisions are Required by Federal Agencies and Private Companies
for Allocating Resources to Reduce Hydrologic Risks
at Large Capital Water Projects

Information about the Likelihood of Extreme Floods (10^{-5} and 10^{-6} AEP)
is Needed Because of the Very High Consequences of Failure
for Loss-of-Life and Economic Damages

Storm-Related Inputs are Dominant Inputs for Modeling

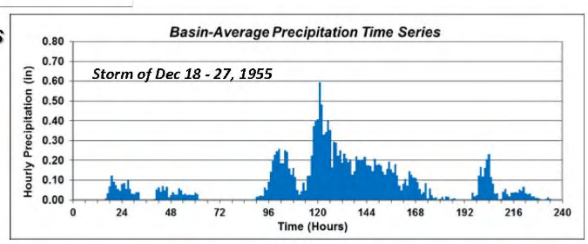
Watershed Precipitation-Frequency Relationship
and Storm Spatial and Temporal Patterns
are Dominant Inputs in Stochastic Flood Modeling





Large regional studies indicate PMP ranges
from 10^{-4} to 10^{-9} AEP in North America

Generally more likely in coastal areas
and less likely in inland areas
with arid to semi-arid climates



”

Major Advancements in PFHA in Past 5 Years

Major Advancements Made in Meteorological Inputs in Past 5-Years for Conducting Probabilistic Flood Hazard Assessments (PFHA) for High Consequence Dams

Majority of Advancements Have Had Little Exposure Outside of Conference Proceedings

Presentation Goal:

Provide Update on Current Capabilities for Storm-Related Components Needed for Stochastic Flood Modeling

Major Advancements in Stochastic Flood Modeling

Methods are in Production Mode:

Storm Typing for Assembling Precipitation Annual Maxima Datasets

30-Year Evolution of SWT Climate Region Method for Regional PF Analysis

MetStorm Software: Storm Spatial and Temporal Analyses

Storm Transpositions using L-Moment Technology

Stochastic Storm Generation of Synoptic-Scale Storms

Stochastic Storm Transposition of Convective Mesoscale and Local Scale Storms

Precipitation-Frequency Areal Reduction Factors (ARFs) – by Storm Type

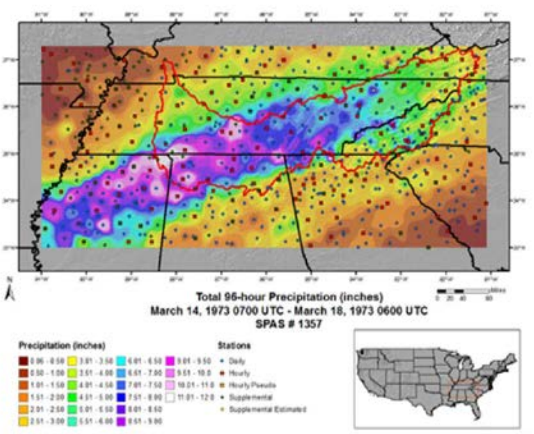
Use of Livneh Reanalysis Datasets to Aid Meteorological Inputs

Major Advancements in Past 5-Years in Watershed Precipitation-Frequency Development

Storm Typing (2014)

Create Homogeneous Datasets for Similar Meteorological Processes for Regional Precipitation-Frequency (PF) Analysis

Synoptic Scale Storms; Convective Mesoscale and Local Scale Storms



Example Synoptic Scale
Mid-Latitude Cyclone (MLC)
March 14-18, 1973
Tennessee, Alabama, Mississippi

Why is Storm Typing Important

Different Storm Types Have Different Characteristics Important for Realistic Rainfall-Runoff Modeling

- *Watershed Precipitation-Frequency Relationship*
- *Spatial and Temporal Storm Patterns*
- *Seasonality of Storm Occurrence*

Preserve as Package

- *Seasonality is a Consideration for:*
  Antecedent Soil Moisture; Initial Streamflow, Reservoir Level, Antecedent Snowpack, 1,000-mb Temperature, Freezing Level

Storm-Related Inputs Must be Preserved as a Package for Realistic Hydrologic Modeling of Floods, Particularly Extreme Floods

Storm Typing

Synoptic Scale Storm Types

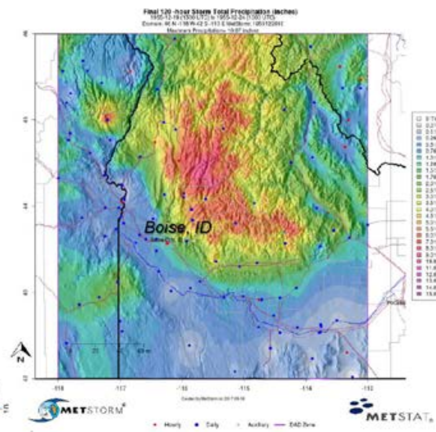
Mid-Latitude Cyclone (MLC)

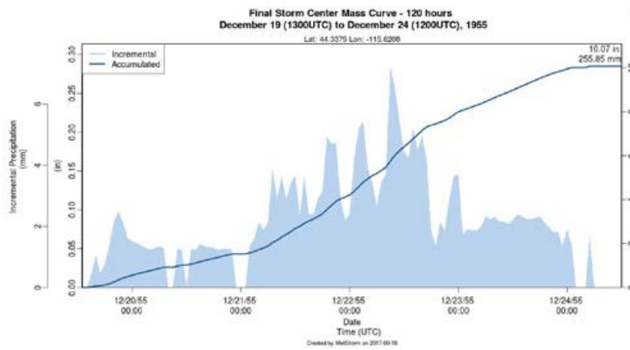
Tropical Storm Remnant (TSR)

Large Areal Coverage

Long-Duration (multi-day)

Low to Moderate Intensities





Max Intensity for

12/24/1955 Storm

0.27 in/hr

Storm Typing

Mesoscale Storm Type

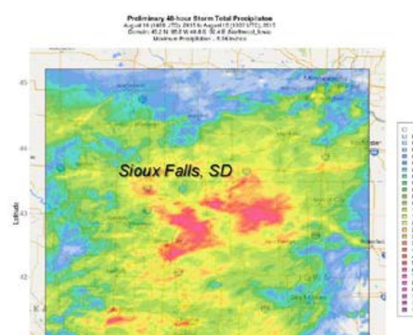
Mesoscale Storm

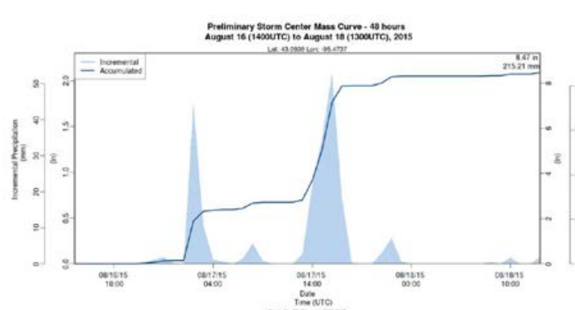
with Embedded Convection (MEC)

Moderate Areal Coverage

Intermediate-Duration (3 to12-hrs)

Moderate to Very High Intensities





Max Intensity for

8/17/2015 Storm

2.10 in/hr

Storm Typing

Local Scale Storm Type

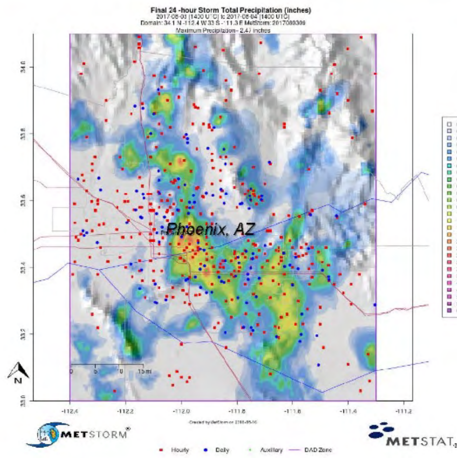
Local Storm (LS)

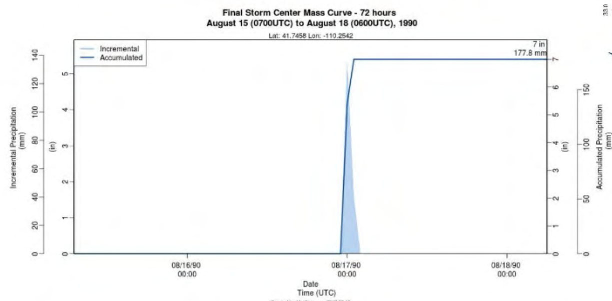
(Convective Event)

Small Areal Coverage

Short-Duration (0.5 to 3-hrs)

High to Very High Intensities





Max Intensity for

8/16/1990 Storm

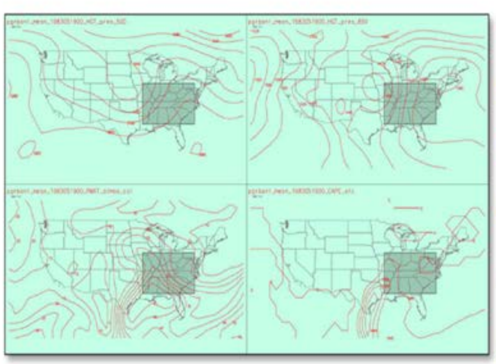
5.00 in/hr

How is Storm Typing Conducted

Several Hundred of the Largest Storms at Different Durations are Manually Storm-Typed by Meteorologists

Expert System is Created based on Metrics from Manually Typed Storms

Database of Daily Storm Types (DDST) is Created for 2° x 2° Grid-cells over Study Area



- *Areal Extent of Observed Precipitation*
- *Surface, 850-mb and 500-mb Heights*
- *Magnitude of Pressure Gradients*
- *Magnitude of Precipitable Water (mm)*
- *Magnitude of Convective Available Potential Energy (CAPE)*
- *Storm Seasonality*

Storm Typing Leads to Flood Typing

Separate Precipitation Annual Maxima Series Datasets are Created for Each Storm Type of Interest

Allows Development of Separate Watershed PF Relationships, Spatial and Temporal Storm Patterns and Seasonality Applicable to Each Storm Type

Separate Stochastic Flood Models are Developed for Each Storm/Flood Type

Allows Separate Hydrologic Hazard Curves to be Developed for Each Storm/Flood Type which Addresses the Problem of Mixed Populations of Floods

Continued 30-Year Evolution of Regional Precipitation-Frequency Analysis

Schaefer-Wallis-Taylor (SWT) Climate Region Method (1989)

Spatial Mapping of L-Moments for Selected Storm Types

Locations where Large Regional Studies have been Conducted

http://www.mgsengr.com/downloads/RegionalPrecipFrequencyReports_2019.zi

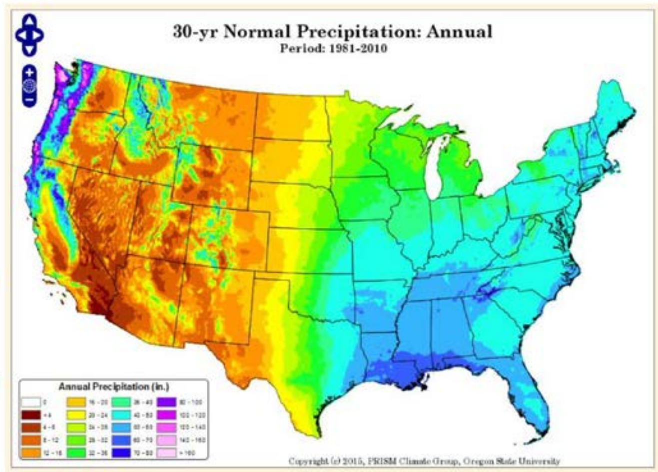
Technical Memoranda: SWT Method; Stochastic Storm Generation (MLC, TSR) and Stochastic Storm Transposition (MEC)

SWT Method ⟶ Spatial Mapping of L-Moments

Experience from Large Regional Studies have shown systematic variation of At-Site Means and Regional L-Cv and L-Skewness with Climatological Indicators such as Mean Annual Precipitation (MAP) and Mean Monthly Precipitation (MMP) for Dominant Months for a Storm Type

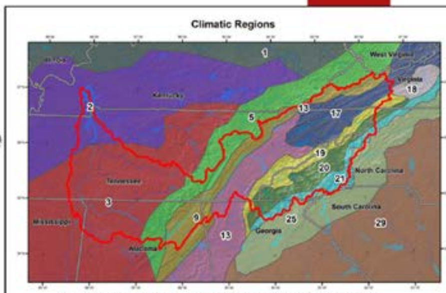
MAP and MMP have provided high explanatory power in areas with a wide range of MAP or MMP

Latitude and Longitude have also been used as auxiliary variables in areas of modest climate variability

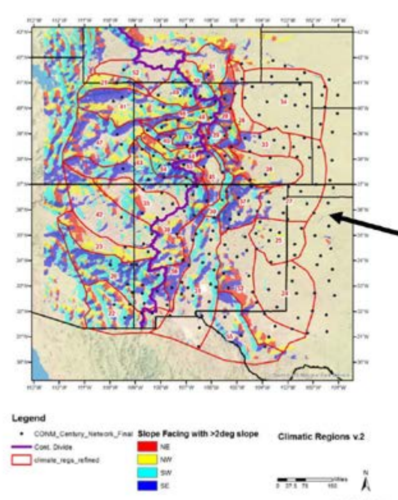


SWT Climate Region Method

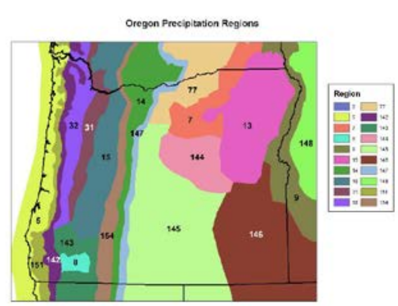
Heterogeneous Climate Regions are a temporary construct to facilitate spatial mapping of L-Moment Statistics for a given Storm Type



Tennessee Valley Study Area
13 Heterogeneous Climate Regions

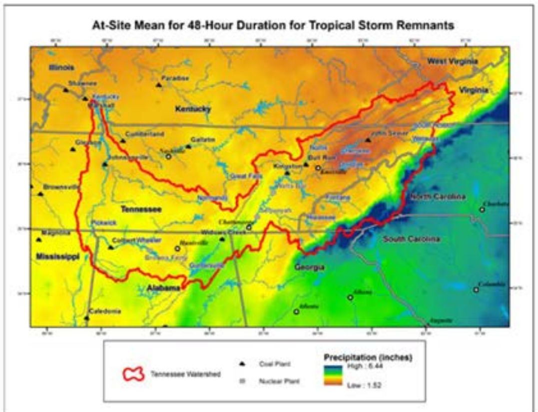


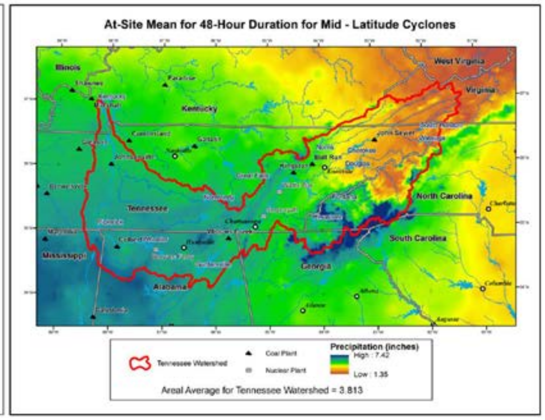
Colorado and New Mexico Study Area
41 Heterogeneous Climate Regions based on MAP, Slope and Aspect of Mountainous Terrain



Spatial Mapping of L-Moments

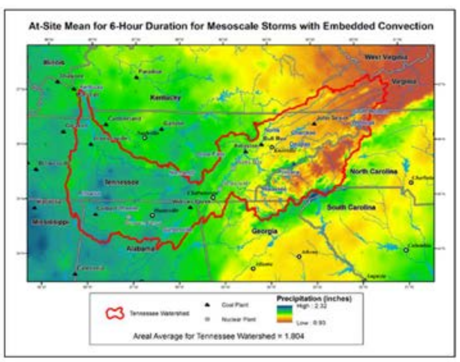
L-Moments Spatially Vary in a Systematic Manner with Climatic, Meteorological and Physiographic Conditions

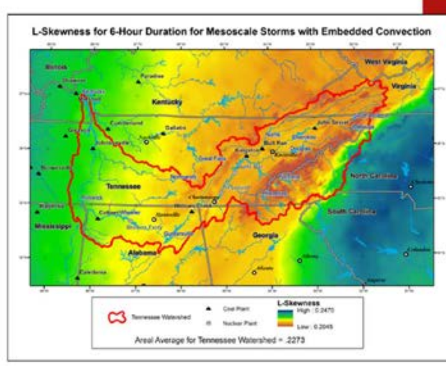




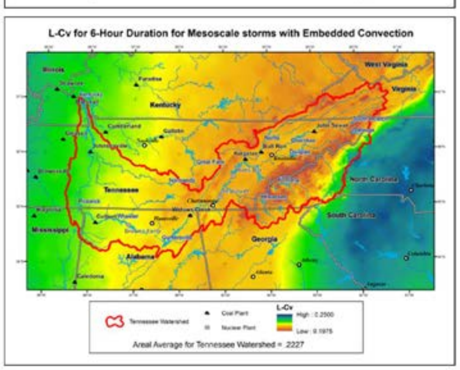
Frequency Analysis of Precipitation Associated with Tropical Storms and Tropical Storm Moisture Sources Now Possible With Use of Storm Typing

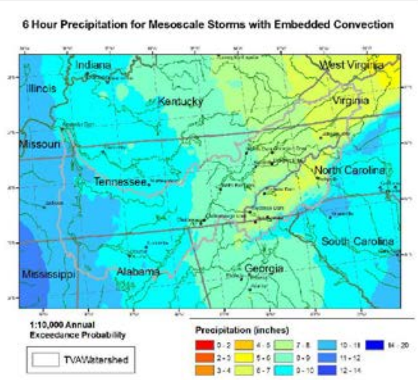
Quantile Estimates for Selected Locations





MEC Storm Type



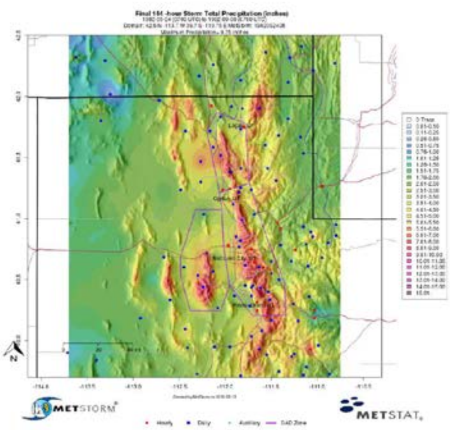


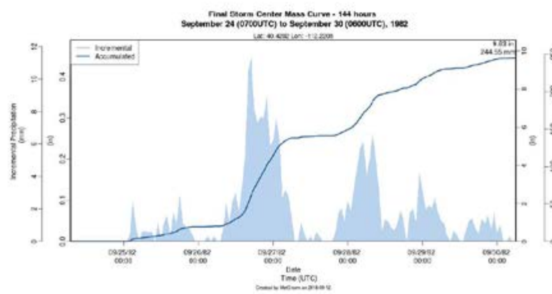
Major Advancements in Past 5-Years in Watershed Precipitation-Frequency Development

<u>MetStorm - Storm Analysis Software by MetStat</u> (2014-2015)

MetStorm is the Second Generation of SPAS
for Spatial and Temporal Analysis of Storms

Adds Capability for Dual-Pole Radar, Satellite Data
and Advanced Spatial Interpolation Particularly for Mountainous Terrain



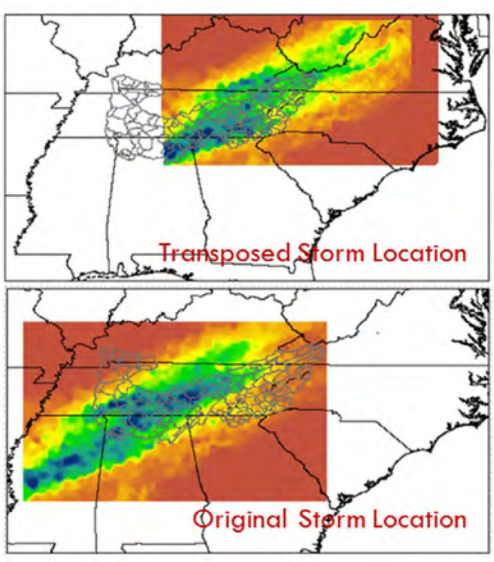


Synoptic Scale Mid-Latitude Cyclone
Wasatch Mountains, Utah

Major Advancements in Past 5-Years

<u>Enhanced Storm Transposition Procedure (ESTP)</u> (2015-2016)

Storm Transpositions using L-Moment Statistics



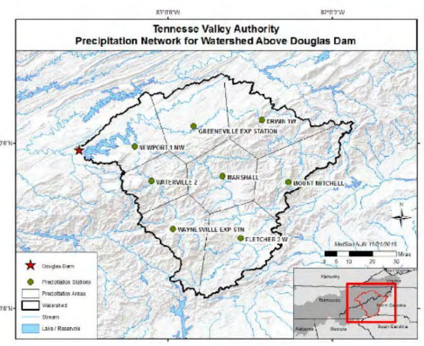
Provides for
Spatial and Temporal Patterns
to be Transposed Whole-Cloth
while Accounting for
Climatic Differences
in Storm Source and Target Locations

Major Advancement Over Past Practice
of Transferring D-A-D Statistics

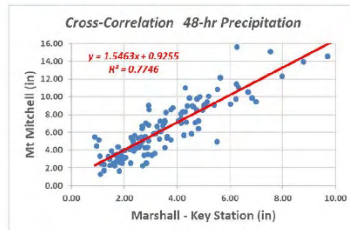
Major Advancements in Past 5-Years in Watershed Precipitation-Frequency Development

Stochastic Storm Generation for Synoptic-Scale Storms (2015)

Use Point PF Findings and Spatial Correlation Structure of Historical Storms to Generate Watershed PF Relationship



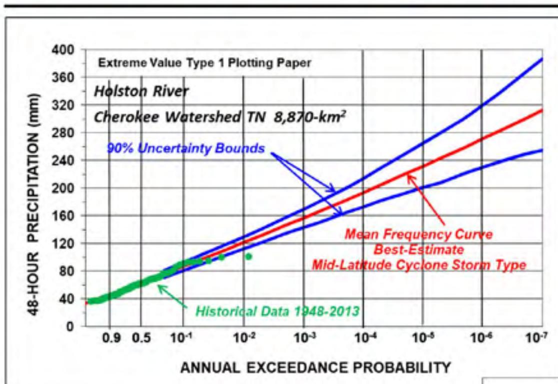
Station Network
Douglas Dam Watershed 4,540 mi²

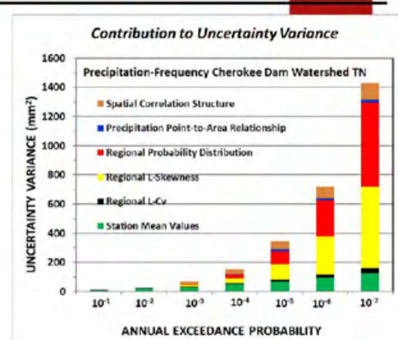


	Marshall	Newport 1NW	Greeneville ES	Erwin 1W	Mt Mitchell	Fletcher 3W	Waynesville ES	Waterville 2
Marshall	1.000							
Newport 1NW	0.709	1.000						
Greeneville ES	0.777	0.899	1.000					
Erwin 1W	0.855	0.772	0.858	1.000				
Mt Mitchell	0.894	0.645	0.693	0.816	1.000			
Fletcher 3W	0.785	0.543	0.577	0.685	0.862	1.000		
Waynesville ES	0.861	0.703	0.731	0.752	0.856	0.808	1.000	
Waterville 2	0.815	0.866	0.890	0.810	0.716	0.608	0.780	1.000

Spatial Correlation Structure 128 Storms

MLC Watershed Precipitation-Frequency Relationships





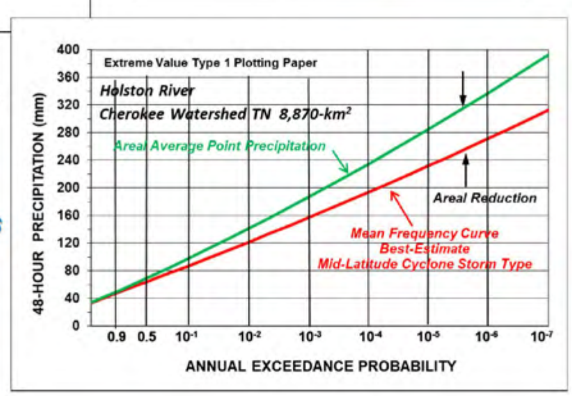
Synoptic Scale
Mid-Latitude Cyclone Storm Type

981 Stations; 50,186 Station-Years

Spatial Analyses 90 Mid-Latitude Cyclones

74 Historical Storms on Watershed

16 Storms Transposed to Watershed

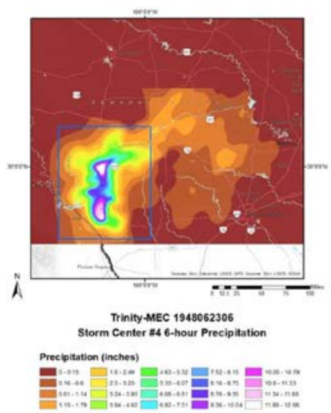


Major Advancements in Past 5-Years in Watershed Precipitation-Frequency Development

Stochastic Storm Generation for Convective Storms (2015)

Use Point PF Findings and Resampling of Spatial Patterns of Convective Historical Storms (Stochastic Storm Transposition) to Generate Watershed PF Relationship for Geographically Fixed Areas

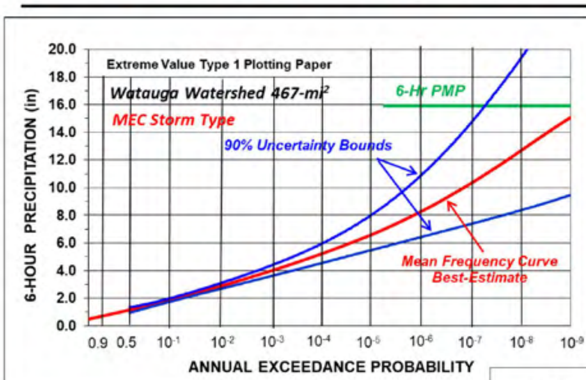
118 Historical Spatial Patterns TVA Study

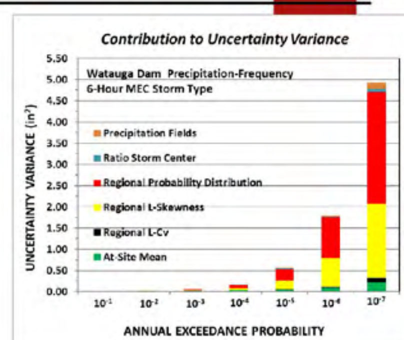


32 Historical Spatial Patterns

Trinity River, Texas Study

MEC Watershed Precipitation-Frequency Relationships





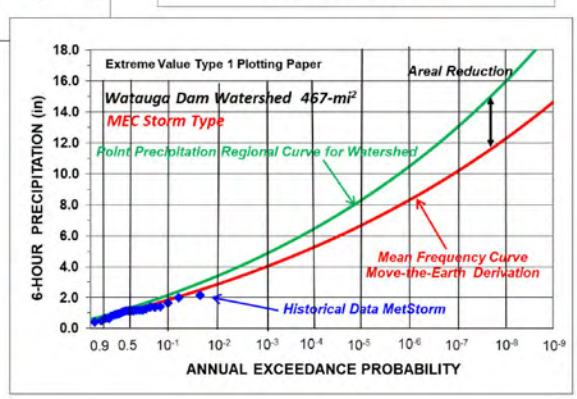
Mesoscale Storm with Embedded Convection (MEC)

340 Stations; 12,039 Station-Years

Spatial Analyses 118 MEC Storms

24 Historical Storms on Watershed

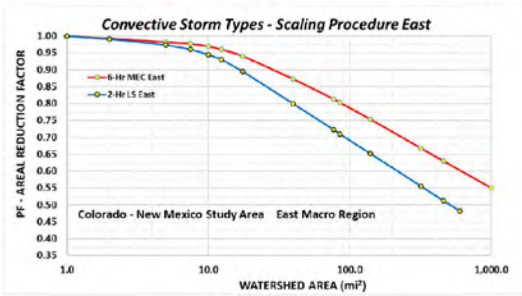
94 Storms Transposed to Watershed

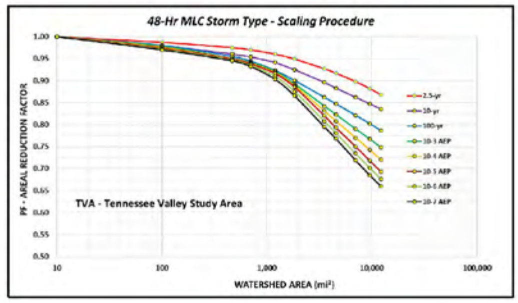


Major Advancements in Past 5-Years in Watershed Precipitation-Frequency Development

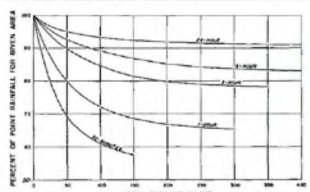
PF Areal Reduction Factors (ARFs) by Storm Type (2016-2018)

Findings from Prior Detailed Precipitation Studies
provide for Development of Precipitation-Frequency Based ARFs
for Converting from Point PF to Watershed PF for Geographically Fixed Areas





NOAA Technical Paper No 29 (1957)

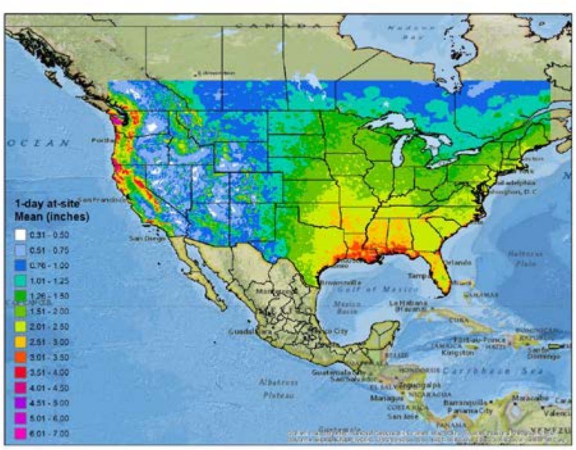


Major Advancement Over Past Practice of Applying Storm Centered ARFs

Major Advancements in Past 5-Years

Livneh Reanalysis Datasets to Augment Meteorological Inputs (2017)

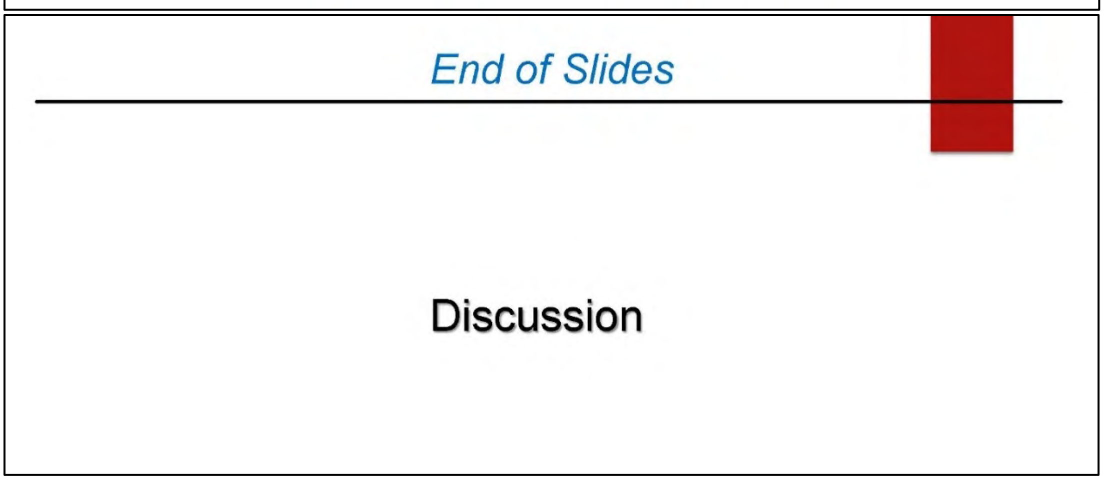
Daily, High-resolution (1/16 degree) Gridded Dataset
Across southern Canada, the United States, and Mexico
Jan 1915 to Dec 2015



Used for:

Storm Typing

Augmenting Spatial Storm Analyses and Storm Transpositions in Data Sparse Areas



4.3.3.4.3 Questions and Answers

Question:

What are the sources of data for your storm typing? You mentioned the reanalysis?

Answer:

In the early studies, we were using gauge data, basically ground-based data. TVA has a long-term network of gauges. There may be as many as 200 gages and over 100 years of record. We set up a network and then we saw that because of the various areas that we work in, the Livneh gave us a little better coverage and helped us identify whether there is a big footprint or small footprint. The other things on that list were the pressure fields, basically the surface and 850 and 500 millibars and the pressure gradients to get an idea of whether this was associated typically with an MLC with a pretty well-defined pressure field. However, I am a surface water hydrologist, and while I have had exposure to the meteorology business for a long time, I am not a meteorologist, so I have made mistakes on a couple of things. There are precipitable water fields from the reanalysis and convective available potential energy (CAPE). Then they also look at seasonality to help inform them as to the various types, when that occurs.

Follow-up Question:

So just to recap, you do have rain gauges and the analysis, or purely reanalysis?

Answer:

It depends on the location. When we did the TVA precipitation analysis, we used rain gauges. When we did the Colorado/New Mexico statewide PMP analysis, we were using Livneh to help us give the spatial footprint.

Question:

On some of the slides you presented earlier, you had both time history plots and spatial maps. Are those time series plots for a single point location within the watershed or are those spatially averaged?

Answer:

Those are at the storm center, because sometimes we presented as basin averages, and this particular dataset was given to us by MetStat.

Question (from the Webinar): This question relates to standard deviations and multiple n-series; is the procedure additive or subtracting with regard to standard deviations?

Answer:

On the variance charts, that is basically a Latin Hypercube approach, where the sources are treated as independent. So, the variances are additive.

4.3.3.5 Factors Affecting the Development of Precipitation Areal Reduction Factors.

Shih-Chieh Kao* and Scott DeNeale, ORNL (Session 1C-5; ADAMS Accession No. ML19156A461)

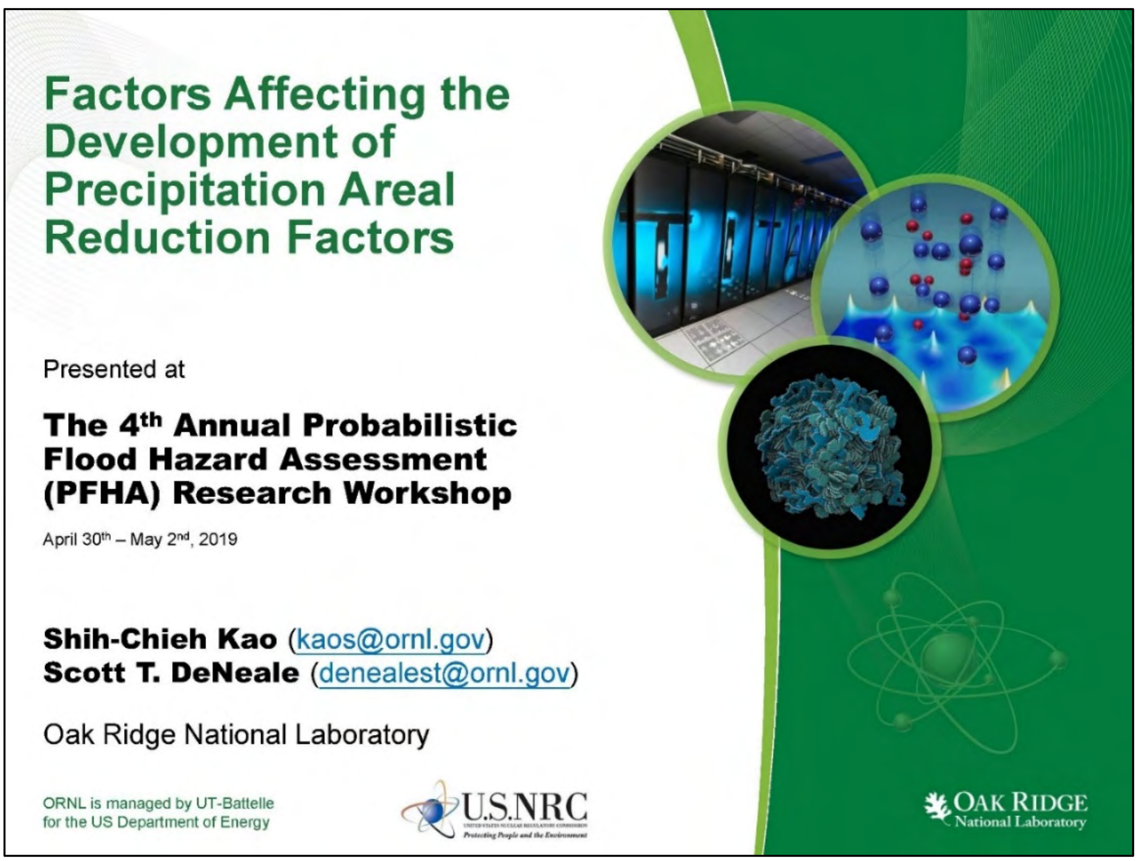
4.3.3.5.1 Abstract

Probabilistic precipitation estimates (e.g., T-year rainfall) are widely used to inform hydrologic and hydraulic simulation, urban planning, critical infrastructure protection, and flood risk mitigation. Such estimates are quantified through precipitation frequency analysis, such as those provided in the NOAA Atlas. Nevertheless, many precipitation frequency products (such as NOAA Atlas 14) only provide point precipitation estimates. For watershed-scale applications, further adjustment through ARFs is needed to establish spatially representative probabilistic precipitation estimates at a large-area size.

Compared to the modern precipitation frequency products, the progress of ARF development in the United States is lagging. Technical Paper No. 29 (TP-29) ARFs published in the 1950s are still widely used in practice. In addition to being based on limited data, TP-29 ARFs do not vary with geographic location, seasonality, or return period and are only provided for area sizes up to 400 square miles. To support the development and implementation of PFHA for U.S. NPPs, clearly the values of ARFs should be updated based on the most recent data, methods, and suitable models.

To help improve our understanding of ARFs, we conducted a comprehensive study to explore factors that should be considered during ARF development. We started by identifying multiple gauge- and radar-based precipitation data products that can be used for ARF development. We then conducted a literature review to summarize recent ARF methods that may address the deficiencies in the conventional approach. Using a watershed-based annual maximum precipitation searching approach, we demonstrated how these factors may quantitatively affect the values of ARFs for three hydrologic regions in the United States. Our results suggest that ARFs could vary widely by return periods, data sources, methods, and geographical regions; thus, there is a need to determine site-specific ARF for unbiased flood estimates. This study will provide a technical basis to help develop ARF guidance for NPP-PFHA applications. The study also demonstrates the values of modern, gridded precipitation products for computing ARFs and offers a framework for ARF evaluation with different datasets and methods.

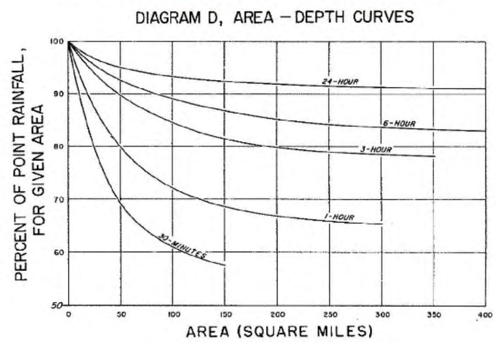
4.3.3.5.2 Presentation



Background – Areal Reduction Factors (ARFs)

- **Current precipitation frequency products (e.g., NOAA Atlas 14) are mostly developed for point rainfall**
  - Not directly applicable for many nuclear power plant H&H applications
- **Areal reduction factors (ARFs) are needed to convert these point estimates to watershed estimates for H&H modeling**
- **Use "geographically-fixed-area" ARF**
  - NOT "storm-centered" ARF
- **ARFs in common use suffer from several key limitations:**
  - Limited / outdated data
  - Small area sizes (up to 400 mi^2)
  - Do not vary with location, return period, or season

Example ARF curves (from TP-29)



Source: Technical Paper No. 29; noaa.gov

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Objectives of this Project

- **Understand and demonstrate how ARFs may vary when using different precipitation data products and ARF methods across different geographical locations, durations, areas, return periods, seasons, and etc.**
  - Task 1: Provide a summary of available precipitation products that can be used to develop ARFs.
  - Task 2: Provide a critical review of available ARF methods with a view to addressing the deficiencies in the commonly used empirical methods.
  - Task 3: Demonstrate use of the most promising method/dataset combinations through selected test cases.
- **Support Nuclear Regulatory Commission (NRC) on the development of future Probabilistic Flood Hazard Assessment (PFHA) guidance on ARFs used by NRC licensees**

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Study Approach

- **Factors affecting ARFs**
  - Area, duration, and return period
  - Different ARF methods
  - Precipitation products to use
  - Geographical locations
  - Seasonality
- **Case study application**
  - Regional comparison
    - 3 hydrologic regions (HUC02), 5 precipitation products, and 6 ARF methods
  - National comparison
    - 18 hydrologic regions (HUC02), 1 precipitation product, and 1 ARF method
- **Evaluation through fitting statistics (e.g., NSE, RMSE, R^2)**
- **Only consider "geographically-fixed-area" ARF**

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Visualizing Spatial and Temporal Rainfall

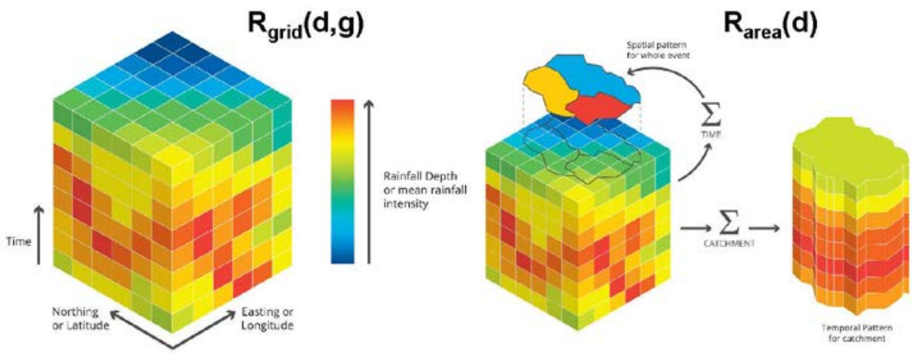
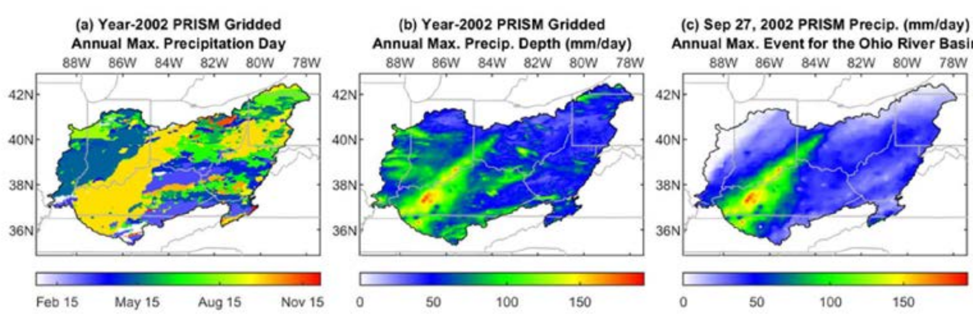


Image Source: Australian Rainfall and Runoff: A Guide to Flood Estimation http://book.arr.org.au.s3-website-ap-southeast-2.amazonaws.com/



Precipitation Products

Precipitation Products	Provider	Dataset Type	Coverage Start	Coverage End	Data Latency	Spatial Coverage	Temporal Resolution	Spatial Resolution
Gauge-only Datasets								
Hourly Precipitation Data (DSI3240)	NOAA National Centers for Environmental Information (NCEI)	Gauge observation	1940	2013	Data since 2014 have not been released (checked 10/17/2017)	U.S. (including AK, HI, PR)	Hourly	Gauge
Gauge-driven Products								
Daymet version 3 (Daymet)	Oak Ridge National Laboratory (ORNL)	Gridded from gauge observation	1980	2017	Annual update	North America	Daily	1 km * 1 km
Daily PRISM Dataset (PRISM)	Oregon State University	Gridded from gauge observation (and partially with radar)	1981	present	Operational (updated automatically)	U.S. (48 states)	Daily	1/24 deg * 1/24 deg (~ 4 km * 4 km)
Livneh CONUS Near-surface Meteorological Data (Livneh)	University of Colorado, Boulder	Gridded from gauge observation	1950	2013	No scheduled update (checked 10/17/2017)	U.S. (48 states), Mexico, & Canada (south of 53N)	Daily	1/16 deg * 1/16 deg (~ 6 km * 6 km)
Radar-driven Products								
NCEP National Stage IV Analyses (ST4)	NOAA National Centers for Environmental Prediction (NCEP)	Merged radar and gauges (with QC)	2002	present	Operational (updated automatically)	U.S. (48 states), excluding California-Nevada & Northwest RFCs	Hourly	4 km * 4 km

- These precipitation products exhibit long temporal coverage, broad spatial coverage, and sufficient temporal/spatial resolution.
- DSI3240 is only analyzed for Region 05 (Ohio).

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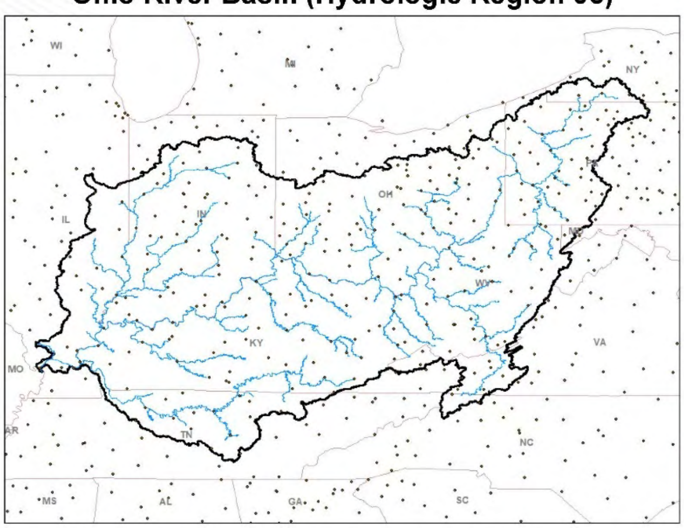
DSI3240 Assessment Approach

Ohio River Basin (Hydrologic Region 05)



***Dots illustrate NCEI hourly rainfall stations which have 30+ years of record**

- **Process 1950–2013 hourly precipitation dataset**
  - 64 years of data
- **Bilinear interpolation of non-missing hourly precipitation to 4-km PRISM grids**
  - Acceptable in the Ohio region given smoother topography. Topographic adjustment shall be needed in other regions.
- **Analyze ARF using the existing PRISM setup**

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General Assessment Procedures

- **Annual maximum series (AMS) searching**
  - *Data*
    - PRISM (1981–2017), Daymet (1980–2017), ST4 (2002–2017), Livneh (1950–2013), DSI3240 (1950–2013)
  - *Duration*
    - All: 1-day, 2-day, 3-day
    - Additionally for ST4 & DSI3240: 1-hr, 2-hr, 3-hr, 6-hr, 12-hr, 18-hr
  - *Season*
    - All season, Warm season (May–Oct), Cool season (Jan–Apr, Nov–Dec)
  - *Grid AMS* (P_{grid}): annually at each grid
  - *Areal AMS* (P_{area}): annually at each HUC08, HUC06, HUC04, HUCac
- **Sample ARF at each areal units (HUCs)**
  - Average AMS
    - (Temporal average of P_{area}) / (Temporal and spatial average of P_{grid})
  - T-year estimate
    - Fitting AMS by GEV, and getting T-year estimates (e.g., $P_{area,10yr}$)
    - $P_{area,Tyr}$ / (Spatial average of $P_{g11,Tyr}$)
- **Regional fitting by different ARF models**

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Sample ARF Calculation

- **R_{grid}(d,g)**
  - **Daily rainfall at each grid**
  - *d*, a day
  - *g*, a grid location within an Area
- **P_{grid}(y,g)**
  - **Annual max. rainfall at each grid**
  - $P_{grid}(y,g) = \max_{d \in y} R_{grid}(d,g)$
  - *y*, a year
  - N_y, total number of years

- **R_{Area}(d)**
  - **Daily rainfall at each Area**
  - $R_{Area}(d) = \frac{\sum_{g \in H} R(d,g)}{N_H}$
  - *H*, the set of all *g* within an Area
  - N_H, number of grid points in an Area
- **P_{Area} (y)**
  - **Annual max. rainfall at each Area**
  - $P_{Area}(y) = \max_{d \in y} R_{Area}(d)$

- **Sample ARF of average AMS**
  - $P_{grid,avg1}(y) = \frac{\sum_{g \in H} P_{grid}(y,g)}{N_H}$
  - $P_{grid,avg2} = \frac{\sum_{y=1}^{N_y} P_{grid,avg1}(y)}{N_y}$
  - $P_{HUC,avg} = \frac{\sum_{y=1}^{N_y} P_{HUC}(y)}{N_y}$
  - $ARF_{AMS} = \frac{P_{HUC,avg}}{P_{grid,avg2}}$

- **Sample ARF of T-year estimates**
  - $P_{grid,Tyr}(g) = GEV(P_{grid}(y,g), Tyr)$
  - $P_{grid,Tyr,avg} = \frac{\sum_{g \in H} P_{grid,Tyr}(g)}{N_H}$
  - $P_{Area,Tyr} = GEV(P_{Area}(y), Tyr)$
  - $ARF_{Tyr} = \frac{P_{Area,Tyr}}{P_{grid,Tyr,avg}}$

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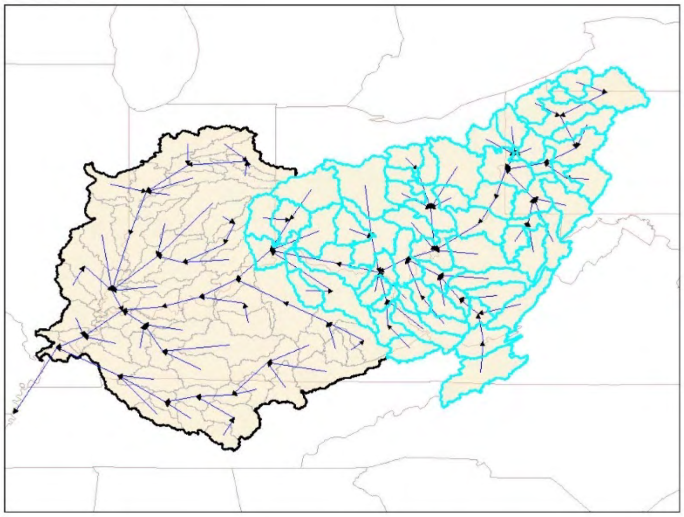
Watershed-based AMS Searching Approach



- **Increase AMS samples to cover a wider range of watershed sizes**
- **Define additional spatial unit HUCac based on watershed connectivity**
  - For each HUC08, using its connectivity with other HUC08s to identify the entire upstream contributing watershed as HUCac
  - Use HUCac to search AMS
- **Use HUC08, HUC06, HUC04, and HUCac AMS to fit different ARF models**
  - 120 HUC08: 290 – 840 km^2
  - 21 HUC06: 4,400 – 54,000 km^2
  - 7 HUC04: 15,000 – 85,000 km^2
  - 46 HUCac: 4,600 – 420,000 km^2

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Selected ARF Models

- **Empirical Methods**
  - M1: Leclerc & Schaake (1972) – fitted formula of US Weather Bureau TP-29

$$ARF(A,D) = 1 - e^{aD^b} + e^{(aD^b - cA)}$$

  - M2: Koutsoyiannis and Xanthopoulos (1999) – fitted UK-NERC ARF relationship (NERC, 1975)

$$ARF(A,D) = 1 - \frac{aA^{(b-c\ln A)}}{D^d}$$

  - M3: Hydrological Atlas of Switzerland Model (Grebner et al., 1998)

$$ARF(A) = \frac{a_0}{(A+a_2)^{a_1}} + a_3 e^{-a_4 A}$$

  - M4: Australian Rainfall & Runoff (ARR) Guideline (Nathan and Weinmann, 2016)

$$\begin{aligned} ARF(A,D,AEP) &= 1 - a\left(A^b - c\log_{10} D\right)D^{-d} \\ &+ eA^f D^g (0.3 + \log_{10} AEP) \\ &+ h10^{iAD}(0.3 + \log_{10} AEP) \end{aligned}$$

- **Dynamic Scaling Model**
  - M5: De Michele et al. (2001)

$$ARF(A,D) = \left[1 + w\left(\frac{A^z}{D}\right)^b\right]^{-v/b}$$

- **Extreme Value Theory**
  - M6: Overeem et al. (2010)

$$\begin{aligned} ARF(A,D,AEP) &= P(A,D,AEP)/P(A^*,D,AEP) \\ P(A,D,AEP) &= GEV^{-1}(1 - AEP|\mu,\gamma,\kappa) \\ \mu(A,D) &= aD^b + (c + d\ln D)A^e \\ \gamma(A,D) &= f\ln A + g\ln D + h \\ \kappa(A) &= i\ln A + j \end{aligned}$$

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M5: De Michele Dynamic Scaling Model

- **De Michele et al. (2001) and (2011)**
  - Uses the concepts of dynamic scaling and statistical self-affinity to find a general expression for the mean annual maxima precipitation as a function of the rainfall duration and area
- $ARF(A,D) = \left[1 + w\left(\frac{A^z}{D}\right)^b\right]^{-v/b}$
  - A, area (km^2)
  - D, duration (hr)
  - Four parameters: v, b, w, z
- **ORNL Fitting**
  - Minimize the root mean square error (RMSE) between ARF samples and ARF model using Matlab *fminsearch* function (Nelder-Mead simplex algorithm; Lagarias et al., 1998)
  - Performance evaluated by Nash–Sutcliffe efficiency (NSE)
  - (4 fitted parameters) * (# of frequency levels)

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Preliminary Results

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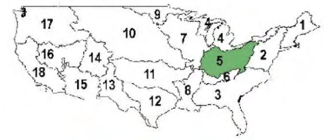
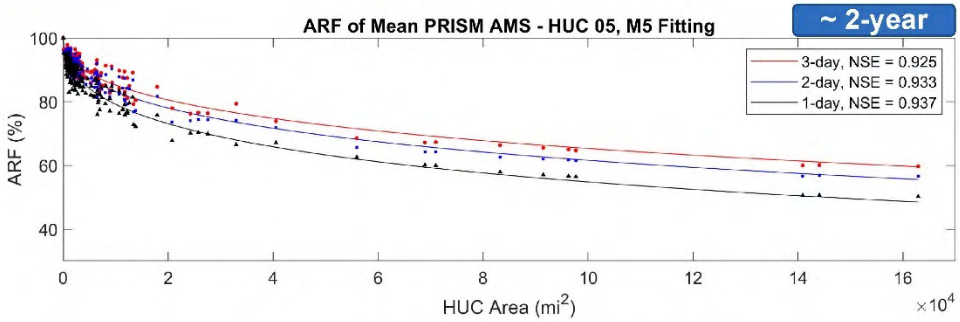
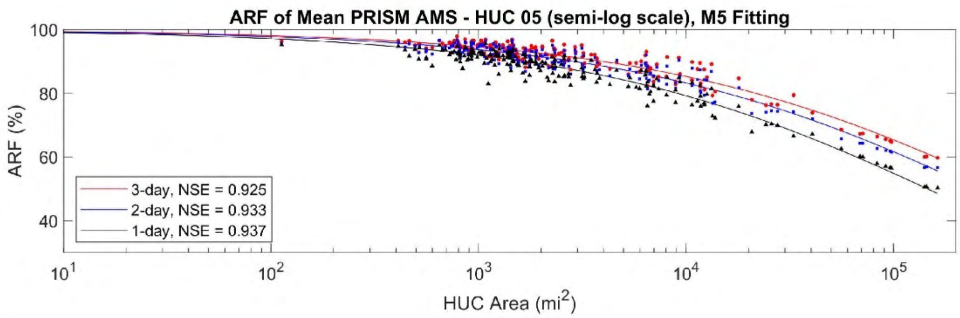
M5: De Michele Dynamic Scaling Model

- Data: PRISM (all seasons)
- Duration: 1-day, 2-day, 3-day
- Frequency level: AMS, 10-year, 100-year
- ARF Fitting: M5







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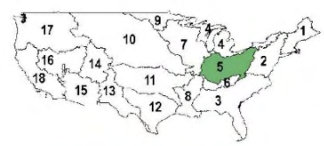
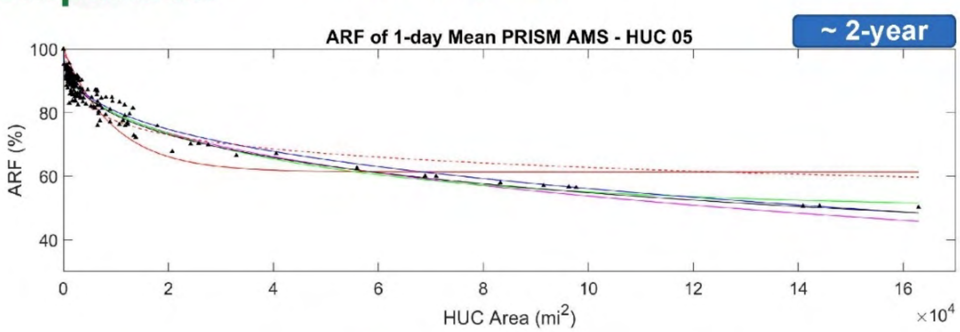
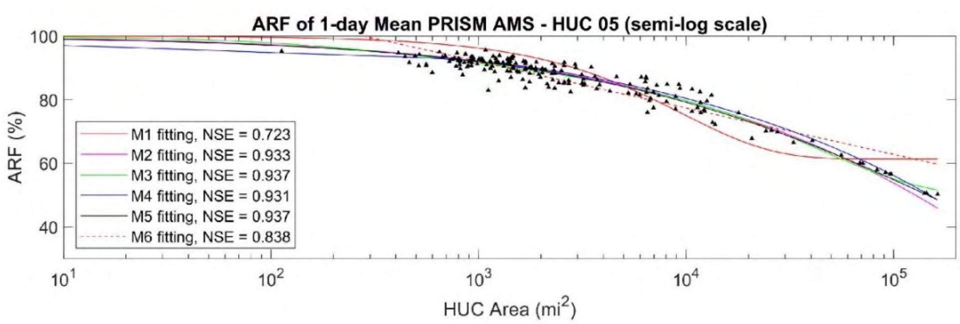
Region 05 Overall M1–M6 Comparison

- Data: PRISM (all seasons)
- Duration: 1-day
- Frequency level: AMS, 10-year, 100-year
- ARF Fitting: M1–M6







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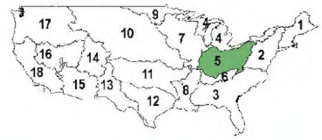
Region 05 Overall M1–M6 Comparison

- Data: PRISM (all seasons)
- Duration: 1-day, 2-day, 3-day
- Frequency level: AMS, 10-year, 100-year
- ARF Fitting: M1–M6



Duration	NSE					
	M1	M2	M3	M4	M5	M6
	Average AMS (approximately 2-year)					
1-day	0.72	0.93	0.94	0.93	0.94	0.84
2-day	0.76	0.93	0.93	0.93	0.93	0.78
3-day	0.75	0.92	0.93	0.92	0.93	0.69
	10-year					
1-day	0.70	0.91	0.91	0.91	0.91	0.82
2-day	0.69	0.89	0.90	0.89	0.89	0.68
3-day	0.73	0.90	0.91	0.91	0.91	0.61
	100-year					
1-day	0.48	0.66	0.67	0.66	0.66	0.60
2-day	0.44	0.67	0.67	0.67	0.67	0.38
3-day	0.60	0.78	0.79	0.79	0.78	0.45

*Red cell highlights NSE < 0.5

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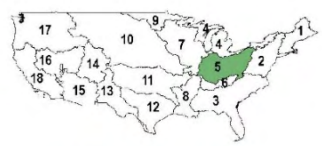
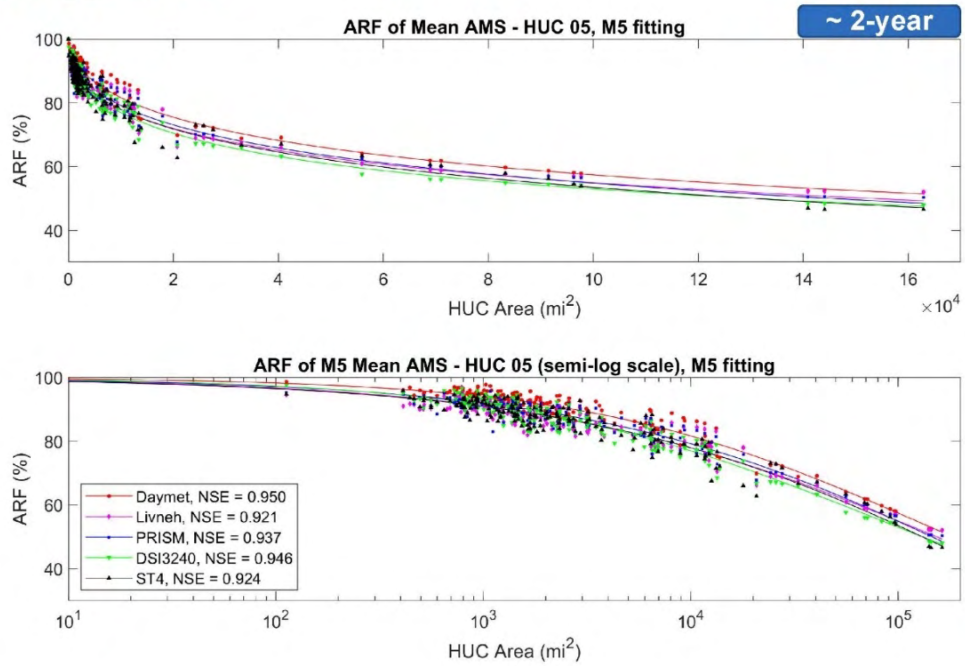
Region 05 Data Source Comparison

- Data: All (all seasons)
- Duration: 1-day
- Frequency level: AMS, 10-year, 100-year
- ARF Fitting: M5



~ 2-year



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Region 05 Data Source Comparison

- Data: All (all seasons)
- Duration: 1-day, 2-day, 3-day
- Frequency level: AMS, 10-year, 100-year
- ARF Fitting: M5

Duration	NSE				
	PRISM (1981–2017)	Daymet (1980–2017)	ST4 (2002–2017)	Livneh (1950–2013)	DSI3240 (1950–2013)
	Average AMS (approximately 2-year)				
1-day	0.94	0.95	0.92	0.92	0.95
2-day	0.93	0.95	0.92	0.93	0.93
3-day	0.92	0.94	0.92	0.93	0.93
	10-year				
1-day	0.91	0.93	0.89	0.91	0.93
2-day	0.89	0.92	0.88	0.92	0.92
3-day	0.91	0.93	0.87	0.91	0.91
	100-year				
1-day	0.68	0.74	0.35	0.80	0.85
2-day	0.70	0.74	0.39	0.77	0.80
3-day	0.80	0.82	0.36	0.82	0.80

*Red cell highlights NSE < 0.5

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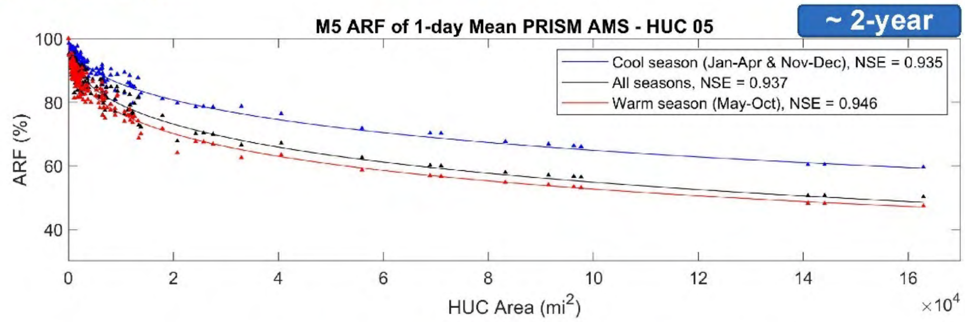
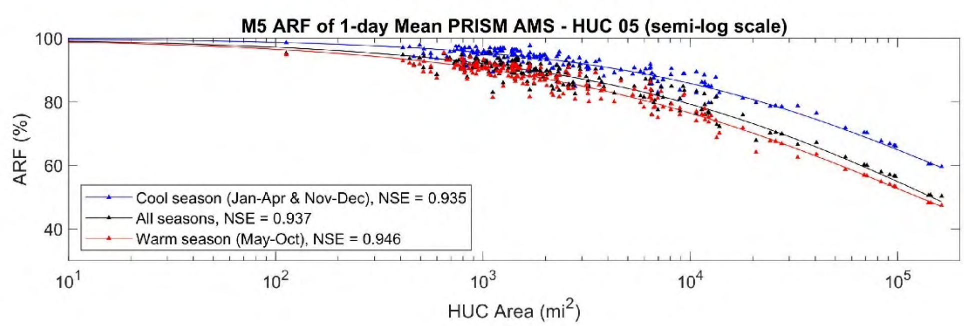
Region 05 Seasonal Variability

- Data: PRISM (all, warm, cool)
- Duration: 1-day
- Frequency level: AMS, 10-year, 100-year
- ARF Fitting: M5

~ 2-year





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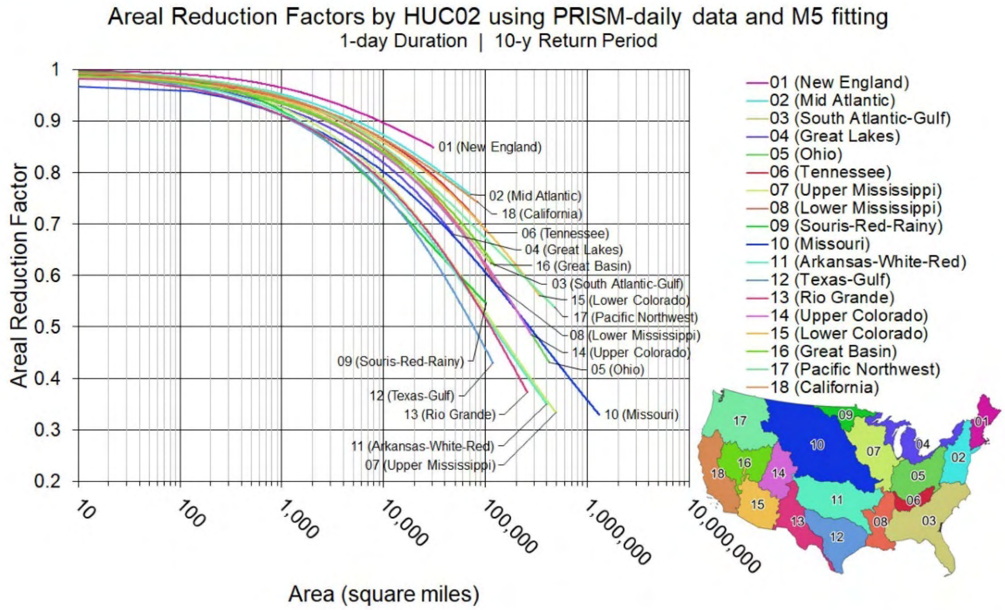
National Comparison (I)



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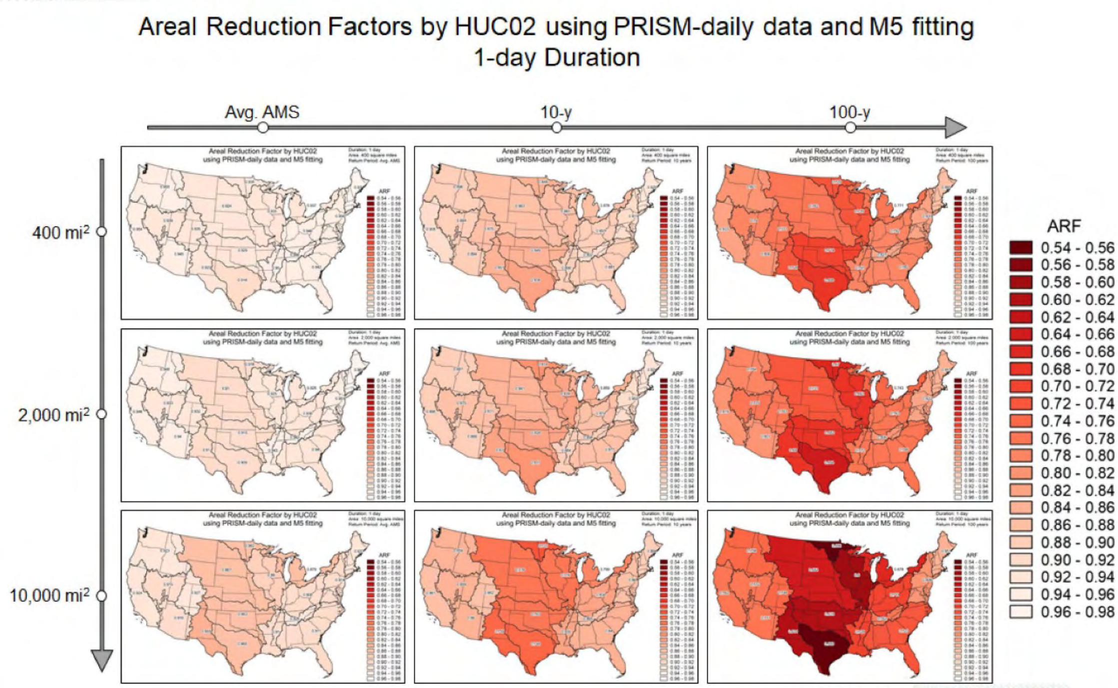
National Comparison (II)



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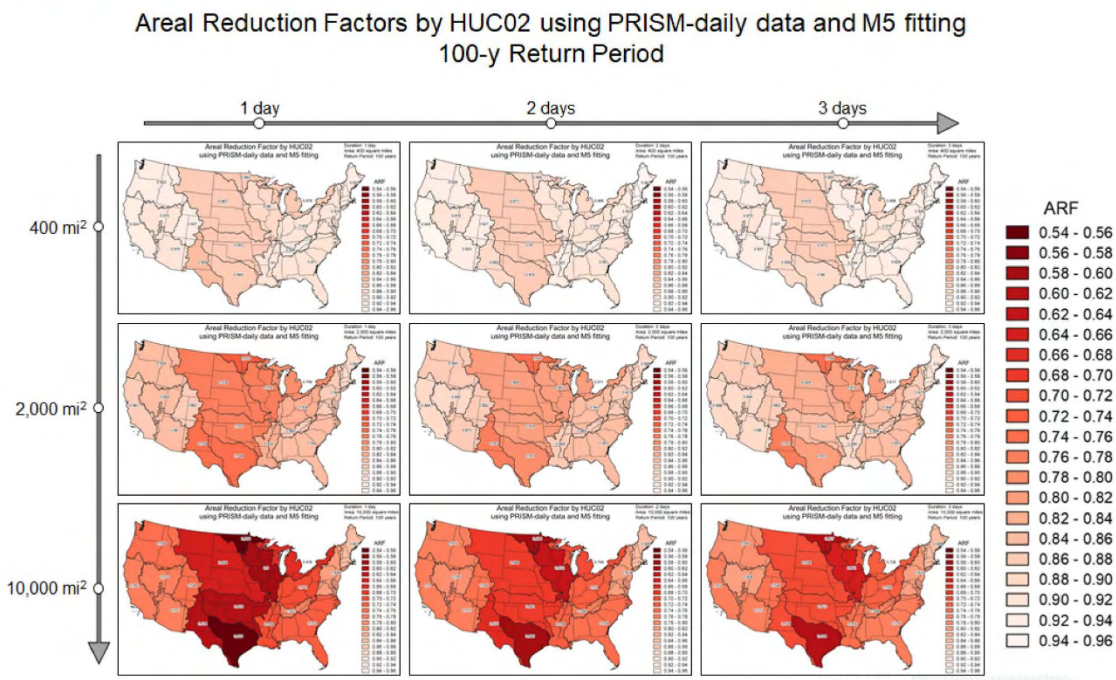
National Comparison (III)



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Preliminary Observations (I)

- **General**
  - Shorter duration, lower ARF
  - Larger area, lower ARF
  - Higher return period, lower ARF
  - Cool season ARF > All season ARF > Warm season ARF
- **Regarding ARF methods**
  - Different ARF methods matter
  - M2 (K&X), M3 (Switzerland), M4 (ARR), and M5 (De Michele) provide better fitting.
  - While M3 (Switzerland) can fit well, it does not include duration as a variable and hence can be more sensitive to sample size and data quality.
  - M4 (ARR) is more difficult to fit (8 parameters), but it includes frequency levels in the model and can be overall more robust.
  - M5 (De Michele) can fit well and has a good underlying theory.
  - While M6 (GEV) has a good underlying theory, it's more challenging for the ARF application. Further ad hoc adjustment is needed.

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Preliminary Observations (II)

- **Regarding data sources**
  - Smaller ARF differences are found, but the differences are not negligible.
  - Data length plays an important role, especially for higher return level ARFs.
  - Difficult to fit one set of parameters for both longer and shorter durations.
  - While gauge data is harder to process, it leads to the best ARF model fitting in Region 05.
- **Regarding inter-regional differences**
  - ARFs are lower in the central US, higher in eastern & western US
  - Texas-Gulf (R12) & Souris-Red-Rainy (R09) are generally the lowest.
- **Overall**
  - The proposed HUCac watershed AMS searching approach work across different regions.
  - High return level ARF remains a major challenge, mostly due to relatively short data record length.

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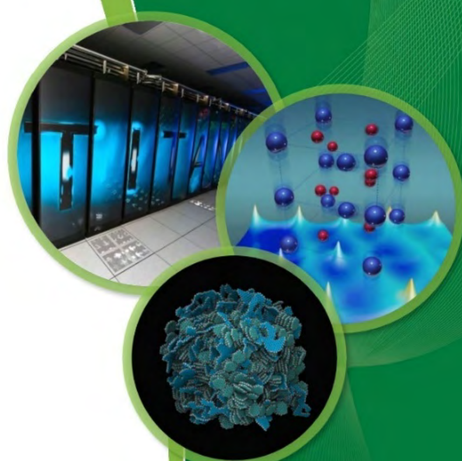
Thank you!

Questions?



Shih-Chieh Kao (kaos@ornl.gov)
Scott T. DeNeale (denealest@ornl.gov)

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4.3.3.5.3 Questions and Answers

There were no questions.

4.3.3.6 Precipitation Panel Discussion. (Session 1C-6)

Moderator: Elena Yegorova, NRC/RES/DRA/FXHAB

George J. Huffman, NASA/Goddard Space Flight Center (GSFC)
Shih-Chieh Kao, Oak Ridge National Laboratory (ORNL)
John England, USACE, Risk Management Center
Mel Schaefer, MGS Engineering Consultants
Guest Panelist: Kevin Quinlan, NRC/Office of Nuclear Regulatory Research (NRO)

Moderator:

To begin, do the panel members have any questions for each other? Everyone is from very different backgrounds—we have satellite scientists, some from PMP work, and an NRC staff member. Do you have any questions?

Moderator:

Shih-Chieh Kao ended his presentation with a very good point. We are very much limited by data availability, both spatially and temporarily. How do we deal with performing these estimates for AEPs for very low frequency events? I think this is a challenge for many years and decades for all of us. How do we deal with this?

John England:

Mel Schaefer referred to “space for time.” In terms of storm typing, I look to our meteorology staff, since I am the hydrologist, to imagine what are the ingredients to cause really big extreme rainfalls that cause big floods, at least for the dam/levee safety program that I work for at USACE, which is still about floods. Those ingredients and scaling up: some of the parts that are basics behind PMP. We may not be using them deterministically, but putting those ingredients in models; whether it's space for time or strong transposition, and getting physical insights from the numerical model is their key pathway towards that, as well as synoptic scale observations and looking at anomalies.

Mel Schaefer:

The term “space for time” is used quite a bit; some have a good feel for it, while others do not. I think the easiest way to think about it is that in most minds, when you first glance at the problem, you note that we have 50 or 60 years of record. So how do we get to one in 100, 1,000, or 10,000? The slides for our work for TVA show that we are using over 1,000 stations, over 50,000 station-years of record. We’re doing not only the state of Tennessee, but the five surrounding states. We’re looking at a very massive area that we’re taking data from. When you actually look at the datasets, you might have 50 or 60 years of record. In the case of TVA, we had a number of stations, maybe as many as 100, with over 100 years of record. But still what you’re trying to do is get out to one in 1,000 or one in 10,000. But the reality is that PF, when you do the point analysis, is obviously based at that particular point. The reality is that these storms are happening spatially, somewhat randomly throughout that area. The easiest place to see it is on thunderstorms. As an example, on the thunderstorms, most people here would agree that the weather forecasters have a hard time predicting out a couple of days. If you just ask what's going to happen 3 weeks from now in a thunderstorm at a city 60 miles away, you do not have a chance if they are independent events. If you change your perspective to thinking about a thunderstorm, a local-scale thunderstorm or even a mesoscale event with embedded convection, each one of those represents a unique observation or realization of how these things take place. When you look at the dataset, something like the TVA dataset, you might have 80 or 100 or 90 events in a single year at different locations randomly. If each one is treated as an independent event because we cannot, from a statistical standpoint, predict what will happen 2 or 3 weeks from now on these very large areas, the result is an independent record length. When you perform "independent equivalent record length" (ERL) and consider such things as storm dates and go through the dataset and look at annual maximum events at those dates, you find that Tennessee had something like an ERL of 4,000 or 5,000. In other words, there were 5,000 separate storm dates over a 70-year period when these thunderstorms have happened. So again, if you change your perspective and are not interested in this location but are interested in the thunderstorm phenomenon and its characteristics, you now have 5,000 realizations of what that looks like. If that is true and we have a way to normalize it by standardizing by the mean at a given location, in an index flood-type approach, we now have an ability to actually have a pretty large dataset to estimate things such as the upper moments like coefficient of L-variation and probability distributions, and so forth. That becomes more problematic as we get down to these really large-scale events because we have fewer of them in a given year—like an MLC or tropical storm, we may only have a couple of them, like in the Tennessee Valley area. Formerly, we just looked at correlation structures. However, with the correlation structure, an ERL used to be performed using drought effect. If you have a drought, and I have an annual maximum and a number of stations in drought, it is increasing the correlation when, in fact, it has nothing to do with big storms in which we are interested. Also, some years you get a little bit more from randomness, you get combinations where more stations in that particular area have a larger event. So, the correlation approach typically used in the past is not a good way to obtain the ERL. Swapping space for time is big, go to storm typing to get information on the homogeneity in the region. Then when we start to get on the spatial and temporal patterns, we are using storm transposition to move it from one location to another. Again, for all of these things, we're trying to get big samples to reduce sampling variability and get more realizations of what these things look like.

Moderator Question:

As far as storm transpositioning, how do you treat that in your analysis or situation?

Shih-Chieh Kao:

I additionally want to say that using numerical weather forecasting models, as John England mentioned, has a good potential as well. If you think that that means we should use numerical weather forecasting models that give you the rainfall depth, it is quite the opposite, as we know that it is not mature yet. But many of the features, like storm structure or reaction to the topography, can be resolved quite nicely in numerical forecasting models with some initial condition perturbation. I think certainly that can be done as well.

John England:

I want to add a comment for those who aren't aware. Mel Schafer said in his presentation that sometimes the research in the practical aspects is shown in conference papers. This is the case for the Colorado/New Mexico extreme precipitation study. If you have gone to the Association of

Dam Safety Officials Workshop, you may be aware of some of the work. The dam safety officials for Colorado and New Mexico put together a team to answer three questions in three different areas. I served on a board of consultants in one part. One task was for the NOAA Earth System Research Laboratory (ESRL), run by Robin Webb in Boulder. Their team looked at bringing HRRR (NOAA High-Resolution Rapid Refresh model) into the analysis. Task 1 was to do PMP across the two States. Mel Schaefer described Task 2 a little bit on precipitation frequency. Task 3 was the NOAA part; that is, how do we bring HRRR into the conversation, describing how you can get thunderstorm triggering on the very high elevations in Colorado and New Mexico and look at those spatial and temporal aspects. It was their attempt at the time to bring in numerical models to part of the picture.

Mel Schaefer:

As a follow-on to that, we actually used the NOAA HRRR model and simulations that they have done on spatial patterns as part of our resampling approach for stochastic storm transposition. Storms that we used were a combination of actual storms that had historically occurred for which we had a combination of gauge data and our radar data. Some of them were from the spatial patterns from the HRRR model, so that was augmented. We used the Weather Research Forecasting (WRF) model to try to recreate some historical events for which there were questions about the accuracy of some of the point measurements. One interesting aspect of PMP is that the Smethport Storm was driven by precipitation. Billions and billions of dollars have been spent on dams with regard to spillways, and so forth, based on preset collected in a pickle jar. Storms in the Cherry Creek in Colorado were based on what's happened in a harsh trough. One of the storms was the Rattlesnake Storm, and there were concerns about it. A rancher measured a certain amount, and researchers were trying to help verify the validity of it. The WRF is also something that has been used, and that I see will likely continue to be used in the future.

George Huffman:

The traditional way of looking at precipitation is in an Eulerian framework would be: there is a physical location (referred to as a station): how much precipitation occurred and how much precipitation was possible? But thinking about the storm in a Lagrangian aspect is starting to be reflected within the field: you can hear it in the discussion in this panel. But just to be really explicit, the storms don't care where they are, except with regard to topographic forcing. Lacking the topographic forcing, if you think about an event like Hurricane Harvey, it wasn't necessarily the most extraordinary rainfall rates. The issue was that the rates happened in the same place. If you get off of the Eulerian framework and think more about what the systems are doing: what's the probable maximum of the system? There's a separate question of whether, by chance, they will line up in the same place. With regard to some of the recent flash flood events near here, there was training, and so the rates were not that extreme, but they happened in the same place. The question is, can we get to the point where we are looking at system rates, and then apply them spatially and in limiting cases? How long did they last in the same place because of either training or redevelopment or something else?

Moderator:

I agree with you. Also, antecedent moisture conditions are very important as well. I think, personally and professionally, that numerical weather models are the way to the future, because you can have all of those factors in your model: soil moisture, some the physically based atmospheric processes going on, and also ingesting some of the reanalysis data. So honestly, numerical weather models are the way to go. We had a project that ended last year working on that, and I hope we will see more of that work going forward.

Question:

This is a question for Mel Schaefer about storm typing. In your presentation, you gave some of the ingredients—the things you are looking at, the pressure gradients, and the different isobars. What happens once you have all that? You mentioned a manual for training, but ultimately, there is an automated system. I assume it is some sort of regression-based algorithm of logistic regression or multiple linear regression?

Mel Schaefer:

This is a topic for the meteorologists. However, when the NRC sends out the slides, I will include Web links to a lot of the different technical memoranda and reports that contain specific information about those kinds of aspects. But a lot of the things on the storm typing are threshold based. As an example, certain aerial coverage with regard to the storm sets a threshold, whether it is synaptic scale, mesoscale, or local scale. Certain levels of CAPE identified whether there was really enough convection that particular day that would suggest that, in fact, it was a convective event in that there was embedded convection inside of the event. So, a lot of it is threshold based. While I do not remember the pressure gradients, there was a certain level of pressure gradient suggestive of a synoptic system moving through that was used as a threshold that also helped indicate a storm type. And so, there was a logic tree. A diagram in the back of the TVA report, which I will give a Web link[11] for, shows the logic and the thresholds that were used to come up with that system.

Moderator:

A lot of groups are working with huge datasets and doing all these analyses for the same time and types of storms. When you are working with your project, how do you deal with that computationally intensive difficulty of working with these huge meteorological datasets but still preserve the resolution, accuracy, and temporal and spatial resolution of the data?

John England:

USACE-specific projects for the dam and levee safety program are triggered by the type of decision being made. We have a hierarchy from some very simple screening level, called periodic assessments, for the dam safety program. They just grab existing information, so the short answer is none of the above. You can use TP-29, for example, even though we don't agree in the field on TP-29's application, and we think we could do better. Then the next level is initial evaluation, where we are trying to make a decision on some major dams. We can go into something like storm typing, where we can probably share the Trinity River study report. Another consideration is the team's ability to handle some of the PF output. Getting into the hydrologic models, we tried to streamline, for that particular study, the product the contractors delivered to USACE. The country is managing a bit more on the data side in the analysis. The handoff was the precipitation estimates and the spatial temporal patterns into Hydrologic Engineering Center Watershed Analysis Tool (HEC-WAT), which we will hear a little bit about tomorrow. There are

[11] http://www.mgsengr.com/downloads/RegionalPrecipFrequencyReports_2019.zip

some things in between there, such as research projects, that indicate we will make an advance to get a better ARF (hopefully working with ORNL).

Mel Schaefer:

The datasets are mostly during the analysis stage. On the hydrological side, we have consolidated everything down to much more manageable pieces for the modeling. As an aside, how do you get out to 10^{-7} or 10^{-8} type of things just from the standpoint of sampling? One of the things that we use is total probability theorem, and George Kuczera from Australia put together a procedure whereby we can use stratified sampling across the watershed, precipitation range, and then sample the other inputs to it. To get to 10^{-8}, we might need a sample run of 10,000. So, we might be completing 10,000 floods, with a stratified sample from precipitation and then run Monte Carlo on all of the other inputs that go with it. In some cases, we'll use a Latin Hypercube approach and in other cases use just straight Monte Carlo.

Shih-Chieh Kao:

First, I want to say that maybe those problems are more challenging because there's more to the application. From the ORNL perspective, the kind of research we are supporting is usually on a national scale and tries to provide national insights. Therefore, we try to use the highest resolution model possible to drive our insight analysis. Today, we try to be as realistic as possible. But the type of work we are doing is not yet for a site-specific application.

John England:

USACE's Angela Durham, in the Northwest Division in Portland, OR, is working on a project in the Columbia River Basin. Soon, I think USACE will release a public Web page that will be useful for operational folks through the division. USACE has processed and used the Web application to deliver frequency-based snow water equivalent grids, for example. USACE is also aiming for PF grids. These could be used in the rainfall-runoff models trying to simplify a little bit of the translation from the meteorological atmospheric side to the production side of hazard curves, or flood forecasting and predictions. USACE's goal is to supply this to anyone in the Pacific Northwest for their use in any way they see fit. The aim is for flood risk management for the Columbia River Basin.

Question:

George Huffman was talking about looking at systems that go through a watershed. You talked about the Tennessee River Valley and also the Ohio River Valley. But you did not discuss land forms and the role of orographics and the direction of the storm. You mentioned storm training. What is the relationship between geomorphology, land form, and storms? When you divide them into types of storms, how do you go about doing that with regard to landforms in the upper watershed and certain basins and mountainous regions? What about east-facing or north-facing landforms?

George Huffman:

Well, the shorter answer is badly. When I was in graduate school, a paper by Rich Pastorally, an undergraduate student, looked at rainfall over the Berkshires in New England. If you know the Berkshires, you wonder, so what? With the radar at the Massachusetts Institute of Technology, it turns out that you can see the differences between the storms where the airflow was from the east, which is upslope of the Berkshires, and then the topography slopes into the Connecticut River Valley, where the flow is from the south where the storm was going up the river valley. If you were riding a bike, you would notice some elevation change. Otherwise, it is minimal. Even the Berkshires are experiencing orographic precipitation. In terms of the satellite estimates, it is really a zero-order problem that is a current area of research. In terms of the gauge analysis, models like PRISM try to do this. When you start down this path, meteorologists always end up doing little toy models. We should be doing a real model, except real models have other problems because you must deal with microphysics. This is current research that we have not figured out yet. One of my colleagues in Japan has done some nice work. Maybe you can get away with characterizing the vertical stability of the atmosphere. Because if you look in South Asia at the Western Ghats, you had one kind of response to orographic forcing, as opposed to western mountains along the coast of Myanmar (Burma). It turned out to be the static stability. PRISM is probably as close as we have right now. But the method is climatological, so if the wind is from a different direction, you are back to the same problem with the Berkshires. If the wind is now going up the Connecticut River Valley, you have a different answer. You need a conditional climatology. But no one is doing that, as far as I know.

Mel Schaefer:

Most of the advances on the hydrology side in the last 6 or 7 years have been primarily because we got out of our silo and started talking to meteorologists and trying to incorporate more reality aspects of how systems actually work and using combinations of data and information from them. That is where most of the advancements have taken place that will continue to be shown in the future.

Moderator:

One of the challenges I have had as an atmospheric scientist is the definition of the word “extreme.” We're talking about extremes in the climate modeling space and extremes for dam safety and extremes for nuclear. There’s no definition for extreme, but the term is used in publications.

John England:

I think I may have a slide on this tomorrow when I will talk about Bulletin 17C. For normal, large, and extreme, the best illustrative cartoon, at least on the hydrology side, is from our friends in Australia. They have a nice graph on a frequency curve that shows large to extreme and further definitions for floods primarily for dam and levee safety. So, extremes usually on the order of 10^{-3} and smaller, 10^{-6}, annual probabilities.

George Huffman:

I would like to take one step into the future, from my perspective. Many satellite estimates these days are made with what are called Bayesian schemes. It’s as if you are looking at the distributions, except then they give you the most probable value, which means you will never come up with an estimate of the rare event because you are always given the most probable value. I have encouraged Chris Kummerow, who is in charge of GPROF (the GSFC profiling algorithm) to blow up the system and tell me the spread. Now he actually has a spread distribution, but its meaning is not clear. But we are having a very serious discussion in the satellite community that the next generation, which actually was intended to solve the uncertainty problem, will give an estimate of the distribution and not a single number. Now, for certain classes of users, you still need a single number. But the really interesting question is when do we start to make estimates from satellites of the probability distribution and then propagate that forward, as opposed to giving one number then trying to make up what the uncertainty must be? I have just laid out 10 years of research, probably. But I think it that has some really interesting features. From the standpoint of the community, it really cares about what the extremes are. If we can start to talk about the real uncertainty and precipitation estimates, where uncertainty is not just in the abstract, in a given synoptic situation, these all look the same. But sometimes you get a lot and sometimes you get a little bit. You can start to tease out what the extremes are, as opposed to really high values and median.

Kevin Quinlan:

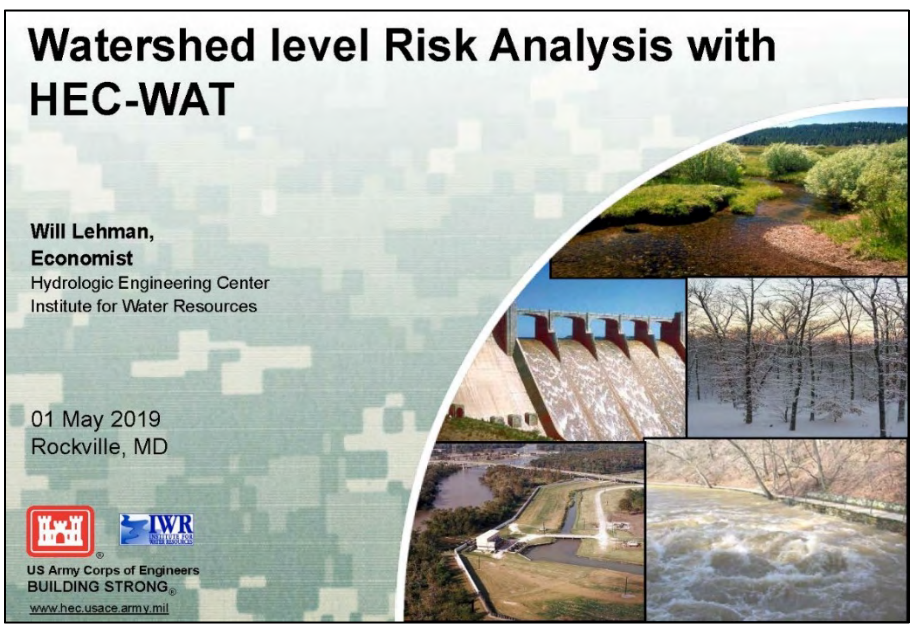
On extremes. I feel that as an agency, the NRC is a little bit all over the place with this, depending on the hazard. I am a meteorologist and only started getting into the precipitation side and the flooding side about 5 years ago, once we started getting in the Near-Term Task Force (NTTF) Recommendation 2.1 flood hazard analysis. I have dealt a lot with wind speeds that are 10^{-6} and temperatures that are either the historical extreme or the 100-year return period. So again, we're really all over the place. Hopefully, we are moving to become a bit more standardized. With groups like this, we can come up with something that is a little more consistent across our external hazards.

4.3.4 Day 2 Session 2A - Riverine Flooding

Session Chair: Meredith Carr and Mark Fuhrmann, NRC/RES/DRA/FXHAB

4.3.4.1 KEYNOTE: Watershed Level Risk Analysis with HEC-WAT. Will Lehmann*, Lea Adams and Chris Dunn, USACE, Institute for Water Resources, Hydrologic Engineering Center (Session 2A-1; ADAMS Accession No. ML19156A462)

4.3.4.1.1 Presentation



What is HEC-WAT?

- Provides a plug-in architecture to allow other computational models to be computed in the program sequence
- Integrates HEC-HMS, HEC-ResSim, HEC-RAS and HEC-FIA models, eliminating manual data exchange.
- Supports systems and watershed-based studies.
- Supports risk and uncertainty evaluations.

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What is HEC-WAT?

- Provides a plug-in architecture to allow other computational models to be computed in the program sequence

HEC- WAT INTEGRATES

- Integrates HEC-HMS, HEC-ResSim, HEC-RAS and HEC-FIA models, eliminating manual data exchange.
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What is HEC-WAT?

- Provides a plug-in architecture to allow other computational models to be computed in the program se...

HEC- WAT INTEGRATES

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- Supports systems and watershed-based studies.
- Sup... risk and uncertainty ...

HEC- WAT Facilitates Evaluation

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HEC- WAT INTEGRATES

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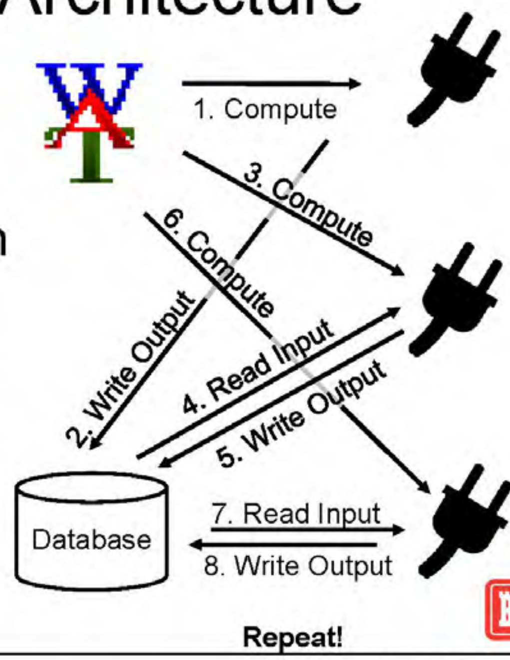
5

Plug-in Architecture

- HEC-WAT Manages the computes through plug-ins
- Plug-ins interact with each other through a centralized database



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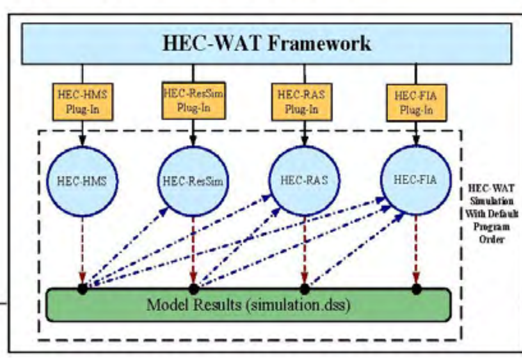
HEC-WAT Model Integration

- Models and tools that implement the Plugin Interface can contribute to the computational process
  - Hydrology - *HEC-HMS*
  - Reservoirs - *HEC-ResSim*
  - Hydraulics - *HEC-RAS*
  - Economics - *HEC-FIA*
- Communication is defined by the Plugin API and facilitated by HEC-WAT
- Data is transferred through a common DSS file.



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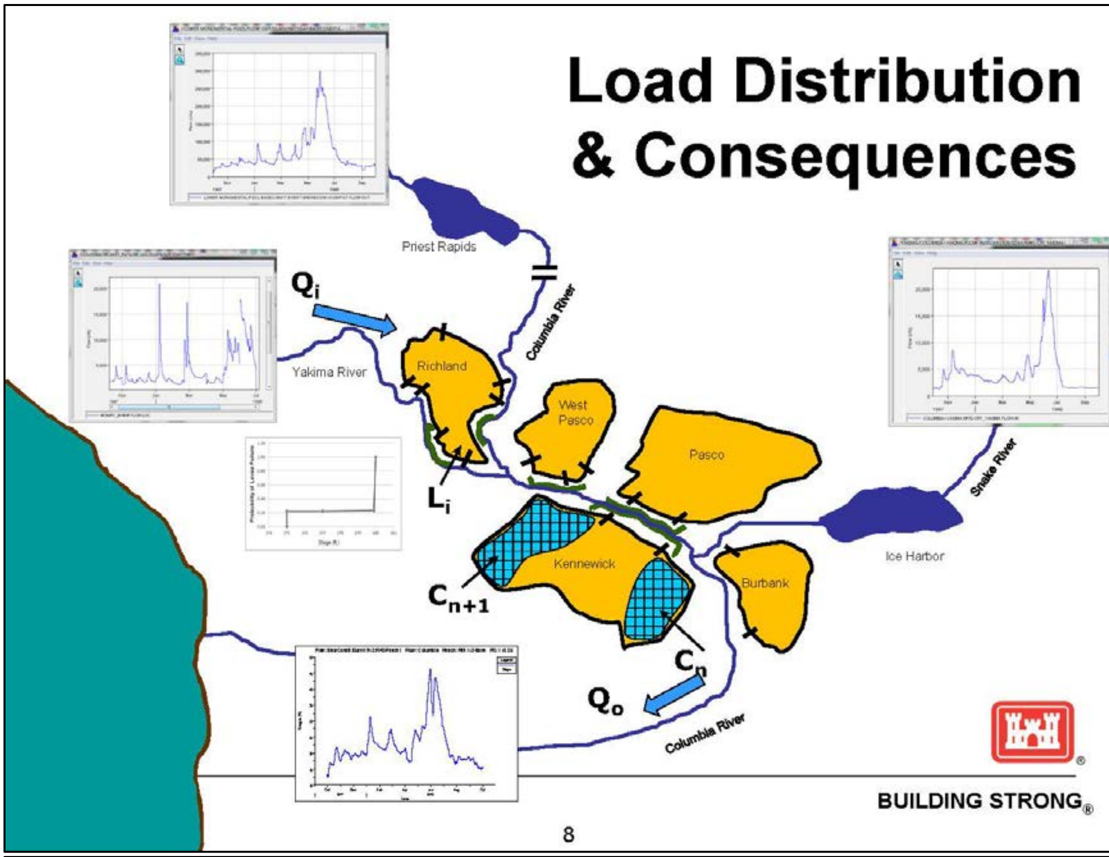
Load Distribution & Consequences



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HEC- WAT Facilitates Evaluation

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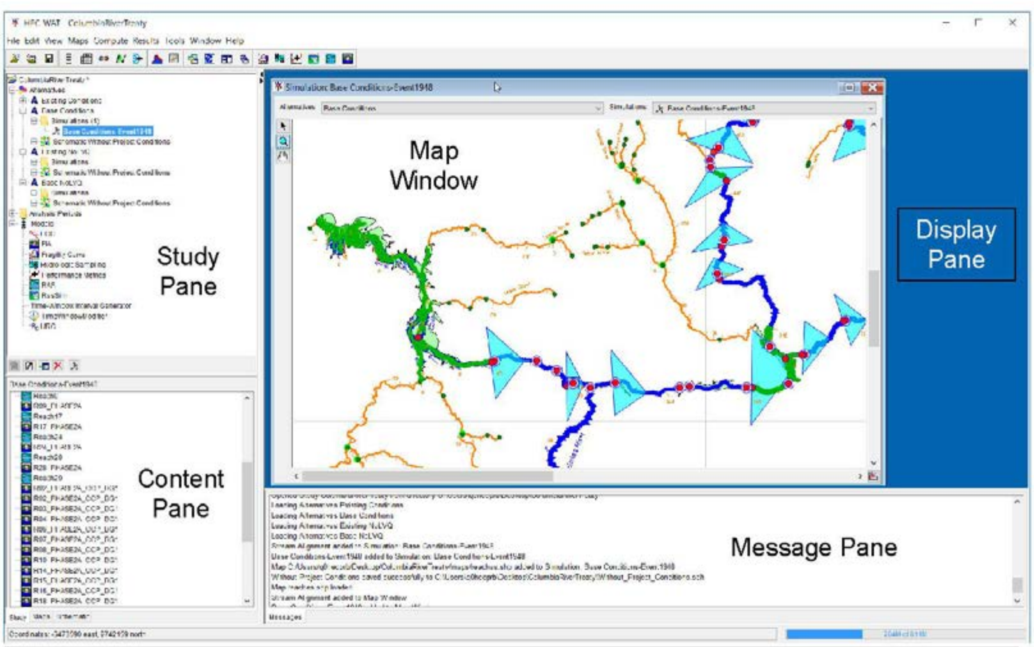
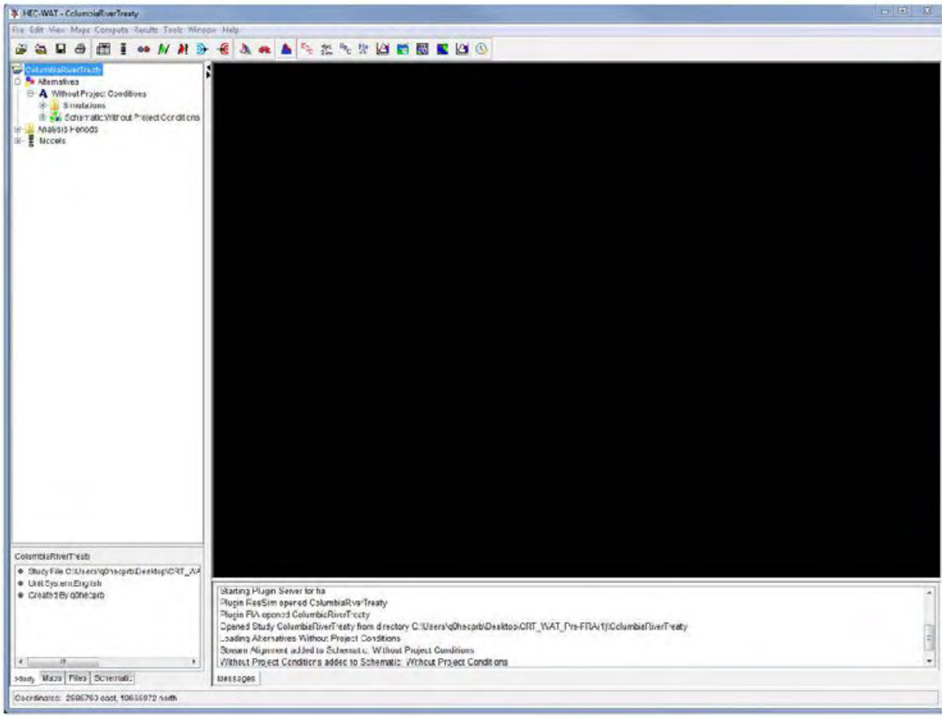
HEC-WAT Workflow

- Import existing models or develop models from within HEC-WAT
- Develop alternatives
- Organize & store data
- Edit models – accessed via plug-ins to view Native model interfaces
- Run modeling software – via plug-ins
- View and compare alternative results

HEC-WAT Interface



Development of HEC-WAT Model



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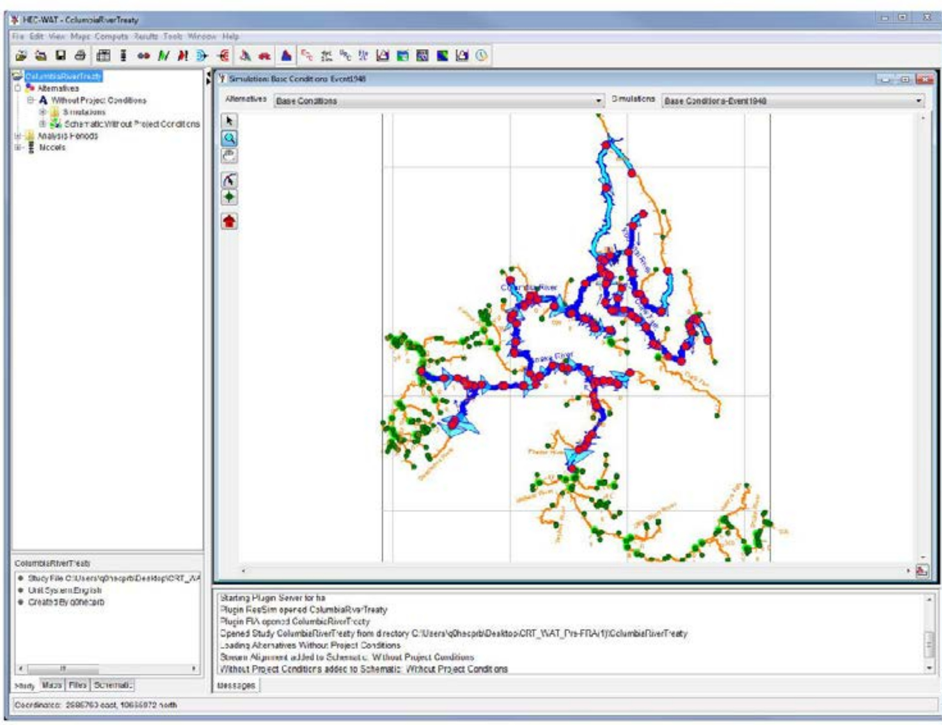
Development of HEC-WAT Model



- ResSim Models

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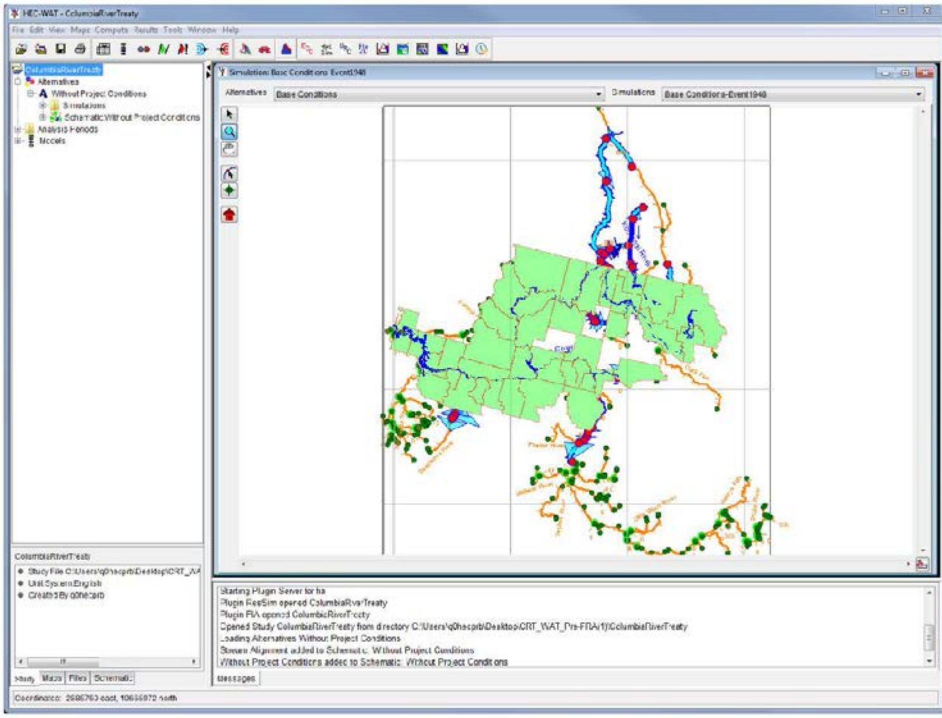
Development of HEC-WAT Model



- ResSim Models
- FIA Models

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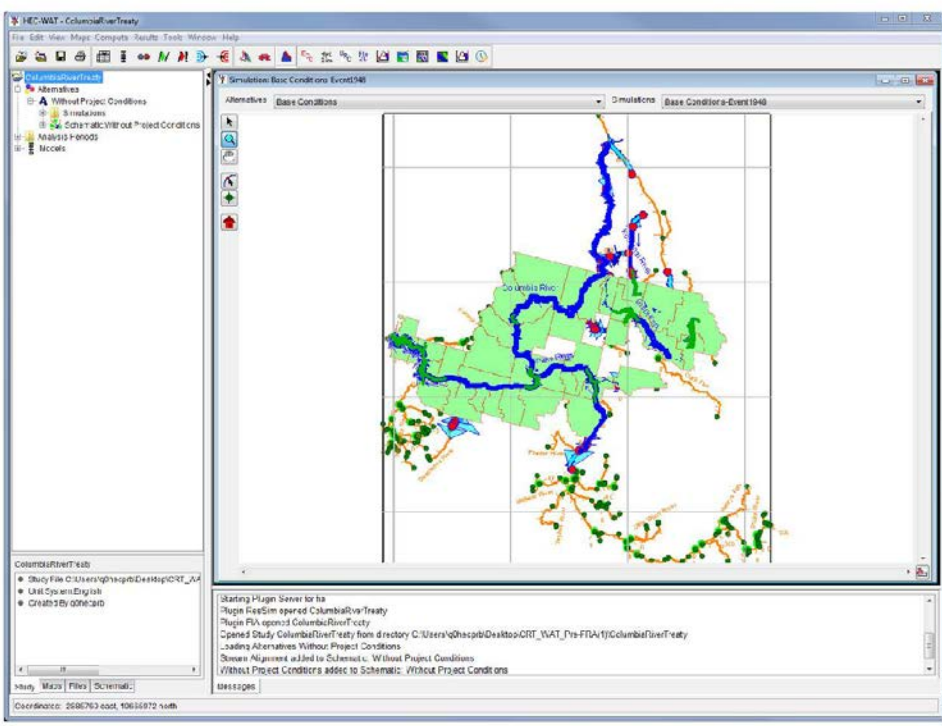
Development of HEC-WAT Model



- ResSim Models
- FIA Models
- RAS Models

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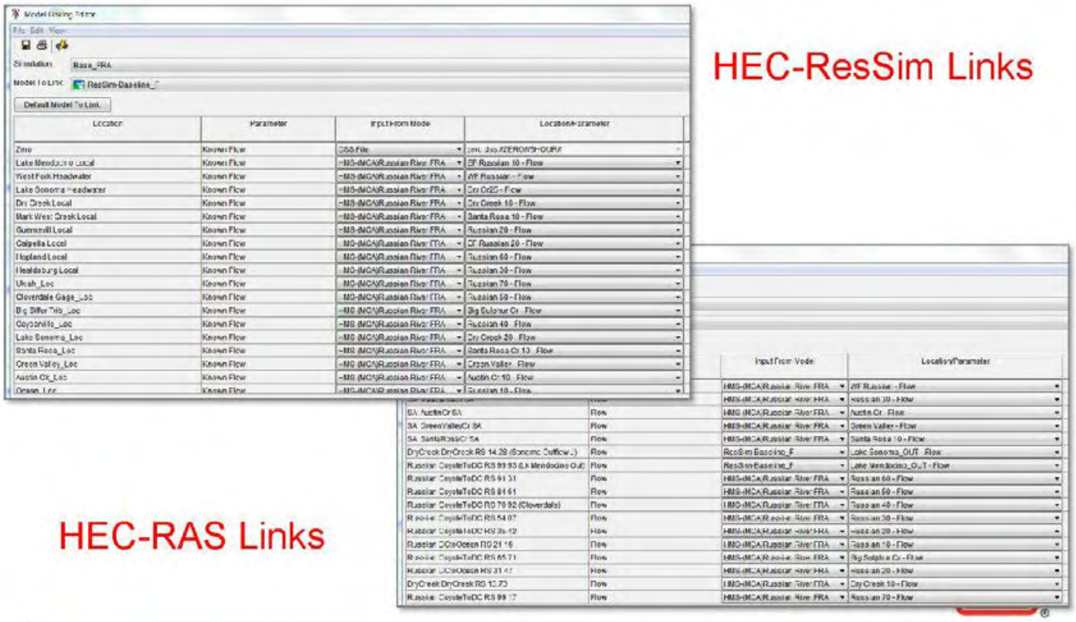
Model Linking



HEC-ResSim Links

HEC-RAS Links

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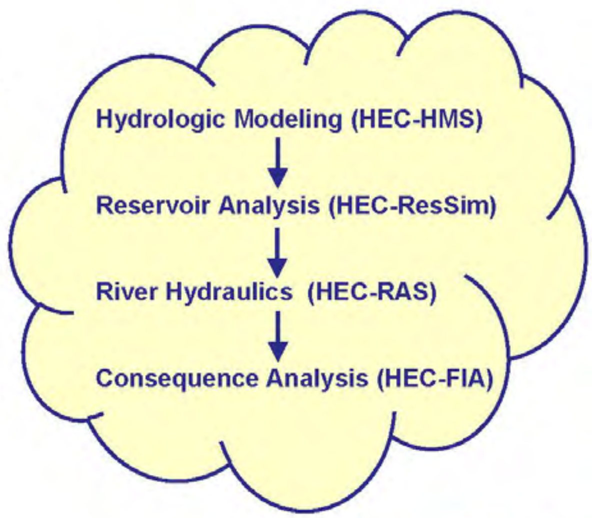
Deterministic Compute

- Single Flood Event
  - Example: 8 January 1986 to 13 January 1986
  - Simplest type of compute
  - Eliminates manual handoffs between models
- Period of Record
  - Example: 1 October 1943 to 30 September 2014
  - Slightly more complex compute



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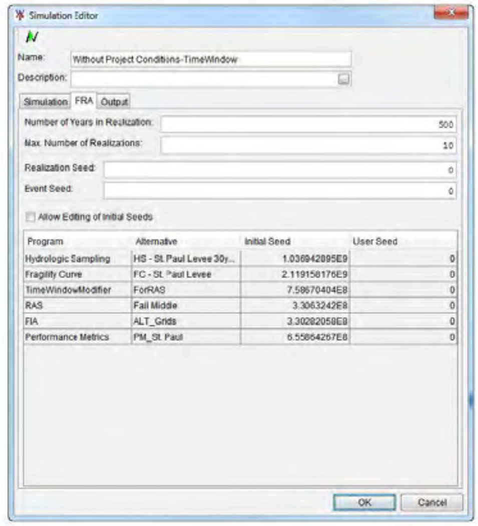
FRA Simulations

- FRA simulations uses a Monte Carlo style compute to support risk analyses.
- Individual applications sample model parameters from a range of values to capture uncertainty.
- Natural variability and knowledge uncertainty sampled separately.
- Maintains consistency between alternatives by allowing use of same initial seeds.



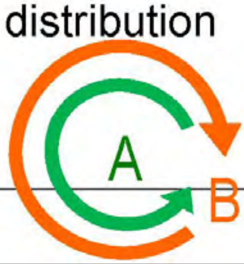
How do we capture a distribution of uncertainty in EAD?

<u>Nested Monte Carlo</u>: *HEC-WAT/FRA*

A. Sample instances of natural variabilities as flood *events*, with enough events to capture the distribution of damage

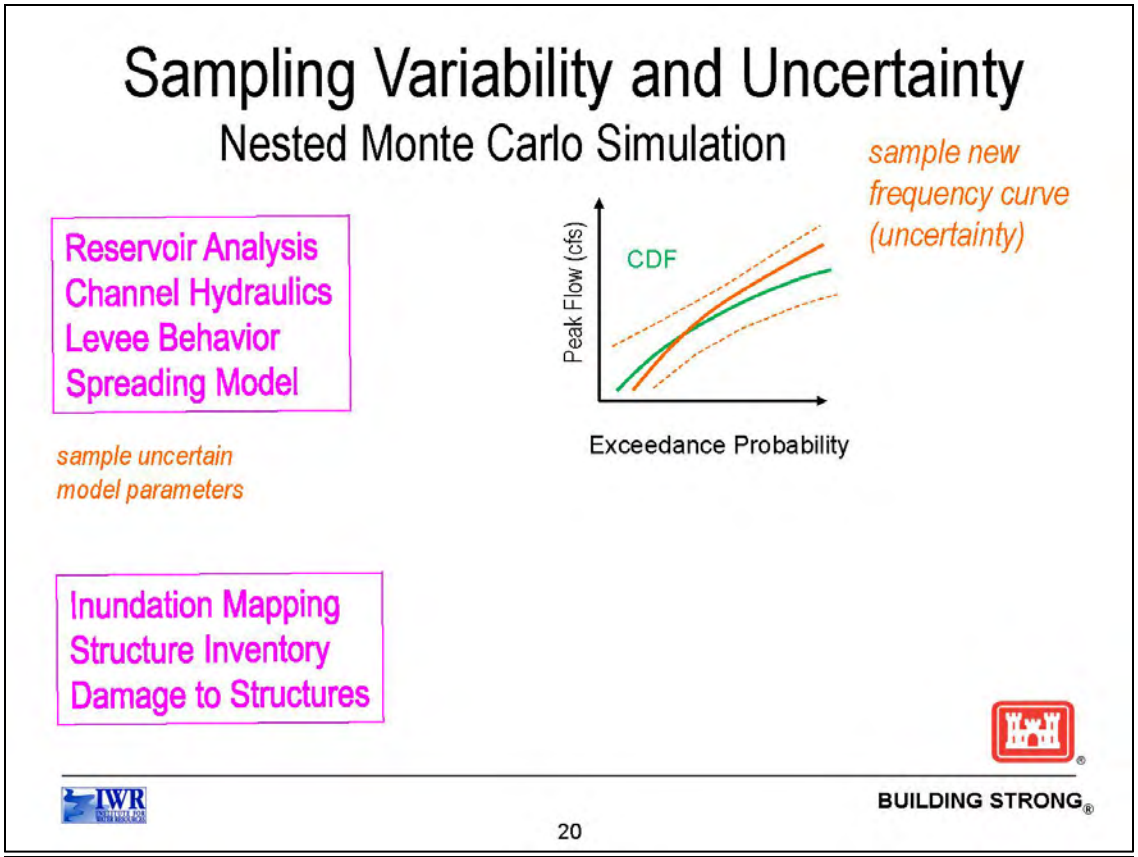
B. Sample instances of knowledge uncertainties in model parameters to get their impact on the damage distribution

1 outer loop B = a realization



inner loop A varies natural variabilities, computes EAD

outer loop B varies knowledge uncertainty, computes EAD distribution


Sampling Variability and Uncertainty
Nested Monte Carlo Simulation
sample new
frequency curve
(uncertainty)
Reservoir Analysis
Channel Hydraulics
Levee Behavior
Spreading Model
CDF
Peak Flow (cfs)
Exceedance Probability
sample uncertain
model parameters
Inundation Mapping
Structure Inventory
Damage to Structures
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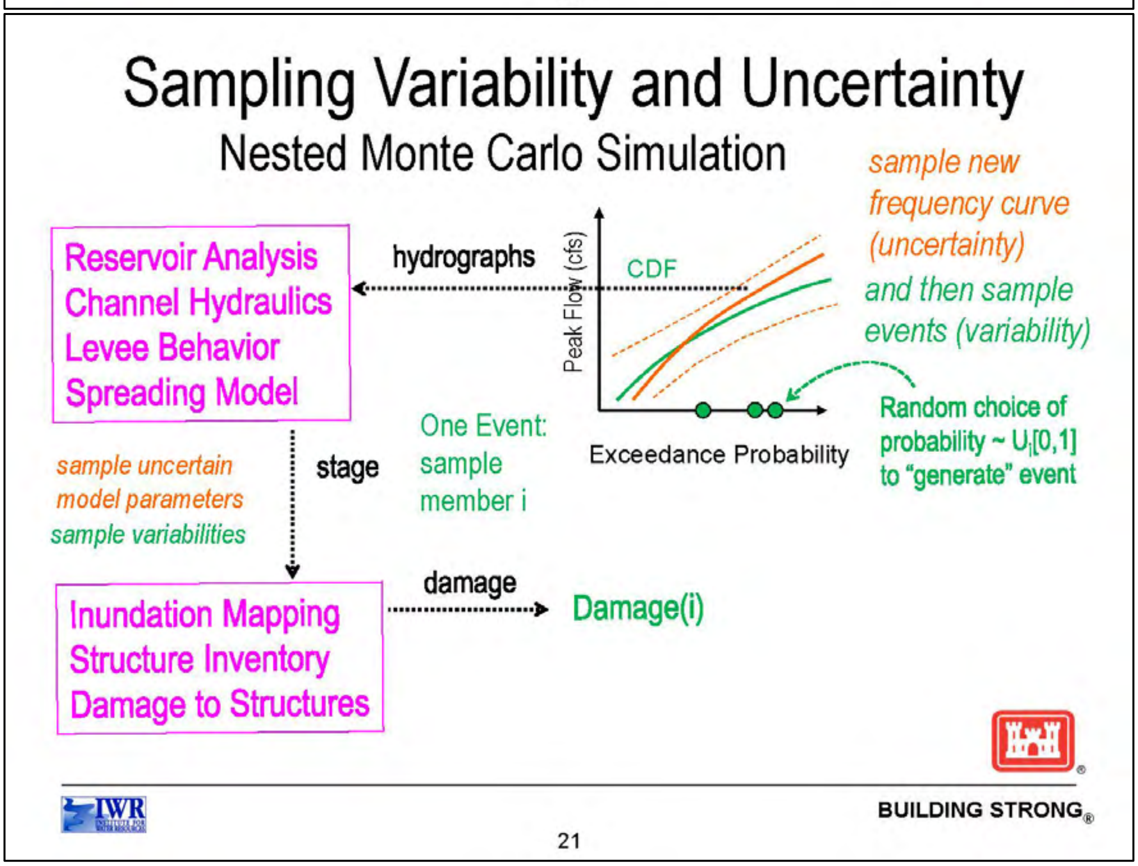
20


Sampling Variability and Uncertainty
Nested Monte Carlo Simulation
sample new
frequency curve
(uncertainty)
and then sample
events (variability)
Reservoir Analysis
Channel Hydraulics
Levee Behavior
Spreading Model
hydrographs
CDF
Peak Flow (cfs)
Exceedance Probability
Random choice of
probability ~ Ui[0,1]
to "generate" event
One Event:
sample
member i
stage
sample uncertain
model parameters
sample variabilities
damage
Damage(i)
Inundation Mapping
Structure Inventory
Damage to Structures
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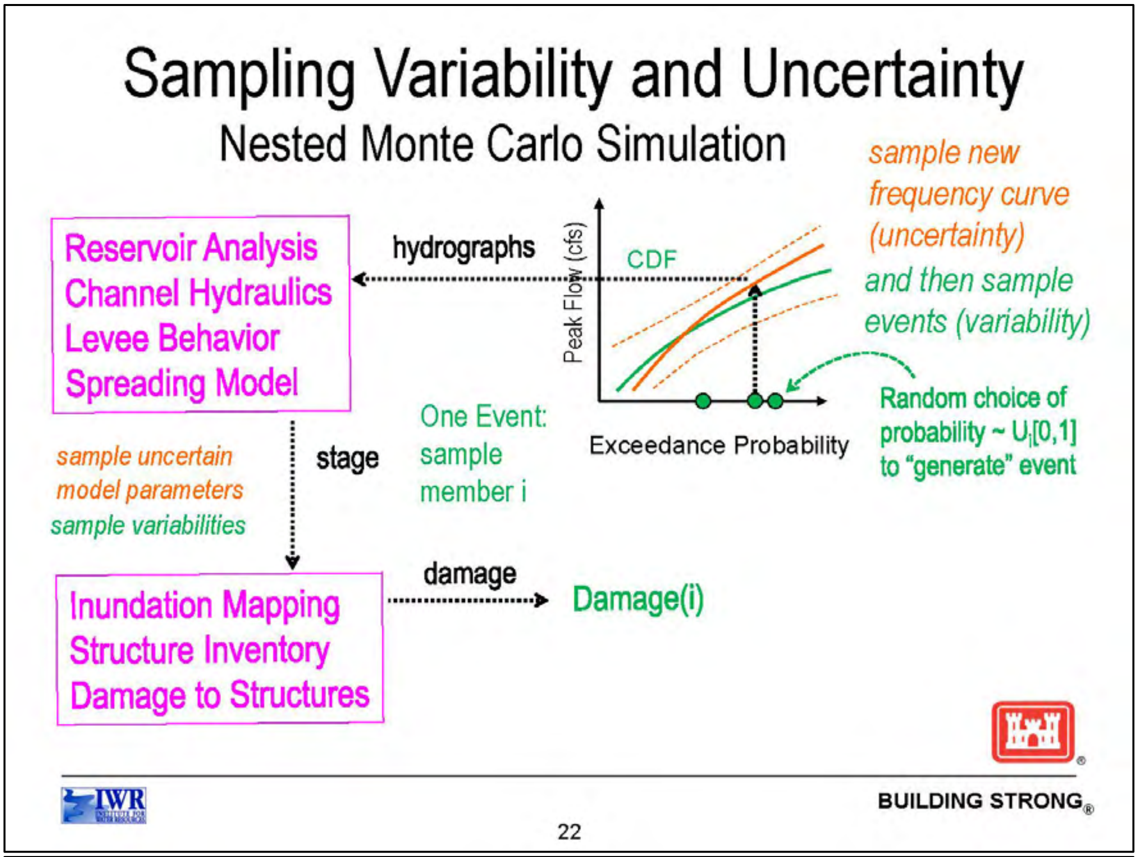
Sampling Variability and Uncertainty
Nested Monte Carlo Simulation
sample new frequency curve (uncertainty)
and then sample events (variability)
Reservoir Analysis
Channel Hydraulics
Levee Behavior
Spreading Model
hydrographs
Peak Flow (cfs)
CDF
Exceedance Probability
Random choice of probability ~ U_i[0,1] to "generate" event
One Event: sample member i
sample uncertain model parameters
sample variabilities
stage
damage
Damage(i)
Inundation Mapping
Structure Inventory
Damage to Structures
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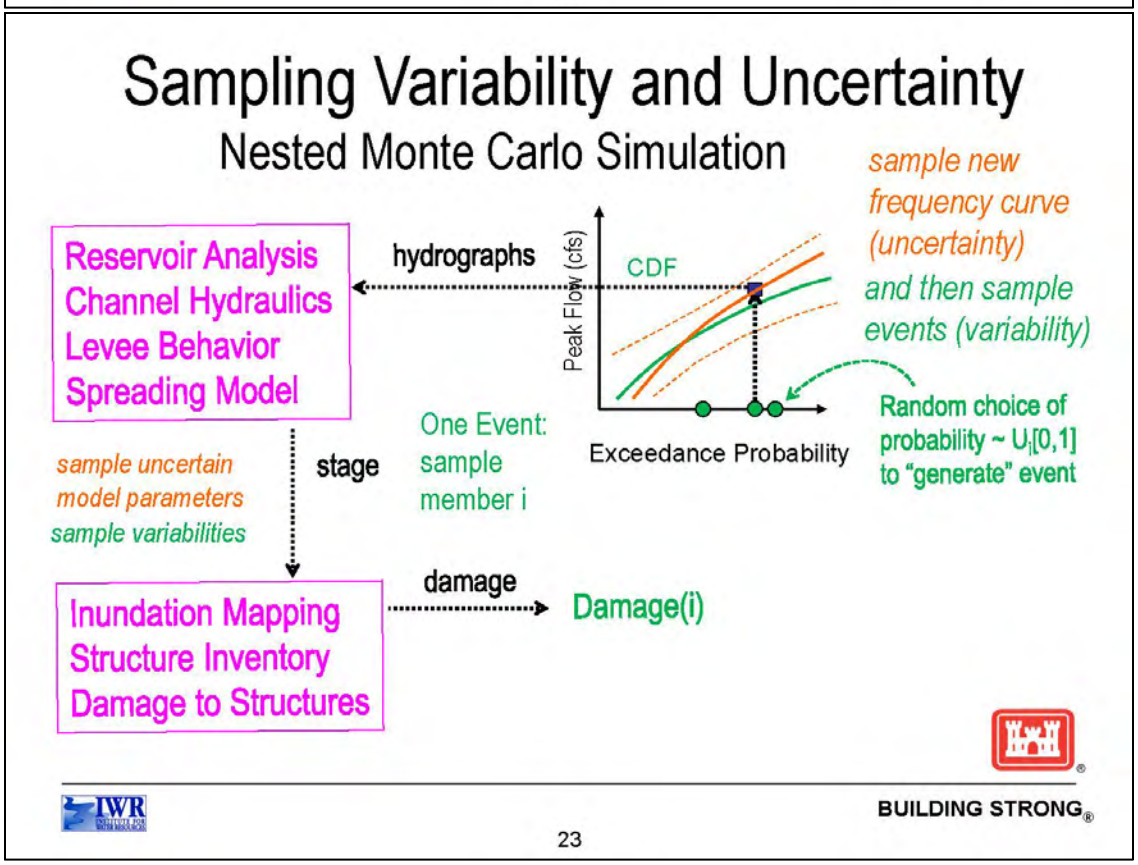
Sampling Variability and Uncertainty
Nested Monte Carlo Simulation
sample new frequency curve (uncertainty)
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Reservoir Analysis
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Exceedance Probability
Random choice of probability ~ U_i[0,1] to "generate" event
One Event: sample member i
sample uncertain model parameters
sample variabilities
stage
damage
Damage(i)
Inundation Mapping
Structure Inventory
Damage to Structures
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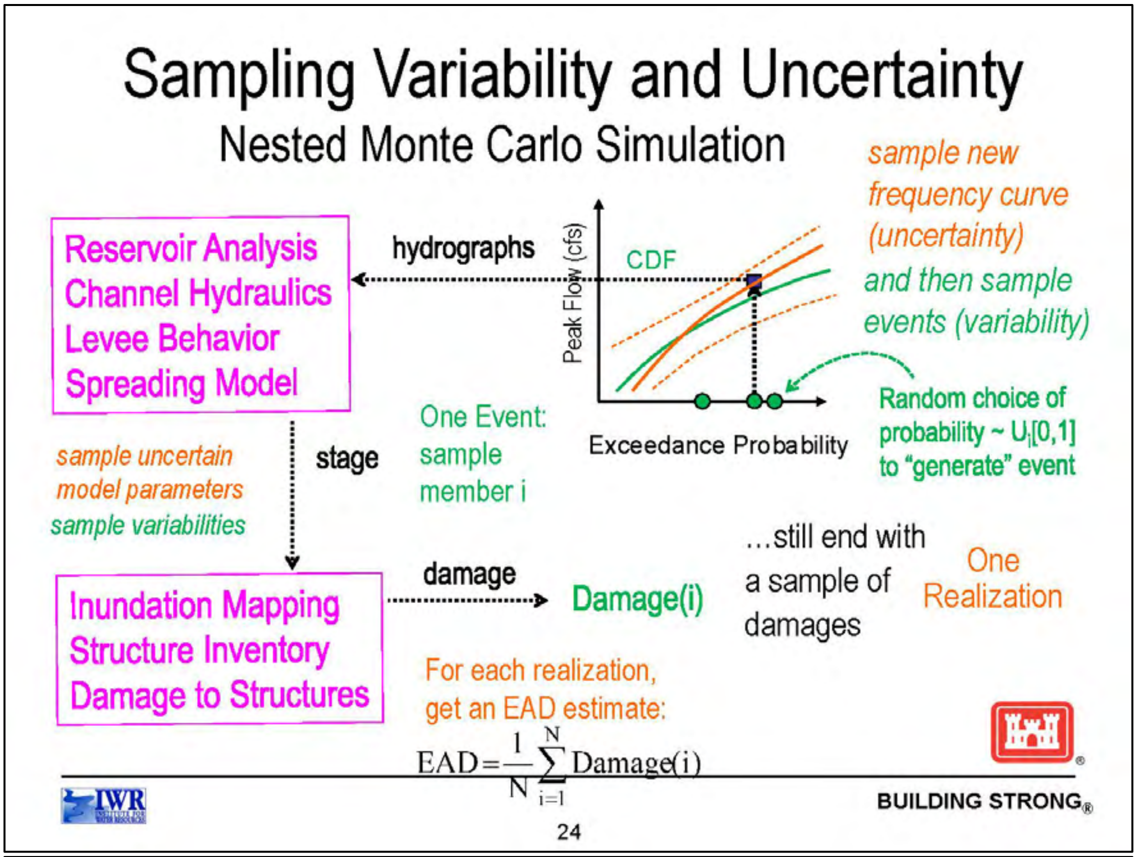
Sampling Variability and Uncertainty
Nested Monte Carlo Simulation
sample new frequency curve (uncertainty)
and then sample events (variability)
Reservoir Analysis
Channel Hydraulics
Levee Behavior
Spreading Model
hydrographs
Peak Flow (cfs)
CDF
Exceedance Probability
Random choice of probability ~ U_i[0,1] to "generate" event
One Event: sample member i
sample uncertain model parameters
sample variabilities
stage
damage
Damage(i)
...still end with a sample of damages
One Realization
Inundation Mapping
Structure Inventory
Damage to Structures
For each realization, get an EAD estimate:
$EAD = \frac{1}{N}\sum_{i=1}^{N} Damage(i)$
IWR
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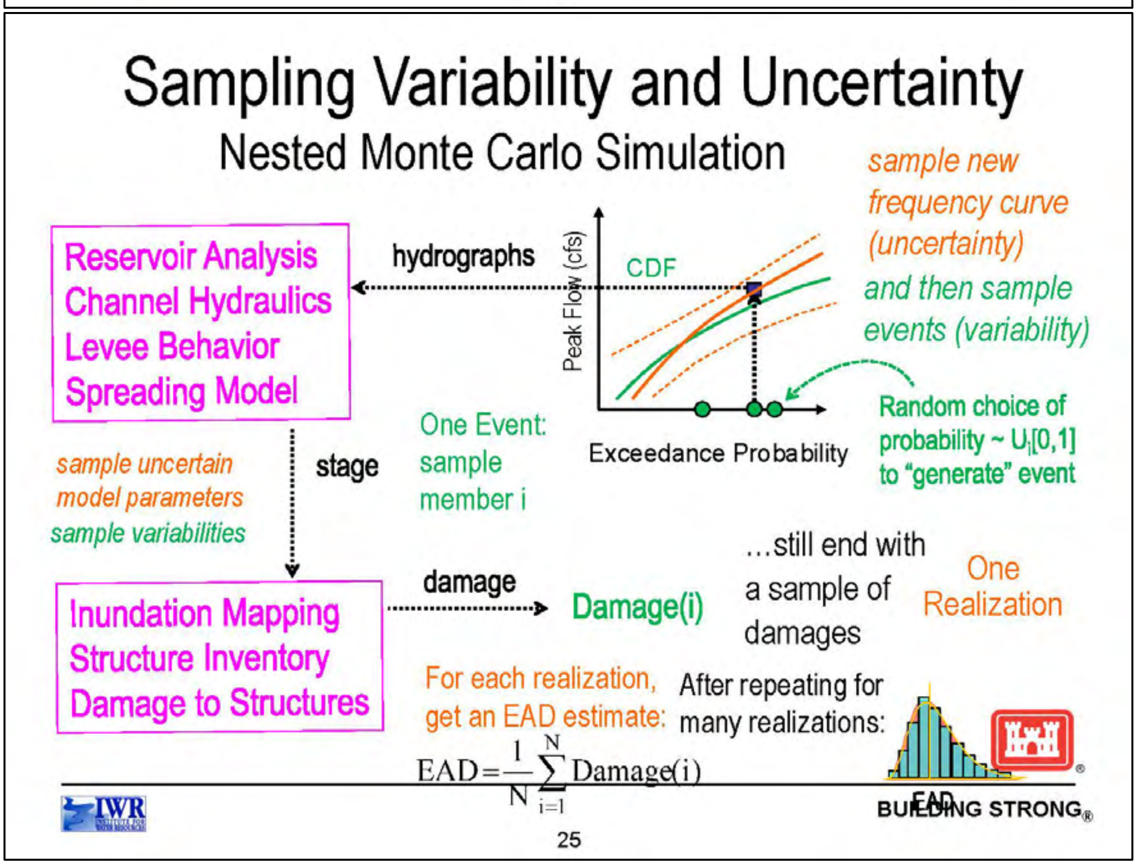
Sampling Variability and Uncertainty
Nested Monte Carlo Simulation
sample new frequency curve (uncertainty)
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Exceedance Probability
Random choice of probability ~ U_i[0,1] to "generate" event
One Event: sample member i
sample uncertain model parameters
sample variabilities
stage
damage
Damage(i)
...still end with a sample of damages
One Realization
Inundation Mapping
Structure Inventory
Damage to Structures
For each realization, get an EAD estimate:
$EAD = \frac{1}{N}\sum_{i=1}^{N} Damage(i)$
After repeating for many realizations:
EAD
IWR
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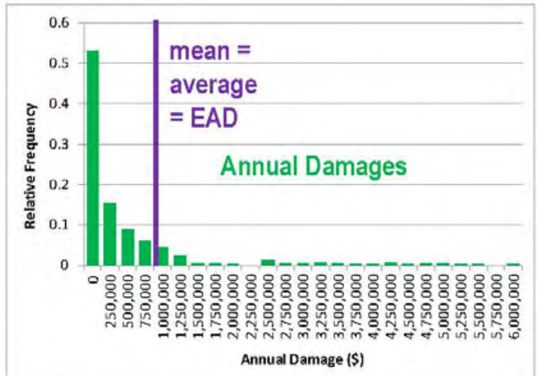
sample of annual damage
from **one realization**
(spans natural variability)
provides 1 estimate of
EAD



sample of annual damage
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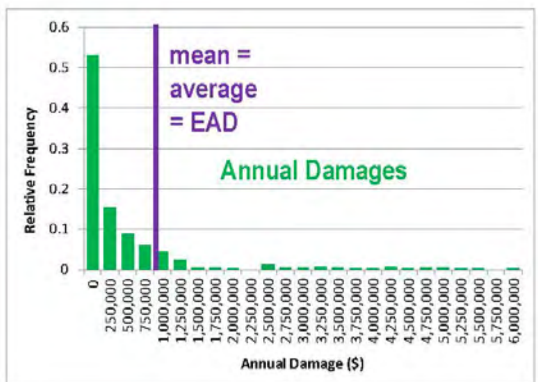
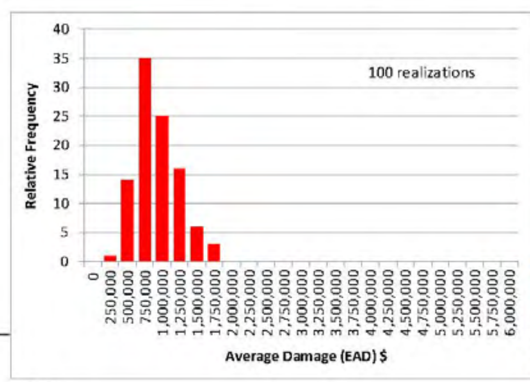
provides 1 estimate of
EAD

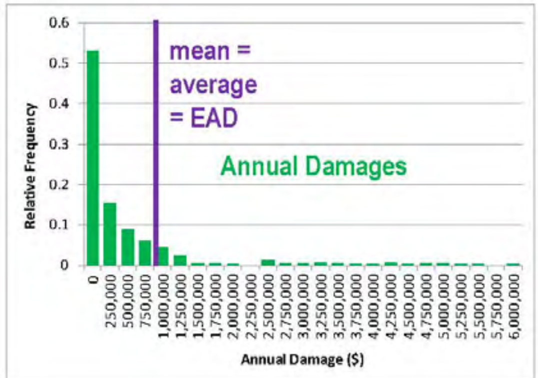




sample of annual damage from **one realization**

(spans natural variability)

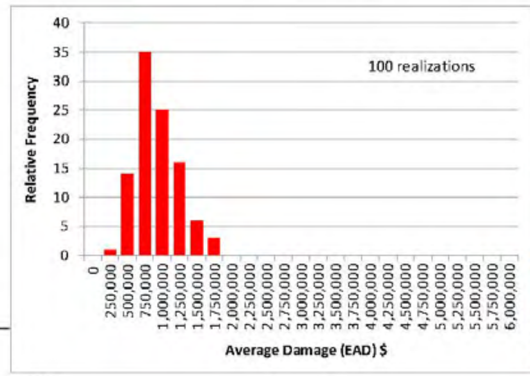
provides 1 estimate of EAD



sample of mean damage (EAD) from **all realizations**

(spans knowledge uncertainty)

provides distribution of EAD



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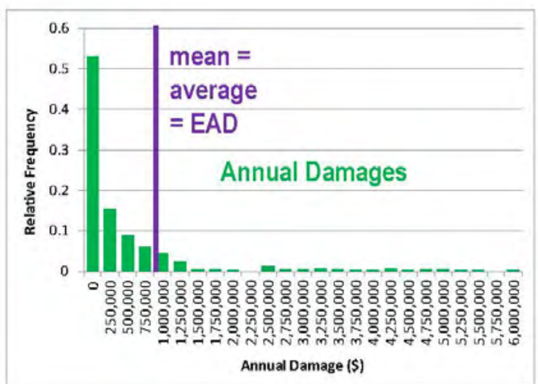
sample of annual damage from **one realization**

(spans natural variability)

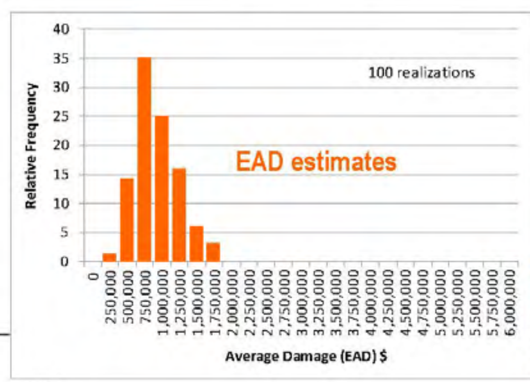
provides 1 estimate of EAD



sample of mean damage (EAD) from **all realizations**

(spans knowledge uncertainty)

provides distribution of EAD



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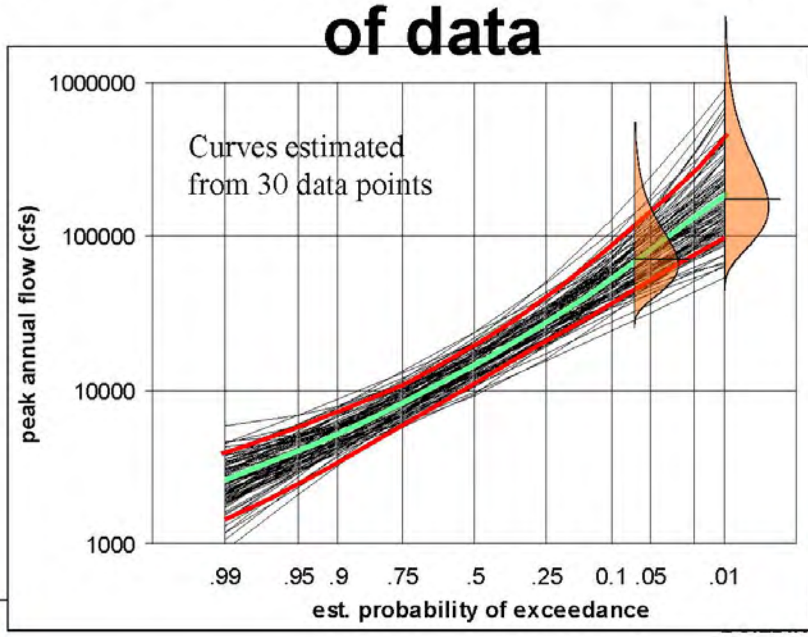
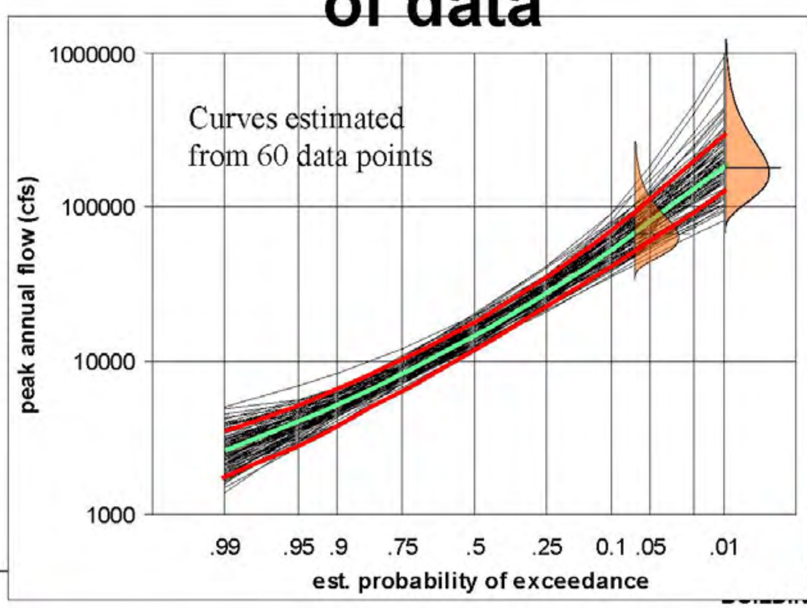
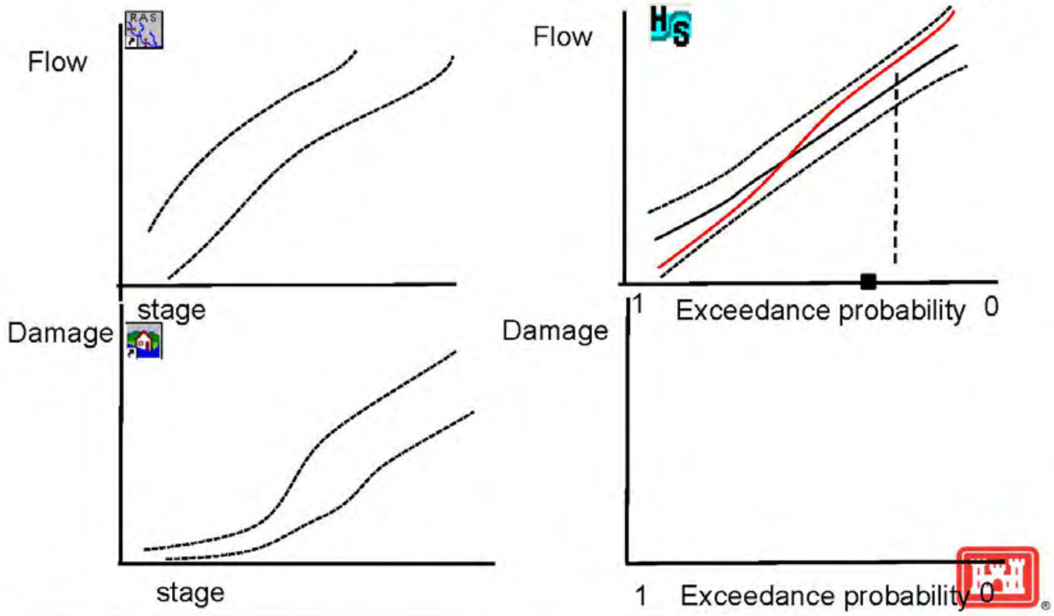
Uncertainty in a frequency curve estimated from 30 years of data



Uncertainty in a frequency curve estimated from 60 years of data



Concept behind event sampling



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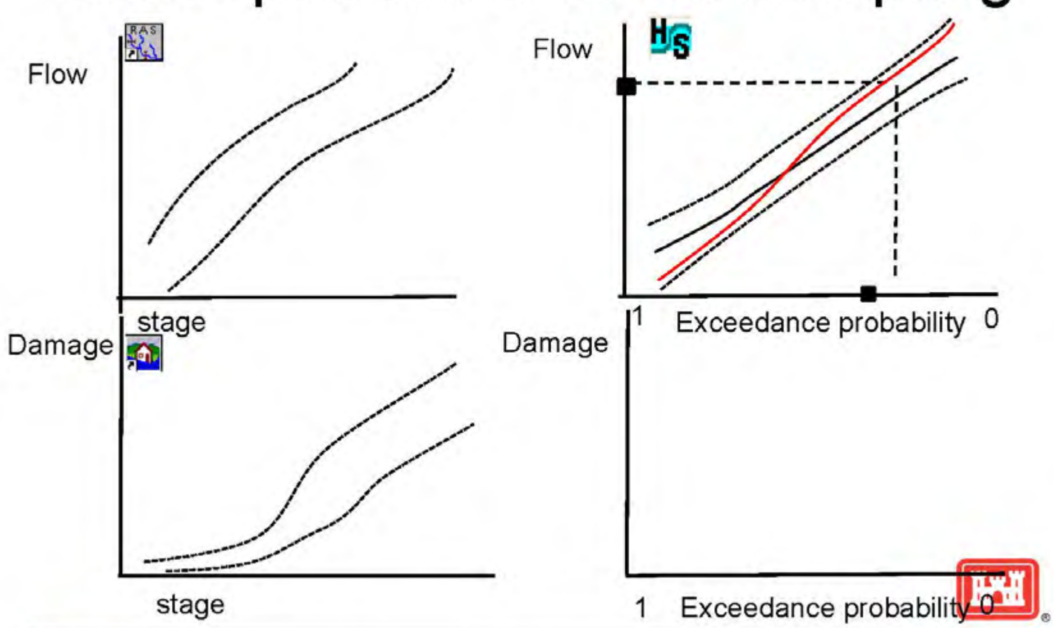
Concept behind event sampling



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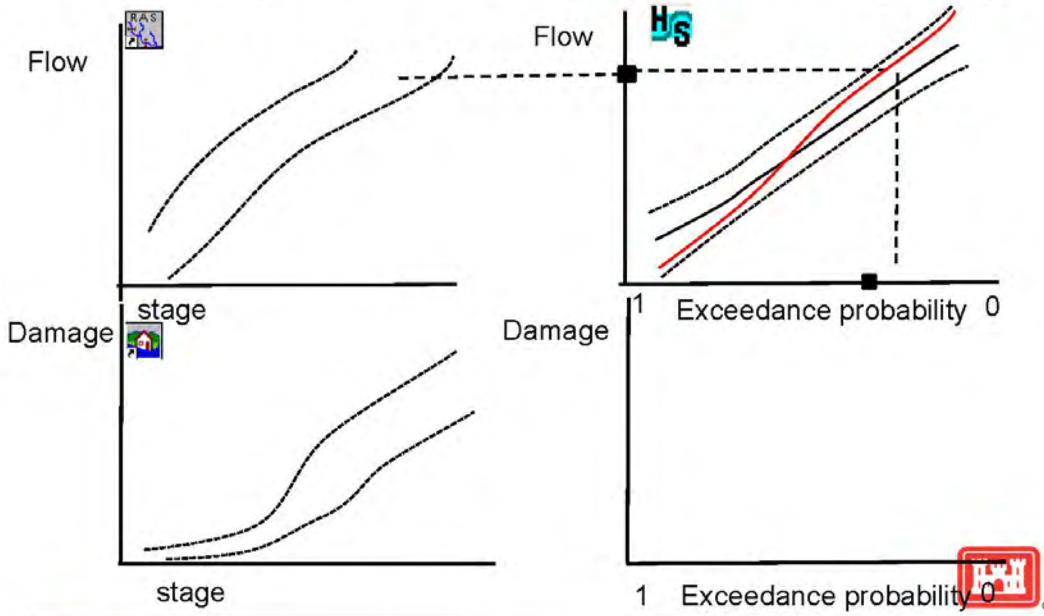
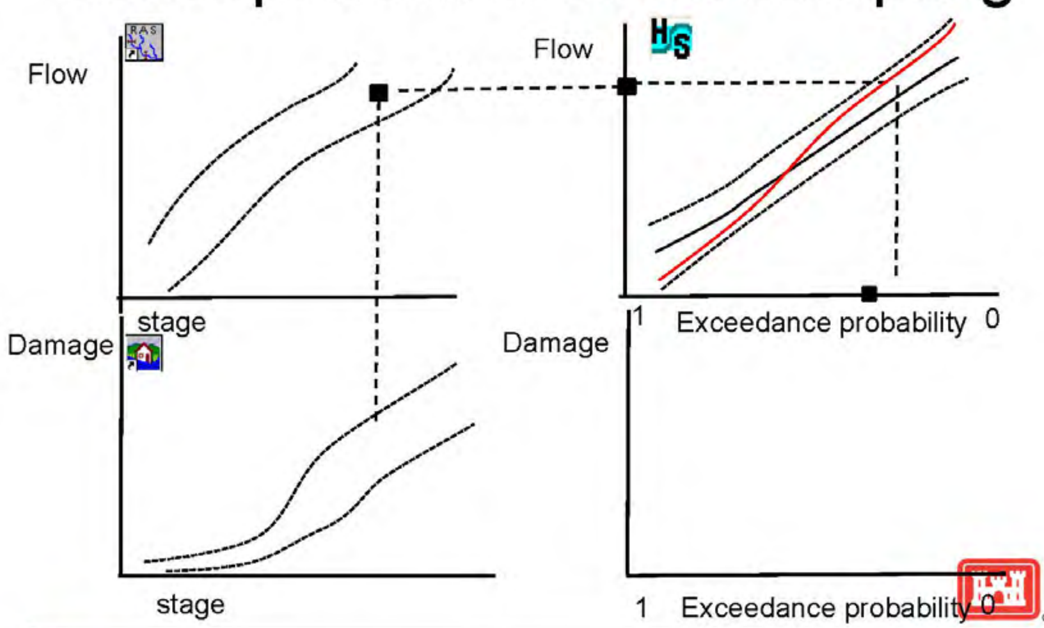
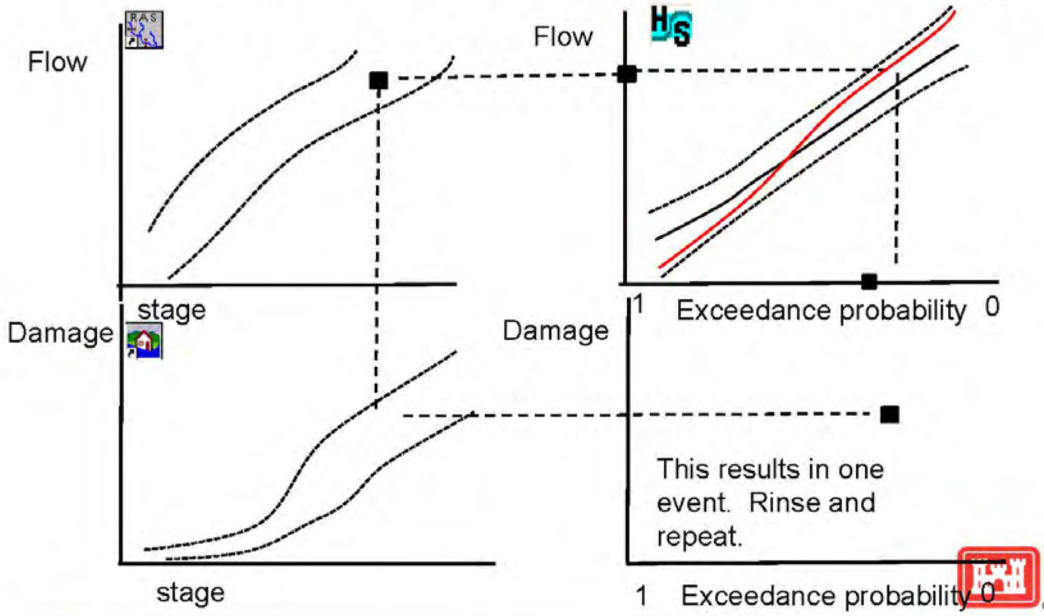
Concept behind event sampling



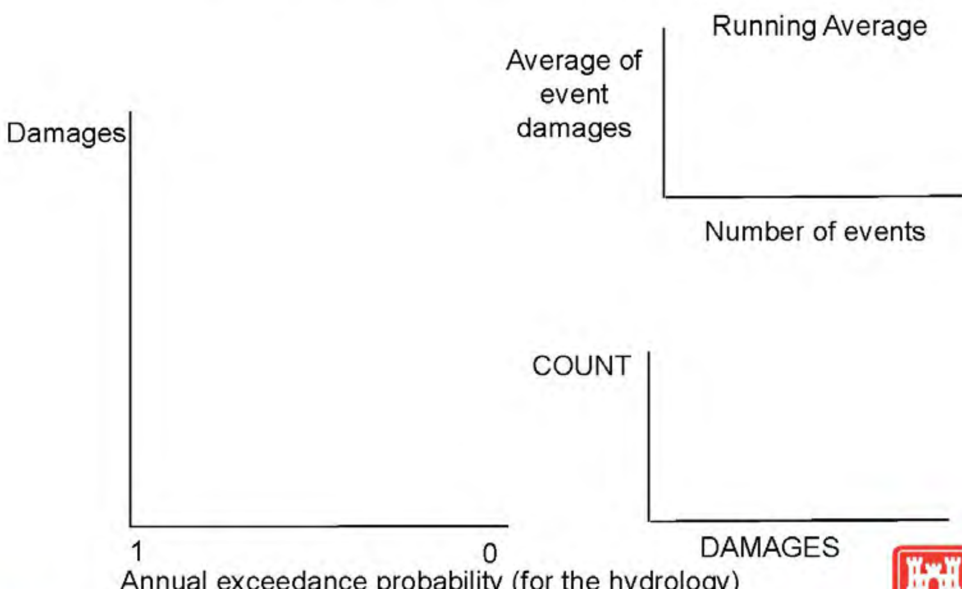
Concept behind event sampling



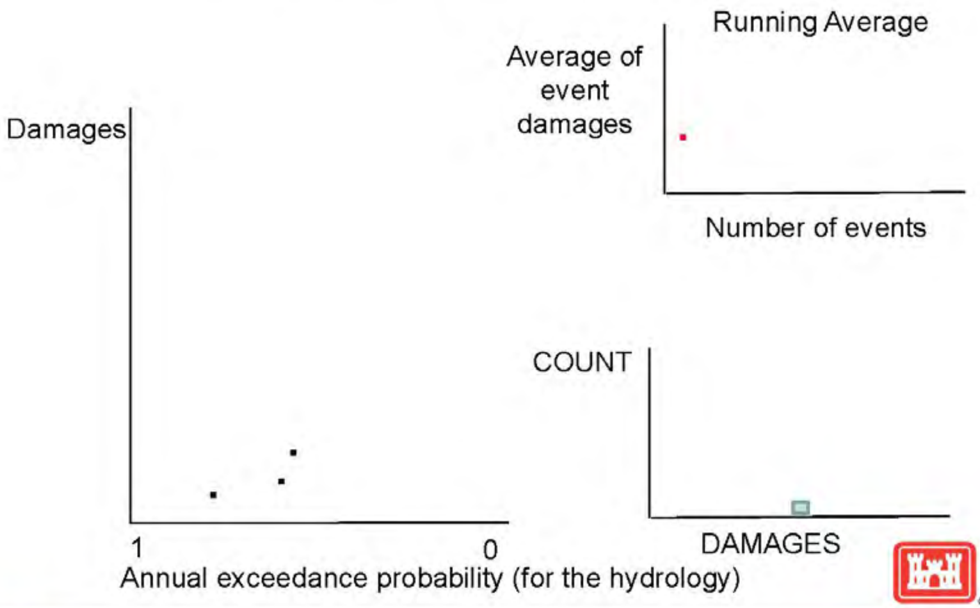
Concept behind event sampling



EVENT SAMPLING



EVENT SAMPLING



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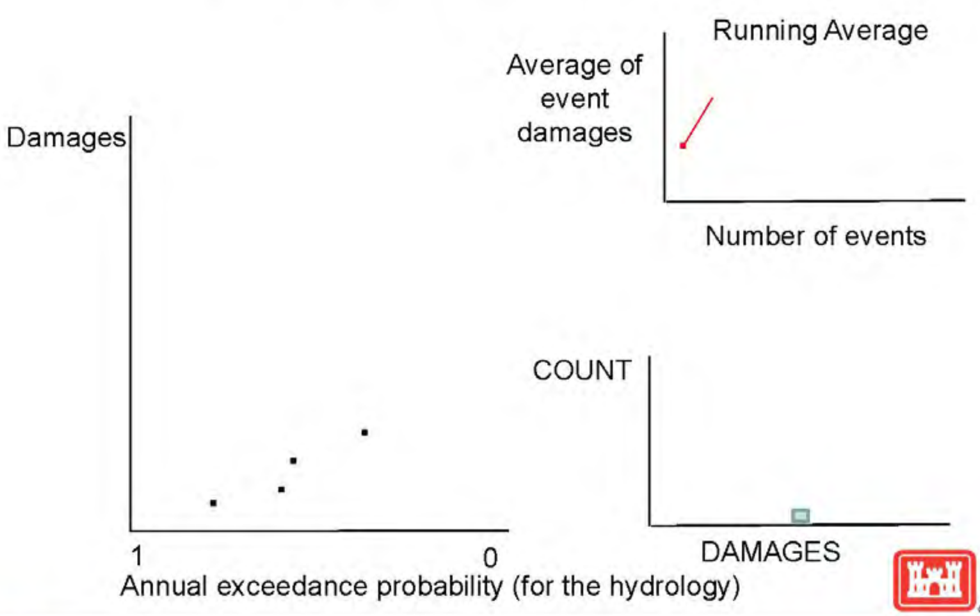
EVENT SAMPLING



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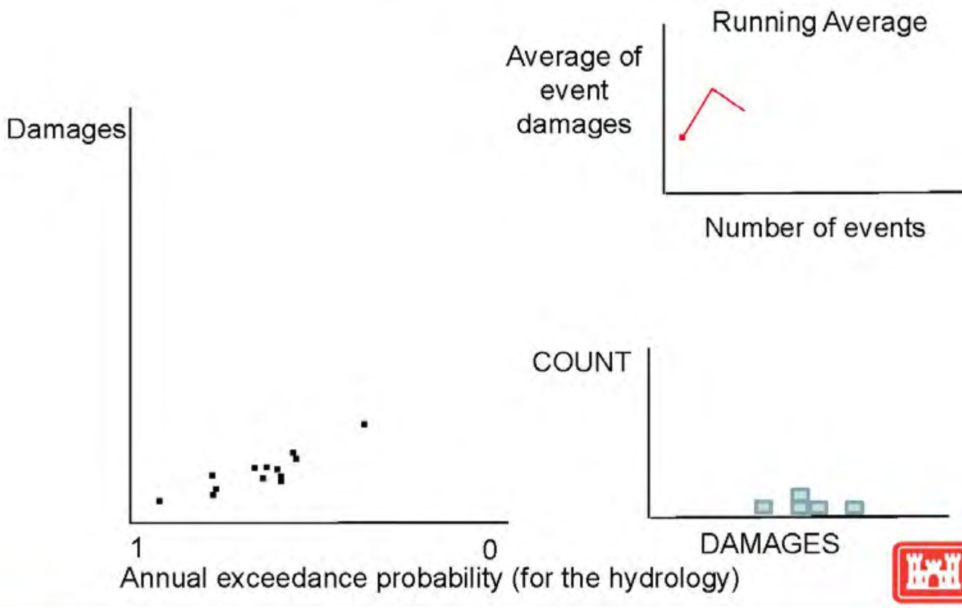
EVENT SAMPLING



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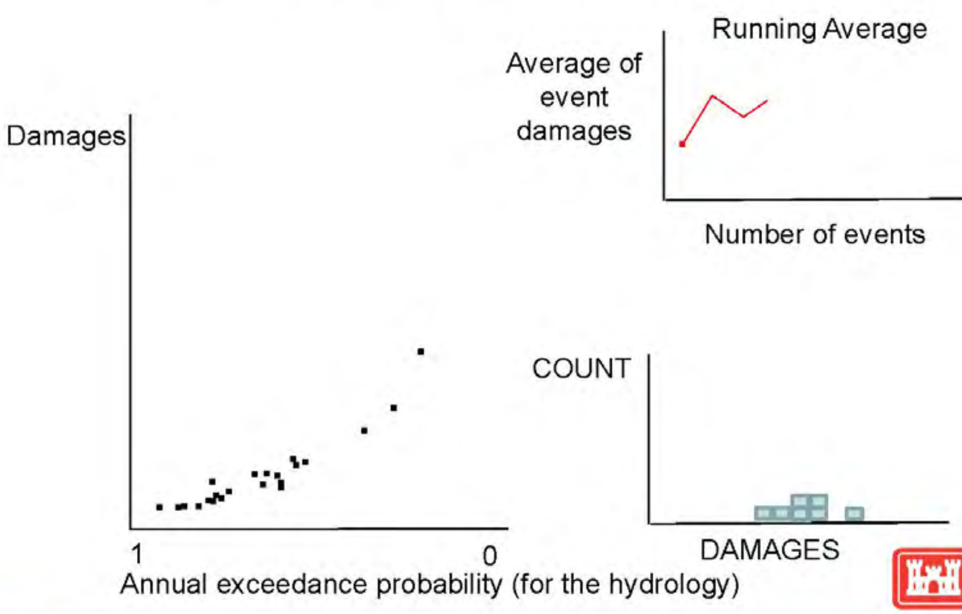
EVENT SAMPLING



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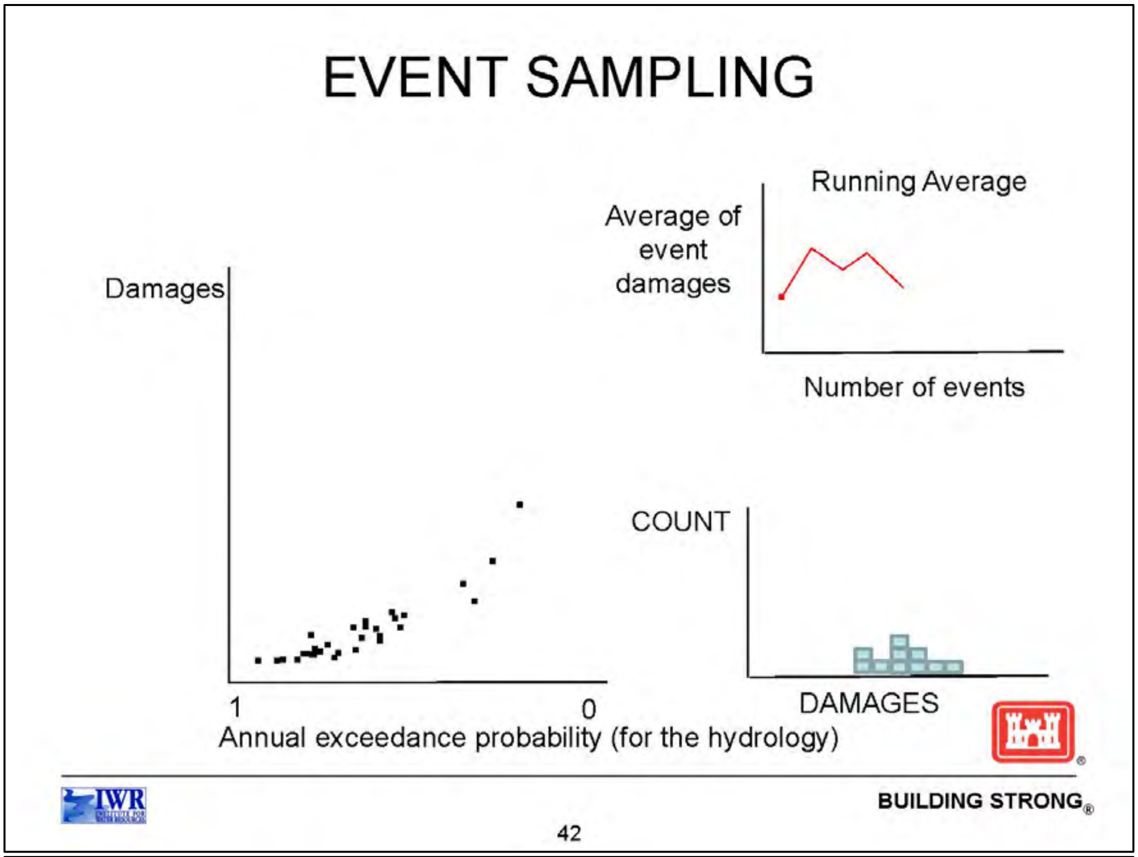
EVENT SAMPLING
Damages
1
0
Annual exceedance probability (for the hydrology)
Average of event damages
Running Average
Number of events
COUNT
DAMAGES
IWR
BUILDING STRONG®
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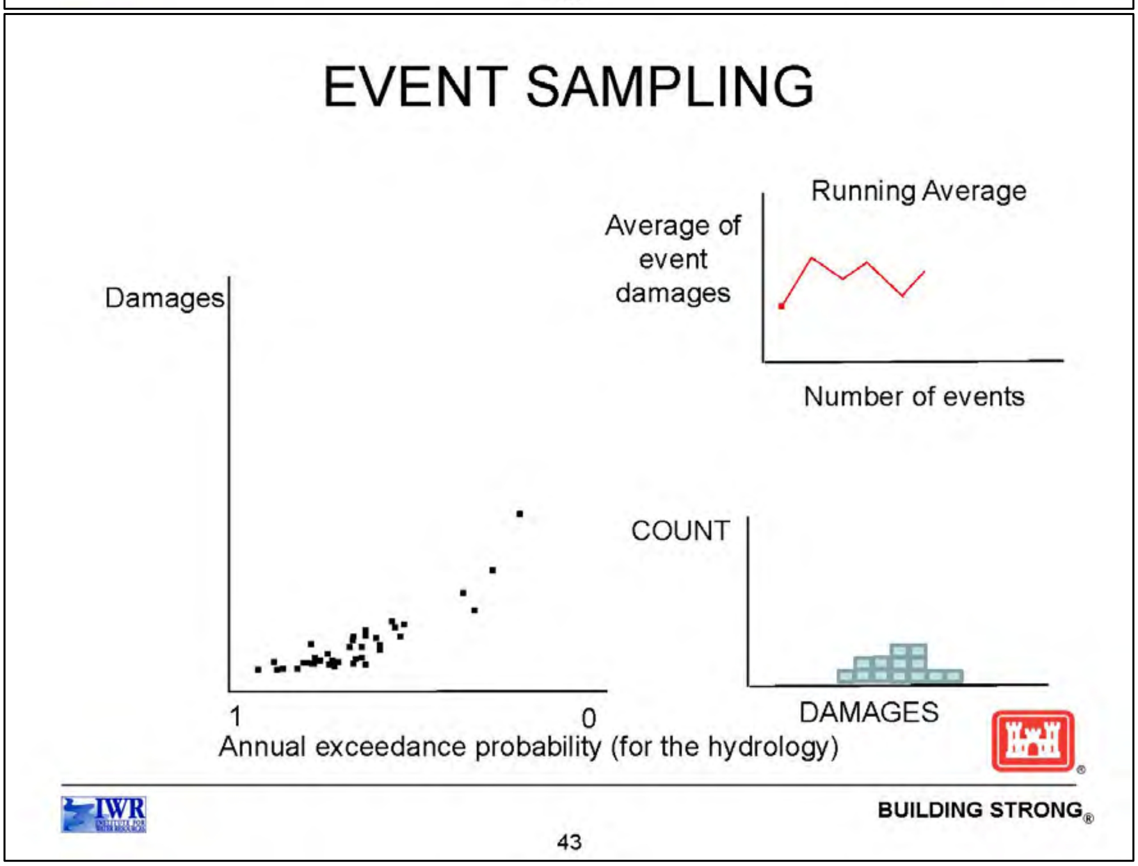
EVENT SAMPLING
Damages
1
0
Annual exceedance probability (for the hydrology)
Average of event damages
Running Average
Number of events
COUNT
DAMAGES
IWR
BUILDING STRONG®
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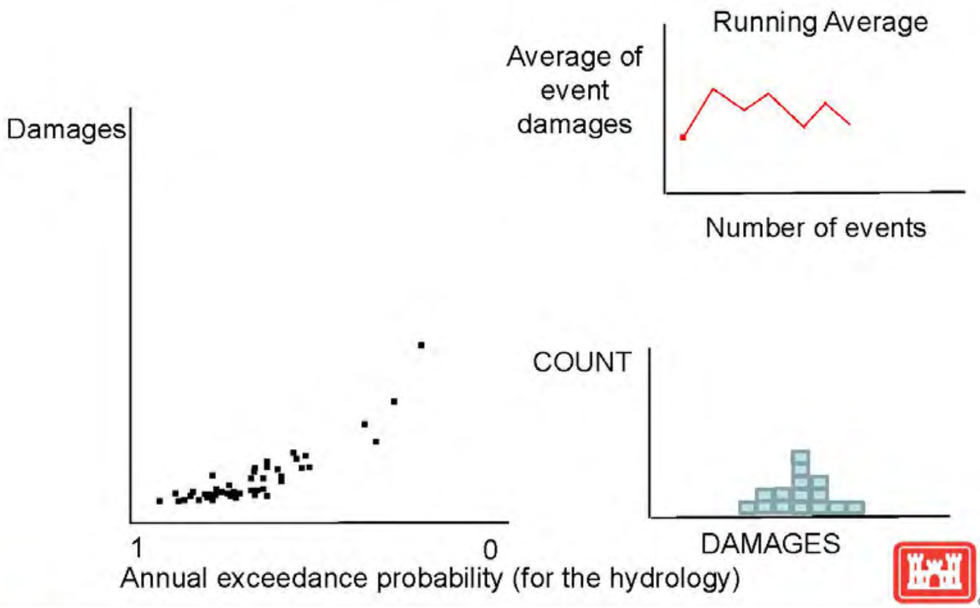
EVENT SAMPLING



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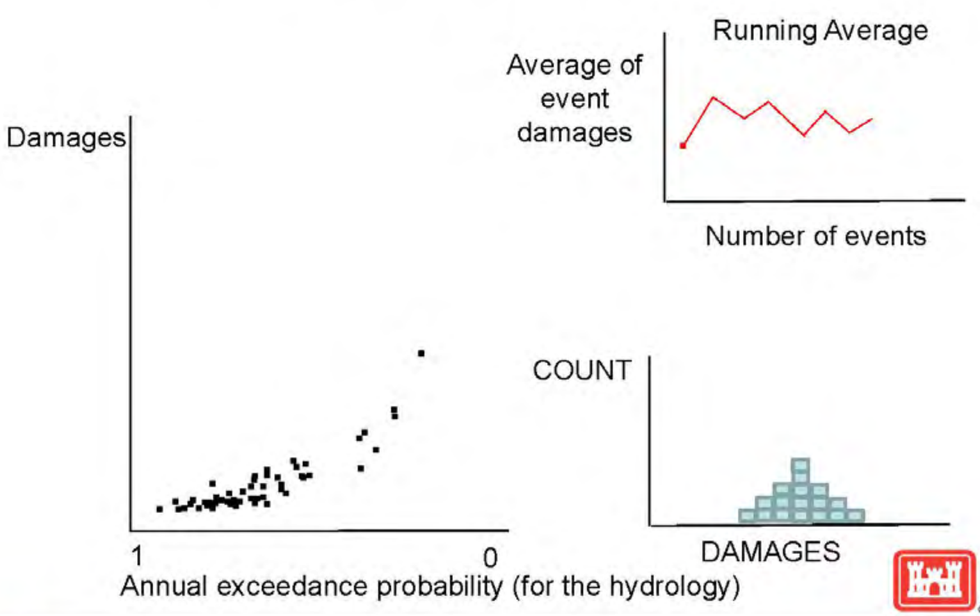
EVENT SAMPLING



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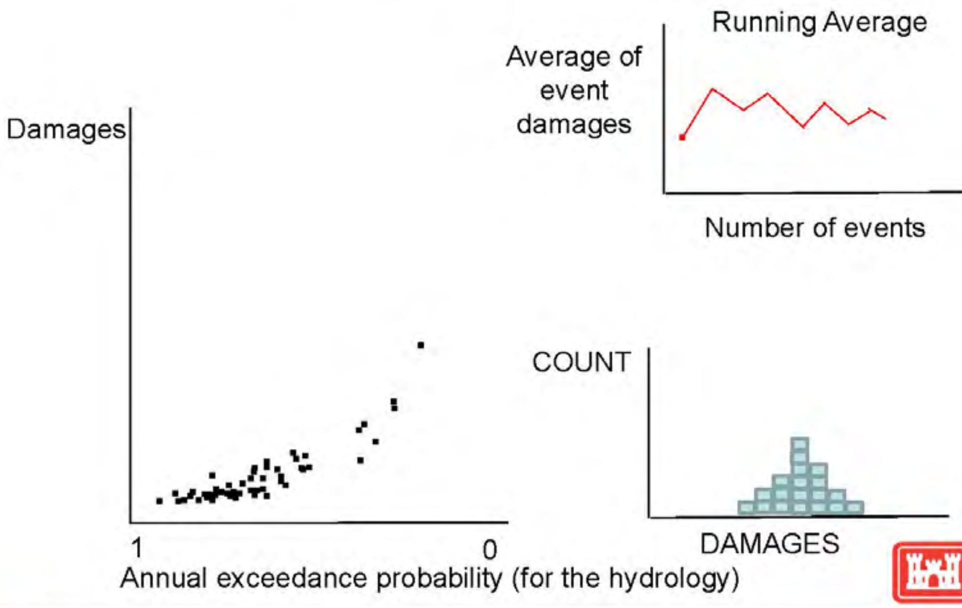
EVENT SAMPLING



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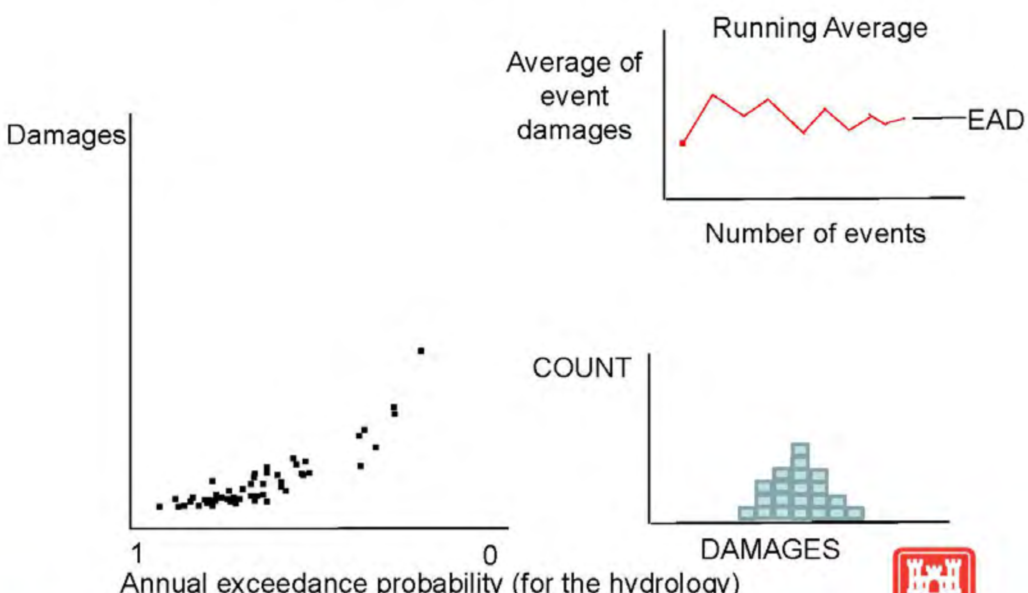
EVENT SAMPLING



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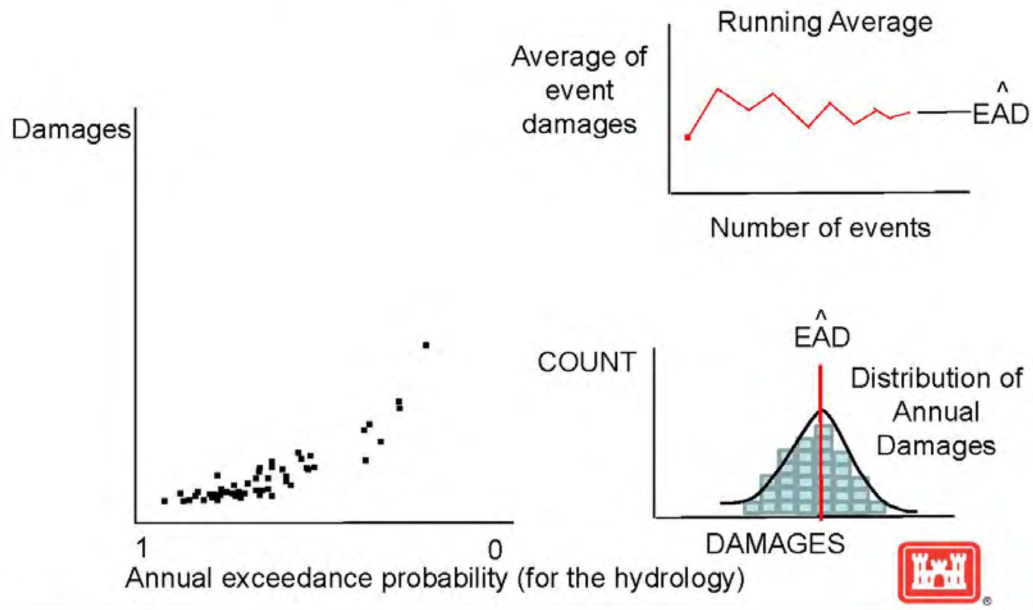
EVENT SAMPLING



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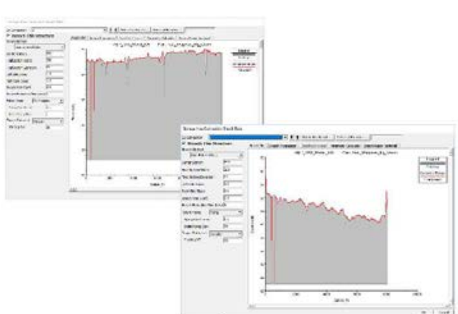
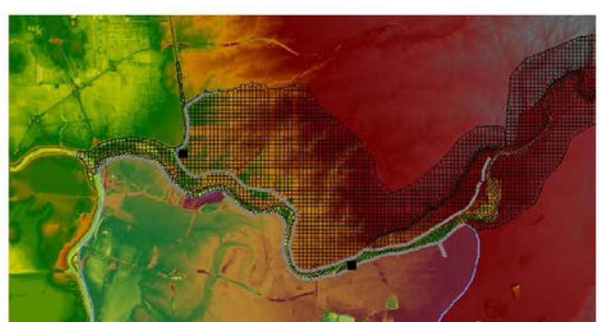
American River Insurance Study

- For stability a 2D channel was linked to a 2D overbank area through a 2D SA connection.
- Two connections were set to breach
- Model development took approximately 8 hours





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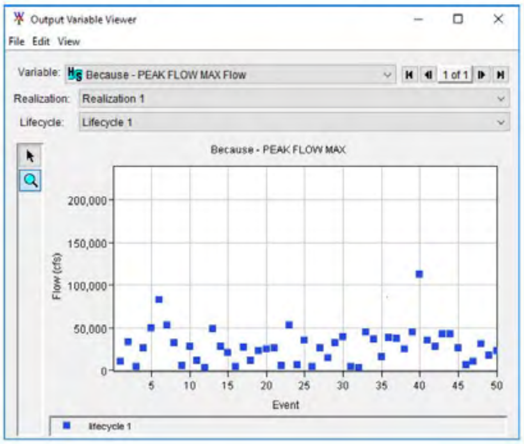
Hydrologic Sampler Events



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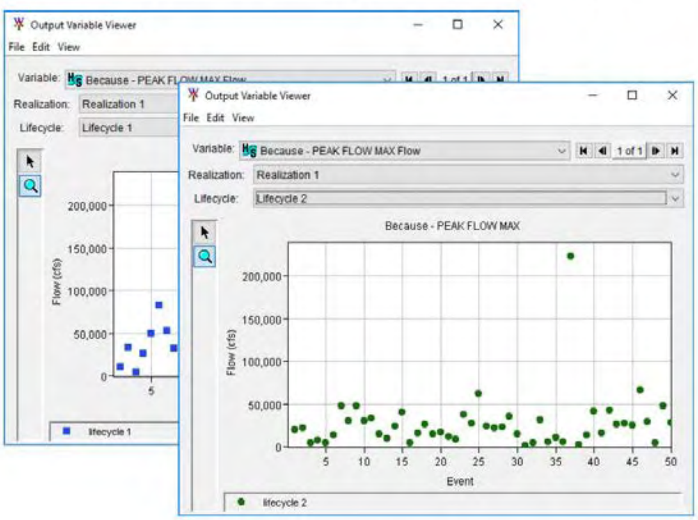
Hydrologic Sampler Events



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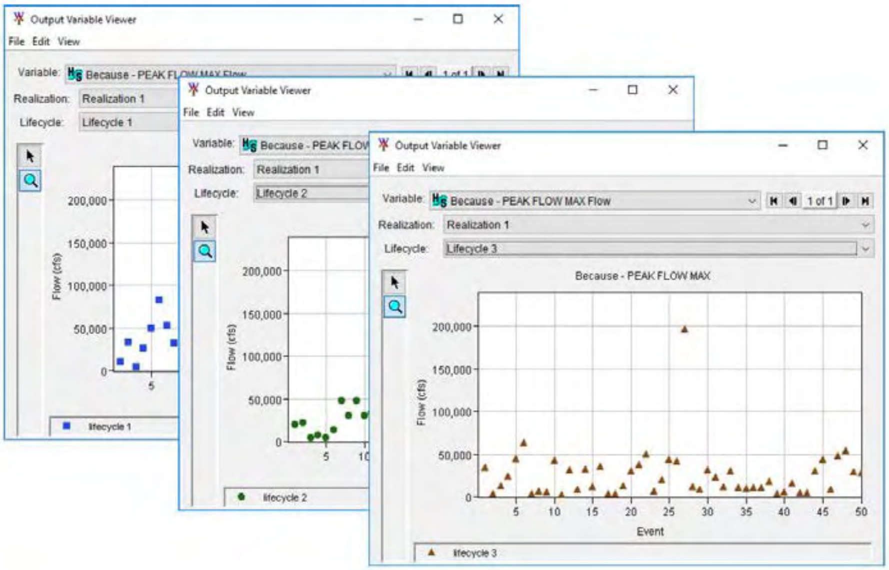
Hydrologic Sampler Events



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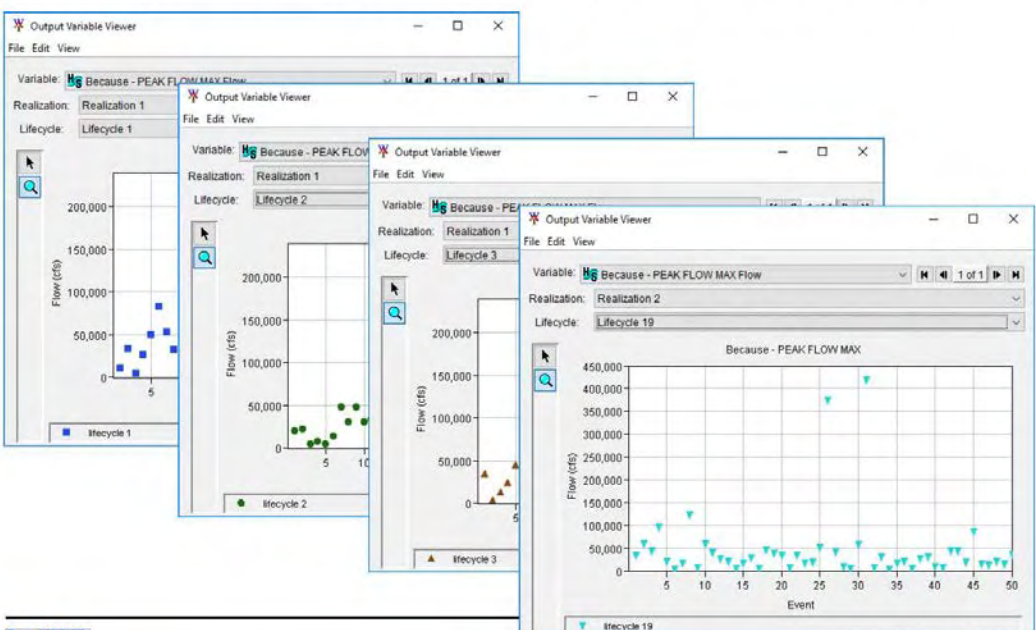
Hydrologic Sampler Events



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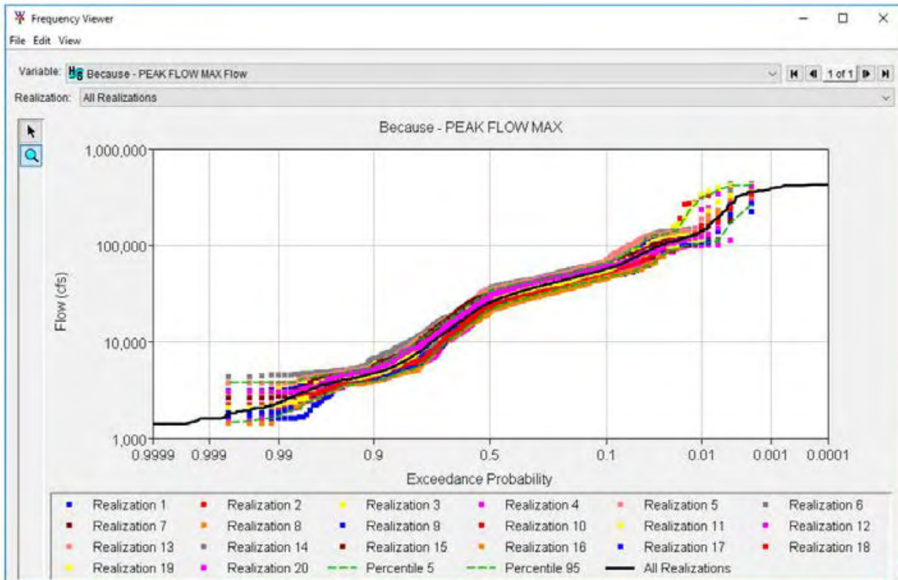

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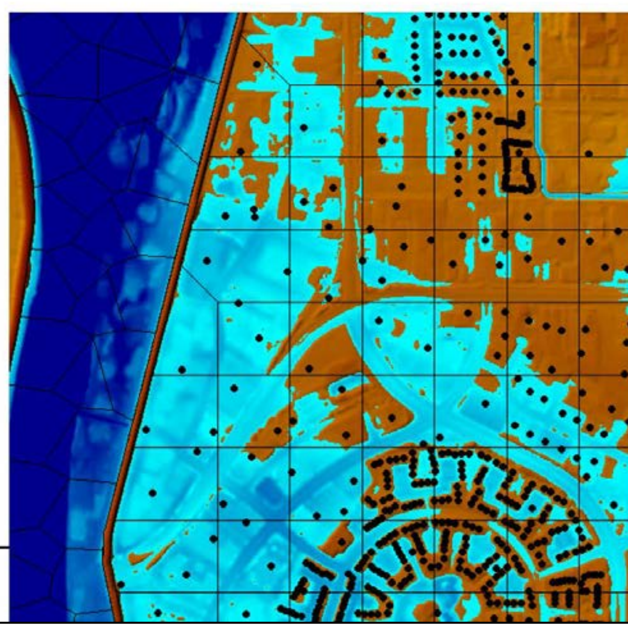
HEC-RAS output by event



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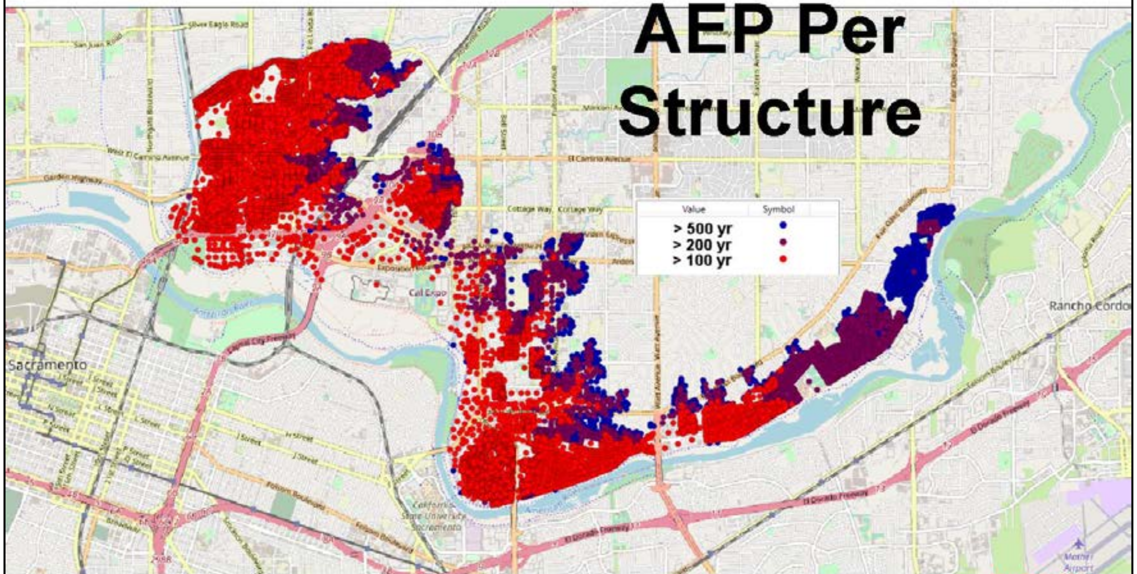

IWR

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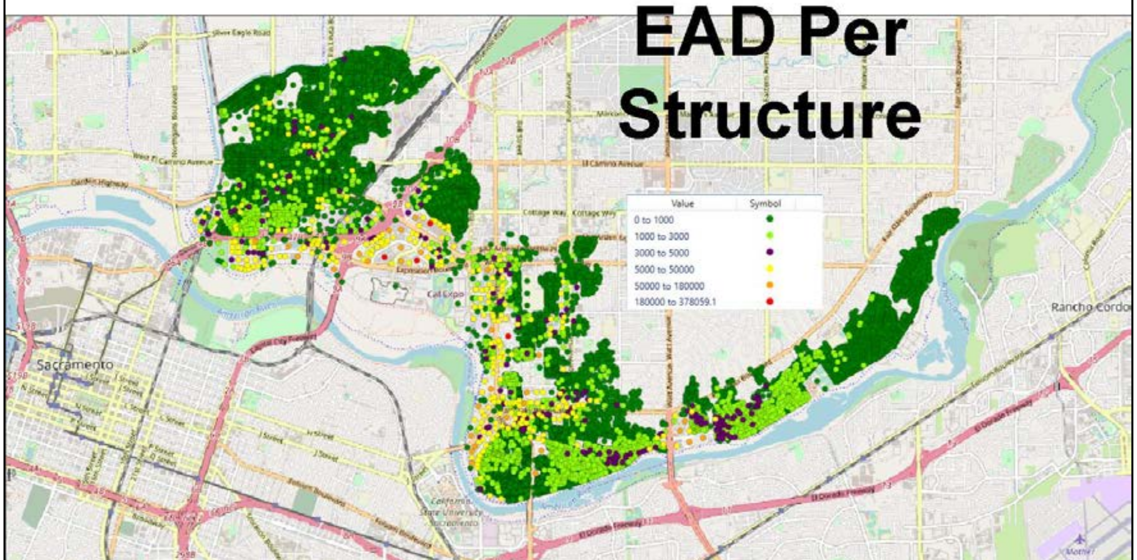

IWR

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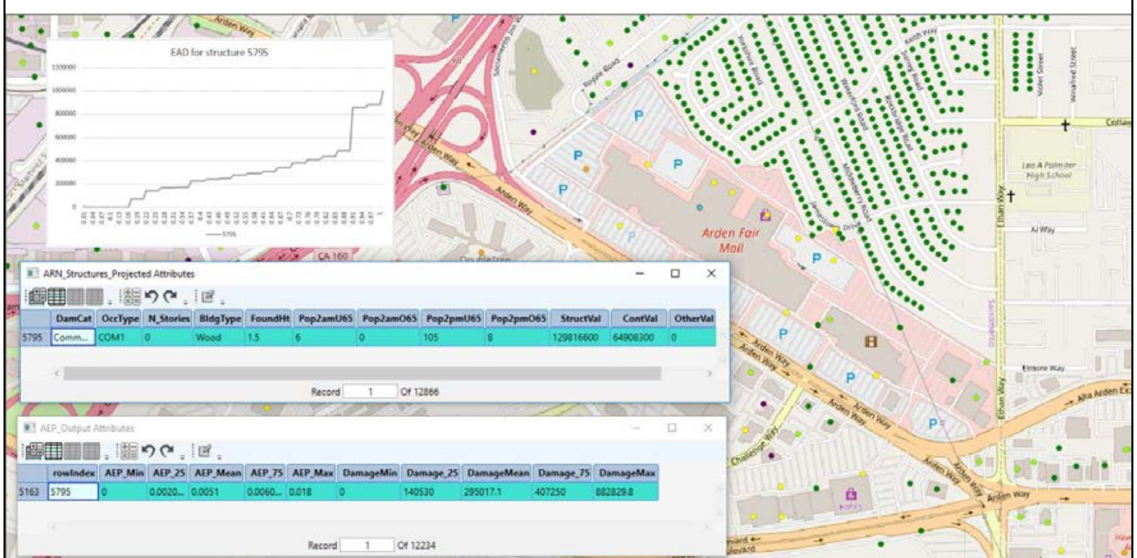


ARN_Structures_Projected Attributes

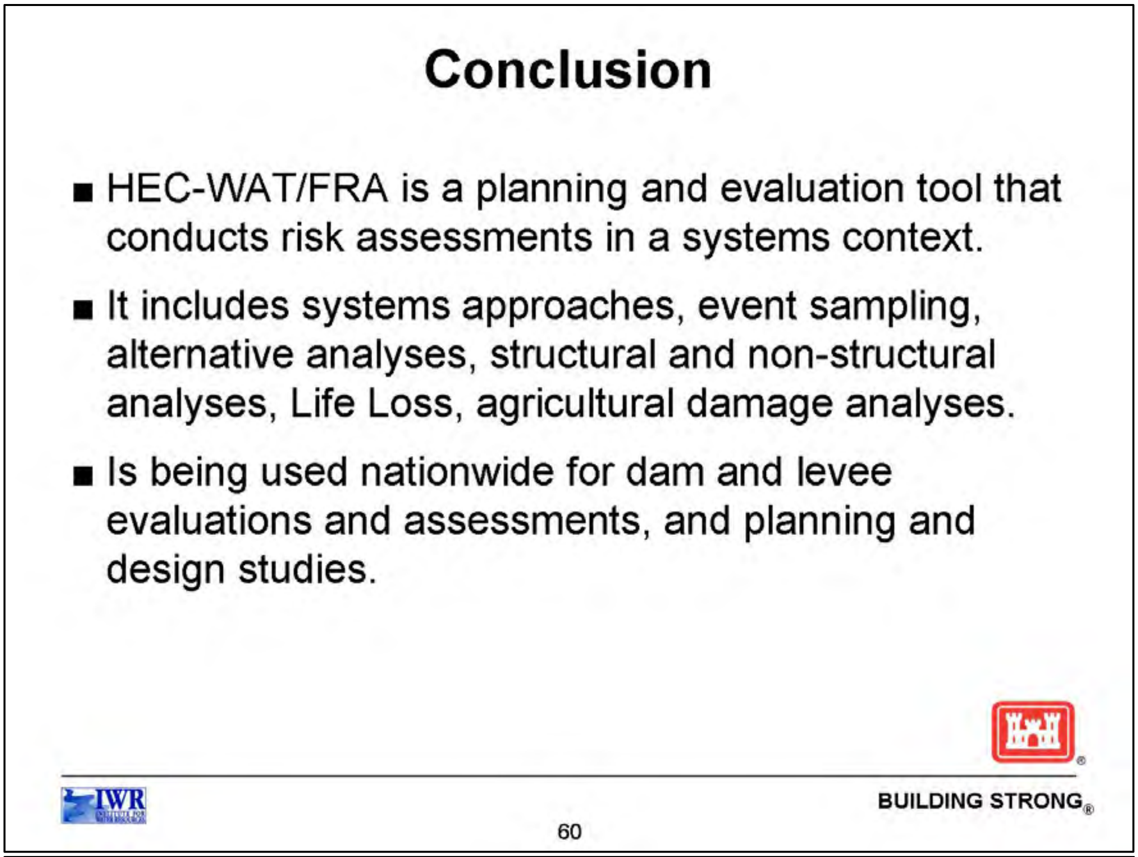
	DamCat	OccType	N_Stories	BldgType	FoundHt	Pop2amU65	Pop2amO65	Pop2pmU65	Pop2pmO65	StructVal	ContVal	OtherVal
5795	Comm...	COM1	0	Wood	1.5	6	0	105	8	129816600	64908300	0

Record 1 Of 12866

AEP_Output Attributes

	rowIndex	AEP_Min	AEP_25	AEP_Mean	AEP_75	AEP_Max	DamageMin	Damage_25	DamageMean	Damage_75	DamageMax
5163	5795	0	0.0020...	0.0051	0.0060...	0.018	0	140530	295017.1	407250	882829.8

Record 1 Of 12234



4.3.4.1.2 Questions and Answers

Question:

I was asked to go back to the slides, so people can read them. [Where has HEC-WAT been deployed?]

Answer:

We have deployed this in quite a few different places. We did it on Trinity River, where we ran stratified sampling and were able to estimate the uncertainty of the million-year event, which is kind of absurd.

Question:

I would like to ask if you are communicating this to a public. Imagine that I live in Sacramento and I'm in a public meeting. How would you convey this information to members of the public, so they have confidence that yes, in fact, your model is coming close to reality?

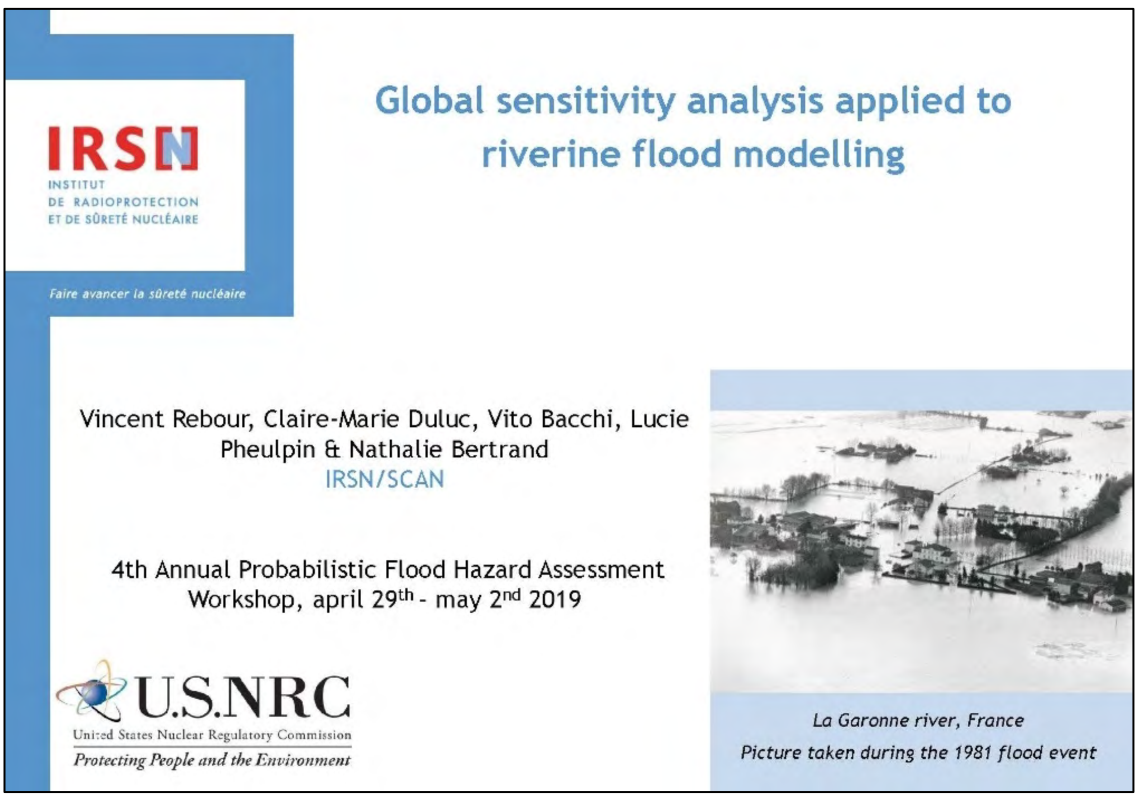
Answer:

That's a great question. I must qualify that I am a model developer and not a public communications expert. First, we have to acknowledge what we do not know. Second, I think that we need to incorporate uncertainty into our estimates rather than rely on static estimates. Right now, we say you are in the 100-year floodplain. That, to me, is one thing I can guarantee is a lie. By describing our inability to estimate perfectly the 100-year floodplain, we are actually improving our ability to communicate to someone. I would communicate our results by representing them as a five-number summary because I think that is a really effective tool to say the likelihood of you getting wet is between zero percent chance and 0.002 percent chance, with the most likely estimate of 0.001 percent chance.

4.3.4.2 Global Sensitivity Analyses Applied to Riverine Flood Modeling.

Claire-Marie DuLuc*, Vincent Rebour, Vito Bacchi, Lucie Pheulpin and Nathalie Bertrand, Institut de radioprotection et de sûreté nucléaire (IRSN) Radioprotection and Nuclear Safety Institute
(Session 2A-2; ADAMS Accession No. ML19156A463)

4.3.4.2.1 Presentation



Presentation outline

I. Context

II. Uncertainty analysis (UA) and global sensitivity analysis (GSA)

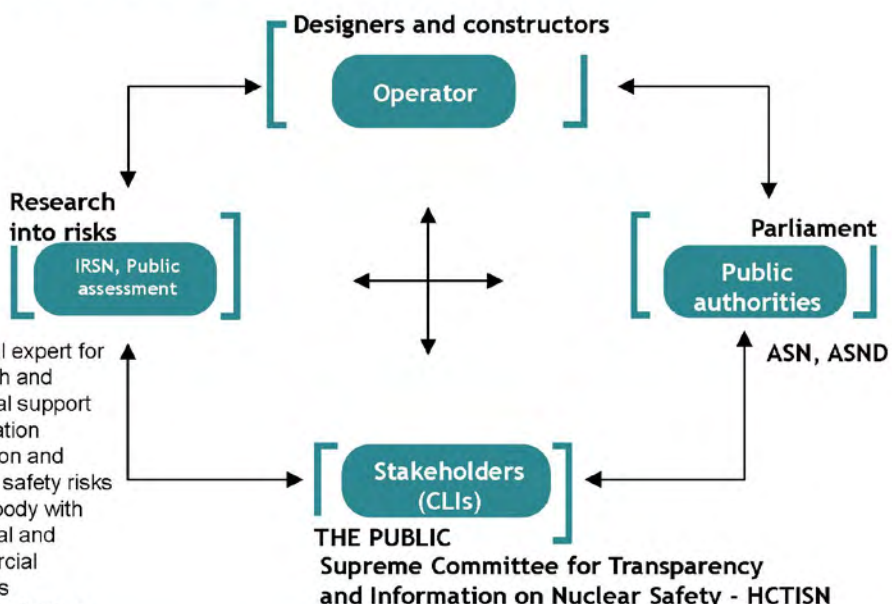
III. Preliminary studies applied to hydrodynamic models

IV. Levee breaches study on La Garonne river

V. Dependent inputs in hydraulic studies

VI. Conclusions and perspectives

Institutional environment



IRSN

- National expert for research and technical support on radiation protection and nuclear safety risks
- Public body with industrial and commercial activities
- 1700 employees

I. Context

French ASN guide "Protection of Basic Nuclear Installations against External Flooding" (2013)

- Uncertainties taken into account through a robust, conservative and deterministic approach
- Upper bound of confidence interval, conservative assumptions defined for initial states...
- Concerning the hydraulic modelling, penalization of the most influencing parameter

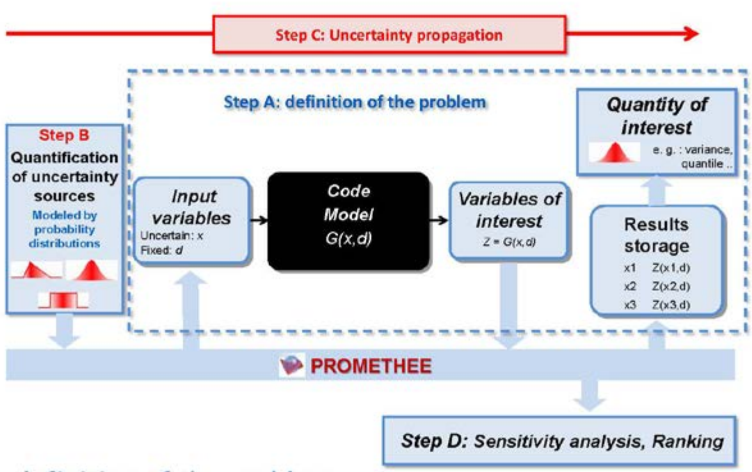
- Identifying the most influencing parameter and giving it a penalizing value is challenging and usually questionable...

⇒ objective to develop a rigorous methodology to identify and penalize the most influencing parameter

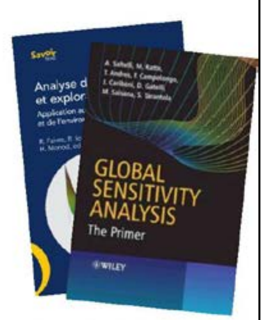
⇒ objective to develop a probabilistic flood hazard assessment method

II. Uncertainty analysis (UA) and global sensitivity analysis (GSA)

Main steps of uncertainty analysis and global sensitivity analysis



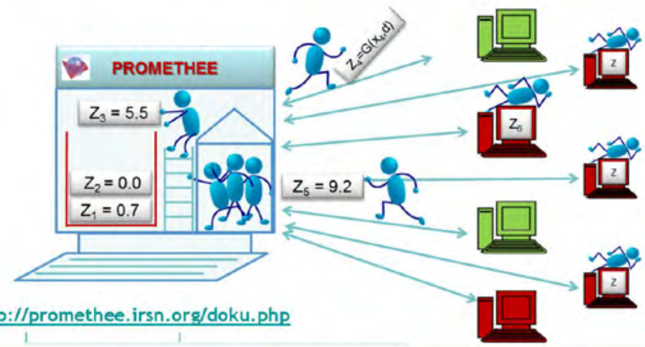
IRSN computational environment PROMETHEE



A : definition of the problem
B : definition of the input affected by uncertainty
C : uncertainty propagation
D : sensitivity analysis ranking

The key role of Promethee in performing UA and GSA

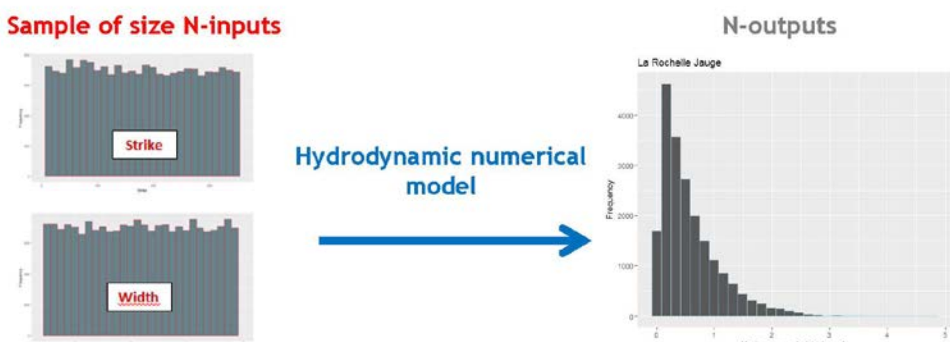
- Promethee environment coupled to different numerical models
  - *Allows the parameterization of any numerical code to carry out a huge number of simulations*
  - *Graphical user interface*
  - *Takes advantage of [R] algorithms to perform uncertainties propagation, sensitivity analysis, …*
  - *Deploys computational resources (e.g. work stations, servers, clusters)*



http://promethee.irsn.org/doku.php

II. Uncertainty analysis (UA) and global sensitivity analysis (GSA)

Steps C : Monte-Carlo sampling for UA



- Law of response : statistic estimation

Mean $E[Y]=\mu_Y=\frac{1}{N}\sum_{i=1}^{N}G(x^i)$

Variance $Var(Y)=\frac{1}{N-1}\sum_{i=1}^{N}\left[G(x^i)-\mu_Y\right]^2$

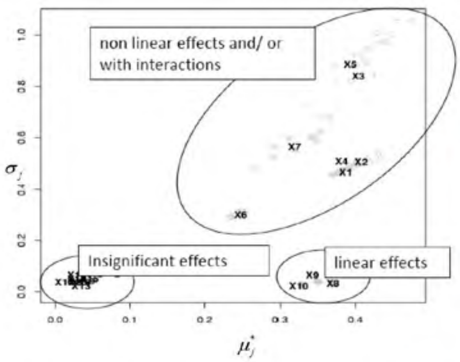
St. deviation $\sigma_Y=\sqrt{Var(Y)}$

Convergence speed $o\left(\frac{1}{\sqrt{N}}\right)$

4th Annual Probabilistic Flood Hazard Assessment Workshop, april 29th - may 2nd 2019 IRSN

Step D: sensitivity analysis

- D.1) Morris screening-method (One-at-a-time) - Morris, 1991



μ_j^* is a measure of influence of the *j-th* input on the output

σ_j is a measure of non-linear and/or interaction effects of the *j-th* input

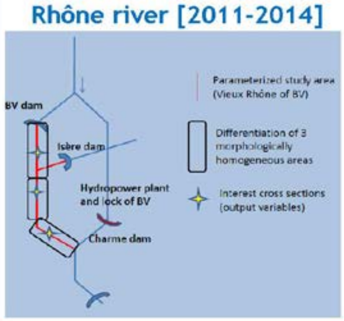
- D.2) Sobol' index computation

$$S_i = \frac{D_i(Y)}{Var(Y)}, \quad S_{ij} = \frac{D_{ij}(Y)}{Var(Y)}, \quad \ldots$$

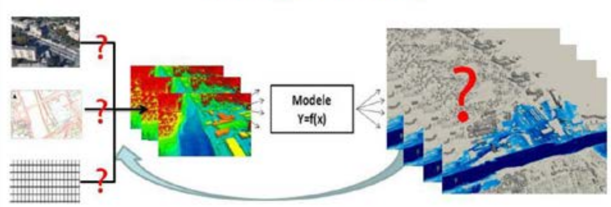
$$S_{Ti} = S_i + \sum_{i<j} S_{ij} + \sum_{j\neq i, k\neq i, j<k} S_{ijk} + \ldots = \sum_{l \subset \# i} S_l$$

- Results of ANOVA (ANanlysis Of VAriance) decomposition
- Quantify the contribution of each input parameter on the output variance
- Independent input parameters

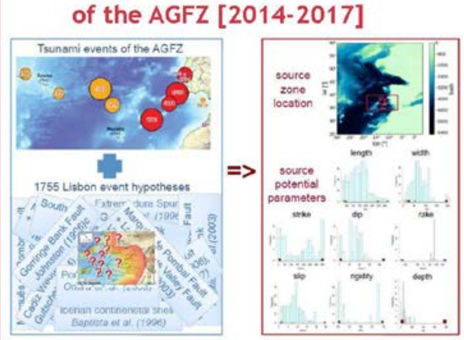
1D hydraulic model of the Rhône river [2011-2014]



Topography with a 2D model [2013-2016]



2D Tsunamigenic potential of the AGFZ [2014-2017]



Flooding and levee breaches study on La Garonne river [2015-2019]

Conclusions of preliminary studies

Interest for flood hazard assessment:

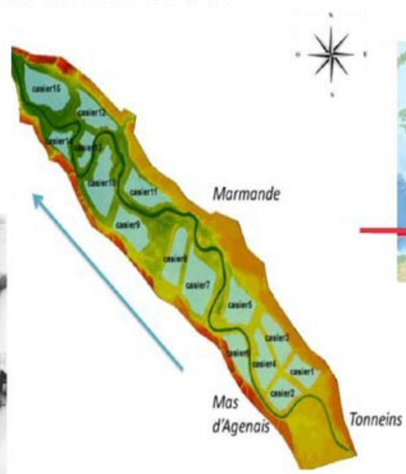
- In the context of nuclear safety UA and GSA allow to *identify the influencing parameters in a rigorous way*
- Identify *some rare combinations* of critical flooding situation that would have not been identified with an expert opinion
- Can be a *complementary approach* to the current state of practices concerning uncertainties on flooding hazard assessment

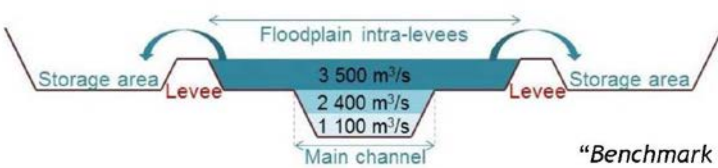
Main challenges:

- Time consuming calculations (interest of meta-model approaches…)
- Dealing with *dependent input parameters*

Case study on La Garonne river

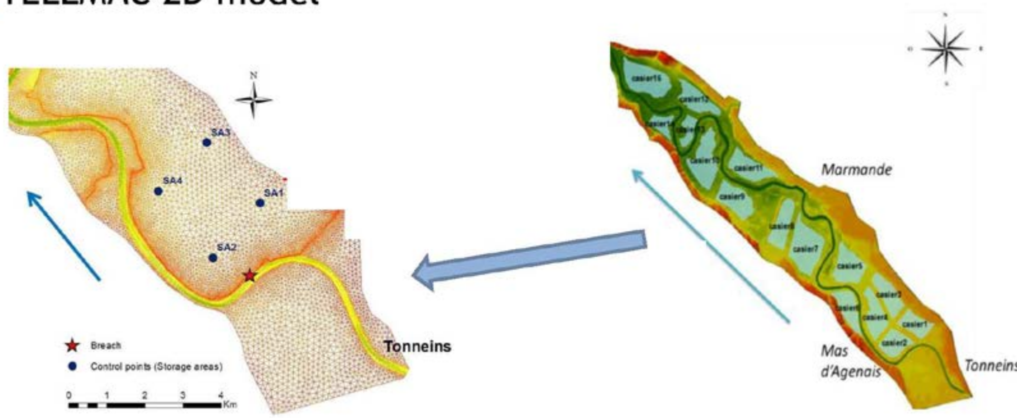
Picture taken during the 1981 flood event (Sudouest.fr, Photo Archives G.L.)





"Benchmark Garonne" project by EDF

TELEMAC 2D model



TELEMAC 2D:

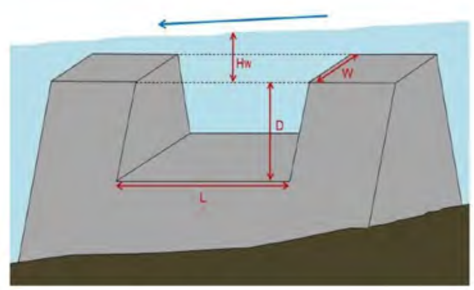
- 82,116 cells with different length varying from 10 to 300 m
- Upstream boundary condition: triangular hydrograph with a flow peak of 3,081 m^3/s
- The peak discharge is achieved after 18 hours and the simulation ends after 5 days

IV Levee breaches study on La Garonne river

Levee breaches study

- **TELEMAC** breaching process : when the water level above the dyke reaches a given value "Hw"
- Uncertain parameters :
  - Overflow **Hw** : from 50 cm below levee crest to 10 cm above

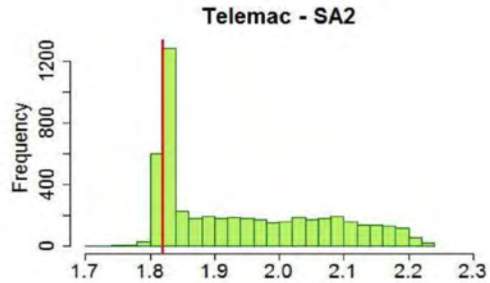
+ 2 geometrical parameters :
  - Depth **D** : from 0 to 100% of the levee height
  - Length **L** : between 40 and 200 m



Levee breach diagram.
The parameters are the length (L), the depth (D), the width (W) and the water level above the crest, that means the overflow (Hw).

- 200 simulations performed => raised to 5,000 with kriging meta-model (validated as a good emulator for reproducing the TELEMAC-2D code behavior)

Uncertainty propagation and GSA



Frequency distributions of the maximum water levels in four storage areas

SA Sobol' indices for the 3 uncertain parameters

⇒ Large variation of water height compared to the simulation without breach (red lines), influence of Depth…

⇒ No dependency taken into account between Overflow, Length nor Depth

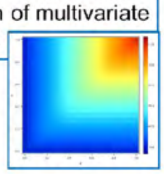
⇒ See *SimHydro 2019, Pheulpin & al - Comparison between uncertainty propagations and sensitivity analyses from two hydraulic models (1D and 2D) of the Garonne River: Application to levee breach parameters*

Dependant inputs taken into account in a simplified case : 1D equations of Saint-Venant, with uniform and constant flowrate and large rectangular sections

Step B: Uncertainty sources quantification

For all parameters, definition of:
- Parameter bounds
- Parameter distribution laws

For dependent parameters:
- Groups of parameters identification
- Copula selection (*e.g.* normal copula) adapted to each group of parameter and definition of the correlation coefficients (*r*)
- Construction of multivariate distributions



Example of a normal copula cumulative distribution function

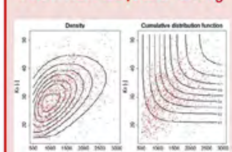
Uncertainty sources quantification

Inputs	Symbols	Units	PDF
Maximal annual flow rate	Q	m³/s	Truncated Gumbel
Strickler coefficient	K_s	-	Truncated Normal
River downstream level	Z_v	m	Triangle
River upstream level	Z_m	m	Triangle
Levee height	H_d	m	Uniform
Bank level	C_b	m	Triangle
Length of the river stretch	L	m	Triangle
River width	B	m	Triangle

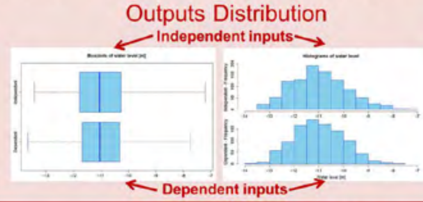
UQ for independent and dependent parameters

Dependent inputs → 3 normal copulas: Q/K_s (r = 0.5) ; Z_v/Z_m (r = 0.3) ; L/B (r = 0.3)

Normal copula Q/K_s

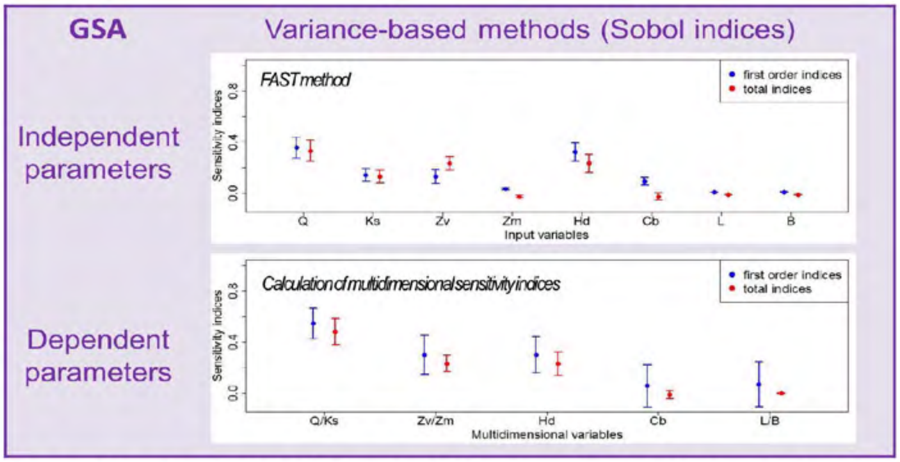


Outputs Distribution



V Dependent inputs in hydraulic studies

Simplified case: global sensitivity analysis



- In this example, the choice of the copula has very few impact on the outputs
- Some parameters (e.g. Zm) can have more influence once included in a group than considered independent

⇒ More information : see *IRSN EGU 2019 poster (Pheulpin & al)*

Application to a real case study (perspective)

Step A: Problem specification

Input parameters:
- **Fixed**: Time step, grid resolution, *etc.*
- **Uncertain**:
  - Hydraulic parameters: hydrograph parameters, Strickler coefficient, *etc.*
  - Breach parameters: length, depth, time formation, *etc.*

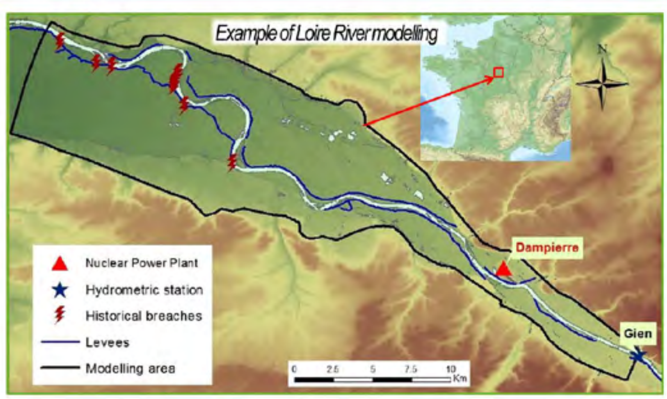
↓

Independent parameters or not?

Variables of interest
- Water levels at certain location in the flood plain (*e.g.* near the breaches)

Quantities of interest
- Probability, variance, *etc.*

Hydraulic and levee breach modelling: Example for the Loire River
- 50 km-long reach modelling, between Gien and Orléans
- 2D modelling with Telemac-2D
- Numerous levees along this reach with known historical breaches



Conclusion of recent and on going studies on riverine flood modelling

- Uncertainty quantification related to levee behavior during an inundation event can be a very difficult (but essential) task
- Additional uncertainty associated to the chosen numerical model representing the breach process (1D vs 2D…)
- Theoretical framework available to take into account dependencies, data needed to characterize dependencies
- Interest of meta-models and inversion approach to control calculation time

Probabilistic Flood Hazard Assessment (perspectives…)

<u>Riverine flood</u>

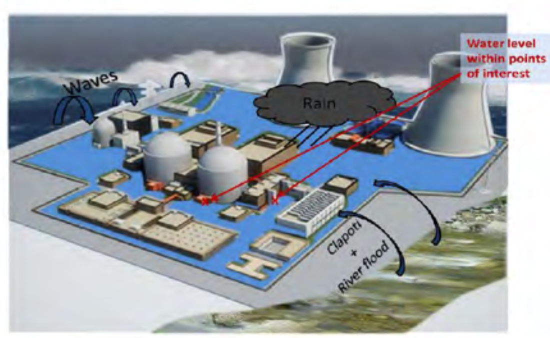
- objective of including a probabilistic assessment through uncertain input parameters (e.g. peak flow rate distribution and duration of flood…)
- propagate uncertainties or use inversions methods to define the probability of some outputs safety criteria

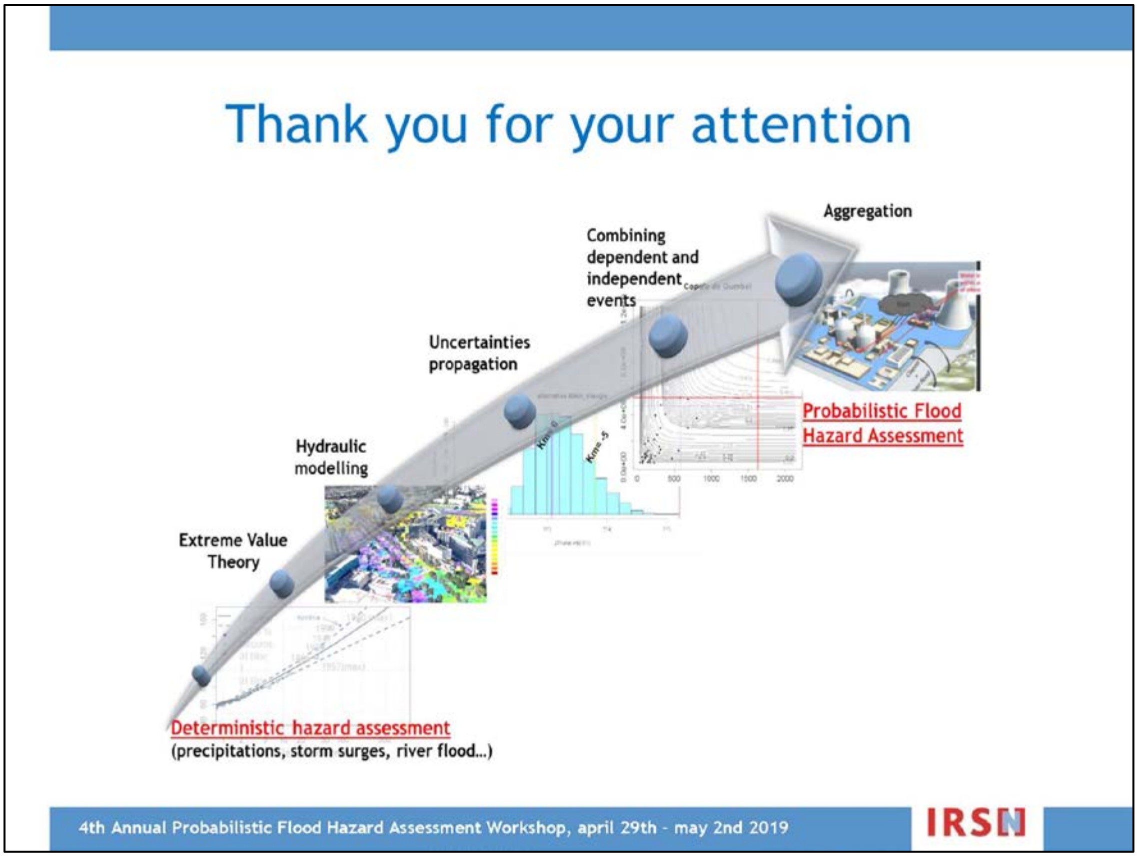
⇒ *See Bacchi & al, CMWR conference in June 2018*

<u>Combining hazards</u>

- on going PhD

⇒ see *Ben Daoued & al “Modeling coincidence and dependence of flood hazard phenomena in a Probabilistic Flood Hazard Assessment (PFHA) » (under revision)*





4.3.4.2.2 Questions and Answers

Question:

Would you take some additional steps on the failure mechanisms? Besides overtopping, do you have a framework? Can your framework be flexible so that you can do seepage through the levee as well?

Answer:

That should be very interesting to have a different set of failures. But you are limited by what the model can take into account, and we simplified it with only overtopping for the study. With Hydrologic Engineering Center River Analysis System (HEC-RAS), I think it is possible to make more failure modes because the model is very well developed to take into account different parameters. If we have knowledge to supply boundary conditions, and that is not an easy point, we should try to complete the study with different types of failure.

Question:

For the uncertainty source quantification, how did you determine the probability density function (PDF) for each parameter?

Answer:

For the moment, it's an expert point of view given to us to define the bounds of the possible values for the input parameters and also for the shape of the distribution itself. We basically use uniform laws or triangle laws if we think there is a best nonvalue. That is the state of practice now.

Question:

Have you thought about epistemic uncertainty, specifically for the Loire test case? You have pointed out that there are historical areas that have had levee failures. Have you considered randomizing the levee failures in space?

Answer:

Yes, that is a very challenging issue, and our study does not take it into account. There is only the bridge. We have the previous studies with different locations of the bridge, but we were limited; we had the same parameter value for each bridge at the same time, which is not realistic. We have to find something that will take into account this complexity of special possibilities for bridges.

4.3.4.3 Detection and Attribution of Flood Change Across the United States.
Stacey A. Archfield*, Water Mission Area, U.S. Geological Survey (Session 2A-3)

This presentation was cancelled due to illness.

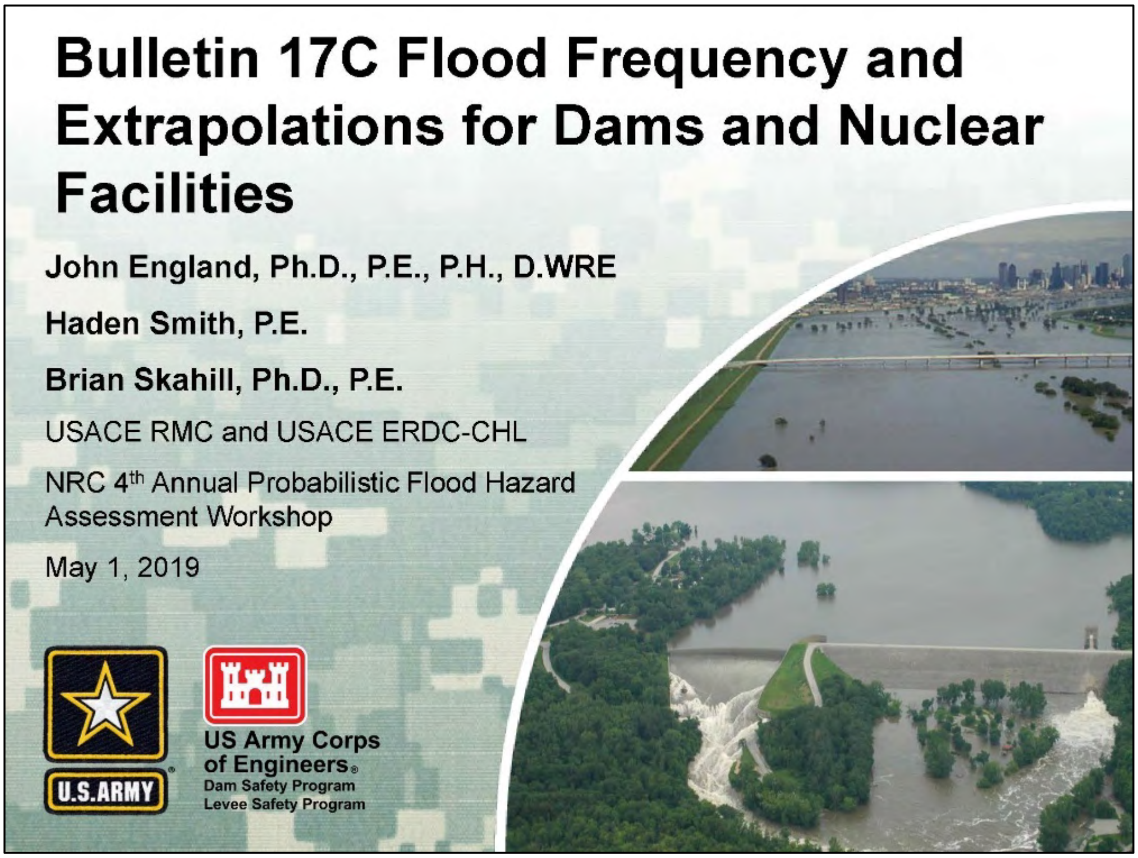
4.3.4.4 Bulletin 17C: Flood Frequency and Extrapolations for Dams and Nuclear Facilities.
John F. England* and Haden Smith, USACE, Risk Management Center; Brian Skahill, USACE R&D Center, Coastal and Hydraulics Laboratory (Session 2A-4; ADAMS Accession No. ML19156A464)

4.3.4.4.1 Abstract

Flood frequency guidelines have been published in the United States since 1967 for nationwide flood risk management and flood damage abatement programs. These "Guidelines for Determining Flood Flow Frequency" have undergone periodic revisions. Bulletin 17C is the latest revision to these flood frequency guidelines. It was published in March 2018 and is available at https://doi.org/10.3133/tm4B5. Bulletin 17C contains statistical procedures using the Expected Moments algorithm (EMA) and the log Pearson Type III (LP-III) distribution that efficiently and effectively utilize extreme flood data, including historical, paleoflood, and botanical information. Interval flood data are now included in flood frequency, such as large floods that exceeded some level, floods in a range, and/or floods that were less than some value. The Guidelines include procedures to properly estimate the extreme flood right-hand tail of the flood frequency distribution by carefully eliminating the influence of small floods or zero values called potentially influential low floods. An enhanced focus is on collecting at-site and regional data on extreme floods, including expanding the record in time with data from historical and paleoflood sources. Extraordinary floods, those that are the largest magnitude at a site or region and substantially exceed other observations, are of critical importance and are included by judicious use of flow perception thresholds and longer time frames than the number of years at a gaging station. The Guidelines include a new section called "Frequency Curve Extrapolation" that provides guidance on estimating flood probabilities less than 0.01 AEP and relevant for dams, levees, and nuclear

facilities. In these situations, such as to estimate AEPs in the range of 10^{-3} to 10^{-6}, a flexible, three-step approach using multiple lines of evidence is recommended. These three elements are (1) utilize EMA and LP-III with expanded historical, paleoflood, and extraordinary flood data at the site (temporal information expansion), (2) expand and improve regional skew models (spatial information expansion), and (3) expand and include regional independent information such as from extreme flood rainfall-runoff models within the watershed or other physical and causal information. Information can be combined and weighted using quantile variances or other procedures. An overview of this approach is presented with example flood hazard estimates for dam safety.

4.3.4.4.2 Presentation



Outline

- Risk-Informed Decision Making (RIDM)
  - Dam and Levee Safety
- Bulletin 17C Overview
- Extrapolation Guidance in Bulletin 17C
- Key Ingredients for PFHA
  - Rainfall-Runoff
- Some Methods to Weight and Combine Hazard Curves
- Some PFHA Examples for Dam Safety

Oroville Dam, Feather River, Oroville, CA
770 feet
(tallest embankment dam in US)
Spillway Failure February 2017

Web resources indicated by URLs or underlined text
example - Flood Hazards

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2

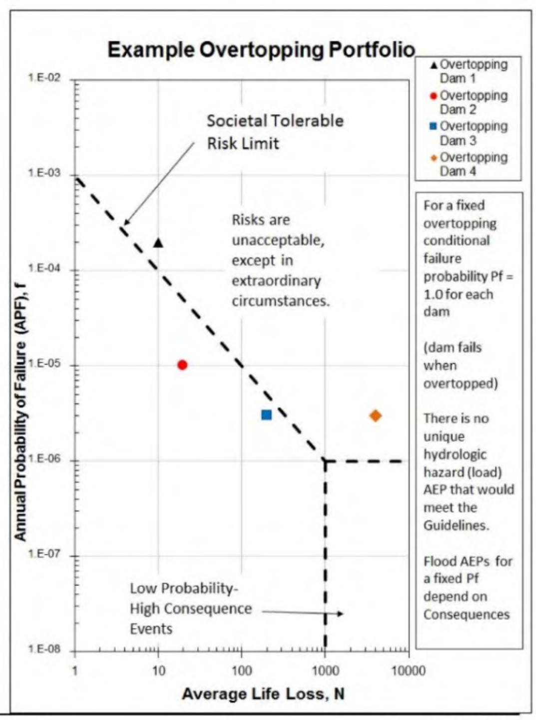
Acknowledgments—Greg Karlovits (USACE-HEC) precipitation frequency; Keith Kelson (USACE-DSPC) paleoflood data; Angela Duren (USACE-NWD) rainfall-runoff, streamflow hazard curves, many analyses; and David Margo (USACE) reviews, ideas, collaboration, and testing.

Risk-Informed Decision Making (RIDM) for Dam Safety

Risk Guidelines f-N chart

Annualized Loss of Life
1 in 1,000 (0.001) per year
(diagonal line)

Hydrologic Hazard
Annual Exceedance Probability
(AEP) (design flood)
not a fixed value
depends on failure probability
and consequences



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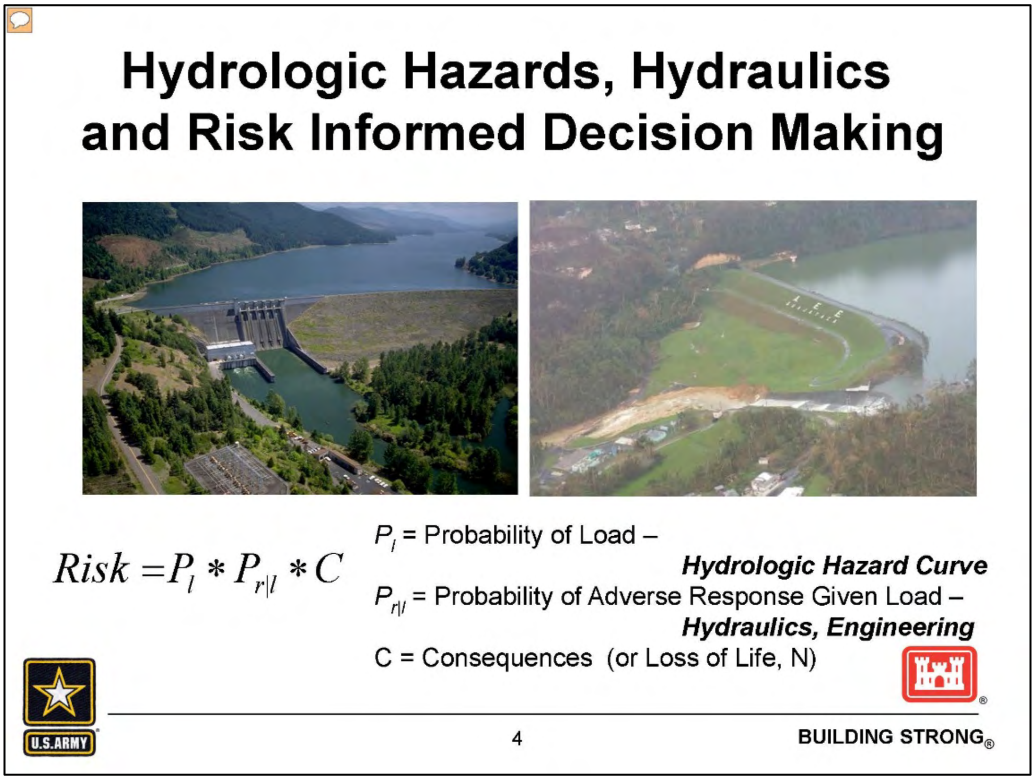
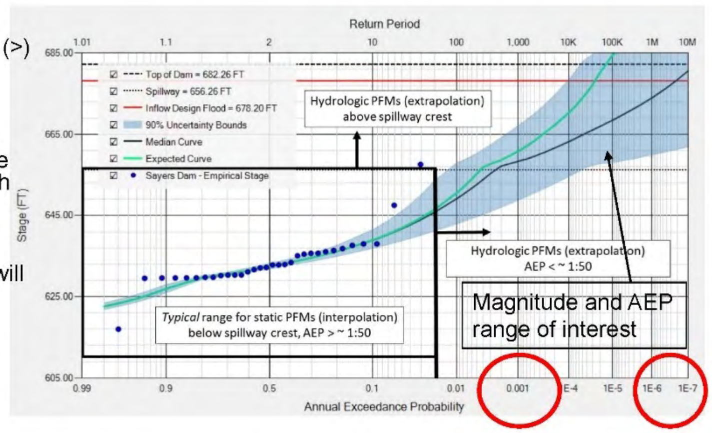


For a dam, a series of dams, or a system of dams, assess hydrologic risk for overtopping, spillway-related potential failures, gate misoperation, or other hydrologic failure mode. Example: Guajataca Dam, PR—spillway stilling basin failure and erosion and failure of spillway chute during Hurricane Maria (2017). Gates at Lookout Point Dam, Willamette River Basin.

Example Hydrologic Hazard Curve – Stage Frequency

- Annual probability that stage will be exceeded (>)
  - **Same applies for discharge, volume, velocity, etc.**
- Risk estimates need the full range of values, with uncertainty (*focus on Expected Curve*)
- Range that drives risk will depend on PFMs and consequences
  - *< 1 in 10,000 (dams)*
  - *< 1 in 1,000 (levees)*



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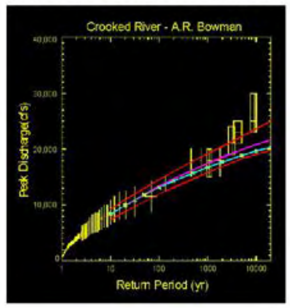
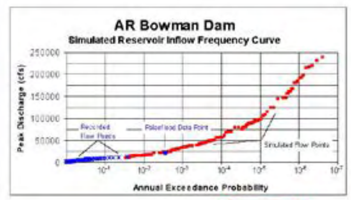
Hydrologic Hazards and Risk-Informed Overtopping Improvements

- A.R. Bowman Dam, Prineville, OR
- New 6-foot parapet and spillway wall raise, completed ~ 2011
- Hydrologic Hazards – basis for risk design – Paleoflood studies and Stochastic Rainfall-runoff modeling





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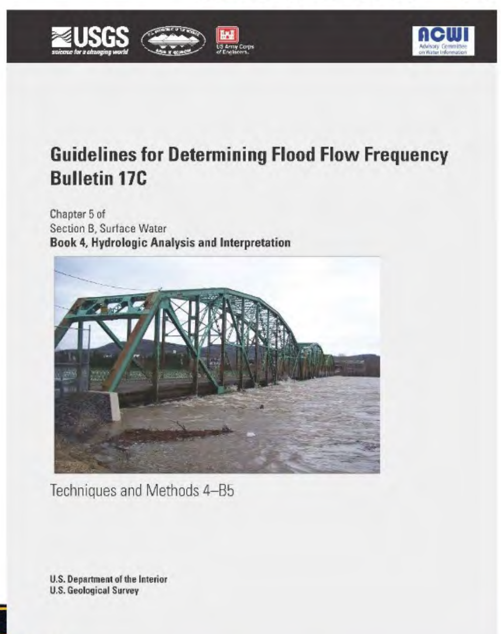
Bulletin 17C Overview


USGS science for a changing world

ACWI

Guidelines for Determining Flood Flow Frequency
Bulletin 17C

Chapter 5 of
Section B, Surface Water
Book 4, Hydrologic Analysis and Interpretation

Techniques and Methods 4–B5

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

- Log-Pearson Type III distribution
- Method of Moments
  - ► Expected Moments Algorithm
  - ► Diverse Data
- Weighting of at-site and regional skew
- Accurate Confidence Intervals

https://doi.org/10.3133/tm4B5

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https://acwi.gov/hydrology/Frequency/b17c

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Applicability of Bulletin 17C Guidelines

Page 36:

- Accurate determination of floods for small AEPs (0.01) generally requires more data; estimations of floods for AEPs smaller than 0.005 generally require augmentation of the systematically observed flood records with general regional information, insight from precipitation records, or paleoflood information.

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This is the very last section in the main report of Bulletin 17C.

Comparisons of Frequency Curves - Bulletin 17C

Pages 31-32 [synopsis]:

- Other procedures for estimating floods can sometimes be used for evaluating rare exceedance probabilities, procedures are not standardized. *Guidelines describe the information to incorporate but allow considerable latitude in application*.
- Prior to making comparisons, ensure all data at the site and within the region have been adequately considered and incorporated into the frequency analysis. In this way, the flood frequency curve may reflect the following: **temporal information** such as historical and paleoflood data; **spatial information** such as regional skew and watershed characteristics; and **causal information** such as hydroclimate information and mixed-population data.

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Frequency Curve Extrapolation - Bulletin 17C

Page 34:

- The amount of extrapolation depends on the *quantity and quality of flood information* at the site of interest, data and information within the larger region, *the designs and decisions to be made, and tolerance for uncertainty in the extrapolated results*. It is not simply based on the at-site data record length; there are variations in quantity and quality of flood information, as well as in the purposes of the designs and decisions to be made using the flood frequency estimates. *A flexible approach using multiple lines of flood evidence for extrapolation is appropriate.*

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Frequency Curve Extrapolation - Bulletin 17C

- As described in the section Comparisons of Frequency Curves, **all types of analyses should be incorporated** when estimating flood magnitudes for exceedance probabilities **less than 0.01 AEP**. … Include additional information as follows [p. 34].

1. Expand flood data in time at location of interest;
   [Temporal information expansion - Merz and Bloschl (2008)]
2. Expand and improve regional skew models; and
   [a particular form of Spatial information expansion - Merz and Bloschl (2008)]
3. Expand with regional independent information
   [Spatial and Causal information expansion - Merz and Bloschl (2008)]
   - Extreme floods from rainfall runoff in watershed
   - Regional frequency estimates (streamflow or rainfall-runoff)
   - Physical and causal estimates
4. Carefully examine the upper tail and quantify uncertainty.

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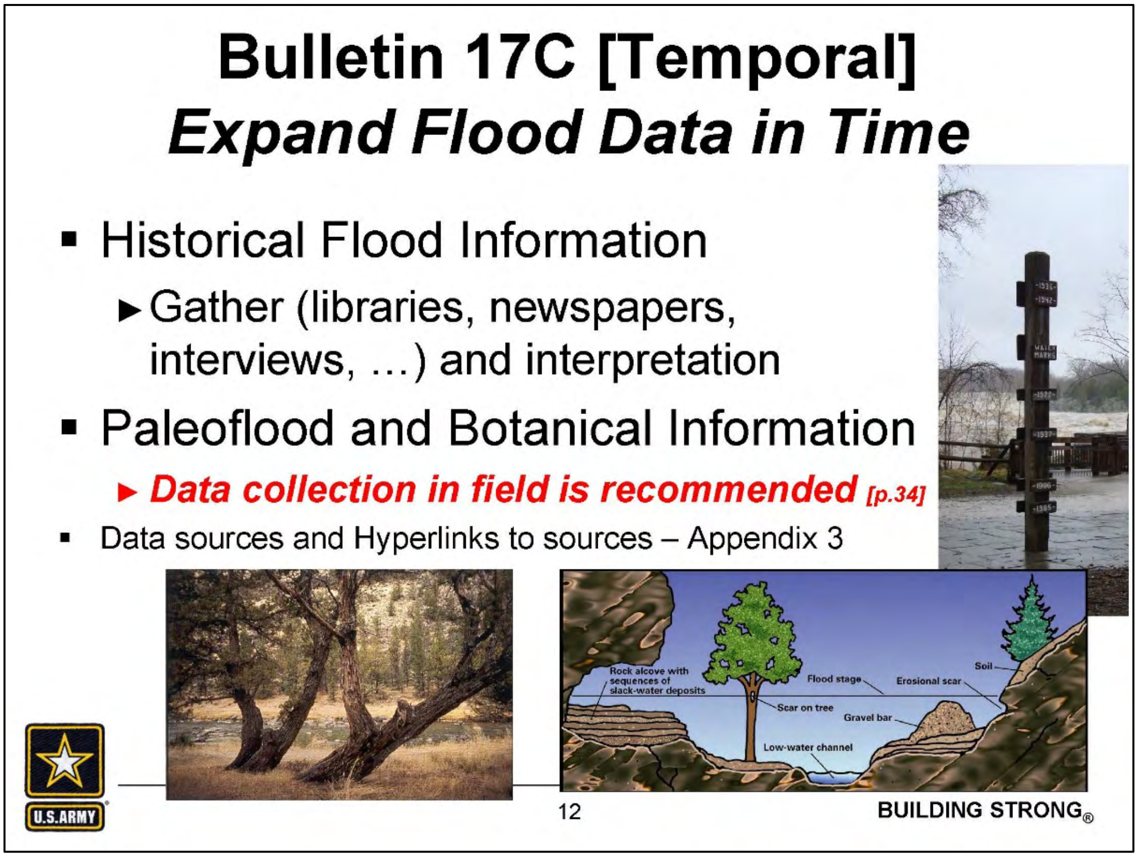
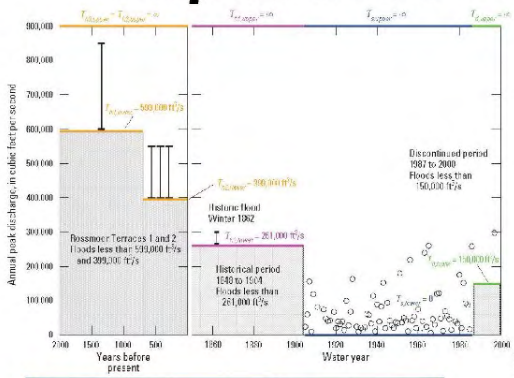
See page 34 and sections titled, “Comparisons of Frequency Curves” and “Weighting of Independent Frequency Estimates.”

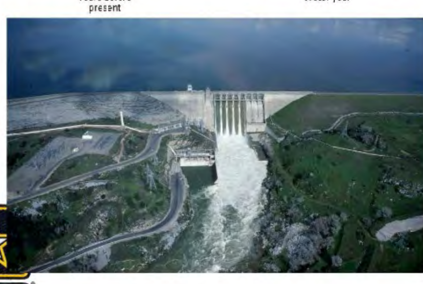


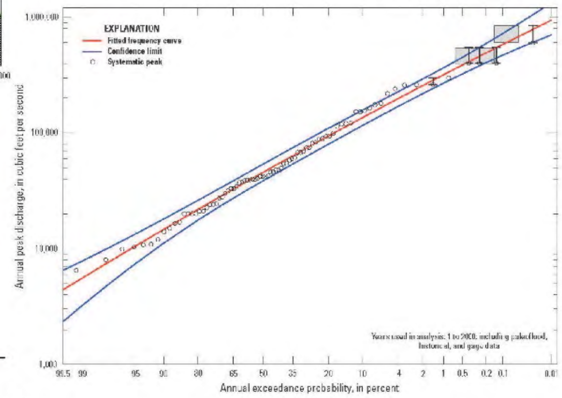
Bulletin 17C [Temporal]
Expand Flood Data in Time



- Hydrologic hazards for Dam and Levee Safety, with longer historical and paleoflood records

(see **Frequency Curve Extrapolation** section and Appendix 10 Examples)





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Expand with Regional Independent Information

Frequency Estimates from Rainfall-Runoff Models

- **Physics**
  - ► Rainfall-runoff model, flood typing, processes
    - (spatial rainfall, infiltration, snowmelt, channel routing, etc.)
  - ► Extreme precipitation mechanisms/classification
    - (storm type, season, …)
- **Key Ingredients**
  - ► Regional Extreme Storm Data Catalog: space-time patterns
    - https://maps.mmc.usace.army.mil/esd/
  - ► Storm Typing – classify annual maxima for precipitation frequency
  - ► Regional Annual Maximum Precipitation Frequency (critical duration) **[Spatial]**
  - ► Rainfall-runoff watershed model and calibration data **[Causal]**

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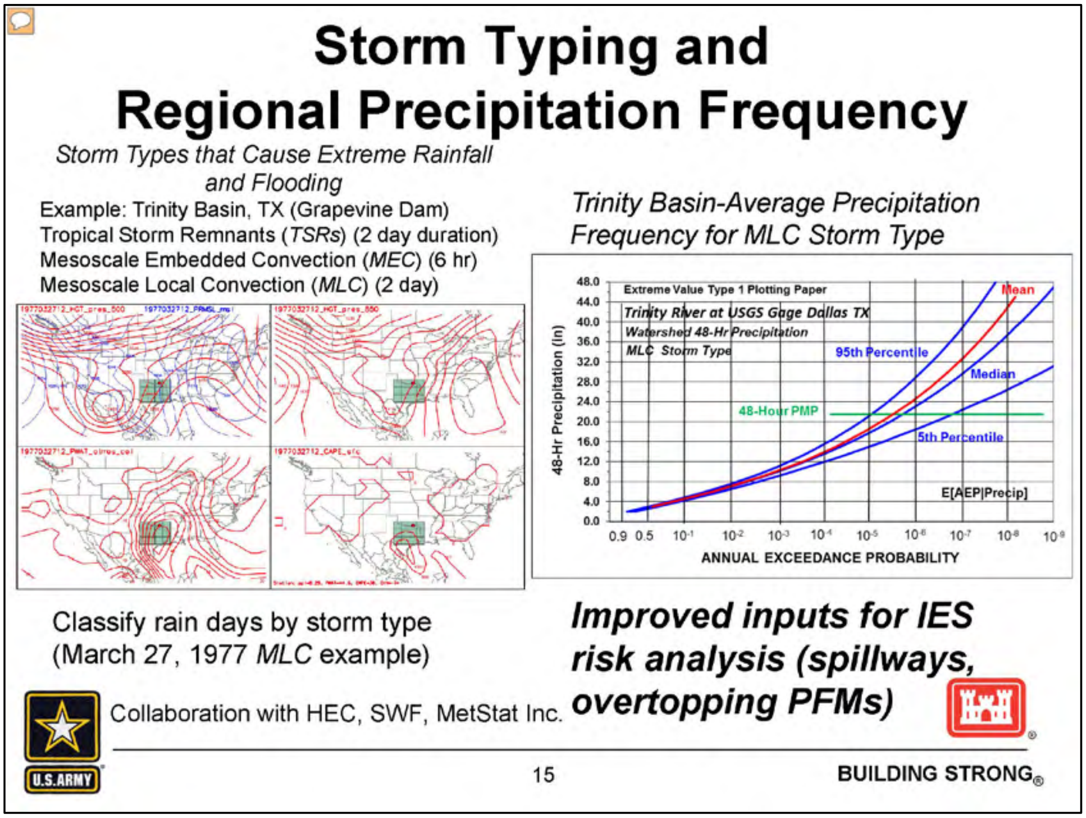
Here, we utilize a particular type of regional information applied to watershed of interest: rainfall-runoff modeling with precipitation frequency.



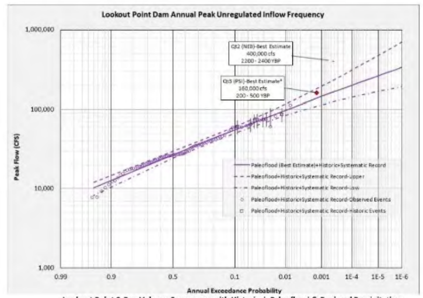
Example of spatial (regional precipitation frequency) and causal (specific population) information.

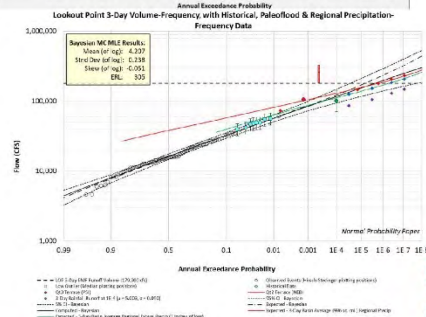
The four-panel figure at left displays 500 millibars pressure contours, 850 millibars pressure contours, precipitable water, and CAPE used to classify storm type.

The grapevine precipitation frequency curve (at right) is very steep based on MLC regional data and the regional Kappa distribution.

Combining Flood Hazard Curves

1. Hydrologic hazard curve from streamflow, historical, paleoflood data [Temporal]
2. Hydrologic hazard curve based on precipitation frequency and rainfall-runoff relations [Spatial and Causal]





Example concepts – draft work in progress

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Example concepts—draft work in progress.

Methods to Weight and Combine Hazard Curves

- Qualitative, Expert Elicitation
- Weighting of Independent Estimates (Bulletin 17C Appendix 9)
- Formal Bayesian Methods

Viglione et al. (2013) WRR https://doi.org/10.1029/2011WR010782

Skahill et al. (2016) ERDC https://apps.dtic.mil/dtic/tr/fulltext/u2/1002919.pdf

Qualitative, Expert Elicitation

- A.R. Bowman Dam, OR (USBR, 1995-2006)
  - ► Regional precipitation frequency and stochastic rainfall-runoff modeling
  - ► Streamflow with paleoflood data
  - ► Cadre weighted curves based on data, record lengths, uncertainty

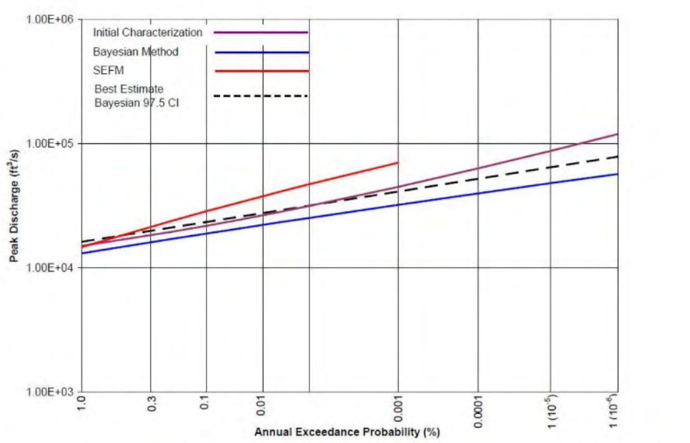

Figure 6-8.—Best estimate (Bayesian 97.5 percent) weighted peak-discharge frequency curve for A.R. Bowman Dam, Oregon.

See Swain et al. (2006)

Weighting of Independent Estimates [Bulletin 17C]

Bulletin 17C [p. 33, Appendix 9]

- Weights are based on quantile variance and are assumed to be unbiased and independent.
- Weight given to each estimate is inversely proportional to its variance.
- Weighting is done when reliable estimates of quantiles and variances are available.
- Evaluate estimates prior to weighting

$$X_{weighted,i} = \frac{X_{site,i} \times V_{reg,i} + X_{reg,i} \times V_{site,i}}{V_{site,i} + V_{reg,i}}$$

Rainfall-runoff quantile variance is a challenge
Can be represented by the Effective Record Length (ERL) based on flow frequency and precipitation frequency.

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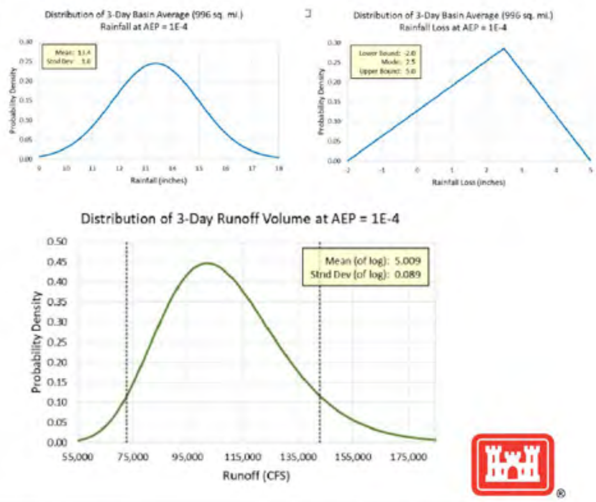
Formal Bayesian Methods

Prior on Rainfall-Runoff

$$h(Q_T) = N(\mu_{Q_T}, \sigma_{Q_T})$$

- Utilize Bayesian inference to combine four types of information
  - ► Streamflow gage records
  - ► Historical/Paleoflood data (discrete interval floods)
  - ► Non-exceedance information (right-censored)
  - ► Rainfall-runoff quantile at 10^{-4} [causal prior from spatial rainfall, loss distribution]



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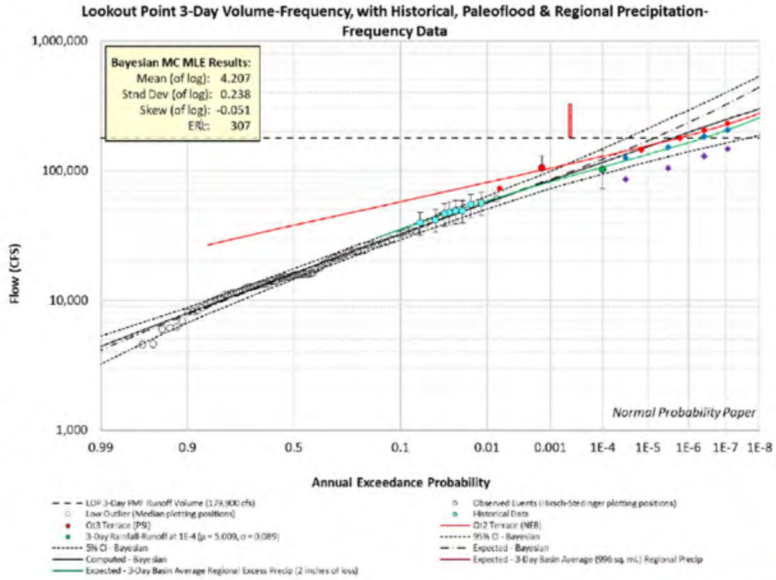
Formal Bayesian Methods

Preliminary Results

- Systematic, historical and paleoflood data
- Regional precipitation frequency
- Rainfall-runoff model discrete events
- Runoff distribution [loss-adjusted precip]

Bayesian Markov Chain Monte Carlo sampler with informative priors [accounts for parameter uncertainty; provides full posterior distribution]



Formal Bayesian Methods

Ongoing Work and Potential Next Steps

- Software development (ERDC-RMC), testing, and application on numerous hydrologic hazard studies for dam safety
  - Comparisons and testing flood frequency portion with existing codes (EMA, FLDFRQ3, FLIKE)
- Documentation of key concepts, complete treatment of priors, inputs, assumptions, applications, etc.
- Exploring generalization to model selection and models
  - Weight and combine multiple parents GEV, LP3, GPA
- Advancement on additional Spatial and Causal information and its value
  - Snow water equivalent (SWE) [max stable estimates]
  - Spatial rainfall constraints, runoff processes, routing, etc.

Questions/Comments/Discussion?

Spencer Dam,
Niobrara River, NE
(upstream of Gavins
Point Dam)
March 16, 2019

john.f.england@usace.army.mil
https://sites.google.com/a/alumni.colostate.edu/jengland/research

Extras for Discussion

Physical Limits to Rainfall and Floods and Upper-Bounded Frequency Distributions – Are They Useful?

Is there a physical limit? Is it increasing in the presence of climate variability/change? Should upper-bounded distributions be used? What processes and physics are included?

Examples: EV4, LN4, TDF (transformed extreme value) Or 5 parameter Wakeby*?

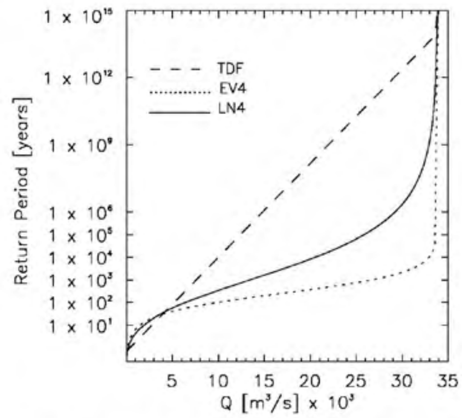


Fig. 3. TDF, EV4 and LN4 different behaviour approaching the same upper limit. Parameters for each distribution function are the same than in Fig. 2 (central): the case study data with the ML-PG estimation method.

* Harold A. Thomas, Harvard U. (Wakeby distribution)

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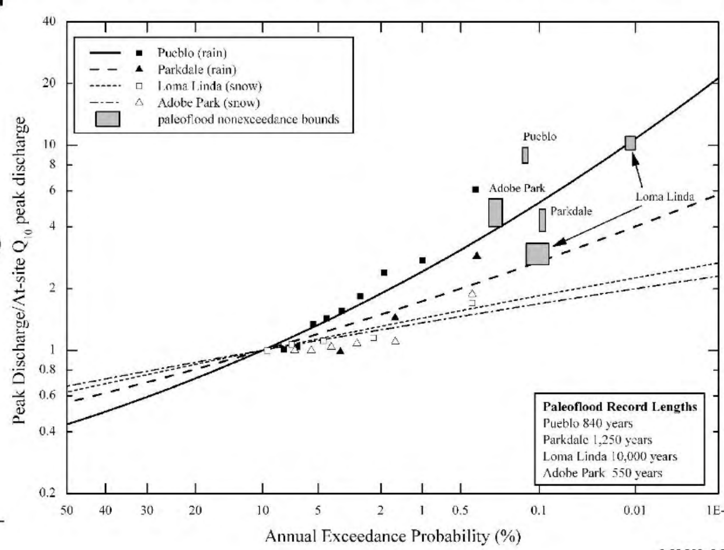
Hydrologic Hazard Principles – Causal Information

Causal Information: utilize hydrological understanding of flood-producing factors.

Example – transition from snowmelt runoff to rainfall runoff within a large watershed

England et al. (2010) Geomorphology



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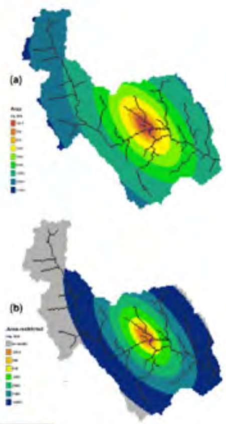
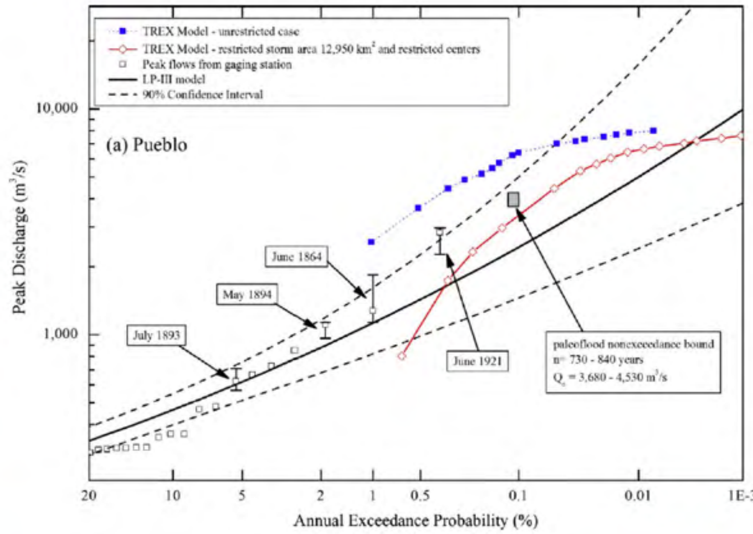
Qualitative, Expert Elicitation

Paleoflood data/flow frequency

2D Rainfall-Runoff model

Spatially-varying rainfall

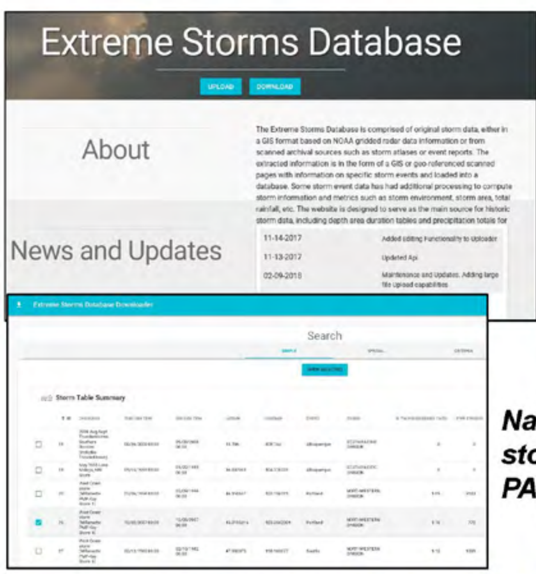


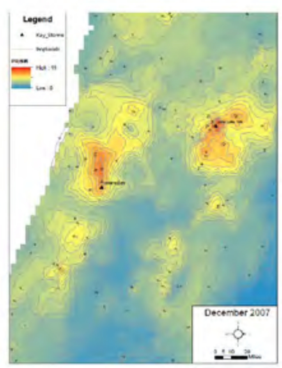


13,000 sq km Arkansas River, CO

England et al. (2010) Geomorphology; (2014) J. Hydrology

Extreme Storm Data



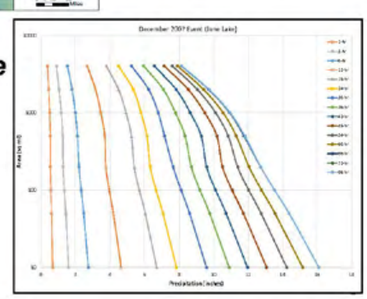


December, 2007 storm

Updated space-time precipitation estimates for Willamette basin: Lookout Point, Hills Creek, Green Peter, Foster Dams (and others)

Lead: Angela Duren (NWD)

National extreme storm data for PA, SQRA, IES



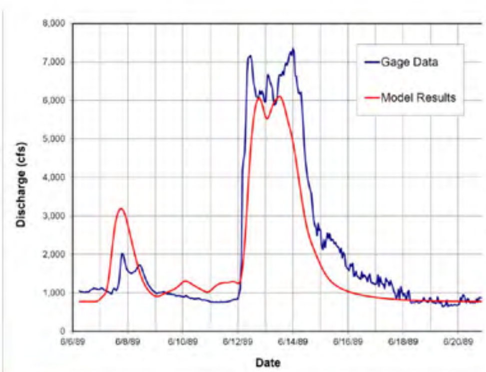
https://maps.mmc.usace.army.mil/esd/

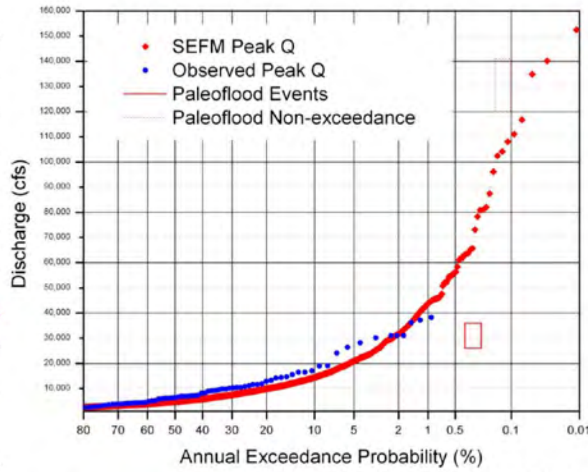
Lead: Charles McWilliams (NWO)

Rainfall-Runoff Calibration and Weighting with Paleofloods

2-stage Model Calibration: (1) observed flood hydrographs; (2) estimated frequency curves (peak/volume).

Determine best inputs, parameters, and their distributions





Altus Dam, OK - Reclamation

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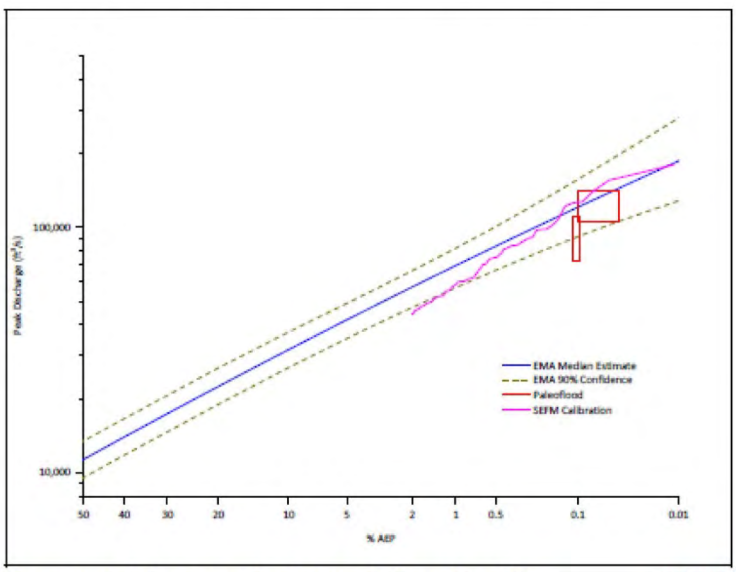
Rainfall-Runoff Calibration and Weighting with Paleofloods

Friant Dam, CA (USBR)

Stochastic Event Flood Model

(Wright et al, 2013)



https://sites.google.com/a/alumni.colostate.edu/jengland/file-upload/Friant_Report_final_compress.pdf

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4.3.4.4.3 Questions and Answers

Question:

You stated that this flooding event in the upper Midwest was a joint snowfall-rainfall event. As an outsider to this whole process, how do snowfall and snowpack factor into these sometimes pretty catastrophic events in the spring?

Answer:

As shown in the videos on YouTube, the ice jam drove the breaking of these gates. This is a run-of-the-river dam, so there was not really a dam failure that was going to cause loss of life. Yet, the people that run this small power dam on a small river were affected. The idea is, if you can tailor two things, one is your structure of interest, such as a levee, dam, or nuclear reactor, and the other is things that might break that. Using the global sensitivity analysis, you can factor in and identify the key factors of your structure up front and then look at the factors in the rainfall-runoff model that you should include. This simulation actually has one of the bigger factors on volume, the snow melt. We did not put any uncertainty on that. But it was a big factor that caused the volume of the water that filled the reservoir in this particular case. It means spending a bit more time on what is inside your model to determine whether you have included those factors. In a lot of cases we do, and, in some cases, we don’t. It’s a case-by-case situation and an evolving learning process. We found that out for this particular dam in the Willamette River Basin in western Oregon. After doing all the modeling, we found that one of the key factors that we overlooked was a sensitivity. We could have done a better job on the timing of the rainfall. Because the decision criteria to open gates and move water out had a lot to do with the assumption you did in this sample, we had a couple patterns and that was a key factor. We knew we could have done a better job refining that piece.

Question:

I’ve observed that the storm surge modeling community fairly routinely uses the JPM. There is an actual error term in there, and the community tries to model the errors, because we know that when you get the really big storm surge we are not really sure of the quality of the physics or the numerical output of our models. Should we be doing this in riverine flooding?

Answer:

Yes; we first want to identify the target in broad terms. Adding error terms will inflate our uncertainty. We are still wrestling with some of these things. But the challenges at 10^{-3}, 10^{-4}, and 10^{-5} mean that we want to try everything possible as I described. That is challenging for a lot of people to even do. We have challenges operationally getting precipitation frequency analyses that are credible estimates that we can feel comfortable with. We are spending a bit more time on that. We are also trying to spend more time on data collection on paleofloods. So, adding error terms is good. But we also then have to go backwards and make sure that our simple models are at least somewhat close. Our model is essentially a simple loss-adjusted model that is very similar to work by Électricité de France (EDF) in France, the GRADEX. We take a constant loss off of this red curve to get the green curve to put into the analysis because we are really actually uncomfortable with all these rainfall-runoff dots, the diamonds, which suggest the curve drops farther than the historical and paleoflood information. We are wondering if we are comfortable with this. So, this is in-process work that we can add some features to.

Question:

This is probably a bit of a sensitive question. It gets to the influence of the experts, in the sensitivity of the experts' inputs on the results. What quality controls do you have in place over the experts? How well calibrated are the experts, what firsthand experience do they have? The answer is usually none. How do they set out their logic? Is there any guidance in the document in relation to controlling the quality of the expert opinions that are going in? We know that when you put randomness in, you get randomness out.

Answer:

We do not have formal, written guidelines on selecting experts like the SSHAC process yet for this. We do use open peer review. We try to go to the literature as some sort of validation of the science and the methods behind it. In addition to formal peer review of the report and analysis, we expect to eventually send it to journal publication. We also perform software validation. You also alluded to the choice of inputs and defining those inputs clearly. This is preliminary work and we have some good ideas. We have done some very simple things like a triangle distribution here, some normal, triangle, and log normal—all okay and they make sense. In choosing those, we want to have a feedback loop. We have independent judgments made by myself and the team. Then we have some reviewers who serve as a re-caliper in terms of the technical parts. We actually may want to corrupt the process with some decisionmakers and do the best technical things we do and then see if it really matters to the decision. Let's get the curve anchored to 10^{-5} up here and then do some sensitivity. We pick something at 1 in 1.000. Does it change the answer and order of magnitude? We will defer the formal review of expert elicitation and Bayesian analysis to at least push forward to go into a Bayesian route as opposed to strictly frequentist. Another coworker of mine will touch on a little bit of this and the sensitivity of data into the analysis. The influence of these data has an overwhelming effect, rather than the priors you put on the analysis in the first place.

4.3.4.5 Riverine Paleoflood Analyses in Risk-Informed Decisionmaking: Improving Hydrologic Loading Input for USACE Dam Safety Evaluations. Keith Kelson*, USACE, Sacramento Dam Safety Production Center; Justin Pearce, USACE, Risk Management Center; Brian Hall, USACE, Dam Safety Modification Mandatory Center of Expertise (Session 2A-5; ADAMS Accession No. ML19156A465)

4.3.4.5.1 Abstract

USACE dam safety assessments consider potential hazards (loading), system responses (fragility), and associated consequences as part of the risk assessment of its national dam portfolio. Where possible, paleoflood data are incorporated in dam safety evaluations to reduce uncertainties in the hydrologic loading component of the risk assessment. To date, the reaches of interest to the dam safety assessments have focused primarily on riverine paleostage indicators (PSI) and nonexceedance bounds (NEB), rather than established characterization methods using slackwater deposits, cave-deposit stratigraphy, dendrochronology, or others. For sites deemed justified within the risk-informed decisionmaking framework, the geomorphic or hydrologic conditions commonly are not ideal—whether because of sparsely preserved PSI or NEB, channel geometric nonstationarity, temporal hydrologic nonstationarity, processes that shift stage-discharge relationships (e.g., ice jams, debris blockage), and a host of other possible

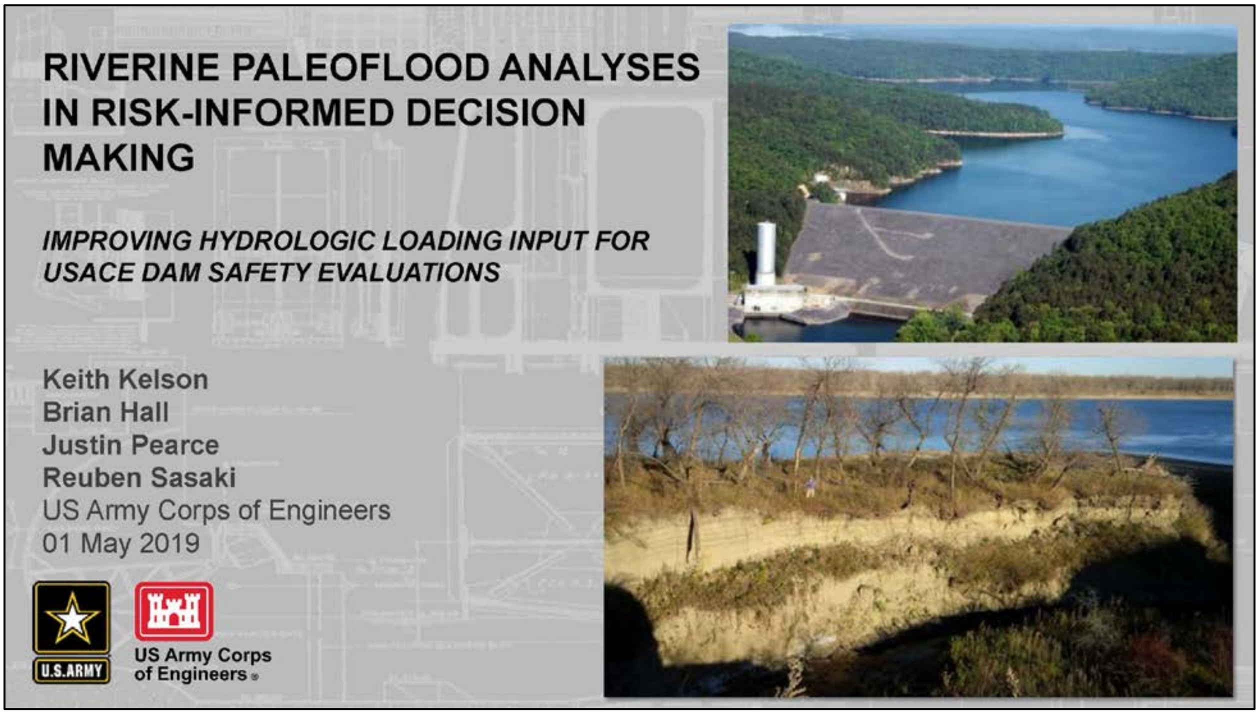
problems. These challenges are addressed during site selection in order to eliminate or minimize uncertainties that could diminish applicability of the results to the risk assessment.

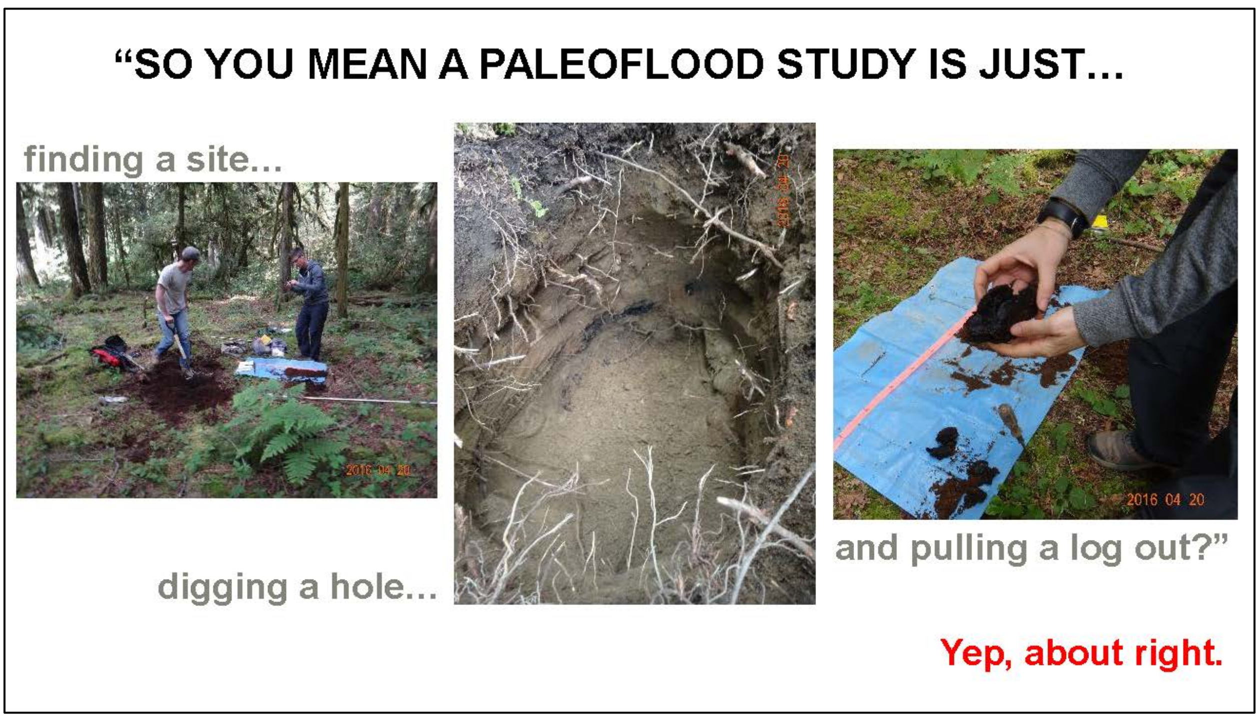
Data collection in riverine settings demands an integrated approach among geomorphic, hydrologic, and hydraulic disciplines. Following initial geomorphic identification of feasible riverine reaches, the peak flood of record (FOR) is defined or estimated, using systematic gauge data, historical observations, and reservoir-inflow calculations. The existing probable maximum flood (PMF) for the site is used or refined, as needed for the risk assessment. Existing hydraulic models are utilized to develop information on the extents and down-valley elevation of both the FOR and PMF, which are then used to constrain geologic and geomorphic field reconnaissance. Geologic/geomorphic field efforts focus on characterizing flood-related PSI (e.g., high-discharge fluvial terraces, stranded slackwater deposits, biologic features) or noninundation NEB (e.g., undisturbed alluvial fans, well-developed relict soils), and obtaining numerical or reasonable relative age estimates for the PSI and NEB. For the riverine reaches, the down-valley longitudinal profiles of the PSI and NEB are compared to floodwater surface elevations generated from either 1-D or two-dimensional (2-D) HEC-RAS hydraulic modeling of various discharges between the FOR and the PMF. Discharges associated with the PSI and NEB are estimated through comparing the geomorphic field observations, historic hydrologic data, and HEC-RAS hydraulic modeling.

Uncertainties are captured throughout the analysis and explicitly calculated or subjectively estimated for inclusion in flow-frequency calculations using the Bulletin 17C methodology. For analyses using riverine PSI or NEB analyses, primary sources of uncertainty are (1) ranges in estimated ages of PSI and NEB, (2) ranges in roughness and energy gradient for various discharges, (3) water depth and velocity required for sediment deposition (for PSI) or erosion (for NEB), and (4) inherent variability of the water surface and the PSI or NEB geomorphic datum in the down-valley profile. These potential uncertainties are captured via sensitivity analyses or acknowledged within ranges of paleoflood discharges or timing. The best estimates and ranges in discharge and age for each PSI and NEB are included into flow-frequency statistics through use of perception thresholds and flow intervals (ranges in discharge).

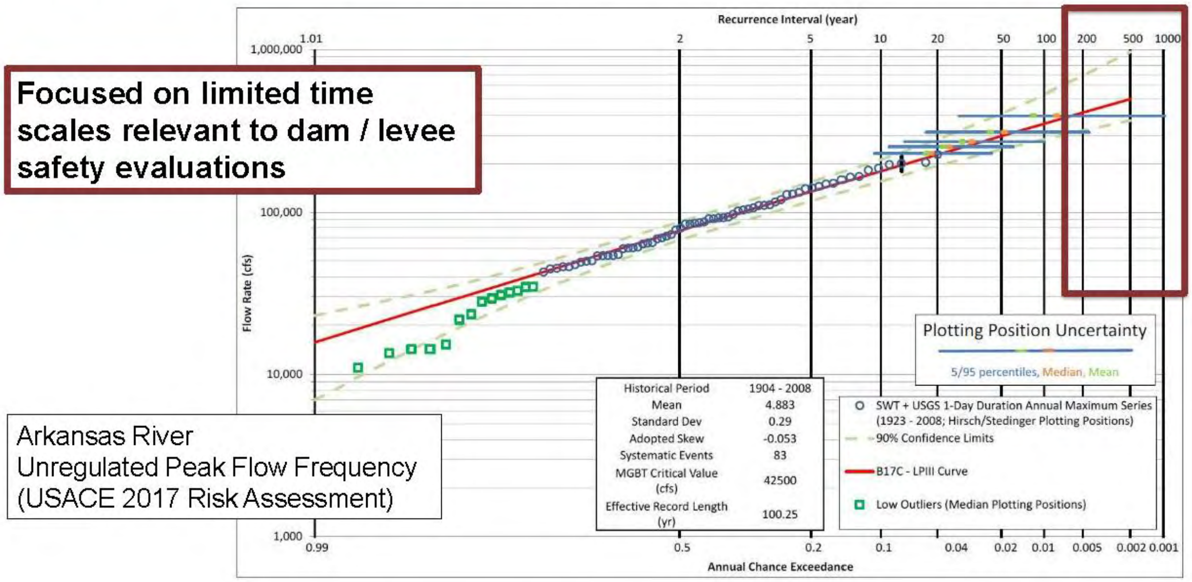
This approach has assisted multiple recent and ongoing USACE analyses for dam safety. Flow-frequency curves incorporating paleoflood information can be compared to those based solely on systematic and historical information. Often, the paleoflood analysis prompts reevaluation and improvement of the historical record, which extends the ERL regardless of prehistoric data. The analyses have allowed interpretations that shift flow-frequency curves both up and down or provided a basis for narrowing confidence bands in existing curves. At this time, there appears to be no systematic shift for greater or lesser frequencies of given extreme discharges, when comparing flow-frequency curves using paleoflood data and those using only systematic and historical data. While uncertainties can be significant in paleoflood analyses, conscientious site-selection, data collection, and analytical efforts allow uncertainties to be minimized and captured for appropriate inclusion in risk-informed hydrologic loading estimates.

4.3.4.5.2 Presentation

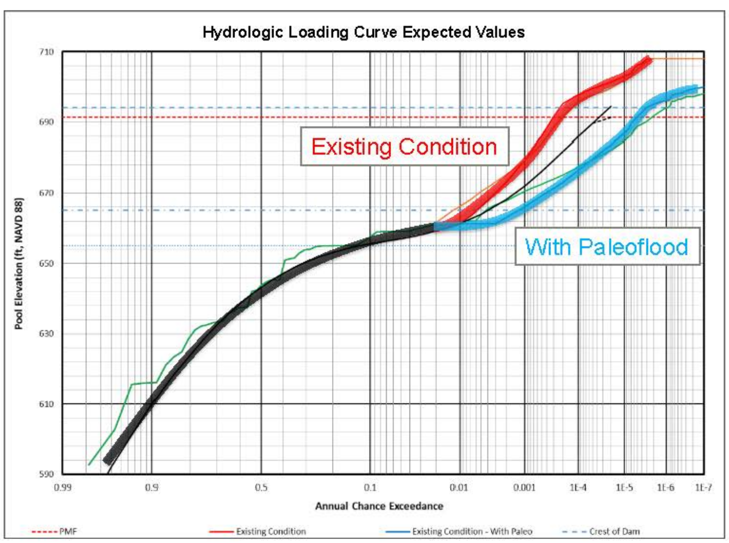


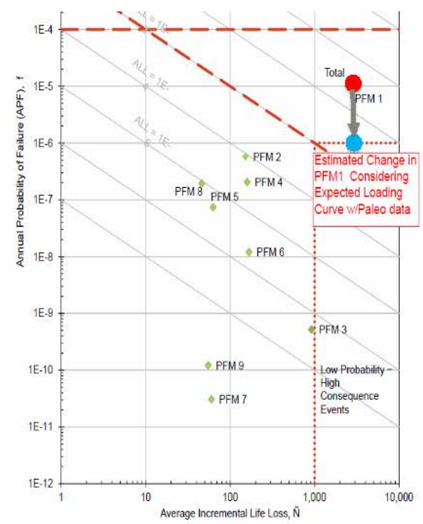


PALEOFLOOD ANALYSES FOR DAM / LEVEE EVALUATIONS



IMPROVE CONFIDENCE IN HYDROLOGIC LOADING

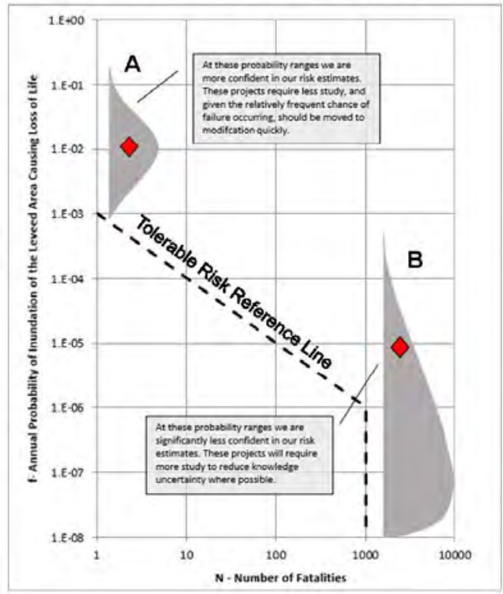




ADDRESS UNCERTAINTY IN HYDROLOGIC LOADING

Projects "A" and "B" have similar risk, but different failure probabilities and different consequences

- Project A has lower knowledge uncertainty.
  - More data will likely not change mitigation decision.
  - Should progress from evaluation to preliminary design
- Project B has greater knowledge uncertainty.
  - More data could be beneficial and have an increased chance of changing the decision.
  - Project may progress slowly from evaluation to preliminary design



PALEOFLOOD ANALYTICAL FRAMEWORK

Portfolio Screening
- Which sites are viable for yielding paleoflood data?
- For which facilities would paleoflood data be useful?

Reconnaissance
- Is it possible to obtain paleoflood data?
- Would data result in narrower uncertainty or better confidence?
- Results should not be considered in risk assessments

Issue Evaluation
- Obtain expected values and estimate reasonable range
- Will additional data narrow level of uncertainty and/or improve confidence?
- If uncertainties are acceptable, may be considered in risk assessments

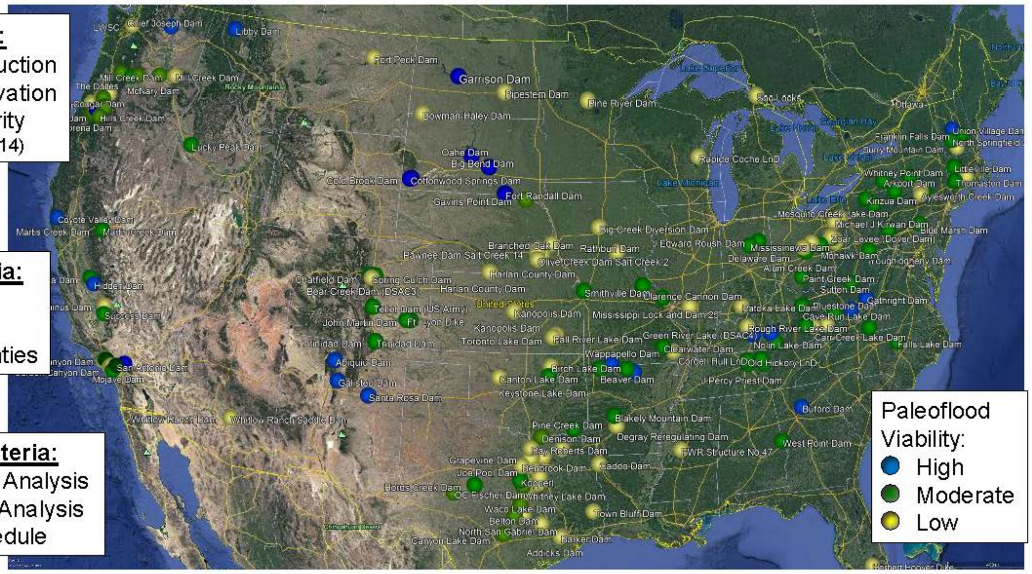
Detailed Characterization
- Focus on characterizing uncertainties in hydrologic loading
- Develop understanding sufficient to support modification / design

PORTFOLIO SCREENING: PALEOFLOOD VIABILITY

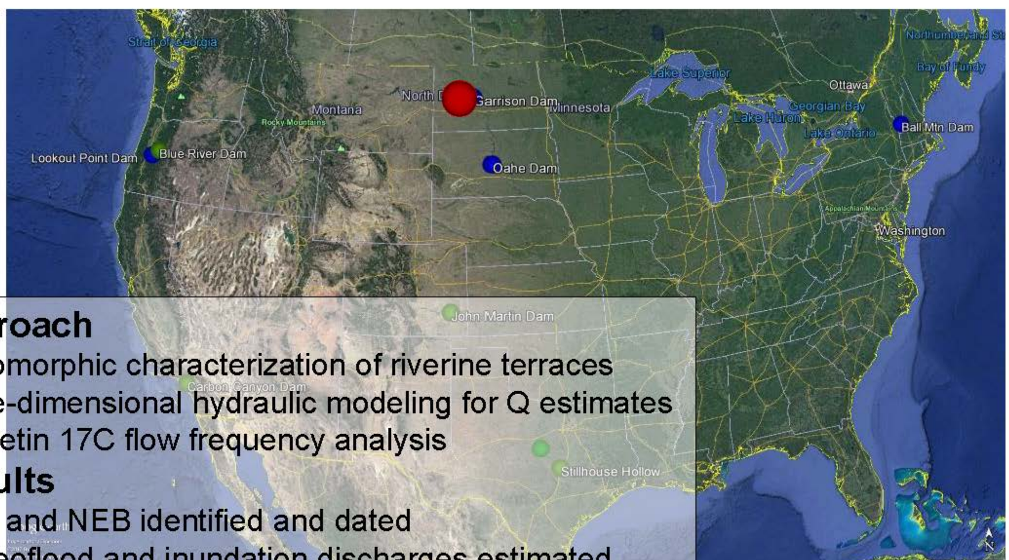
Geologic Criteria:
- Sediment Production
- Deposit Preservation
- Valley Stationarity
  (O'Connor et al., 2014)

Hydrologic Criteria:
- Credible PFM
- OT Risk Driver
- Large uncertainties

Programmatic Criteria:
- Upcoming Risk Analysis
- Imminent H&H Analysis
- Favorable Schedule



FIRST: GARRISON DAM (ND)



Approach
- Geomorphic characterization of riverine terraces
- One-dimensional hydraulic modeling for Q estimates
- Bulletin 17C flow frequency analysis

Results
- PSI and NEB identified and dated
- Paleoflood and inundation discharges estimated

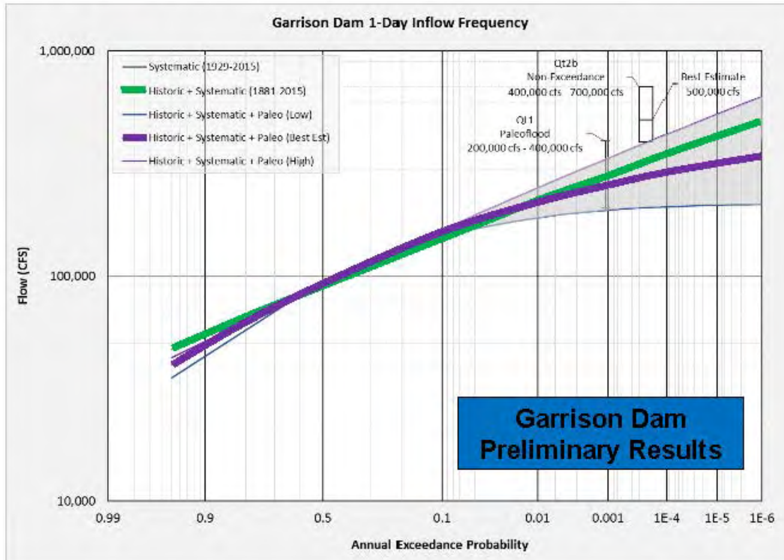
GARRISON DAM (ND) PALEOFLOOD SUMMARY

Conclusions

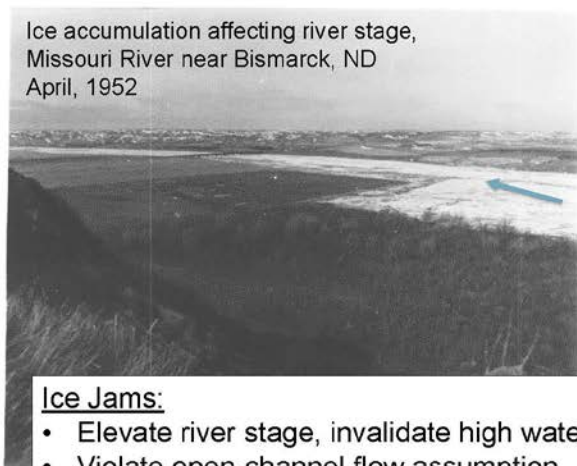
- Paleodischarge estimates are **consistent with** frequencies predicted by systematic + historic data within range of uncertainty
- 1D HEC-RAS model is good approximation of 2D model

Lessons Learned

- Pre-field preparation is mandatory
- Coordinate with local dam operations personnel
- Avoid systems affected by ice jams



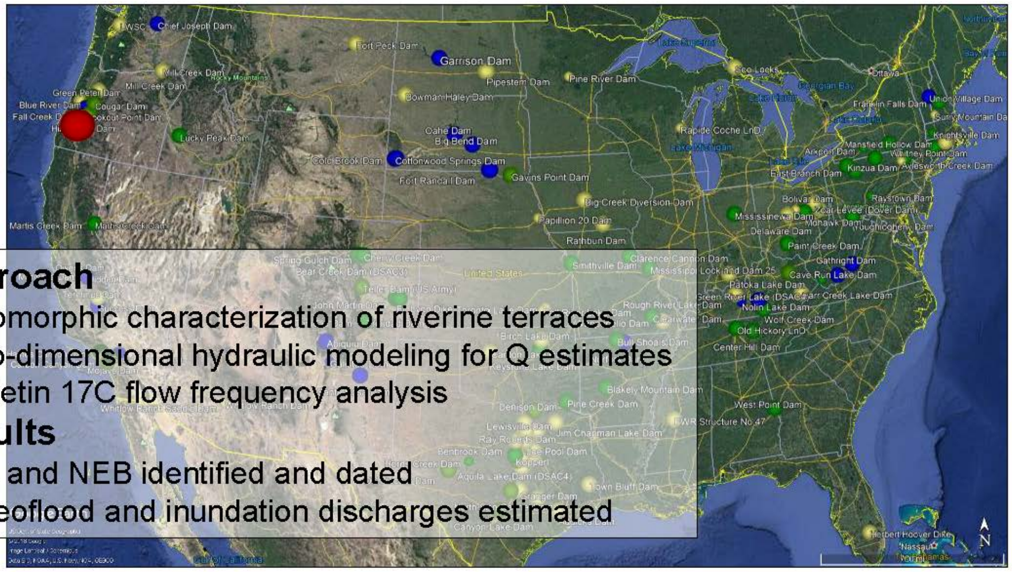
COMPLICATIONS: BEWARE OF ICE JAMS



<u>Ice Jams:</u>

- Elevate river stage, invalidate high water marks
- Violate open-channel flow assumption
- Affect stage-discharge curve
- Complicate paleodischarge estimation

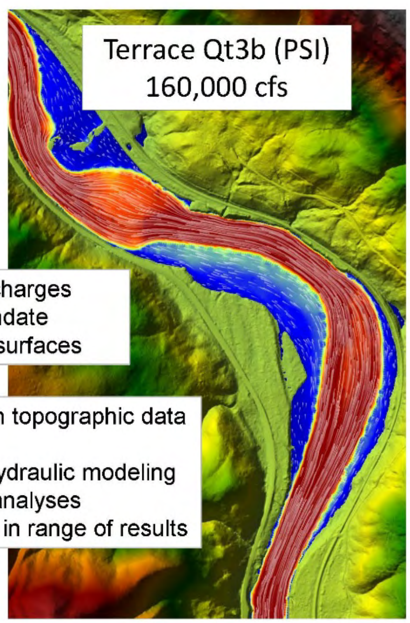
SECOND: LOOKOUT POINT DAM (OR)

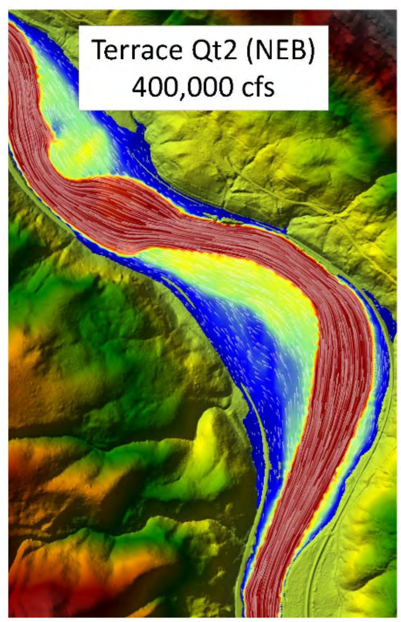


Approach
- Geomorphic characterization of riverine terraces
- Two-dimensional hydraulic modeling for Q estimates
- Bulletin 17C flow frequency analysis

Results
- PSI and NEB identified and dated
- Paleoflood and inundation discharges estimated

2D HEC-RAS DISCHARGE ESTIMATION





Estimated discharges needed to inundate fluvial terrace surfaces

High-resolution topographic data allows for
- Improved hydraulic modeling
- Sensitivity analyses
- Confidence in range of results

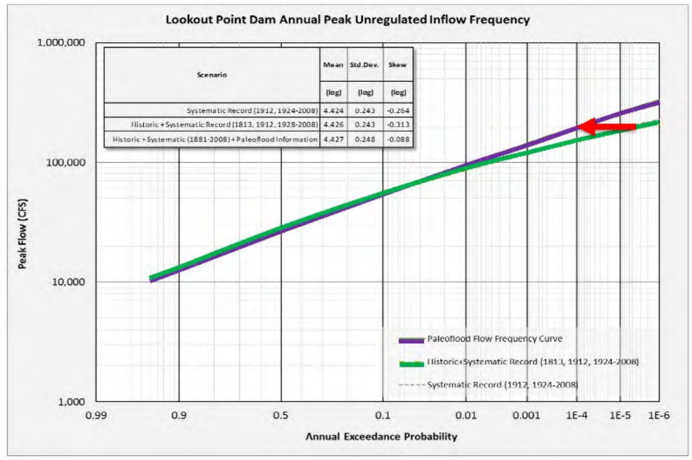
LOOKOUT POINT DAM (OR) PALEOFLOOD SUMMARY

Conclusions

- Very high discharges are **more frequent** than predicted by systematic + historic data within range of uncertainty
- Increased equivalent record length

Lessons Learned

- Pre-field HEC-RAS model helps identify key localities
- Team with local hydrologic experts



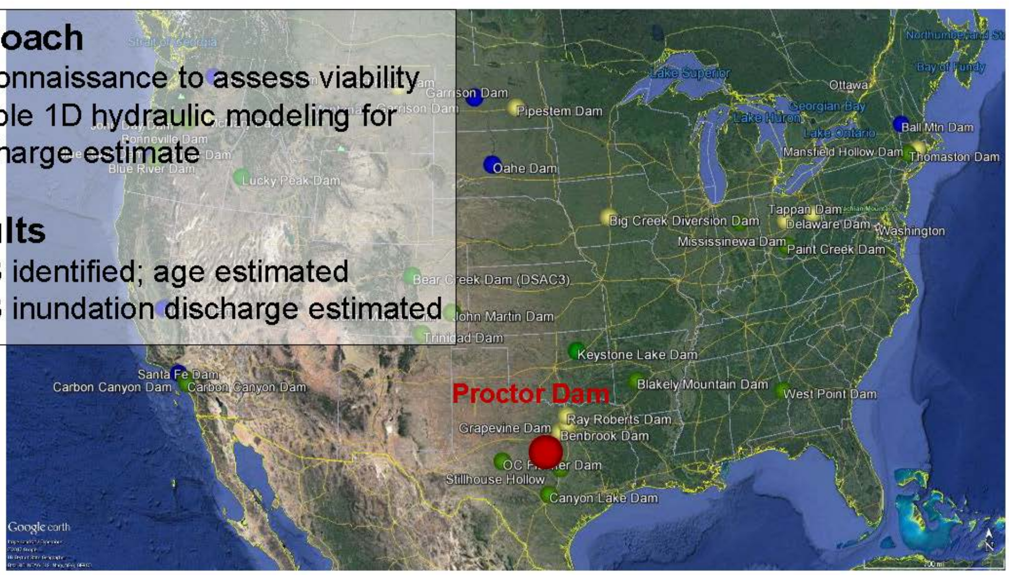
PALEOFLOOD RECONNAISSANCE: PROCTOR DAM

Approach

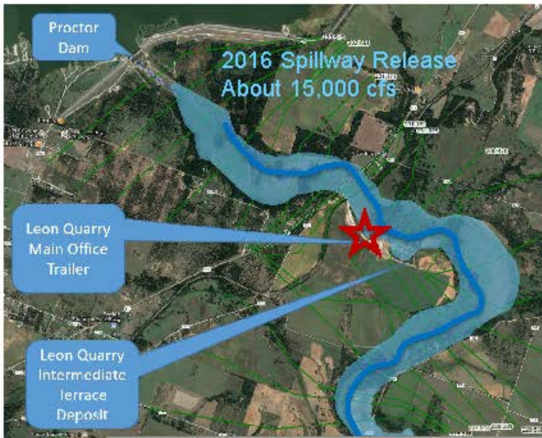
- Reconnaissance to assess viability
- Simple 1D hydraulic modeling for discharge estimate

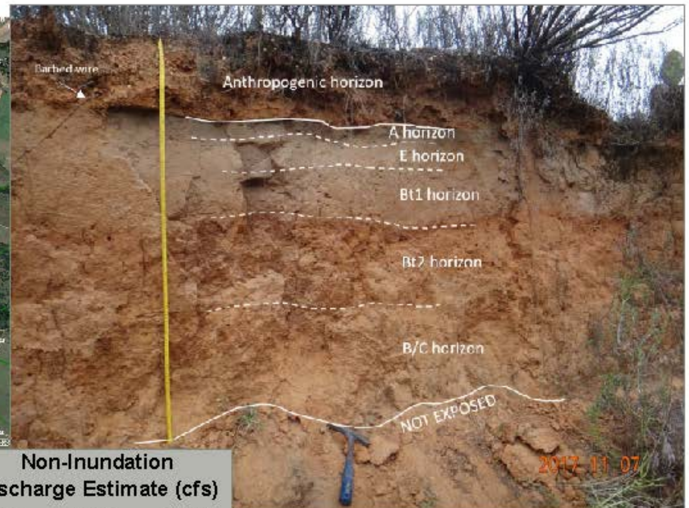
Results

- NEB identified; age estimated
- NEB inundation discharge estimated



PALEOFLOOD RECONNAISSANCE: PROCTOR DAM





Feature	Age Estimate (yrs ago)			Non-Inundation Discharge Estimate (cfs)		
	Young	**Best**	Old	Low	**Best**	High
Eolian deposit, Leon Quarry	2,000	**3,500**	5,000	90,000	**105,000**	160,000

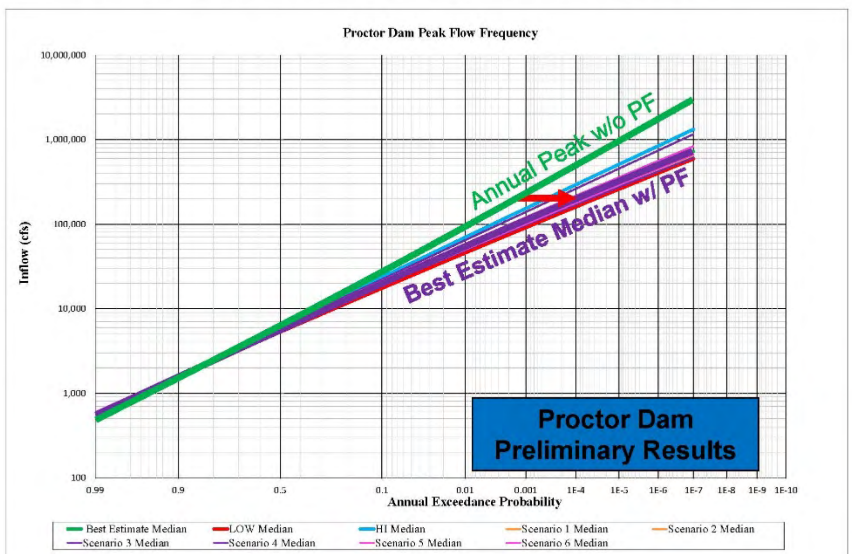
PROCTOR DAM (TX) PALEOFLOOD SUMMARY

Conclusions

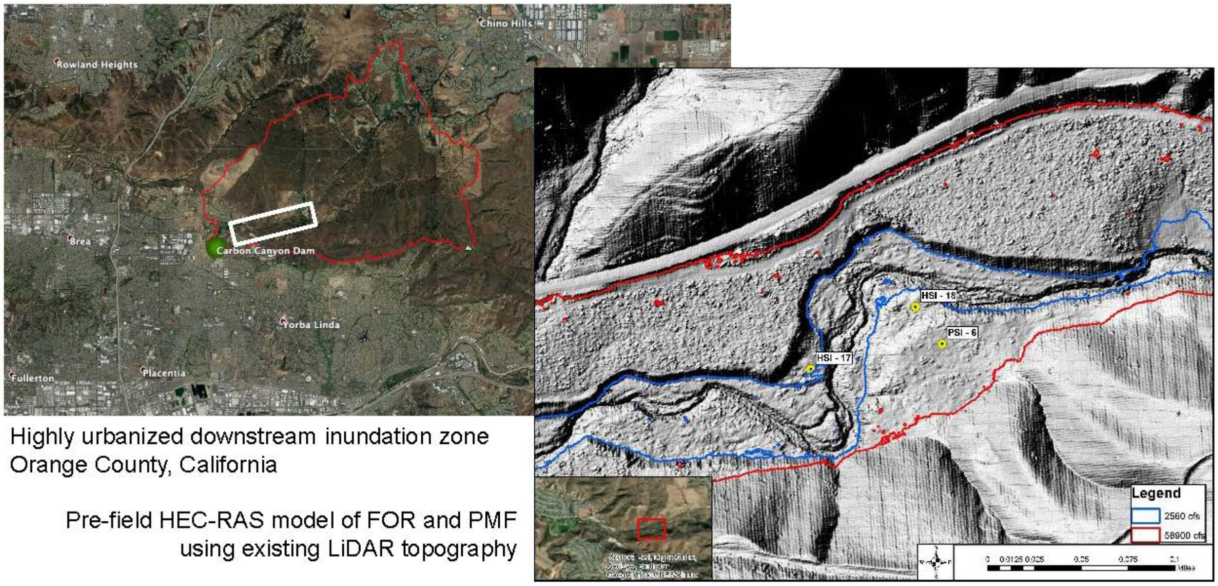
- Successful recon: NEB identified
- Possible shift of FFC to right
- Additional information could be developed with G&G and H&H efforts

Lessons Learned

- Caution needed when using reconnaissance-level information
- Preliminary data should not be considered in decision process



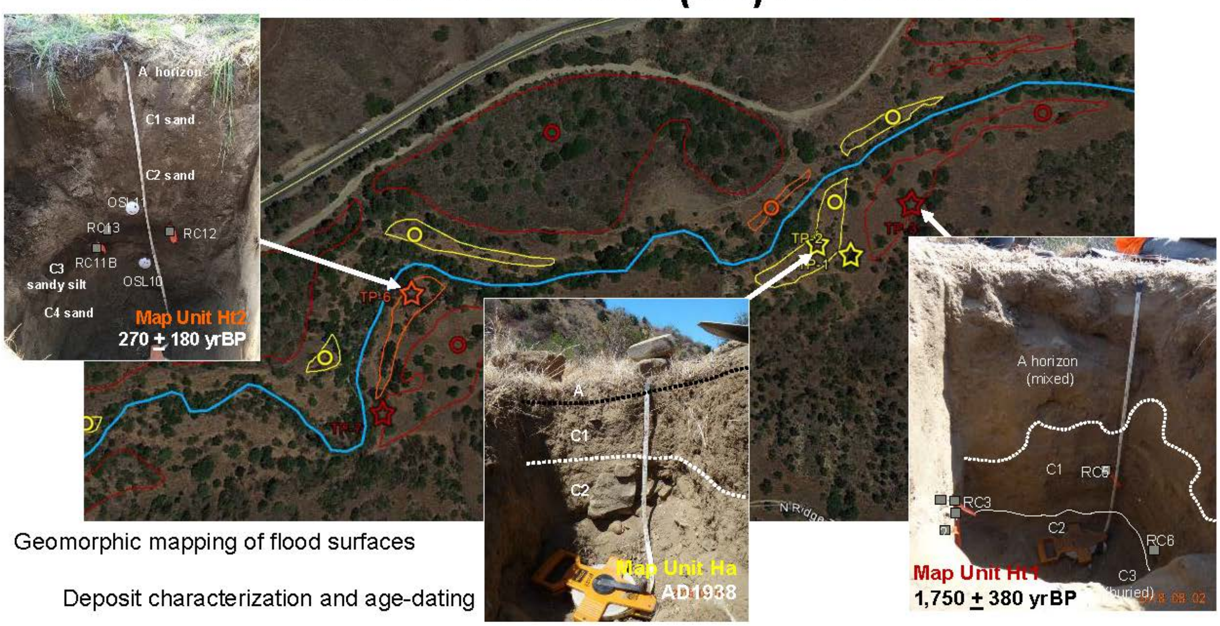
CARBON CANYON DAM (CA) PF APPROACH



Highly urbanized downstream inundation zone
Orange County, California

Pre-field HEC-RAS model of FOR and PMF
using existing LiDAR topography

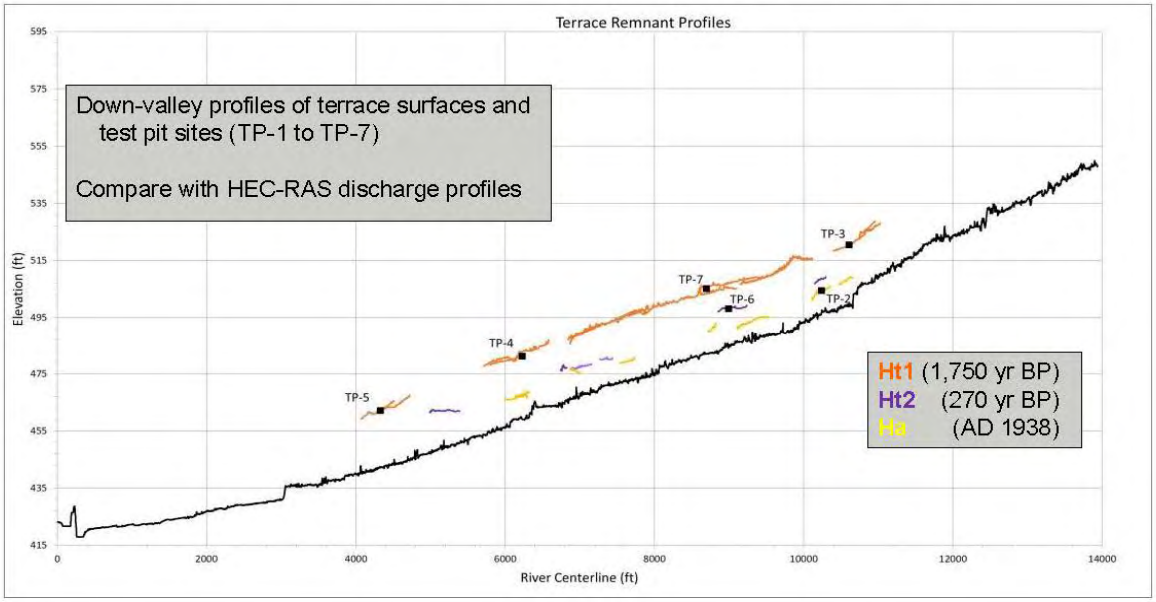
CARBON CANYON DAM (CA) PF RESULTS



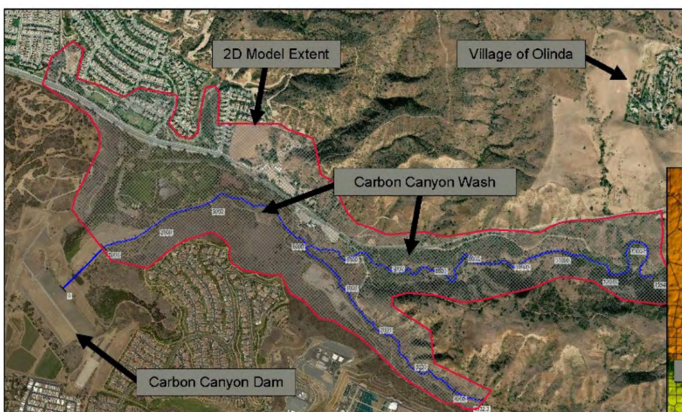
Geomorphic mapping of flood surfaces

Deposit characterization and age-dating

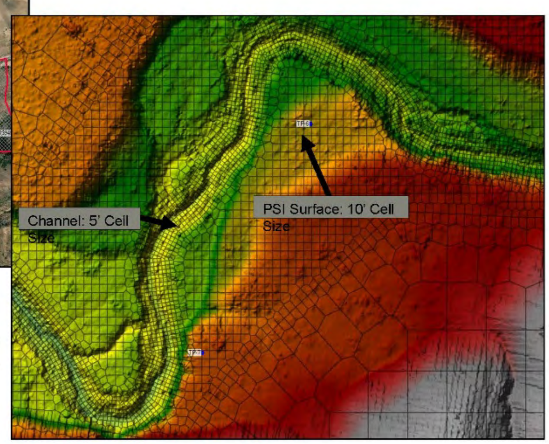
CARBON CANYON DAM (CA) PF RESULTS



CARBON CANYON DAM (CA) PF RESULTS

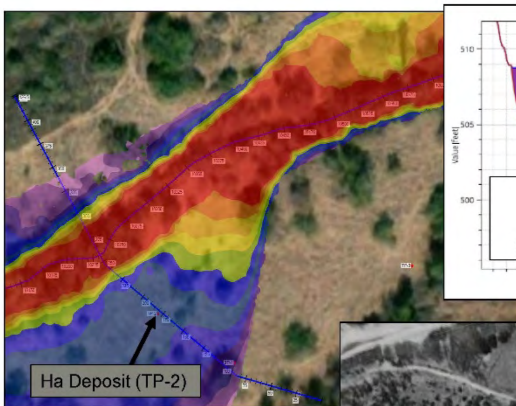


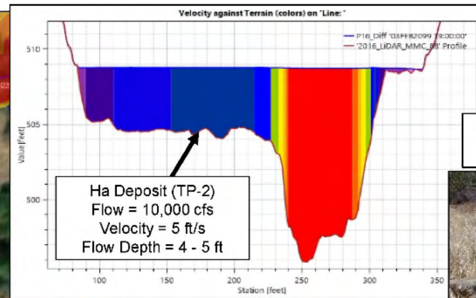
HEC-RAS 2D model extent



HEC-RAS 2D model grid sizing to best represent LiDAR topography

CARBON CANYON DAM (CA) PF RESULTS



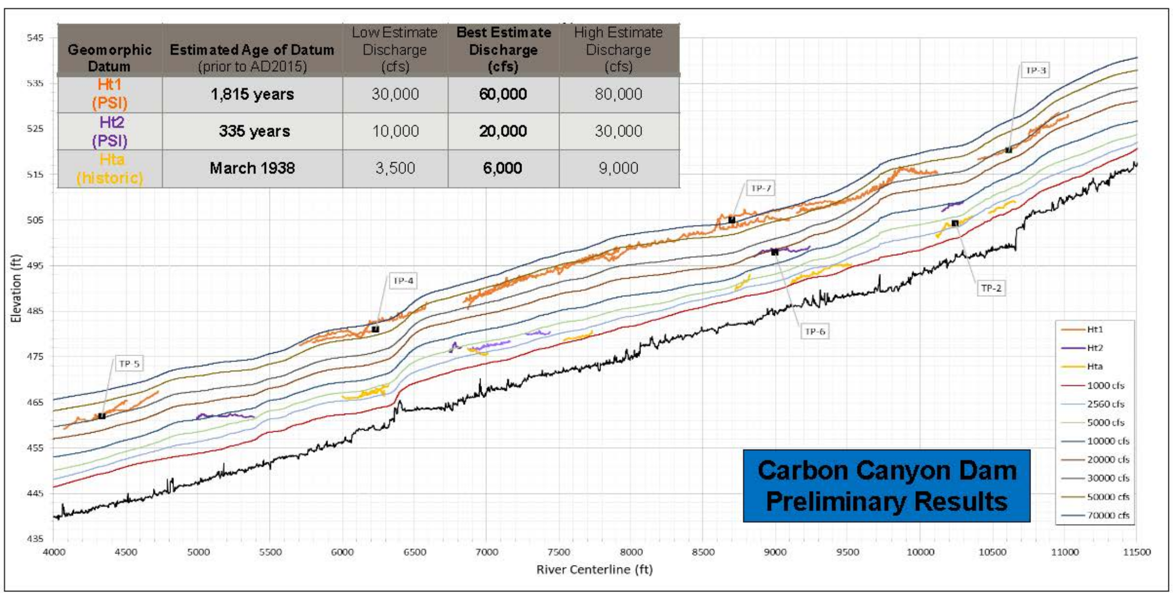


HEC-RAS cross-sections used for estimating flow velocities and bedload transport

Large concrete boulder in TP-2 deposit coincides with 1938 flood extent

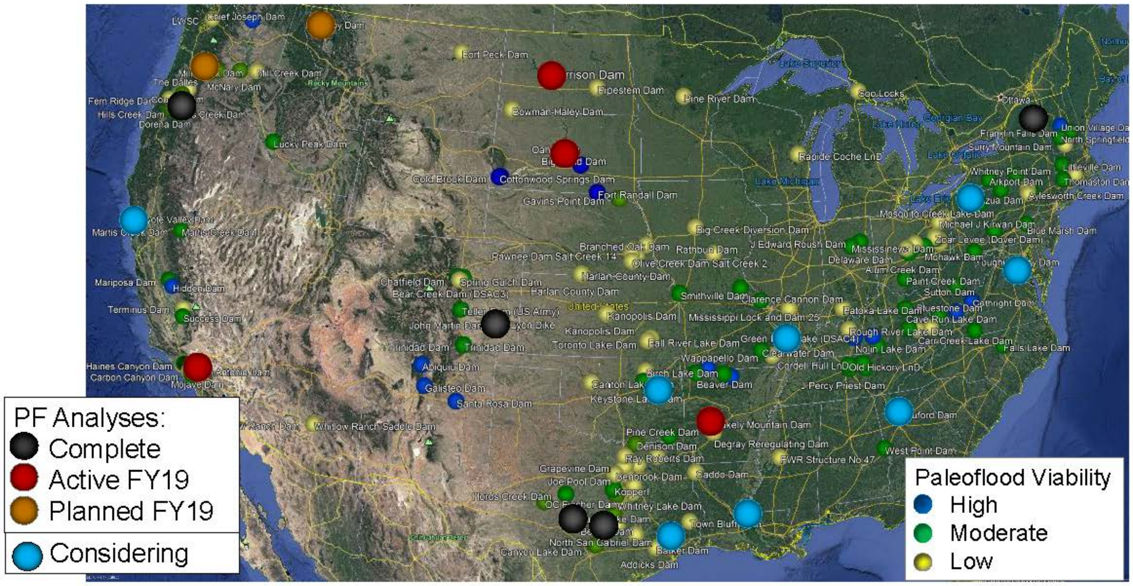
Carbon Canyon Flood Terrace 1938 flood

CARBON CANYON DAM (CA) PF SUMMARY



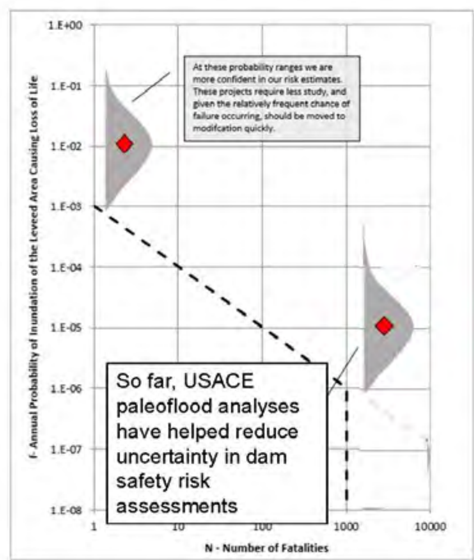
Geomorphic Datum	Estimated Age of Datum (prior to AD2015)	Low Estimate Discharge (cfs)	Best Estimate Discharge (cfs)	High Estimate Discharge (cfs)
Ht1 (PSI)	1,815 years	30,000	60,000	80,000
Ht2 (PSI)	335 years	10,000	20,000	30,000
Hta (historic)	March 1938	3,500	6,000	9,000

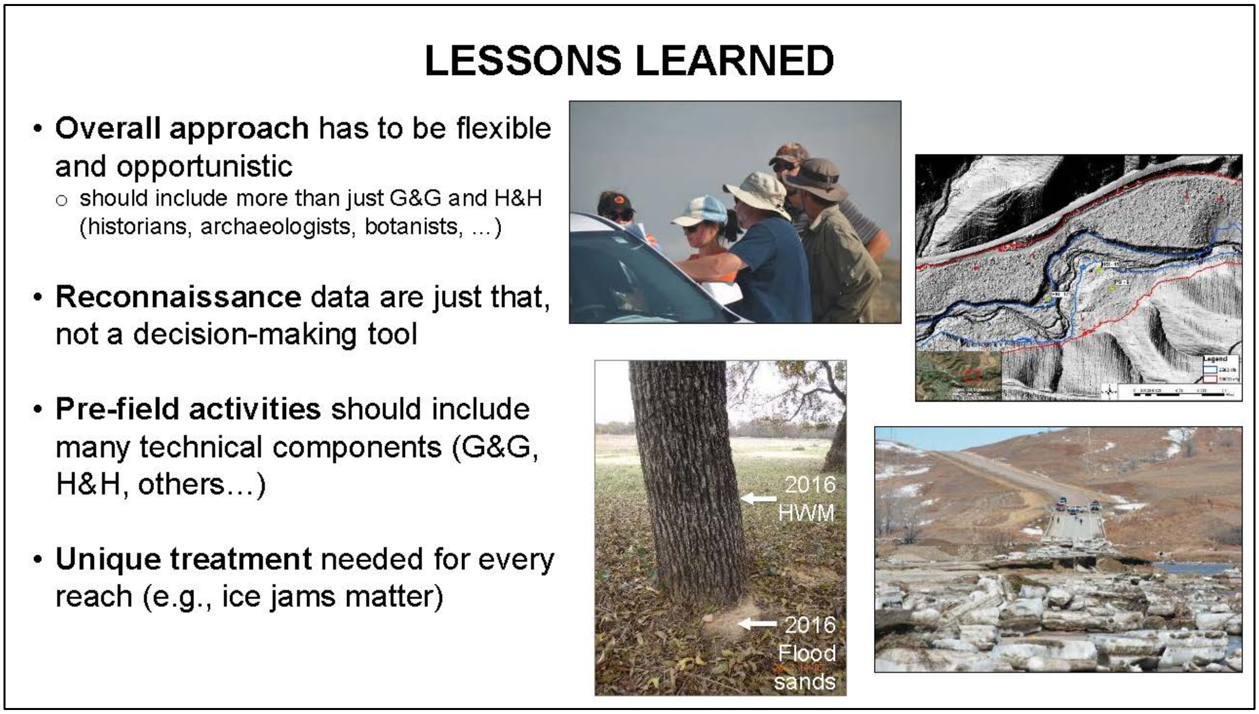
RECENT, CURRENT, AND POSSIBLE FUTURE ANALYSES



CONCLUSIONS

- **Screening criteria** appear effective for USACE dam portfolio
- **Paleoflood analytical techniques** are viable across range of site conditions
- **Riverine terraces** are just one of several viable tools available for paleoflood analyses
- **Uncertainties** in paleodischarge magnitude and timing can be captured and documented
- **Analytical uncertainties** do not invalidate paleoflood analyses





4.3.4.5.3 Questions and Answers

Question:

I'm fascinated by how some people look at paleofloods and evidence as basically a treasure hunt. Go find a single piece of evidence, and then from that, make some conclusions. I like what you said about the boulder that rolled down the stream and you could see the evidence of it moving and so it says something about the energy of the system at the time that was deposited. Thinking about trying to reconstruct what the event and the features and the processes were at the time it was deposited, it isn't just finding a log, but it's the material surrounding the log. Is that highly chaotic material? Therefore, is that a high-energy regime? Or was it a series of very thin sediments, like clay, around it, which would be indicative of a much quieter energy regime? When you do this, do you actually try to reconstruct what happened at the time of the paleo event and understand the processes?

Answer:

Yes, that is what geologists do. As sedimentologists, we look at these test pits and the stratigraphy in these exposures. The grain size characteristics, the bedding, and the laminations all tell us how that deposit got there. In the case of the large concrete boulder, it was not just a large concrete boulder encased in a sand body. It was actually within a bed of other similarly sized boulders that were imbricated. It's a geologic term or sedimentologic term that indicates that there is transport in a waterway and environment. Those different clasts were implicated. We use little clues like that as geologists and sedimentologists, to determine that this was a flood deposit. The alternative is there are some places where we dig these pits, and they are clearly windblown sands. We can tell the difference between a windblown sand and a water-lain sand. That's important because a windblown sand has not experienced being laid down by water. That becomes an NEB. But a waterlain sand, even if there are no big boulders, just laminated sand, that tells us this was water transported. Whether it was by a flood or just a little rivulet is another debate, but it was at least waterlain, and we use that information. We also use, on the lookout point hydrological model (slide 12), the modeling in the HEC-RAS capability. In the red part in the central thread of the channel, there are little white flow lines, scaled to velocity. So, we are actually looking at the velocities along the channel here. In the blue part, the velocities are relatively low. There's uncertainty and we can nitpick, but basically, it's a lot lower velocity up on this terrace than it is in this channel. When we find some sand in here, and gravel down in here, that reflects that the modeling reflects reality. We have comfort in the model. We use both the sedimentological characteristics and the geologic characteristics that we encounter, and we use the modeling input to double check the results.

Question:

It seems like there's a lot of information in the paleo record from just different locations. Are other universities and other researchers using paleo data? Are you able to take advantage of other studies?

Answer:

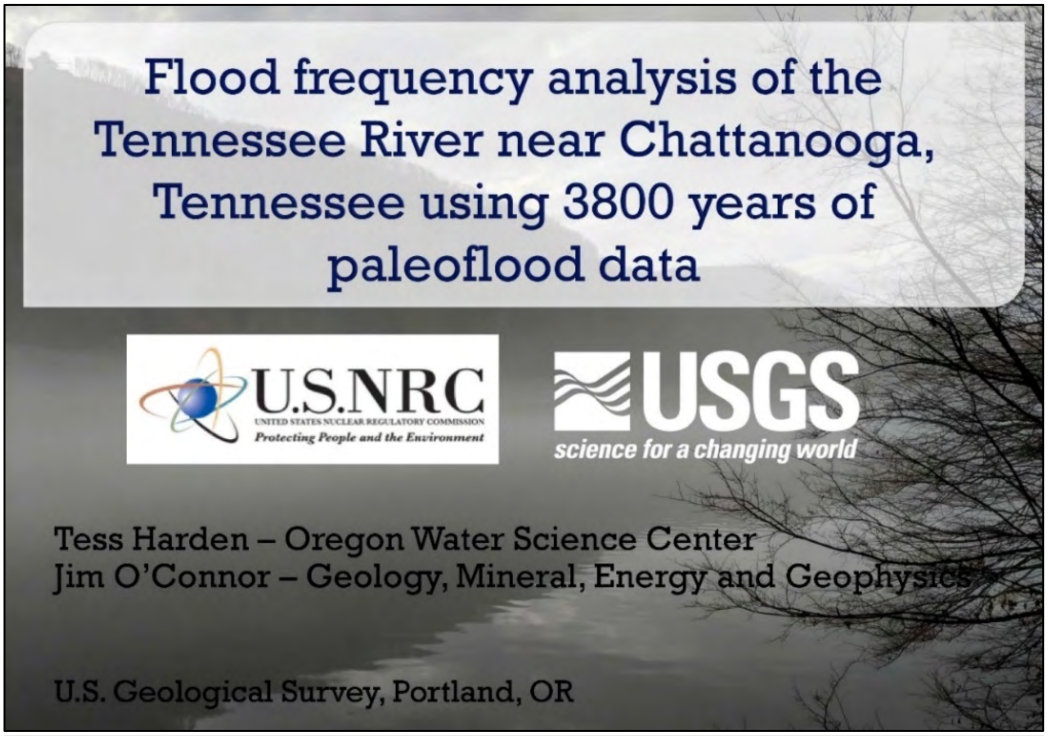
We are definitely not the only people doing this: Tess Harden and Jim O'Connor have been doing this at the U.S. Geological Survey (USGS) for a long time. John England and his group at [when he was at] USBR have been working on this as well for a long time. Academic research is in process throughout the country and we are just tagging on. By no means do we think we are the only ones doing this; we are actually just trying to catch up. The hard part is that the hydrologic and geographic regimes are so different across the country that academic researchers are looking at different aspects. For example, in the western United States, where most of USBR dams are located, they use certain types of features. In other places, such as Tennessee, which Tess Harden will talk about later, there are other techniques. Those in academia are performing some new research evaluating the frequency of flooding within oxbow lakes. There are multiple avenues of academic research. Most of the research is academic, and a lot of it is in Europe, particularly France, Germany, and Spain. We are trying to just tap into that and are not at the forefront of this. We are just applying the techniques that people have developed over the last 20–30 years to our particular facilities.

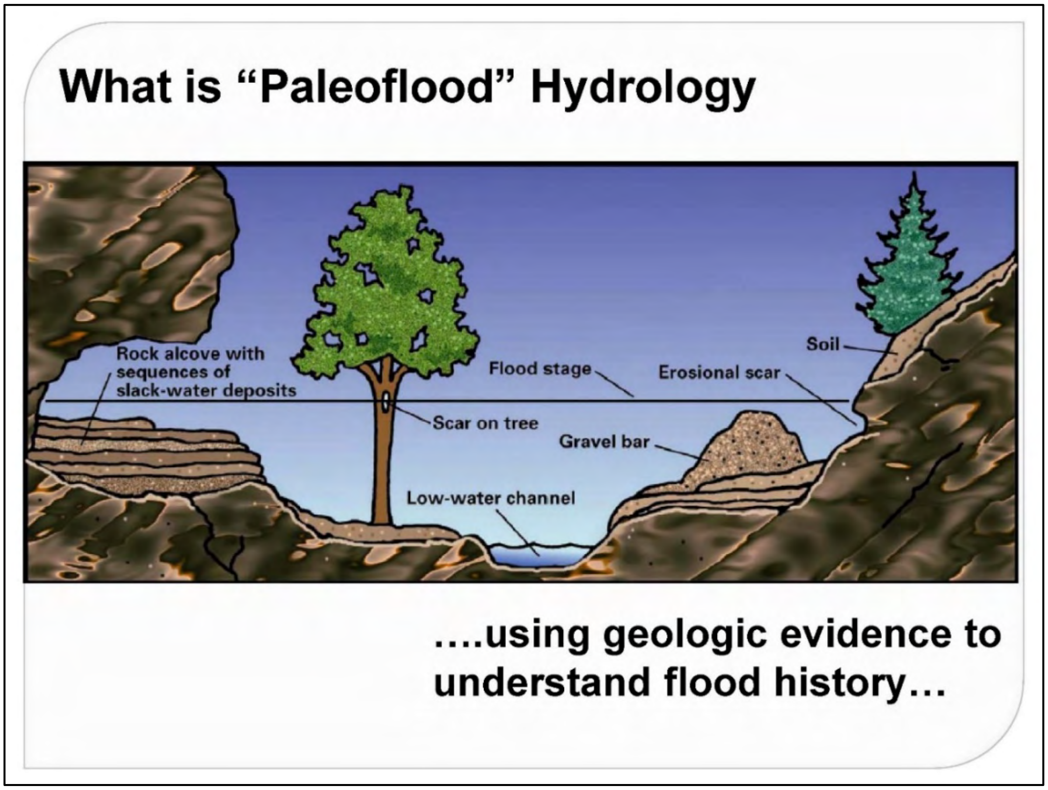
Joseph Kanney, Organizing Committee:

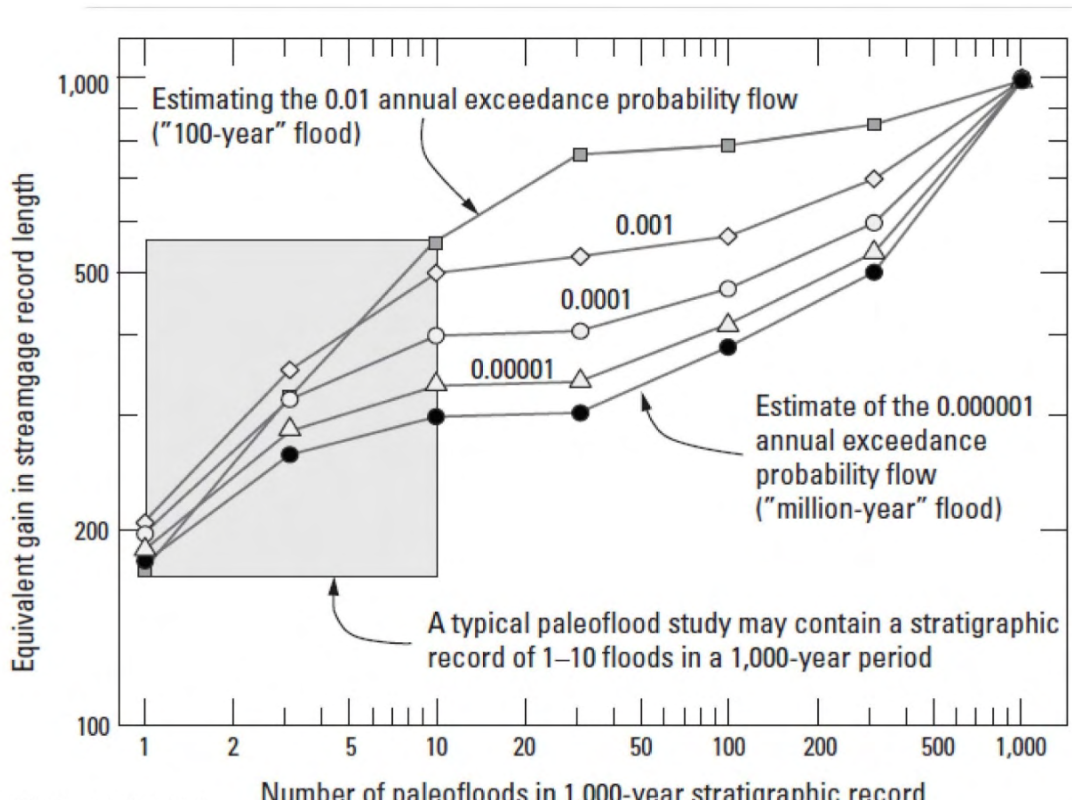
The report that Keith Kelson talked about, O'Connor et al. 2014, was actually a result of a project with the NRC. The researchers took a very broad look at several different river basins within the United States; came up with a set of metrics and an index to rate them; and gave them a high, medium, or low viability for paleoflood study.

4.3.4.6 Improving Flood Frequency Analysis with a Multi-Millennial Record of Extreme Floods on the Tennessee River near Chattanooga, TN. Tess Harden*, Jim O'Connor and Mackenzie Keith, U.S. Geological Survey (Session 2A-6; ADAMS Accession No. ML19156A466)

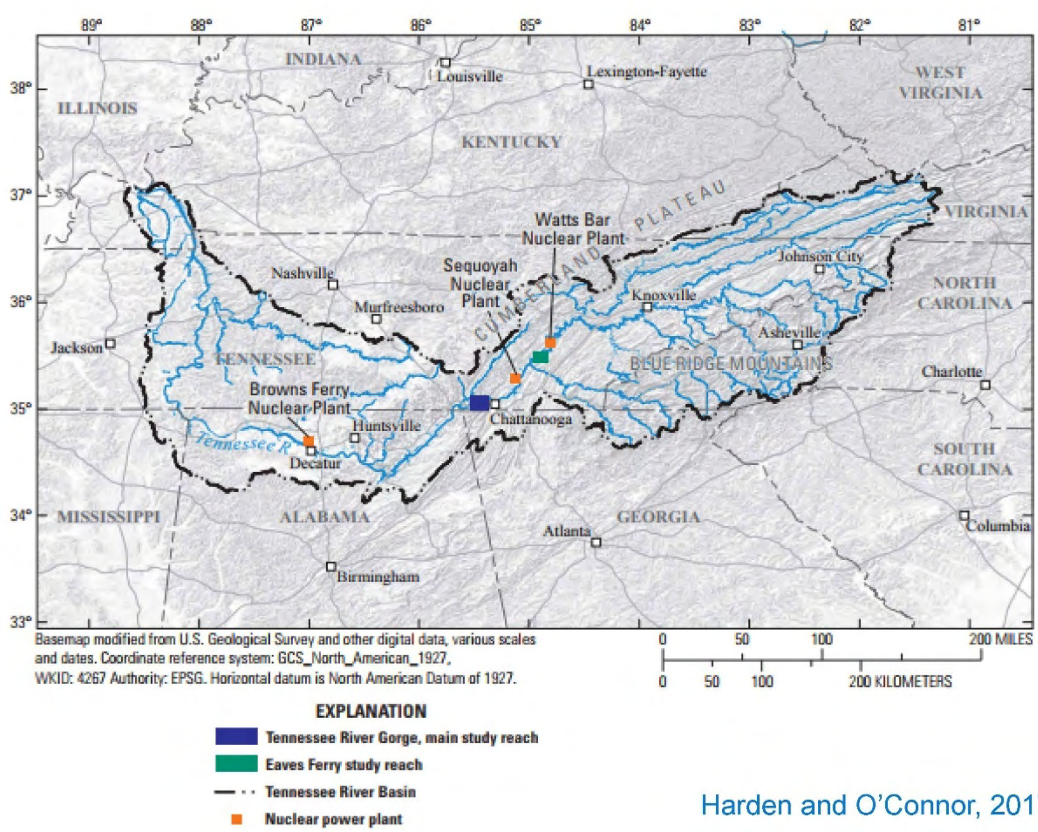
4.3.4.6.1 Presentation



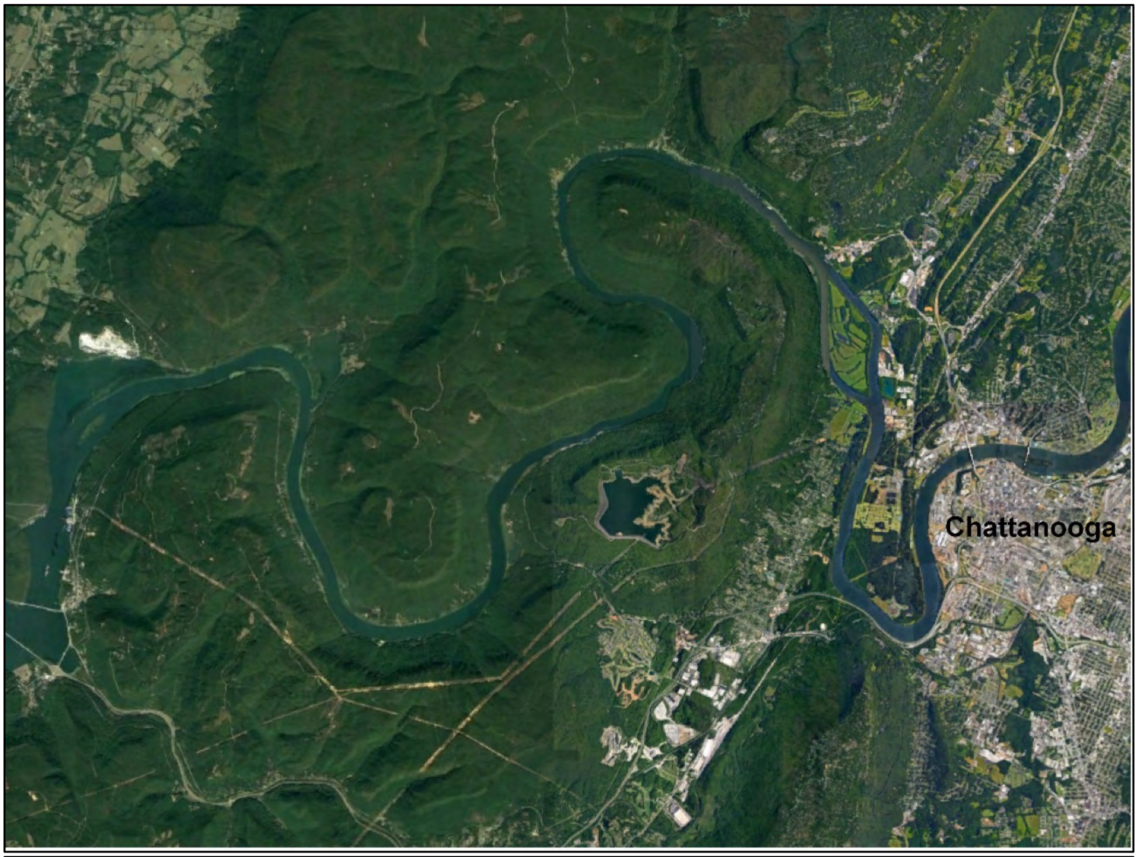


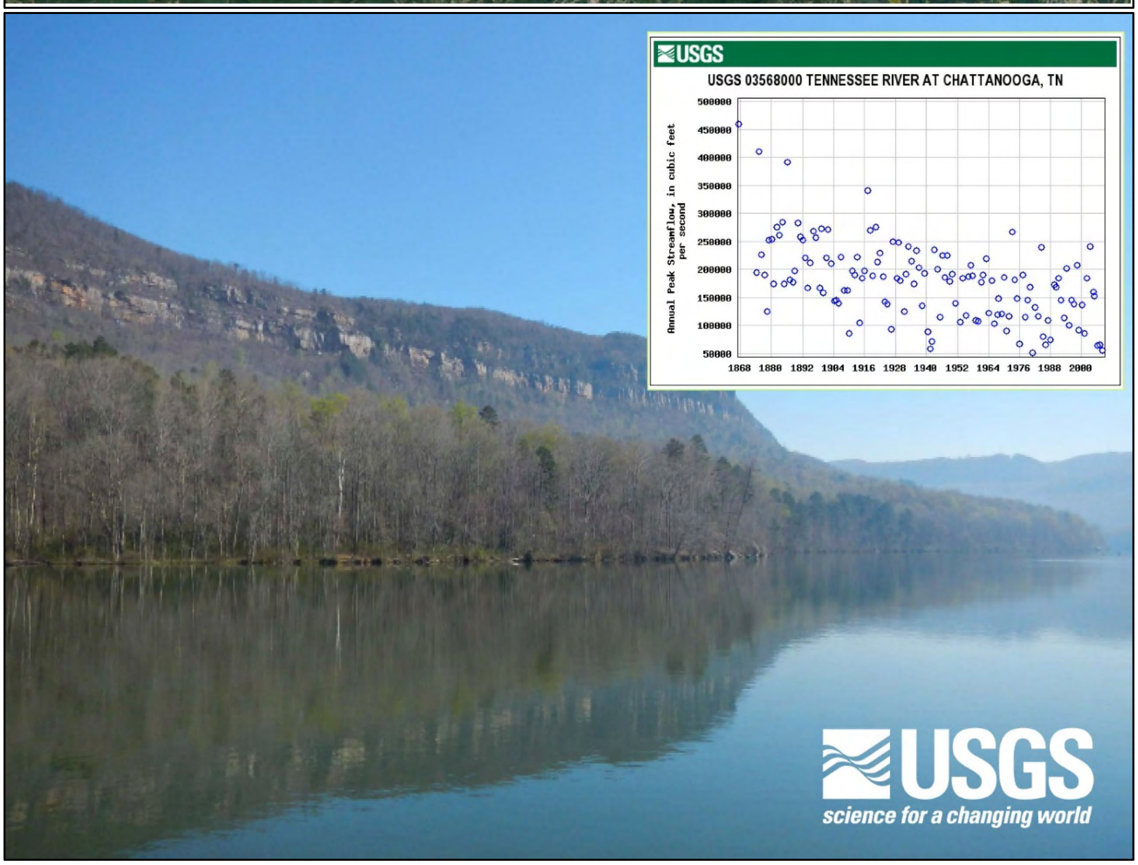


O'Connor and others, 2014



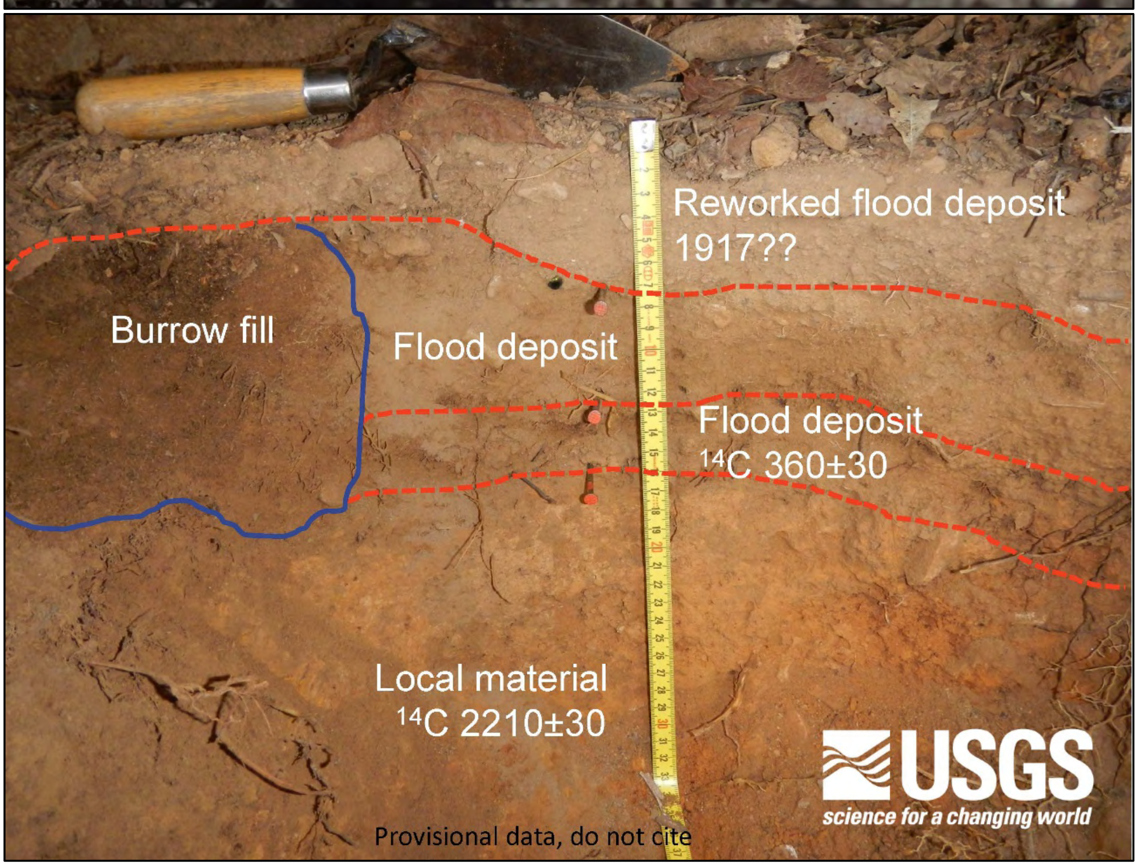
Harden and O'Connor, 2017

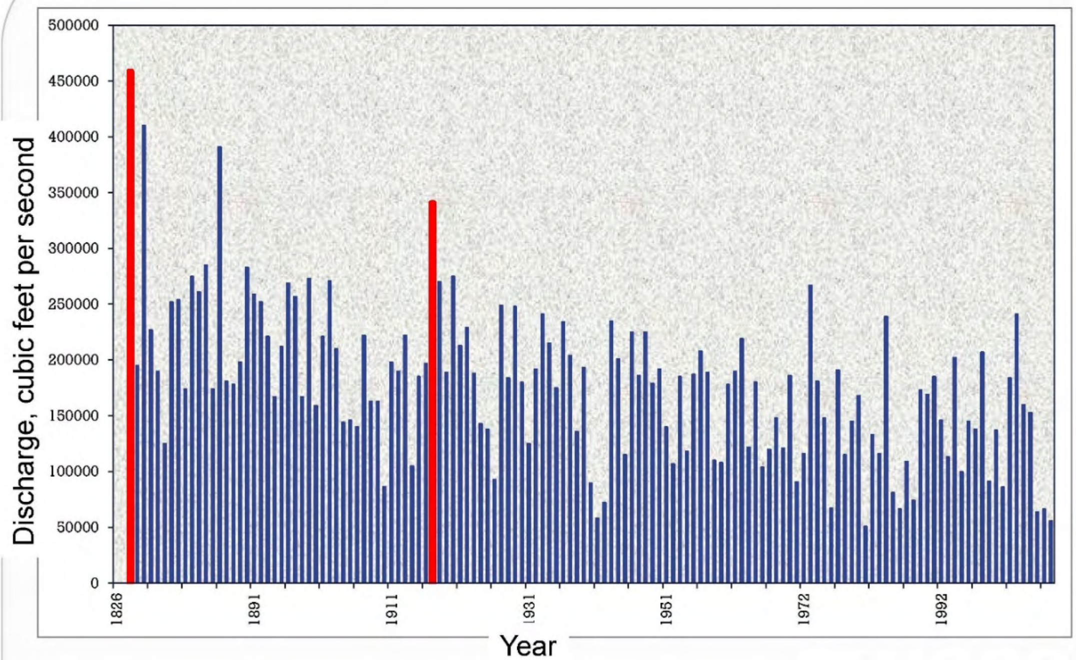

Chattanooga


USGS
USGS 03568000 TENNESSEE RIVER AT CHATTANOOGA, TN
Annual Peak Streamflow, in cubic feet per second
500000
450000
400000
350000
300000
250000
200000
150000
100000
50000
1868 1880 1892 1904 1916 1928 1940 1952 1964 1976 1988 2000
USGS
science for a changing world


USGS
science for a changing world

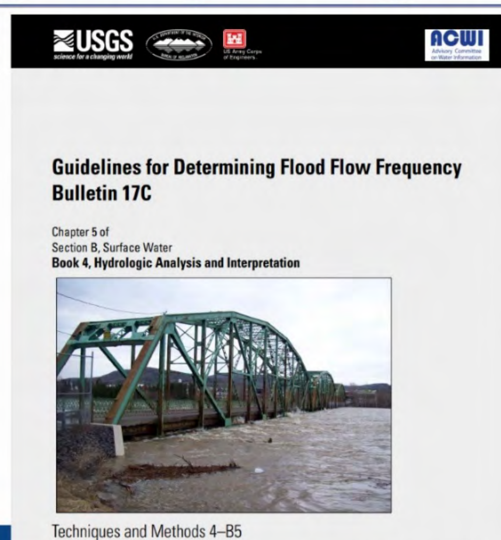

USGS
science for a changing world


Reworked flood deposit
1917??
Burrow fill
Flood deposit
Flood deposit
14C 360±30
Local material
14C 2210±30
Provisional data, do not cite



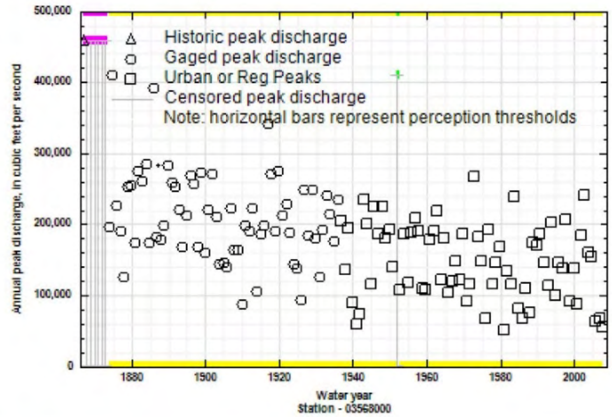
Frequency Analysis

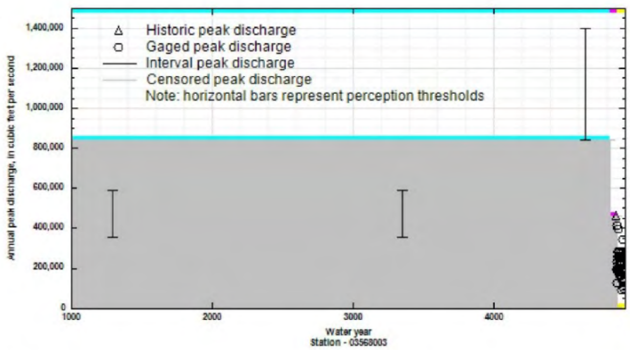
- Bulletin 17C
- EMA
- Discharge uncertainty and perception thresholds
- LP3 distribution
- USGS PeakFQ



England and others, 2018

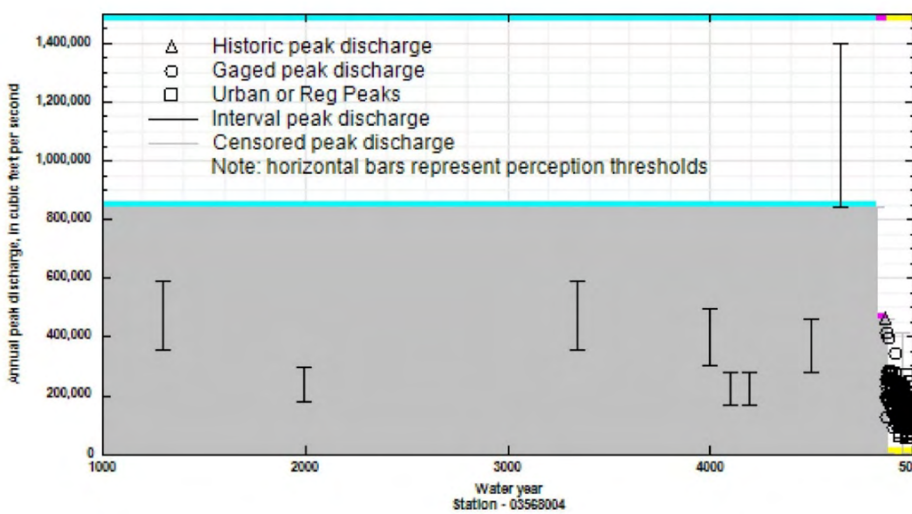
Gaged record only at Chattanooga ~1867-2008





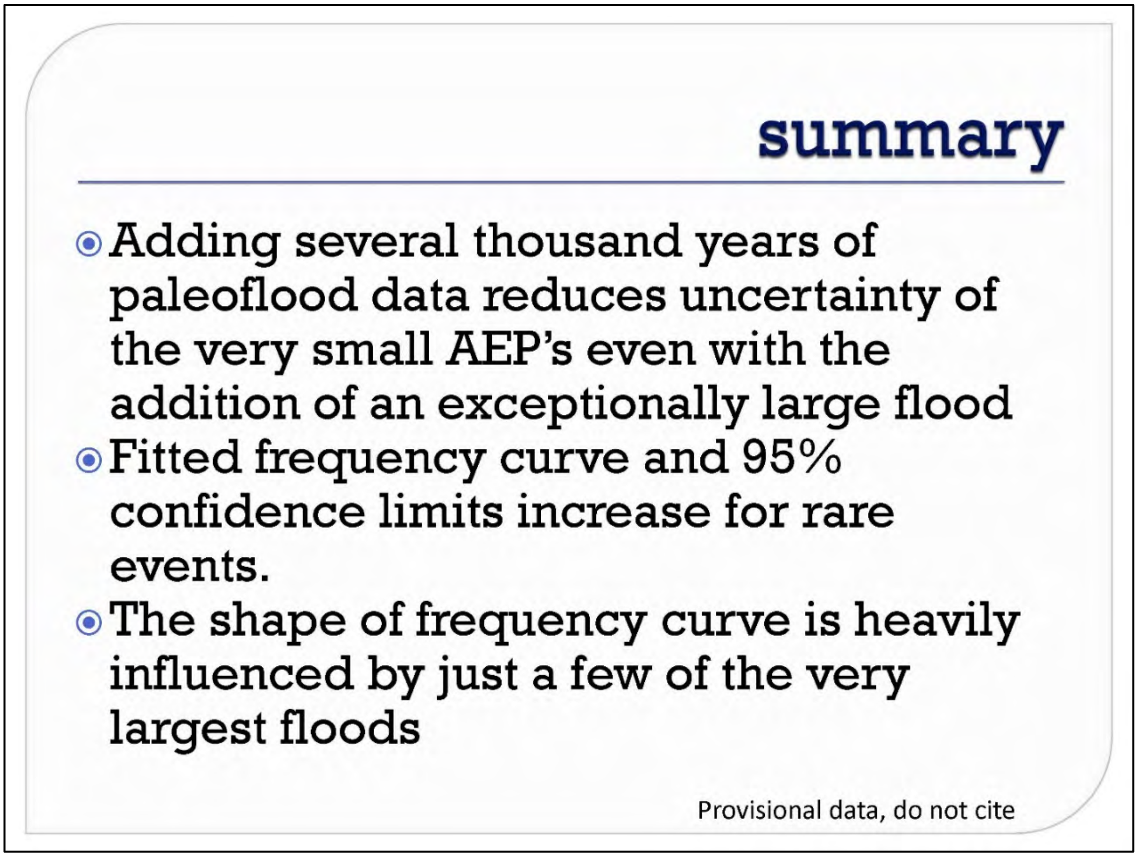
Gaged plus paleofloods (at benchmark) sites ~4000 years of record

Provisional data, do not cite



Gaged record plus all 8 paleofloods

Provisional data, do not cite



4.3.4.6.2 Questions and Answers

Question:

On the frequency plot, it looks like the slope of the peaks is a little flatter than the slope of the final curve. Is that partly influenced by the dams that are storing water on the Tennessee River Basin or did you back out the pre-dam speaks?

Answer:

I did not use the regulated part of the record. This is pre-dam. The early part of the record still provides about 40 or 50 years of records, since they began in 1867 and has been continuous since about 1874. I think the first part is really influenced by these lower floods, and then the big tails are influenced by our big paleoflood.

Question:

Your third slide showed a number of curves with a so-called gain in a record period versus the number of paleofloods. The one in a 100-year flood line sort of crossed the rest of the other lines. Do you know why, or is it random?

Answer:

Unfortunately, Tim Cohn, who passed away a couple of years ago, created this curve and performed the statistics. We are trying to have someone to recreate this, so we can put it in different publications, something similar using real data. We are looking for volunteers. I do think that these paleofloods will not have that much influence on the 100-year or the 200-year flood. A good gauge record will have more influence than in some of these other floods. You really start getting the increase if you have more information on these rarer floods.

Question:

When you have only one event, you start to set a middle and, going with just precedents, you gain a lot of information. With regard to the censored value, the censored flood: you observed several floods but only used one here?

Answer:

We use three, but this does not account for the perception thresholds. This chart gives just the number of paleofloods and how that affects the curve at these certain flood quantiles. Then we add these perception thresholds where we had information about floods. We do not know each individual flood magnitude. We are just adding information that the floods did not exceed a certain level. This graph does not take that into account.

Question:

You know you have several huge floods, even if they are below a certain threshold. This is very important information, the frequency analysis. Why does your calculation not take it into account?

Answer:

Although we have information on eight floods, we used only the benchmark site and considered the three floods because this was just more of a sensitivity analysis. These are the three biggest floods and the floods we have the highest confidence in and found over and over. This site is very similar to the record at this site. We are pretty confident that these floods occurred, and they are the largest floods. For the sensitivity analysis, let's put that large flood in a frequency analysis and see what it does. Then we added the other floods. We were confident these happened, but there is slightly less evidence or there is more uncertainty with, for example, the age, although the actual age of the flood is much less important than the timeframe and flood frequency. You should use all your floods in your overall approach, but this is more of a sensitivity analysis. Sometimes it really affects the curve in the analysis if you take one flood out, and sometimes it doesn't. In this case, it just does not affect the curve. It is probably a combination of the perception threshold and the large flood that was really driving the curve. The other floods just did not have that big of an effect. But for best practices, you would use all these floods because you do actually have information about them.

Question:

With regard to the hydraulic modeling of the paleo floodplain, did you adjust the topography to match the time? Are you using current topography?

Answer:

TVA actually created and modified the model. It represents the topography before the intervention of building dams and other structures. However, when the dams and other such features are taken out, there is always the question of whether the environment shown in the model really looks like it did when these floods occurred. That is why we pick our sites where we do. There is no human activity in the gorge, no human modification. In 1867, the river is flowing across bedrock. Even later than that, before the dam, the river was flowing across bedrock, so it has not moved much. This is limestone, but it is very resistant and is not going to change much in 4,000 years. Since the dams were installed, there is probably a little more alluvium at the bottom. I do not know when TVA performed its surveys, but even if I had a couple feet of alluvium, the cross section is like a V. This alluvium is at the very bottom of the V, so it is not going to change the stage very much. Even with some of these unknowns, I think it is fairly safe to assume that it has not changed much in just 4,000 years. That is the benefit of having a stable bedrock site.

Question:

I do not always think in terms of channels, I also think in terms of watersheds. If, for instance, a river has been developed, it could have become regulated. I am more interested in knowing the paleo history of the watershed. Do people look at the tributaries that feed into these major river systems and wonder, "I may not see it in the Susquehanna River, but I could see it in some of the very large tributaries like Pine Creek, Lycoming Creek, and they may be where I'll find the paleoflood evidence and not in the main valley because of human development."

Answer:

That's an excellent point. Some of these are more modified channels, then tributaries are an excellent place to find information about more than just tributaries. If you do a basinwide study, you can look at all the tributaries and get flooding data, and maybe it will be a similar signal but maybe it will be different. Hopefully, it will be somewhat similar if you get these large storms over these basins. You can also find some mainstem flooding in these tributaries. Those are good places to look to find that. In heavily modified areas, they are a good place to look if they are not modified as well.

4.3.4.7 Riverine Flooding Panel Discussion. (Session 2A-7)

Moderators: Meredith Carr and Mark Fuhrmann, NRC/RES/DRA/FXHAB

Will Lehman, USACE/IWR/Hydrologic Engineering Center
Claire-Marie DuLuc, IRSN
John F. England, USACE, Risk Management Center
Keith Kelson, USACE, Sacramento Dam Safety Production Center
Tess Harden, U.S. Geological Survey

Moderator:

I would like to start by opening this up to the panel to see if the panel members had any ideas based on what they heard that they'd like to talk about or ask their co-panelists.

Keith Kelson:

You said that there is no change in the curves? Even with the additions, that small amount of change, with the additional paleoflood information with respect to the systematic? Is this correct?

Tessa Harden:

Between adding just three floods and adding the eight floods, there was very little change. Between adding just the gauge record and the paleoflood record, there is quite a bit of change.

Keith Kelson:

Is there value in going to the extra effort to define eight events versus less effort to define one, two, or three?

Tess Harden:

There certainly is value because you do not know if there is value until you get to the end. This is the first case where I've seen that the extra floods did not really have much effect on the curve. But there is definitely value because you can't say at the beginning of the study that you will just look for the three biggest floods or look just at this level. You can't say until after the fact. This is kind of a unique find, I think. I'm sure there's some limit. It's definitely worth finding as many floods as you can that you have confidence in. You do not want to just do it and have low-quality data. The largest number of high-quality flood data points, or intervals, is definitely the best.

Keith Kelson:

As a follow-up to either John England or Will Lehman, can you explain why, if we had paleoflood and it was well constrained, it did not actually change with respect to the systematic, historic record? Is there value in doing the paleoflood? Since it did not change, you can look back and say, well, I don't know why we did that because it didn't actually change.

John England:

It may not change your median model, your frequency analysis, but in part of my presentation, I alluded to our expected curve. When you roll in full uncertainty, the value will be portrayed with a reduction; in some cases, that uncertainty. It comes back to the decisionmaking. Can you tolerate using a 50- to 100-year gauge record, extrapolate into 10^{-6}, and trust that the resulting time interval represents, and that the distribution represents, the complete tail. In my view, adding that piece of information gives you qualitative results. That it does not change the number is beside the fact. That gives you additional, precisely subjective confidence on the model you chose to perform the extrapolation and then the uncertainty about that. But then we want to roll it into the HEC-WAT. Then trying to couple, does that really mean something in terms of the consequences and the risks for the project of interest?

Will Lehman:

One of the things Tess said about the additional floods, they were more uncertain about their details. The added information of the eight floods in conjunction with their uncertainty may have yielded the result that they observed. Had they been more certain about those, then we would expect the confidence intervals to come in.

Claire-Marie DuLuc:

It's very interesting that certain information gives a big advantage to the bias and framework. John England, what about the predictive, which requires some quite different information from what we use with the frequencies effort? How do you propose to deal with this concept? I don't think the word "Bayesian" occurs in Bulletin 17C.

John England:

My coworkers and I had some long discussions when preparing this report. They wanted to go Bayesian and thought that I would disagree. The short answer is no, because, historically, in USBR, we got into this in the mid-1990s. We jumped into using geology and paleoflood information. I was working on updating so it took a long time to do both and Bulletin 17C. That was a straitjacket at the time for floodplain management using straight frequentist. What I mean by straitjacket is the committee. The committee chose to implement an improvement. We decided to keep log Pearson and moments estimation, so straight frequency. At the same time, Daniel O'Connell at USBR was doing Bayesian maximum likelihood. We thought we could include multiple distributions and some model uncertainty and take into account paleoflood ages. The engineers were disturbed because it was like you saying, "It's between 1,000 and 3,000 years." We said that you could put a uniform distribution and account for that uncertainty in ages, just like the flows. One of the flows in one of today's examples had a best estimate 60,000 cubic feet per second for one event. It was tested, and 30,000 was a lower estimate and 80,000 was a higher estimate. So that larger uncertainty sometimes is very discomforting for some people who run hydraulic models and like precise answers. The Bayesian framework can readily account for that, routinely. Broadly speaking, we are headed towards using Bayesian approaches when we have these more complicated dam safety, critical problems. Bulletin 17C does a lot for the frequentist side. For more frequent floods, we want to combine them. We need to use both the scientists' and the engineers' knowledge—so not necessarily relying on the fancy Bayesian and Monte Carlo or these expected moments with these complicated perceptions thresholds. Look at plots, evaluate your data, and then make some inference based on that. We have to keep the human involved in the calculations, not just have the statistics take over.

Question:

John England and Will Lehman, from the dam safety perspective, as flows increase during reservoir operations, you get to a point where you can no longer influence the flow. Have you considered how much the reservoir operators' decisions influence the results, looking at probability of getting to those extreme levels at dams? Second, there is a lot of uncertainty in knowing what the reservoir operators will do. How do we account for that?

Will Lehman:

When you are overtopping your dams in these very infrequent events, dam operation will have less of an impact, while in the lower frequencies, it can have a tremendous impact. Within the HEC-WAT, we would be able to evaluate a system of dams operating together in concert. These big systems such as Trinity present interesting artifacts. Because of the storm centering on the storm patterns, you would see certain reservoirs operate in certain ways that would help other reservoirs alleviate the pressure in the system. That is based off of the guide curves that you input into the HEC-ResSim model. With regard to the incorporation of deviation from operation curves, we have conducted a lot of analysis on forecast-informed reservoir operations and are considering how different duration forecasts help us to make decisions to evacuate pools earlier. We see that there can be a much better treatment for flood risk in the mid-range frequency events. The system operates like a system and needs to be modeled it that way.

John England:

Will Lehman described the Trinity River system, which is in Texas, above most of the dams that are above Dallas. We have five dams: of those we have two in series and one in a levee section protecting downtown Dallas. All those facilities are working in conjunction to provide flood risk benefits and management for the city of Dallas and other parts of Dallas or the Fort Worth metro area. The HEC-WAT is a nice way to incorporate that. The challenges, in my view, are that it affects the flood risk management. Those operations are critically important at frequencies 1 in 100 and 1 in 500. You can use that to explore deviations. On the dam safety side, beside the HEC-WAT, we have a reservoir frequency analysis tool. It's pretty simple to do reservoir stage frequency curves. Yet it has to go back to the users' input, and the input there is very simple. It's not using the beauty of a little logic that's in HEC-ResSim. The user enters outflows, rating curve, and storage relationship. You have to still calculate sensitivity or global sensitivity to do perturbation to identify what happens when there are mistakes or changes in operations. [Those operational errors] will have to be constructed, usually, for this little simple tool outside, one at a time. The other challenge we have on the dam safety side is accidents happen, such as at the Oroville Dam in Northern California. We have very large spillways, which may not operate as intended and fail in this situation. We can sort of throw out the frequency part. I can't speak directly from a USACE position, but I can say that spillway has operated for flows of equal magnitude or slightly less many times in the past. This accumulation in the drain caused the spillway issue. We use the risk process to deal with these challenges. Yet we need all these things, these ingredients, to help with characterize that; whether it's HEC-WAT, or global sensitivity or the full frequency stuff.

Will Lehman:

The Trinity River has two dams in series. If the upstream one fails, it can't pass the flood. In the HEC-WAT, we are also assisting in inline failure locations throughout that system and the subsequent failures of levees and reservoirs, which is what happened in reality.

Question:

Keith Kelson, is the use of archaeological data, such as paleo-Indian sites located on or adjacent to Pleistocene terraces, helpful in your analysis?

Keith Kelson:

Absolutely; archaeologists provide context for the sediments and age dating. For example, on the Missouri upstream of Bismarck, there are archaeological sites that have been demonstrated to have been flooded. The occupants left the site after that flooding. We can almost identify to the year when that flood occurred. Archaeological data provide an incredible gauge to figure out whether something such as flooding occurred or not.

Tessa Harden:

We do try to avoid archaeological sites and not dig them up. A lot of the relevant information can be found in the literature.

Question:

What are the similarities and differences in using paleo data for coastal big flood events? Who if anyone is at the forefront of doing this?

Tessa Harden:

My knowledge of coastal and storm surge is limited to what I heard yesterday, essentially. But there have been studies, I think, of the marsh areas that use the same principles as far as sediments and stratigraphy. I am not sure about doing more hurricane counts. For surge, it may be useful to know if the water is making it into certain areas and you find out if there is a limit of the deposits. After big events such as hurricanes, there is always talk that we have seen this before. There was effort with the coastal community and the river community after Hurricane Harvey to try to determine whether the records mesh. I don't know of anyone doing that.

Keith Kelson:

There are definitely people working on paleohurricane stratigraphy. This is not an area of interest to USACE because coastal areas are not locations for dams, but there are definitely groups that are working on that and they could likely be identified through an Internet search of "paleohurricanes." Riverine cases are also influenced by storm surge, like Washington, DC. In North Dakota, we have the ice jam problem, where you have the tidal influence and potential storm surge. If you were to do a paleoflood geologic analysis and find evidence of a flood, you would have to figure out whether that came from the ocean or the mountains, to be simple. To my knowledge, no one has considered a case with that dual source, ocean and riverine, although it could be done.

John England:

I can't recall whether it is researchers at the State University of New York, Stony Brook or at Woods Hole who are in the marshes in New England. Both Massachusetts and Connecticut are very interested in tracking hurricanes that pass through Long Island; direct hits after Hurricane Sandy. The 1938 hurricane went up the Connecticut coast and so people in that community are working on it. Usually, it's the geologists and oceanographers.

Comment (Joseph Kanney):

In O'Connor et al. (2014), the USGS Scientific Investigations Report 2014-5207, that I talked about earlier, we did a review of paleotsunami and paleosurge research. Although a little bit dated now, but there is a survey of what the state of practice and the state of the research was on paleosurge deposits at that time. It was not very optimistic. There's a lot of difficulty with preservation of those sediments if you are in a bay area with a lot of frequent storm surge with sediment that gets reworked a lot. There is more to it, as described in that report.

Moderator:

My impression is that a lot of historical data are available for storm surge because of the records that tend to be kept for shipping and for various types of harbor work. There may not be paleo data, but there might be a way to get back at what occurred and there may be reliable records.

Keith Kelson:

This brings up an interesting point, about our historical record. Is it good enough? It applies to what you just said and also applies to the riverine. In some cases, I think it's probably true on the Tennessee River near Chattanooga, or if you have multiple large events in the historical record, either because the historical record is long enough, or because that's the way the system works. But think about the extremely flashy systems in Southern California, where we do not have as long an historical record, but we have no historical events that are even close to anything that we're seeing in the paleoflood. Either our window is too narrow, or the return period on these really big floods is longer than our window. Whether the paleoflood information makes a difference or not depends in part on what the system is like. It might change the curve a little bit, where you have multiple large historical events, but it's going to change the curve a lot, either greater or lesser, if you don't have very many historical large events.

Question:

How do you deal with nonstationarity? How do you handle a site where you may just have one piece of data from a flood, and you are not accounting for nonstationarity or climate change?

Keith Kelson:

Understanding how the system works is important: the runoff processes, given certain meteorological inputs. It is important to understand that system and to look back in time to help us understand those runoff processes. If you will project forward using meteorological models, you also need to understand how those models work based on past history. If we do not look at the longer record, then our models are only as good as what we have from that limited historical period.

Follow-up Comment:

I was glad that during your presentation you had that slide where you lowered the annual exceeding probability for low-frequency events. You said this should not be used for decisionmaking, that you have to take that with a grain of salt and not start modifying guidance and regulatory action based on these data. It is the same thing for GCM. It's a tradeoff of what you're getting out of paleoflood data and models. We need all the data we can get.

Will Lehman:

We talked a lot about downscaling the GCM. I think there is a lot of benefit to that. There are other ways to make decisions and have full definition of the likelihood of something occurring. For example, you can look at a kind of a bottom-up approach, where we look at the variability that's expected. We run through a stratified sample of the expected outcome across certain parameters and see how it impacts our ability to perform as a system. With this, you can describe when you would start to have regrets for not taking action, and then monitor how we progress towards that end across time to enable us to make decisions. It's a bit of a different approach. Coupling that with downscaling, once you have these response surfaces, effectively, you can actually take the downscaled models, assign to them some predictive ability, and create a surface that has a probability distribution on top of it to say, what's the likely outcome? I think that we might need to start heading that direction. We've been doing that with the HEC-WAT.

John England:

With regard to sampling in space, we have relied on work by USGS, principally John Costa, on very small basins. Keith Kelson alluded to Southern California, with really big floods and shorter records. We encourage the teams to look spatially, to look at multiple watersheds to get the signal of the events happening across multiple locations and, as Tess Harden pointed out, at multiple sites to see that signal. This will allow you to state, "We get this broad signal of really big floods happening of about this magnitude." With regard to nonstationarity, we wrestled with this issue when we came out with Bulletin 17C, and so that guidance is really flexible. We advocated there to try to go toward non-time-varying parameters. When we do frequency analysis, we can do distributions like GEV, or log Pearson III. Turns out, we know nothing about the shape parameter, except from theory. There are some interesting parts where you can use rainfall and constrain what that shape parameter might be with the assumption of stationarity. That's where the theory can help you. Second, if you have a really big flood, or the Tennessee flood—something bad so that it's in the paleoflood record—you may never be able to answer the question, "Is the record quasistationary?" But all we know is whether this flood of this magnitude will break our system or cause risks sufficient that we have to investigate it. The frequency analysis does not consider whether it's 50 years in the future or a thousand years ago. What matters is having an event of those magnitudes in the analysis in the first place. The National Academy of Sciences published a wonderful report on tree rings and the Colorado River in about 2000. Those tree ring records show that there are a couple of big droughts in the Colorado River system and the southern and southwestern United States that would essentially break the system. We can additionally encourage people to go look at downscaling from GCM and look at warming in the future. Dave Curtis brought this up yesterday. For a longer time window, you need to do both sides.

Question:

First, related to Will Lehman's presentation about the HEC-WAT model, I understand the model has one component that relates to the damage and inundation elevations. My recommendation is to include the velocity. Right now, the floodplain management for flood insurance uses a factor, the velocity multiplied by the water depth, as a major parameter to estimate the inundation damage. This recommendation may help the floodplain management community to use this model. Second, Bulletin 17C treats the lower value, the lower tail of the flood frequency curve. It has an approach to deal with lower values, outliers, but it has no new approach to deal with the upper tail. You plot it, for example, using a type of plotting position, and then you find out maybe the paleoflood data show the upper tail if it is an outlier. It might be good to have some reasons to justify these upper tail outliers rather than suggest or have any justification or approach to justify them.

Will Lehman:

The Hydrologic Engineering Center Flood Impact Analysis Software (HEC-FIA), which is included in the HEC-WAT does use depth-times-velocity in the damage-driving parameters. If one knew that the structures that they were modeling were in a high-velocity zone, one could use high-velocity depth damage relationships to describe that additional damage. HEC-LifeSim explicitly uses velocity in its ability to assess damages, as well. It would depend upon the plugin, whatever application was there, and whether or not you could address it; also, the modelers' decisions on whether or not it would be used in the output of HEC-WAT. It is kind of handled already, and we can do better.

Keith Kelson:

To expand on that, when we are going through our levee screening tool to assign levee safety action classes, we will use the HEC-WAT information and then qualitatively adjust that action class depending on where the breach occurs. We have some information on spatial variability of fragility of the levee. If that most likely breach location is in an area of high population, then we will adjust that safety action class, depending on the anticipated velocity. You will have a high velocity right at the breach location and it will decrease out from there. We will qualitatively adjust the action class if needed to capture that velocity gradient.

John England:

USGS, USACE, USBR, and FEMA collaborated to produce a document, and progress has been slow in some areas. Bulletin 17C mentions a Web site that has some additional information. About 8 or 9 years ago, we had a frequently asked questions (FAQ) page for Bulletin 17B. Some of the issues you have raised are appropriate for us to put on a Web site for broader dissemination on Bulletin 17C. Particularly, we have a very specific test to take care of the low floods, called potentially influential low floods, because analysis tends to focus on this big flood of interest. Essentially, we removed the influence, and there's a specific test to figure that out. Then you can use perception thresholds. We also made a conscious choice to deviate from Bulletin 17B, which had a high outlier test. We decided that we did not want to use a statistical test to figure out that the largest flood is a high outlier. Instead, we said to plot your data. We have a plotting position formula that includes ways to adjust for historical information. We wrote a whole section on extraordinary floods. Instead of using a statistical test, look at your biggest events and the ratio of the largest flood to the next one. An example in Bulletin 17C describes this for a site in Colorado, where the largest flood was on Plum Creek, about 35 times the next largest one.

You can easily see with the points on a frequency curve that one flood is an outlier, and more information is needed on the paleofloods and the historical record. Look regionally to see where you have a flood of that magnitude that has occurred in other gauges. In this particular example, Plum Creek was a very famous flood in the Denver metropolitan area in June 1965. Multiple gauges were broken. It was a very, very large regional flood. In some other cases, though, you may find out that there's measurement error. We encourage folks to go look at that flood to see if there is an error in the database or the hydraulic calculation. A specific plotting position addresses that and a way to obtain additional information, whether it's an historical record or a paleoflood record on those large events, and then look at that in context. We are in the process of developing an FAQ to explain some of the ingredients that seem to be new to people that we have overlooked in the implementation details. We have Hydrologic Engineering Center Statistical Software Package (HEC-SSP) software, just as USGS has PeakFQ, that has graphs with perception thresholds. It takes time to communicate that, so we have some PowerPoint slides and other resources on my Web site that I can share with you, and we are working on better documentation. The last section of the report discusses what is not included, including topics we have been discussing, such as regulated flows, nonstationarity, and land use changes. Those things are not in that bulletin, and we really would like to have the community help us in those aspects. Particularly on nonstationarity, I had a site visit with my coworkers from the Galveston District on some work on dams in Houston, and the land use change signal is as clear as anything in that part of Texas. That is a very important feature to include in the full frequency but not addressed in Bulletin 17C.

Follow-up Question:

In the United States, we have installed stormwater management plans in a lot of States, which follow these policies. So, there is now physical interruptions in the stochastic process. These physical installations in the watersheds or any kinds of drainage systems will, for the future, maybe the next 20 years, influence the stochastic process in a way we do not know. Is it right to consider this now?

Will Lehman:

Human intervention is natural and will happen, as well as other things. We are remodeling life loss across a 50-year life cycle. For perspective, Hurricane Katrina was the single largest migration since the American Civil War. If we have a Katrina event in our stochastic model, and then we model that the population is coming back for the next event, then we are way off. Many aspects are very difficult to model, and these are excellent questions that need lots of empirical research. Some of them may not be able to be modeled. I am just trying to provide a framework to get closer.

John England:

We could use the HEC-WAT or some other existing tools. Considering your question with stormwater management and floodplain management, from the perspective of FEMA and infrastructure, I would look at Houston with two reservoirs upstream as an example. Some consultants have conducted continuous rainfall-runoff modeling with stochastic rainfall inputs using various continuous rainfall models like the Hydrologic Simulation Program—FORTRAN or even the Stormwater Management model. It’s more of the U.S. Environmental Protection Agency (EPA) domain that could be applied to urban flood problems for floodplain management and take into account changes in the system for present day, and then teach your forecasts. Speaking for USACE, for our Dam and Levee Safety Programs, and in risk assessments, we look at future conditions without action. We take a model, a simple rainfall-runoff model like Hydrologic Engineering Center Hydrologic Modeling System (HEC-HMS), a unit hydrograph. Then we look at changes in runoff response in riverine systems to take into account those potential future conditions as scenarios and look at some upper bound situations. Although one can do a formal framework to integrate all that, we have not quite taken that step.

4.3.5 Day 2: Session 2B - Modeling Frameworks

Session Chair: Thomas Nicholson, NRC/RES/DRA

4.3.5.1 Structured Hazard Assessment Committee Process for Flooding (SHAC-F).

Rajiv Prasad^, Philip Meyer, Pacific Northwest National Laboratory; Kevin Coppersmith, Coppersmith Consulting (Session 2B-1; ADAMS Accession No. ML19156A467)

4.3.5.1.1 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. Risk-informed approaches require full expression of flood hazards probabilistically. The Structured Hazard Assessment Committee for Flooding (SHAC-F) process is expected to support reviews of license applications, license amendment requests, and reactor oversight activities. Pacific Northwest National Laboratory (PNNL) is leading the development of SHAC-F. In previous years, we described virtual studies following a Senior Seismic Hazard Analysis Committee (SSHAC) Level 3 process for local intense precipitation (LIP)-generated flood and riverine floods. These studies indicated a need to define the basic aleatory model, adopt explicit characterization of epistemic uncertainties, document all aspects of the hazard assessment, and describe SHAC-F studies progressively from the simplest to most complex. Lessons learned from these studies contributed to the development of SHAC-F.

SHAC-F is structured at three levels with the levels defined in terms of the purpose of the assessment. Level 1 SHAC-F studies support screening assessments for structures, components, and systems (SSCs) or binning the flood hazard into significant or nonsignificant categories. Level 2 studies are appropriate to (1) refine a screening analysis (e.g., where a Level 1 study could not adequately support binning of flood hazards) and (2) update an existing Level 3 assessment. Level 3 assessments support licensing reviews, design reviews, and probabilistic risk assessment (PRA) for new and existing power reactors. For all three SHAC-F levels, the expected outcome of the study is generation of a family of flood hazard curves appropriate for the purpose of the assessment. Project structures and roles and responsibilities of team members are clearly defined in SHAC-F. The composition of SHAC-F analysis teams is specific to the needs of flooding analyses and depends on the complexity of the study. At all three SHAC-F levels, an appropriately sized participatory peer review panel oversees the hazard assessment.

Data and methods used for SHAC-F are also defined to be commensurate with the purpose of the study. A SHAC-F Level 1 study uses existing data, possibly for an at-site flood-frequency analysis or simplified hydraulics simulation. A Level 1 study may use alternative conceptual models (ACMs) to represent epistemic uncertainty (e.g., various parametric or nonparametric distributions in the case of flood-frequency studies) and may include regionalization and accounting for nonstationarities. A SHAC-F Level 2 study might combine flood-frequency analyses with existing simulation model studies to refine the flood hazard estimation. ACMs in this case could include alternative simulation models that can reasonably represent the flood behavior at the site. A SHAC-F Level 3 study needs to account for spatiotemporal resolution of flood hazard predictions that can support licensing and PRA needs. Existing data can be used in a Level 3 study, but a site-specific, detailed analysis would be needed with explicit accounting of nonstationarities to support licensing timeframes. At all levels of SHAC-F, explicit characterization of uncertainties, both aleatory and epistemic, is required.

4.3.5.1.2 Presentation

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Structured Hazard Assessment Committee Process for Flooding (SHAC-F)

May 16, 2019

Rajiv Prasad,[1] Kevin Coppersmith,[2] and Philip Meyer[1]

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[2]Coppersmith Consulting, Inc.

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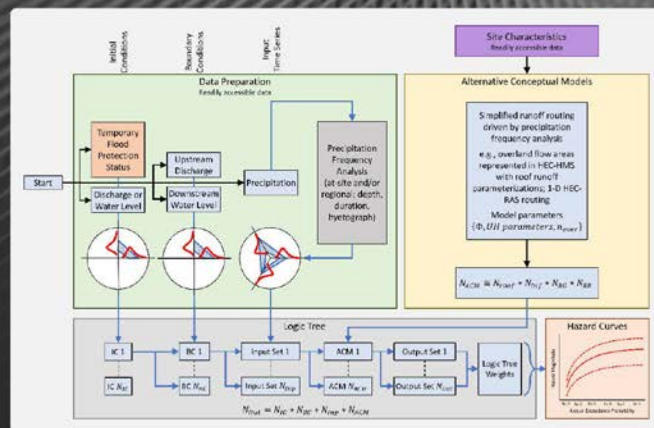

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Motivation

- Flood frequency analysis (FFA) is well established
  - Suitable for at-site estimation of distribution of flood discharge or flood volumes
  - Bulletin 17B, 17C; Asquith et al. 2017
- NRC flood reviews need estimation of dynamic flood parameters and associated effects at very low exceedance probabilities
  - Complete flood hydrographs – temporal flood characteristics
  - Hydrostatic and hydrodynamic loadings – spatial flood characteristics
  - Inundation map – spatial flood characteristics
  - Inundation duration – temporal and spatial flood characteristics
- FFA needs to be supplemented with conceptual flood models
  - Watershed models, site-scale models
  - Introduction of additional uncertainties – epistemic and aleatory
- A structured process to account for all uncertainties is needed
  - Structured Hazard Assessment Committee Process for Flooding (SHAC-F)

2

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Lessons Learned from Virtual Study Approach to Development of SHAC-F

- Need to define the basic aleatory model for PFHA
  - FFA
    - Flood data → Fit selected statistical model → Create flood hazard curve
  - Simulation models
    - Input data, initial and boundary conditions → Drive selected conceptual model → Create flood hazard curve
- Need to explicitly incorporate epistemic uncertainties in PFHA
  - FFA
    - Flood data → Fit alternative statistical models → Create family of flood hazard curves
  - Simulation models
    - Input data, initial and boundary conditions → Drive selected alternative conceptual models → Create family of flood hazard curves
- Need to document all aspects of hazard assessment
  - Participatory peer review
- Need to define SHAC-F studies progressively – simplest to the most complex
  - Note – FFA is generally not possible for Local Intense Precipitation (LIP) PFHA

ACMs

3

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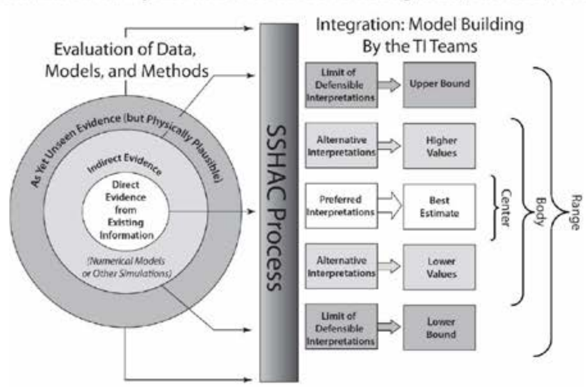
SHAC-F Goals

- The fundamental goal of a SHAC-F 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 flood 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-2213

4

SHAC-F Features

- Five essential features provide regulatory confidence – that a hazard assessment has followed a sufficiently rigorous and transparent process that can be efficiently reviewed by the regulatory agency:
  1. **Clearly defined roles** for all participants, including the responsibilities and attributes associated with each role.
  2. **Objective evaluation** of all available data, models, and methods that could be relevant to the characterization of the hazard at the site. This will often include additional new data collected specifically for the hazard assessment. This process includes identifying the limits of the existing data, gaps in the existing data, and the resolution and uncertainties in the available data.
  3. **Integration** of the outcome of the evaluation process into models that reflect both the best estimate of each element of the hazard input with the current state of knowledge and the associated uncertainty. This distribution is referred to as the center, body, and range of technically defensible interpretations. This will generally involve the construction of hazard input models ... that address both aleatory variability and epistemic uncertainties.
  4. **Documentation** of the study with sufficient detail to allow reproduction of the hazard analyses. The documentation must identify all the data, models, and methods considered in the evaluation, and justify in detail the technical interpretations that support the hazard input models.
  5. **Independent participatory peer review** is required to confirm that the evaluation considered relevant data, models, and methods, and that the evaluation was conducted objectively and without bias. The peer review is conducted following a "participatory" or continual process throughout the entire project.

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5

SHAC-F

- Three levels
- Levels address purposes of various NRC flood reviews
- Project teams and level of effort commensurate with complexity of reviews
- Data and methods commensurate with complexity of reviews
- Probabilistic flood assessment
- Incorporation of aleatory and epistemic uncertainties
- All three levels result in estimation of a family of flood hazard curves

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Level 1 SHAC-F Study

- Purpose: screening
  - Example: Significance Determination Process (SDP)
- Expected assessment results: family of flood hazard curves
  - Example: discharge and/or water surface elevation hazards plus associated effects for a LIP or riverine flood relevant to the system being analyzed in SDP
- Data
  - Readily-accessible data relevant to the chosen flood hazard assessment approach
  - Example: existing streamflow data, stage-discharge relationships
- Models and methods: ACM-L1
  - Statistical models—at-site and/or regional precipitation and/or flood-frequency analyses to drive simplified hydrologic/hydraulic process simulation models
  - Example: FFA (see Asquith et al. 2017) to drive at-site hydraulic stage estimation
- Sources of uncertainty
  - Aleatory: precipitation/streamflow; Epistemic: measurement, statistical models, parameters

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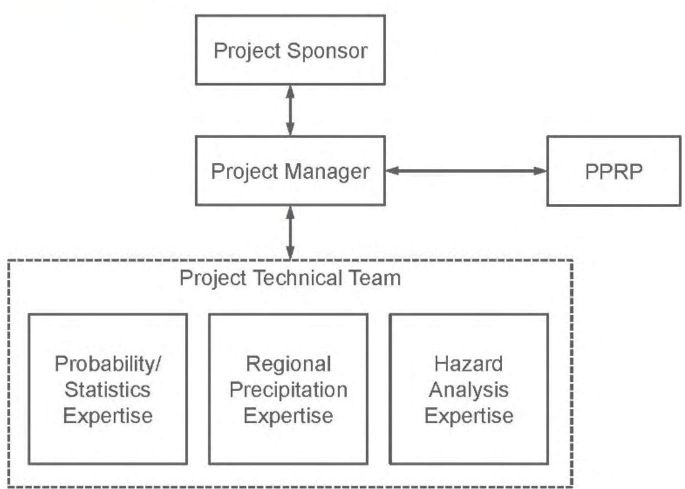
Level 1 SHAC-F Study – LIP Project Team Structure



PPRP: Participatory Peer Review Panel

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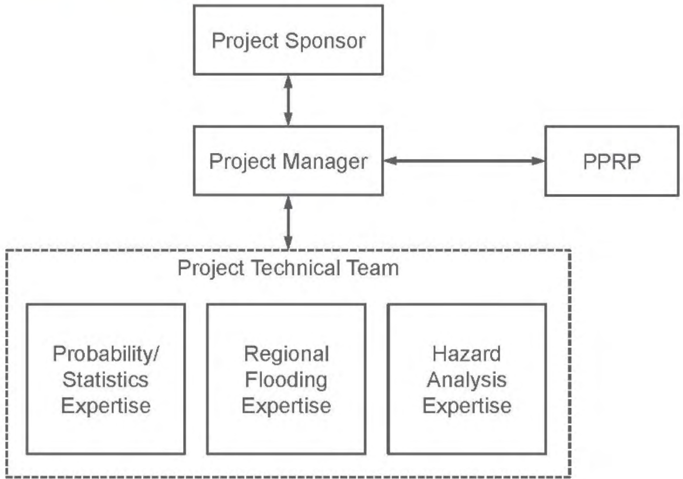
Level 1 SHAC-F Study – Riverine Project Structure



PPRP: Participatory Peer Review Panel

9

Level 2 SHAC-F Study

- Purpose: updating existing analyses or refining screening analyses
  - Example: support corrective actions, update an existing Level 3 assessment, support License Amendment Requests, refine a Level 1 assessment
- Expected assessment results: family of flood hazard curves
  - Example: family of hazard curves plus associated effects for multiple systems/locations of interest for corrective actions or permitting/licensing
- Data
  - More extensive effort to assemble existing data, contact resource experts
  - Example: historical, non-public, reanalysis, available paleoflood, and synthetic data
- Models and methods: ACM-L2
  - Statistical models, process-simulation models with spatial variations, consider nonstationarities
  - Example: frequency analysis incorporating additional data (see Asquith et al. 2017) to drive a watershed model
- Sources of uncertainty
  - Aleatory: streamflow, precipitation, initial conditions; Epistemic: discharge/precipitation/initial conditions measurement, alternative statistical/conceptual models, statistical/watershed model parameters

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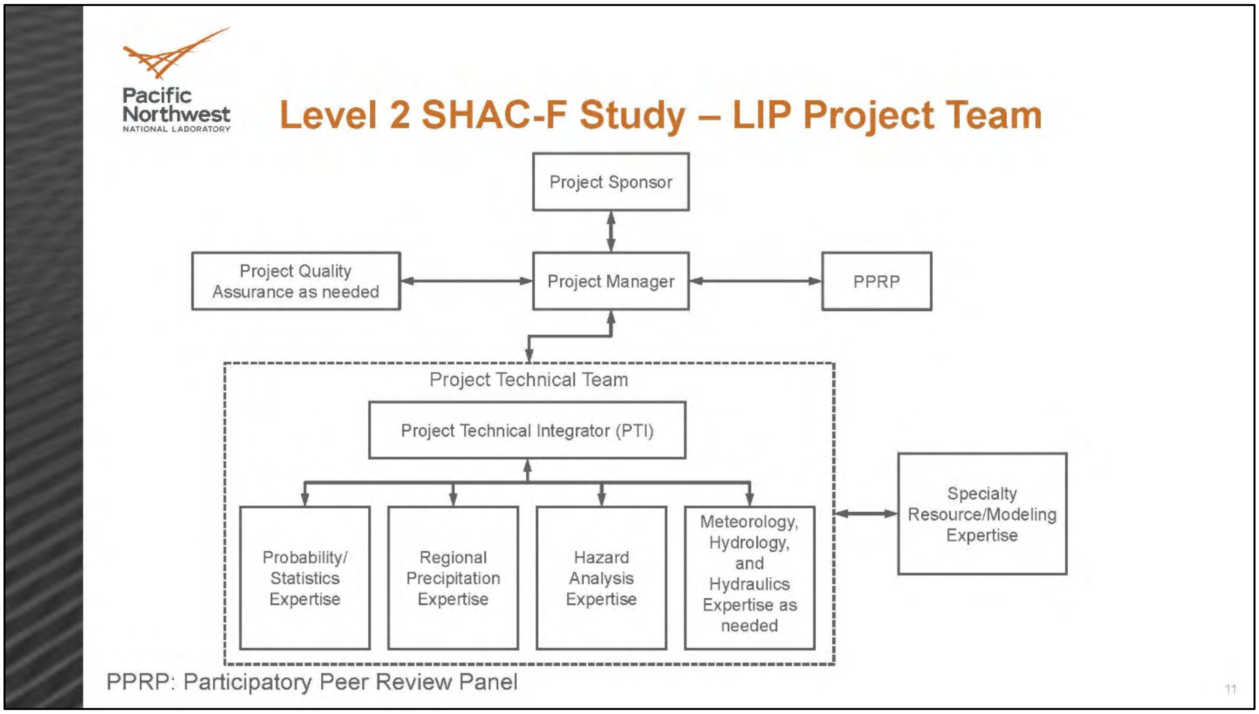
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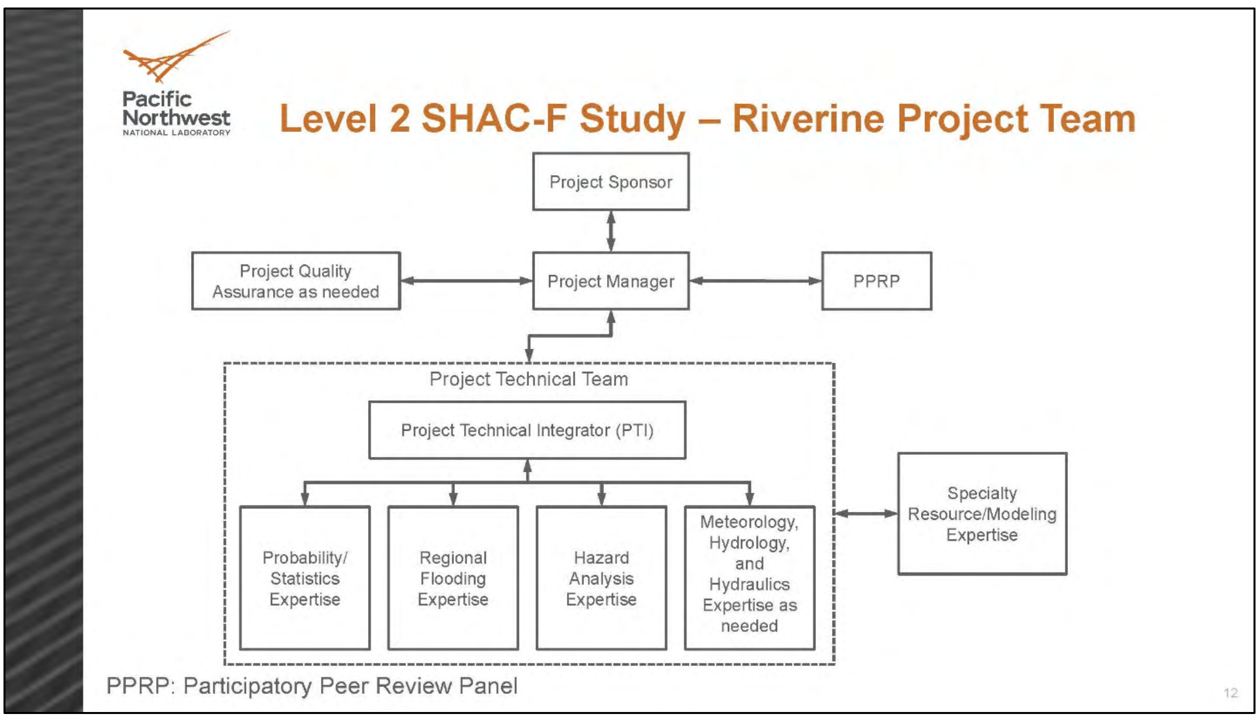
Level 2 SHAC-F Study – LIP Project Team
Project Sponsor
Project Quality Assurance as needed
Project Manager
PPRP
Project Technical Team
Project Technical Integrator (PTI)
Probability/ Statistics Expertise
Regional Precipitation Expertise
Hazard Analysis Expertise
Meteorology, Hydrology, and Hydraulics Expertise as needed
Specialty Resource/Modeling Expertise
PPRP: Participatory Peer Review Panel
11


Pacific Northwest NATIONAL LABORATORY
Level 2 SHAC-F Study – Riverine Project Team
Project Sponsor
Project Quality Assurance as needed
Project Manager
PPRP
Project Technical Team
Project Technical Integrator (PTI)
Probability/ Statistics Expertise
Regional Flooding Expertise
Hazard Analysis Expertise
Meteorology, Hydrology, and Hydraulics Expertise as needed
Specialty Resource/Modeling Expertise
PPRP: Participatory Peer Review Panel
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Level 3 SHAC-F Study

- Purpose: supporting design and/or providing inputs to a PRA
  - Example: support Combined License Application, support License Amendment Requests
- Expected assessment results: family of flood hazard curves
  - Example: family of hazard curves plus associated effects for site-wide hazards
- Data
  - Consider collecting new data
  - Example: paleoflood data, LiDAR surveys, remote sensing LULC data, bathymetric surveys
- Models and methods: ACM-L3
  - Statistical and process-simulation models with spatiotemporal resolution to support PRA; consider nonstationarities
  - Example: FFA incorporating paleoflood data, site-specific watershed models driven with frequency inputs
- Sources of uncertainty
  - Aleatory: streamflow, precipitation, initial, and boundary conditions; Epistemic: discharge/precipitation/initial/boundary conditions measurement, alternative statistical models, statistical/watershed model parameters, alternative process representations in watershed models

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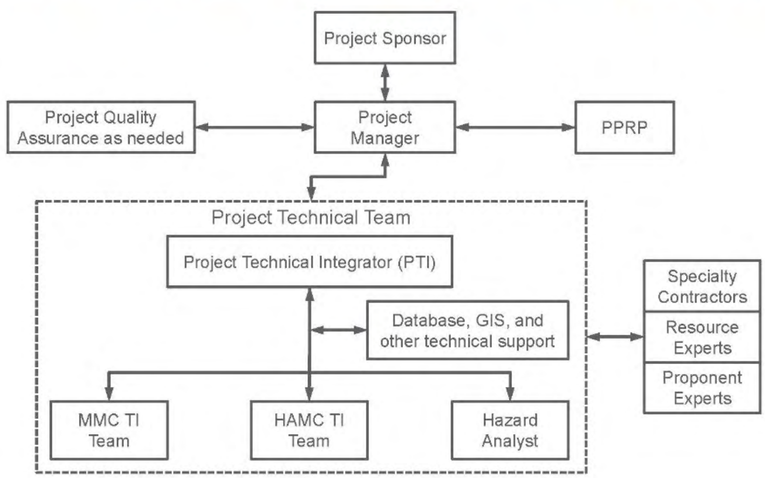
Level 3 SHAC-F Study – LIP Project Team



PPRP: Participatory Peer Review Panel; MMC: Meteorological Model Characterization; HAMC: Hydraulic Model Characterization

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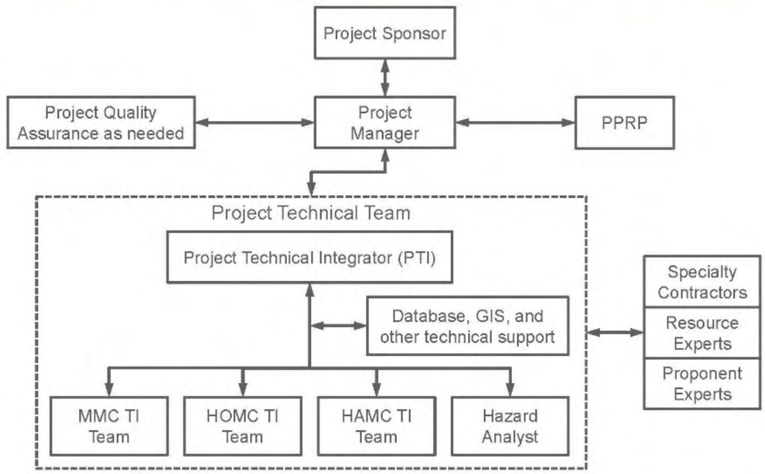
Level 3 SHAC-F Study – Riverine Project Team



PPRP: Participatory Peer Review Panel; MMC: Meteorological Model Characterization; HOMC: Hydrologic Model Characterization; HAMC: Hydraulic Model Characterization

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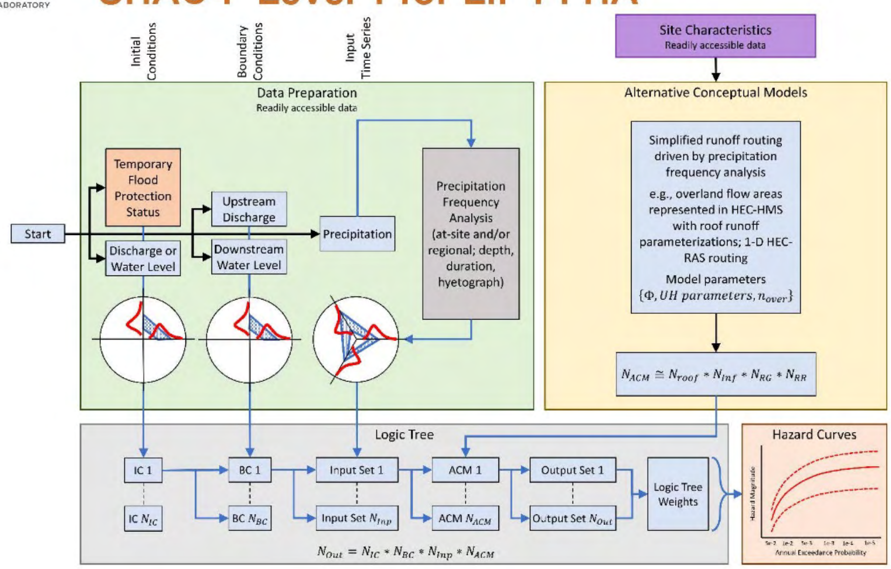
SHAC-F Level 1 for LIP PFHA



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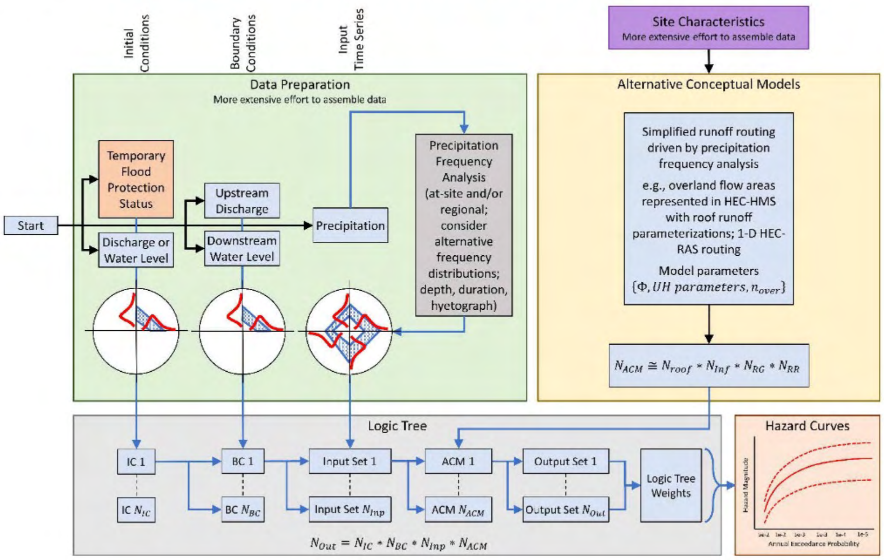
SHAC-F Level 2 for LIP PFHA



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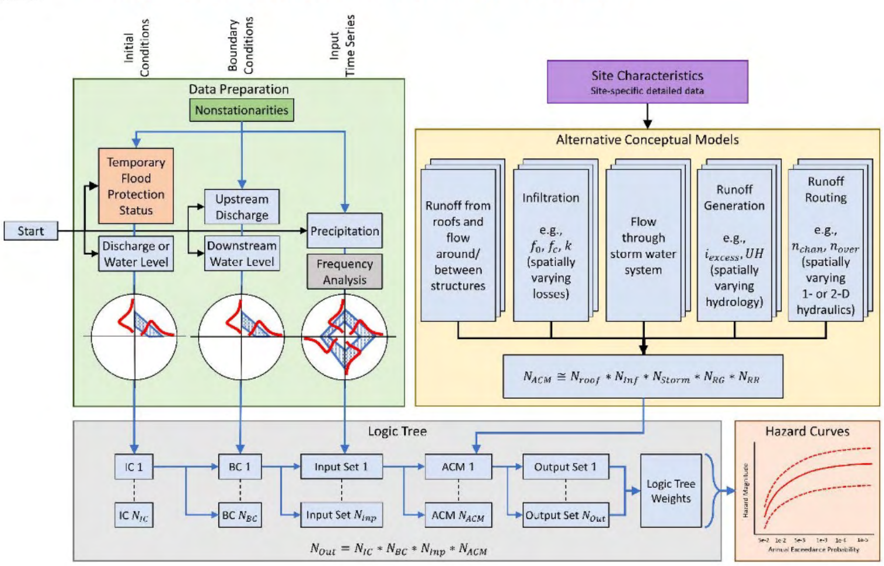
SHAC-F Level 3 for LIP PFHA



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Conclusions

- SHAC-F is tailored after the Senior Seismic Hazard Assessment Committee (SSHAC) process
  - Three levels address purposes of various NRC flood reviews
  - Project teams and levels of effort commensurate with complexity of reviews
- SHAC-F does not require specific models or methods to be used
- SHAC-F does require probabilistic flood assessment with incorporation of aleatory and epistemic uncertainties in estimation of a family of flood hazard curves
- SHAC-F does require documentation with sufficient detail to allow review, reproduction, and update to a PFHA

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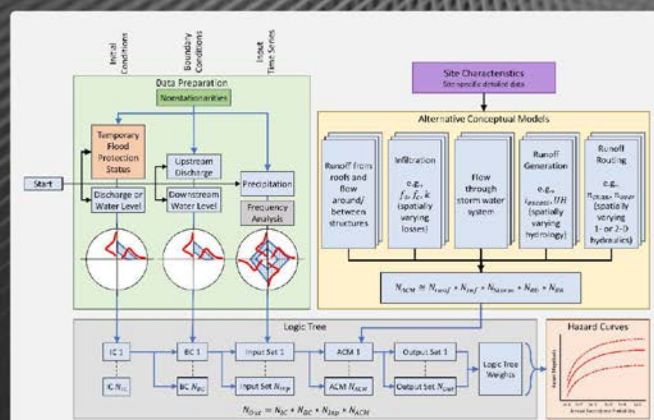
Thank you



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4.3.5.1.3 Questions and Answers

Question:

What value does this SHAC-F have over the present way that people do flood assessments? What can you say the value of this is that warrants the extra cost of organizing and running the SHAC-F?

Answer:

We have known for a long time that probabilistic flood assessments are possible. However, there's a lot of uncertainty, especially when you consider the tails of the distribution that we need to get at; the very low annual exceedance probabilities that we need to define. That is where the epistemic uncertainty starts mattering a lot, because different approaches can either result in more accurate estimates or they can start diverging because you may not have considered some of the processes that are more prevalent in the lower parts of the tail. SHAC-F provides a consistent framework within which to bring all of this information, including both aleatory and epistemic uncertainty. It allows a process that is rigorous and ongoing through the project review. That gives you assurance as a regulator. So, this is more from a regulatory perspective. It provides assurance that when multiple studies are done at different sites, they have followed a consistent similar process and that consistency is reproducible, and there is sufficient documentation of the process, where decisions were made, which models were picked, how the model parameters were estimated. This allows for reproduction or efficient review of this whole assessment process. That is where I think some of the additional expense may be justified. Saying that we can do these things gives the regulator a lot more confidence in trying to come up with what the risk may be, and how that risk is informing some of the decisions that need to be made.

Question:

Is this a published document or is this theory saying we should be doing this kind of thing?

Answer:

This is not a NUREG document yet. We are writing the report currently, and this should be available in the next couple of months, at least to Joseph Kanney, who is our Contracting Officer's Representative. Then it needs to go through the NRC clearance process. We will probably need to go through a review period and then try to update some of the report based on comments. Then the NUREG publication process needs to happen. We are a little bit away from actually having a NUREG.

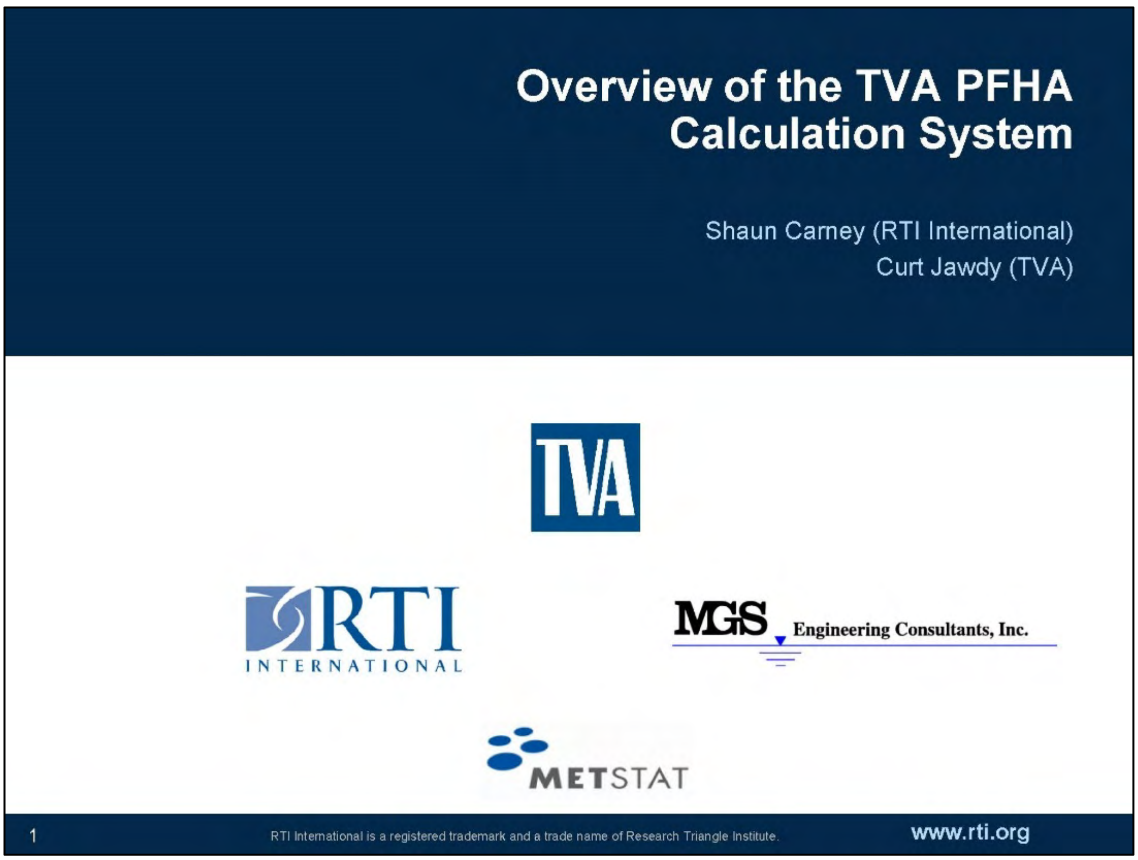
4.3.5.2 Overview of the TVA PFHA Calculation System. Shaun Carney*, RTI International, Water Resource Management Division; Curt Jawdy, Tennessee Valley Authority (Session 2B-2; ADAMS Accession No. ML19156A468)

4.3.5.2.1 Abstract

Around 2015, TVA began a large-scale program to develop inputs to support its risk-informed decisionmaking process, including estimation of economic and life loss consequences along with

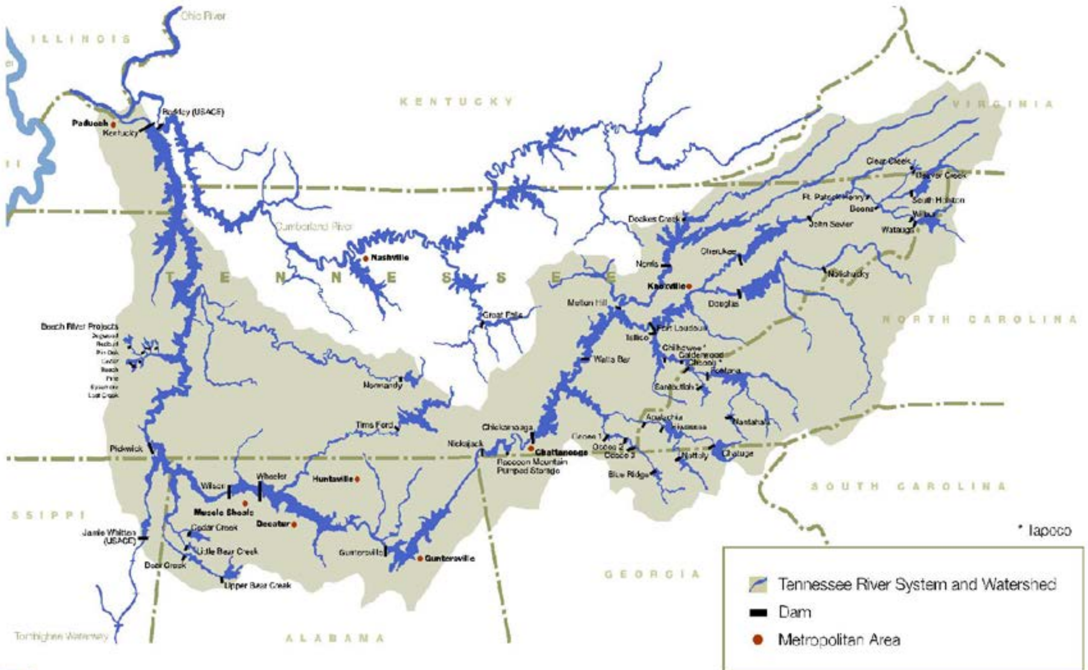
development of hydrologic hazard curves based on PFHA. Through this process, RTI International, MGS Engineering, and MetStat helped build a computational framework for performing the PFHA for reservoirs and other critical locations throughout their system. The framework uses computational modules from the Stochastic Event Flood Model (SEFM) in combination with a suite of hydrologic models and RiverWare operations models. The use of SEFM modules provides flexibility to implement different models within the computational system. MetStat developed a customized storm transposition interface to generate representative storm patterns needed for the stochastic modeling. Other unique aspects of the computational framework include sampling for different storm types, the use of synthetic long-term time series, intelligent sampling and convergence evaluation, both natural and regulated hazard curve development, and advanced data-mining techniques to explore output from tens of thousands of simulations. This presentation will review the unique aspects of the computational framework and will discuss plans for ongoing development.

4.3.5.2.2 Presentation



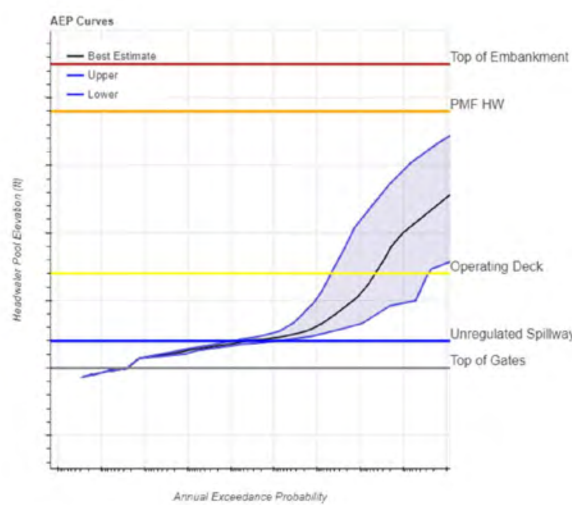
TVA Dams

- 49 dams, of which over 30 are operated as a large system



Probabilistic Flood Hazards Analysis at TVA

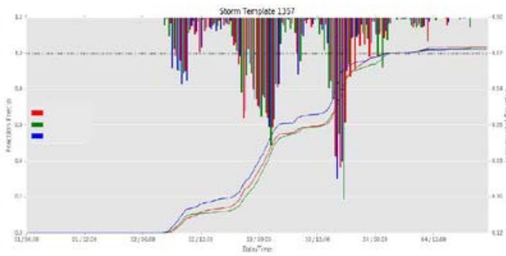
- Began development in 2014
- Application of the Stochastic Event Flood Model (SEFM)
- Applied for 20 unique dams to date
- Supports Risk-Informed Decision Making (RIDM) for dam safety decisions

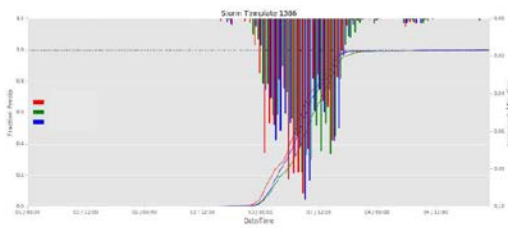


Note axes are intentionally not labeled throughout the presentation to prevent sharing TVA sensitive information

Stochastic Simulations

- Generate thousands of realistic storms and starting conditions
- Simulate hydrologic and reservoir operational response to storms
- Aggregate statistics from each storm to make hazard curves





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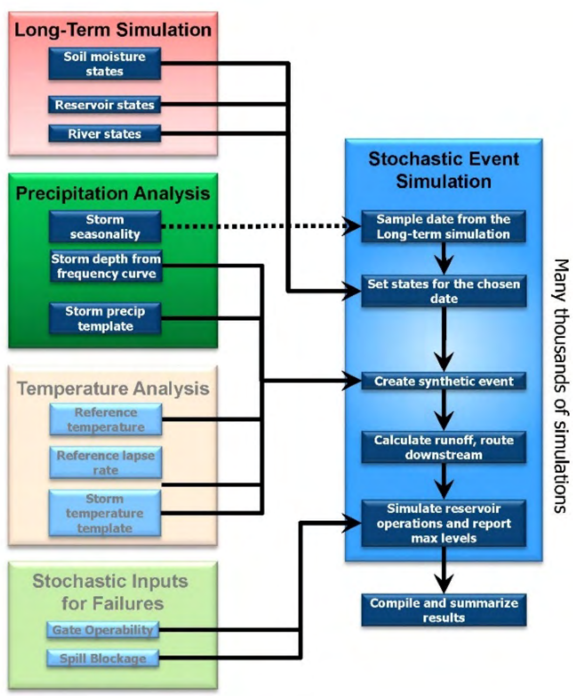
Stochastic Flood Simulation Summary

- Create realistic extreme storms
- Simulate watershed and reservoir system response
- Repeat thousands of times
- Compute statistics from results
- Basins with snow require temperature inputs for snow models
- Next fiscal year will incorporate gate failures for TVA



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MGS Engineering Stochastic Event Flood Model Varieties

SEFM Commercial

- All-in-one software package
- Multiple hydrologic models
  - UBC model
  - SAC-SMA/modified SAC-SMA
- Custom reservoir model with basic operations

SEFM Sampling Modules

- Standalone process executables
- Intended to embed in more complex applications
- Modules
  - Statistical pre-processor
  - Stochastic input time series generation
  - Statistical post-processor

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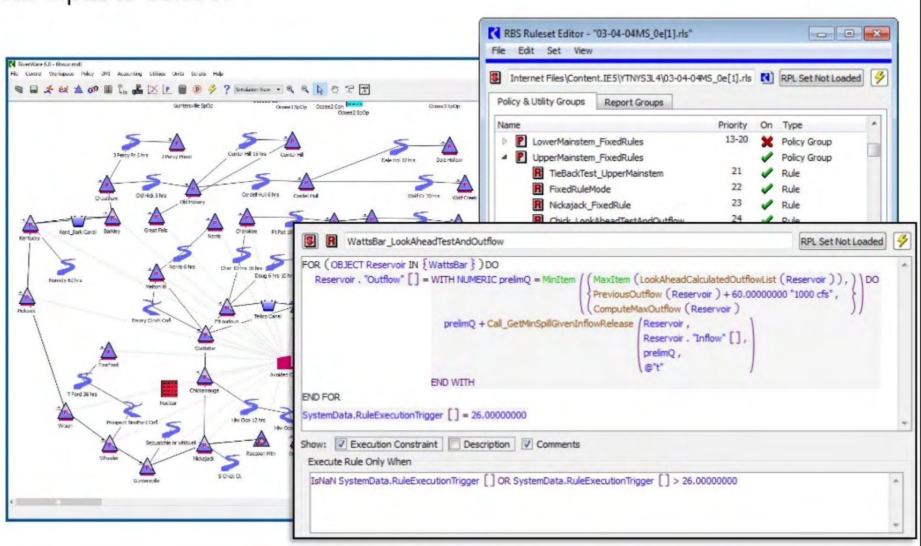
RiverWare Model

- Rule-based model represents operating policy during extreme events
- Allows complex operating rules
- Includes approximated inflow forecasts
- Capability to modify gate availability, outlet capacity
  - Use a scalar input to control



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TVA PFHA System

- Storm Transposition Tool
  - Produce representative storm templates
- Execution framework
  - Long-term, stochastic simulations
- Data management
  - 49 dams, 3 storm types, uncertainty
  - Summary statistics, time series
  - Configuration, inputs
- Analysis Tools
  - Hazards curve comparison
  - Assessment of influences on results
  - Drill-down capabilities

8

Unique Aspects of the TVA PFHA Calculations

- Precipitation-frequency assessed uniquely per storm type
  - Assess, combine hydrologic hazards from each type
- Statistical methods applied to produce 1000-year synthetic precipitation
  - Preserve spatial/temporal characteristics of events
  - More diverse combinations of events/reservoir conditions for stochastic events
- Intelligent sampling
  - Stratified sampling of precipitation
  - Convergence-based sampling with Neyman's optimal allocation to improve sampling efficiency
- Uncertainty limited to precipitation-frequency
  - Other projects consider additional sources

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TVA PFHA System: Current Work

- Improved data storage
  - Scenario input settings
  - Models at time of scenario execution
    - Hydrologic models
    - RiverWare models, rule sets
- Improved run management across multiple servers
- Improved performance for reporting tools
- Goal: better traceability of work

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TVA PFHA System Interface

- Model Controllers
  - Set up inputs for scenarios
  - Execute and monitor simulations
- Hazards Curve Explorer
  - Merge results from multiple storm types
  - Compare hydrologic hazard curves (e.g. different operating policies)
- Scenario Explorer
  - Understand drivers of hydrologic hazard curves
- Simulation Explorer
  - Review simulation-specific settings
  - View time series outputs for individual simulations

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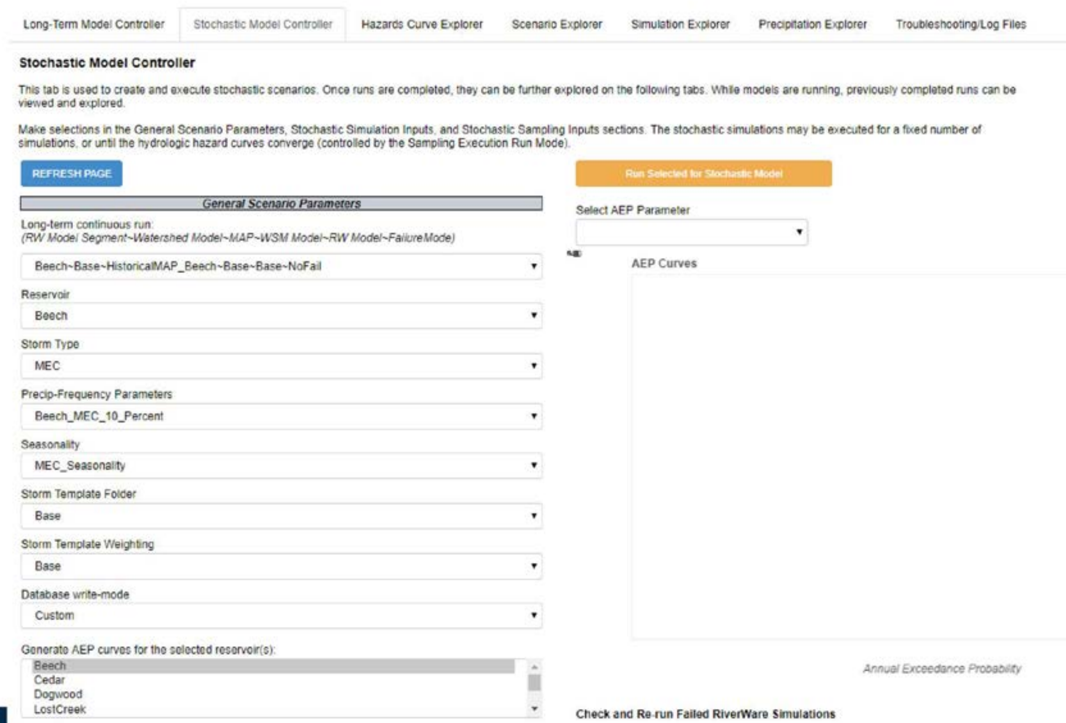
Model Controller



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Hazards Curve Explorer

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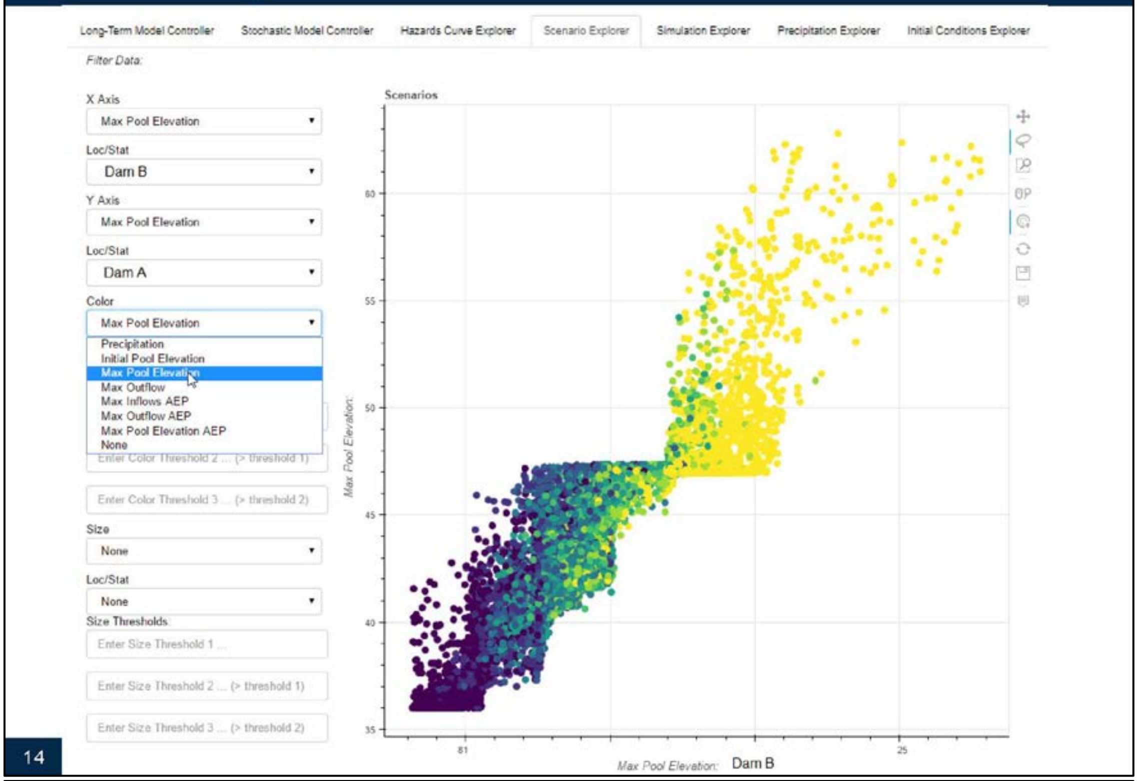
Scenario Explorer



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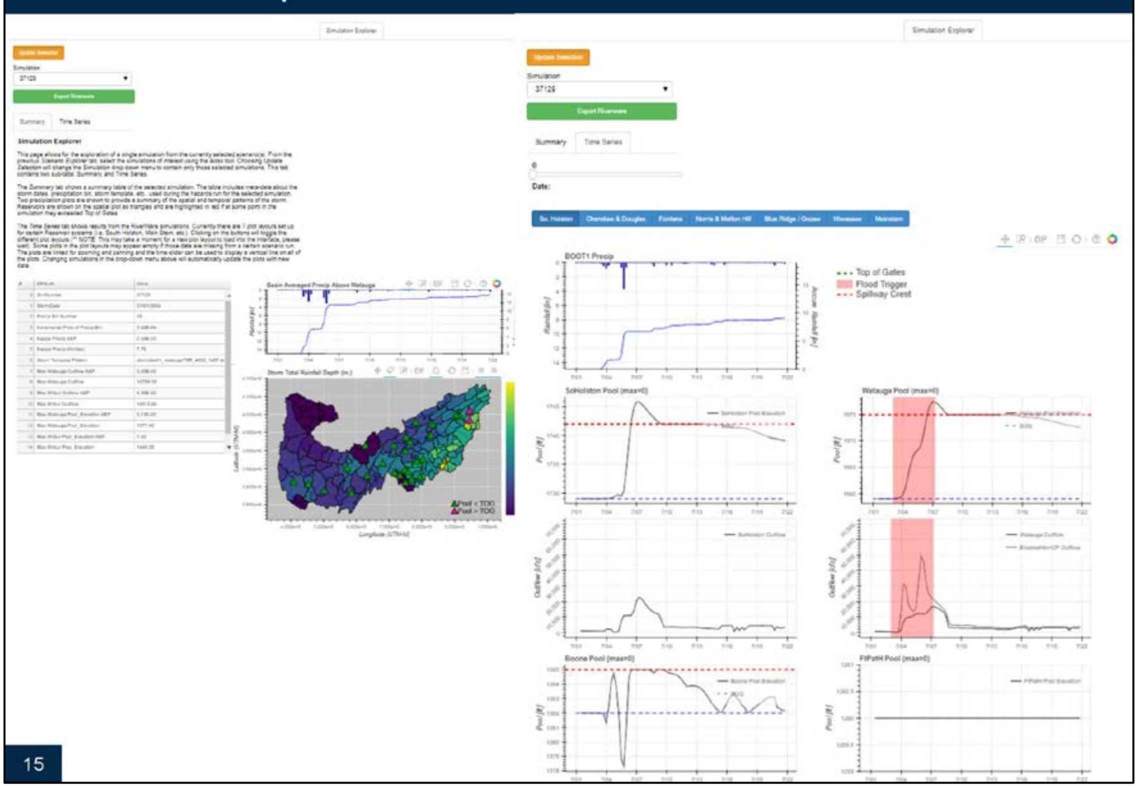
Simulation Explorer



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Analysis Applications

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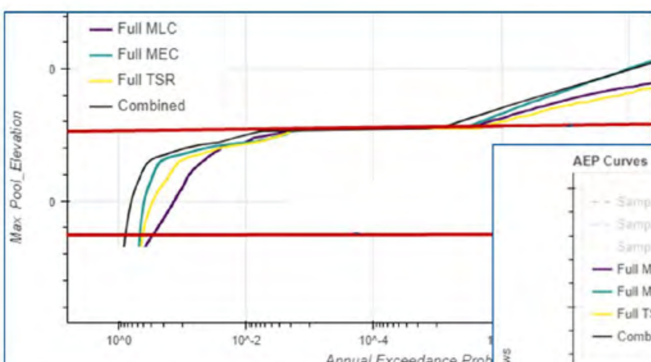
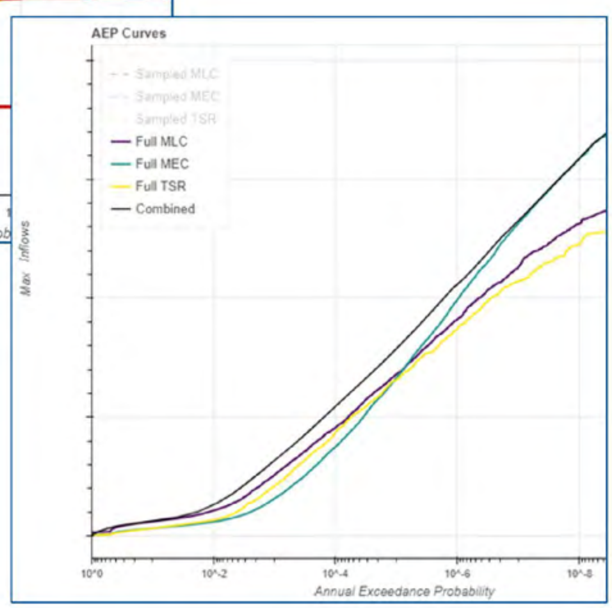
Influence of Different Storm Types





- Different storm types control for different AEP ranges

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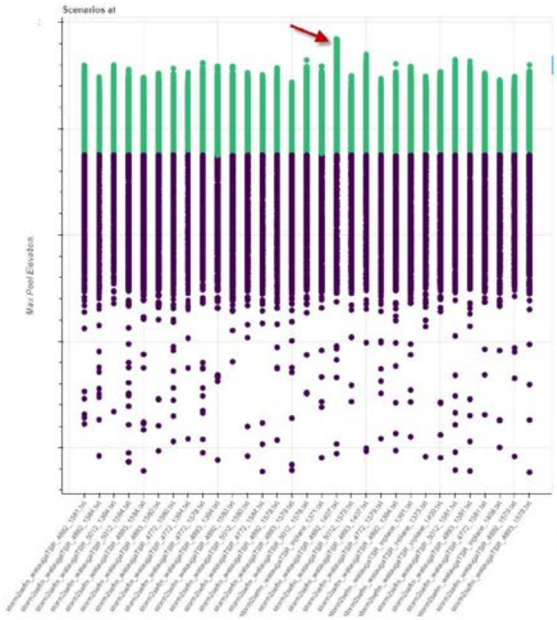
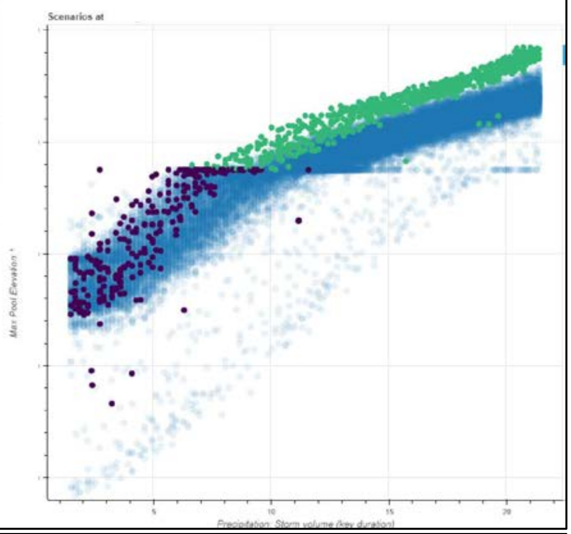
Influence of Storm Patterns



- Storm pattern can have a significant impact



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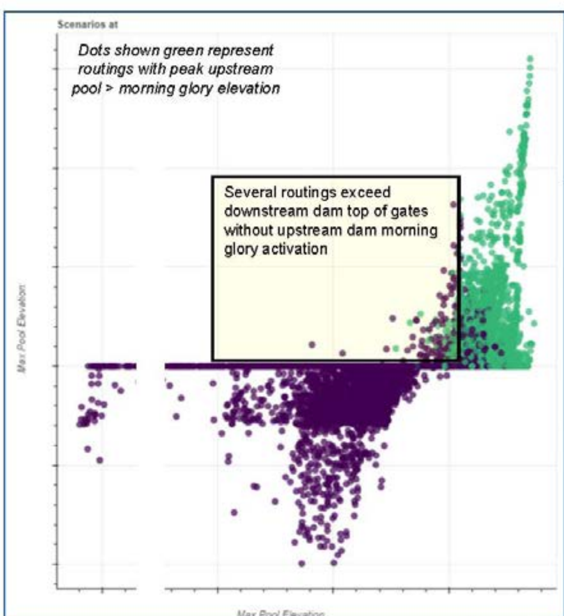
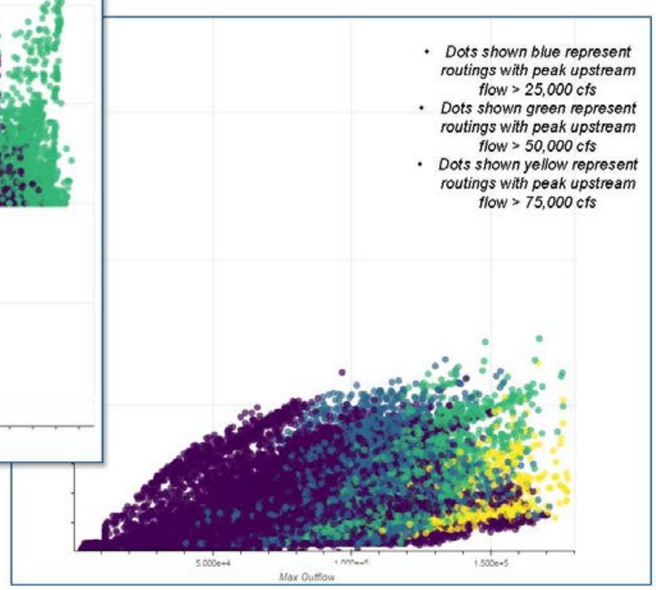
Influence of Other Reservoirs





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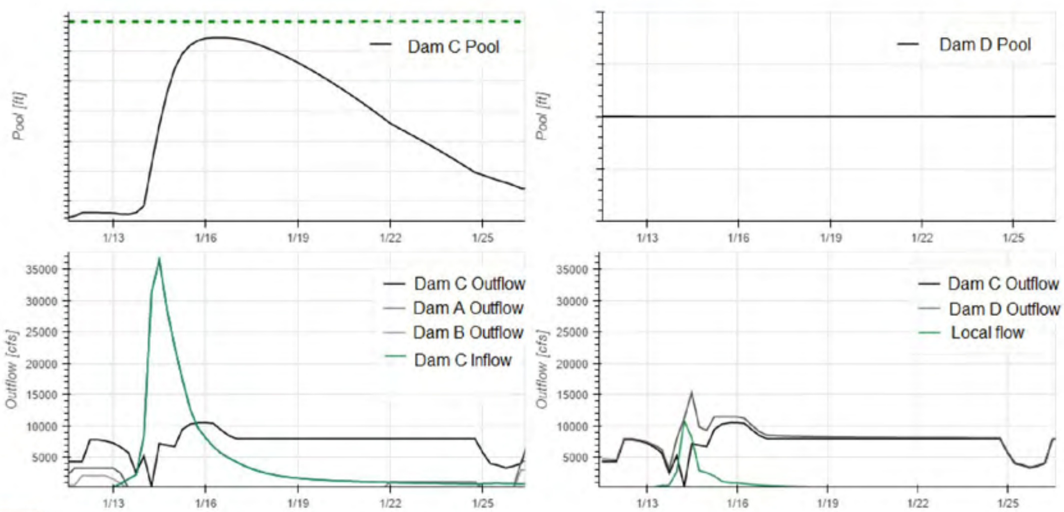
Compare Interim Risk Reduction Operating Policies

- Two different policy alternatives
  - Protect downstream
  - Keep headwater low

Protect downstream



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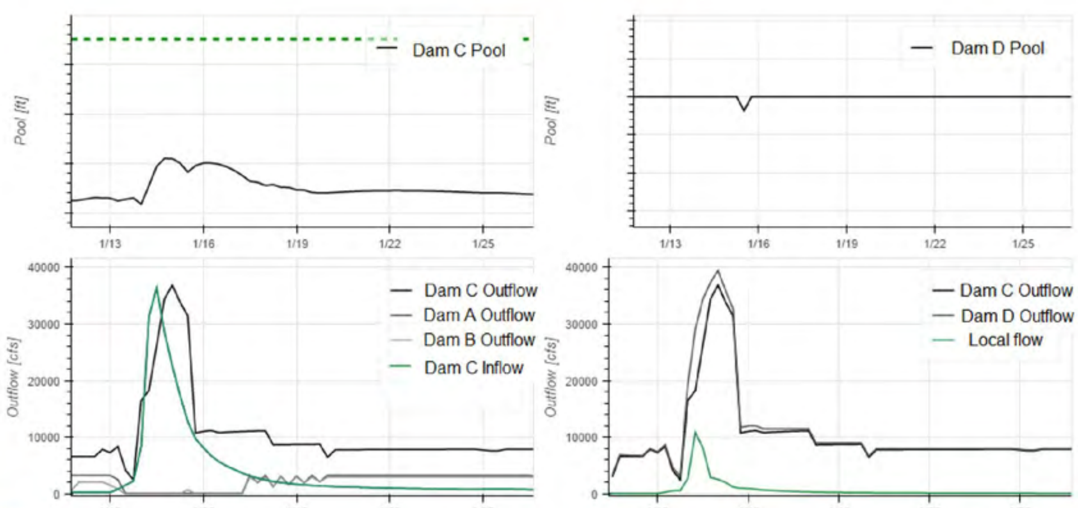
Compare Interim Risk Reduction Operating Policies

- Two different policy alternatives
  - Protect downstream
  - Keep headwater low

Keep headwater low



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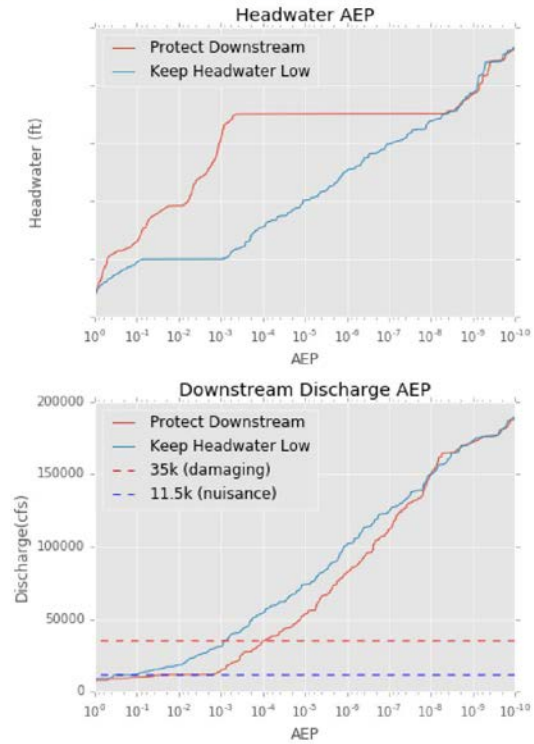
Compare Interim Risk Reduction Operating Policies

- Two different policy alternatives
  - Protect downstream
  - Keep headwater low



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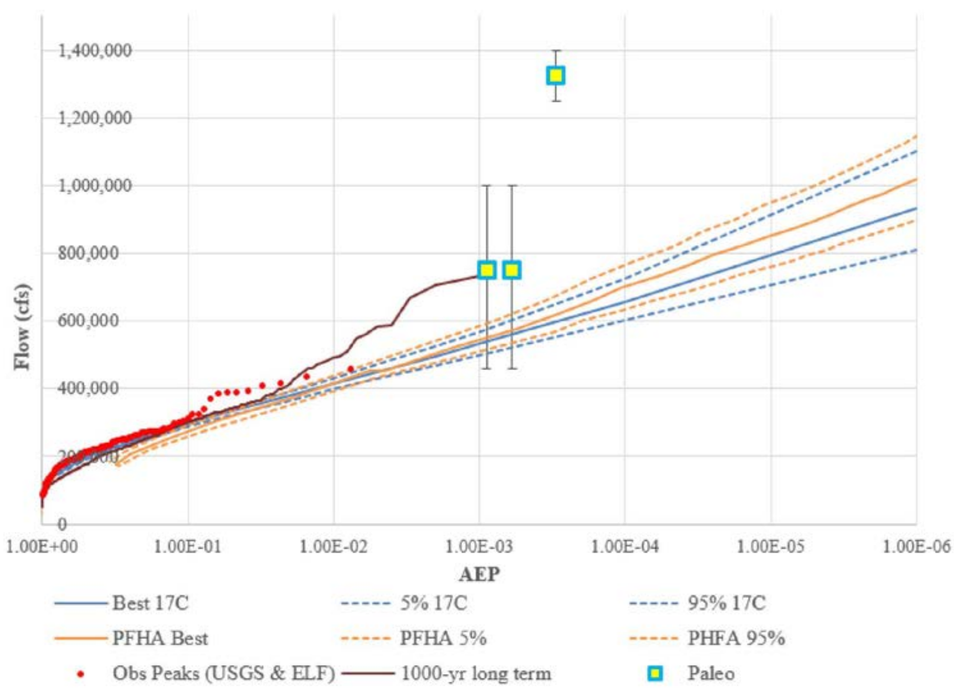
PFHA vs. Flow-Based with Paleo Flow Frequency



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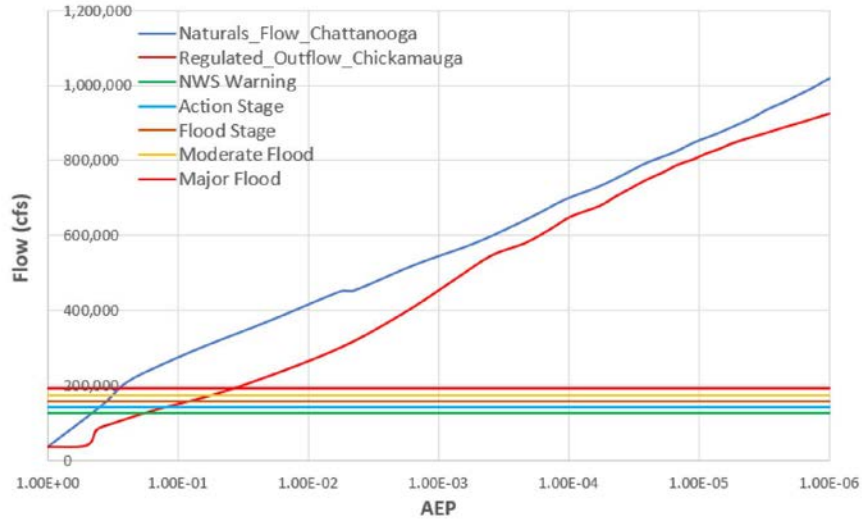
Regulated vs. Unregulated Flow Frequency



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More Information

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mgschaefer@mgsengr.com

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4.3.5.2.3 Questions and Answers

Question:

Slide 23 makes the case for SHAC-F because you've got two totally different results coming from totally different methods. What do you do as a decisionmaker?

Answer:

I think this is a real challenge. We are looking at streamflow-based and rainfall-based information; it is all historical. Then you get this crazy event from the paleoflood perspective. Ultimately, TVA needs to make decisions. This event is really high there, and that's a concern.

Question:

Are synthetic storms, characteristic storms, and storm templates referring to the same thing?

Answer:

I think so; they come from the work of Mel Schaefer and his team. They were looking at the precipitation frequency, so the volume of the storm event and the probability of that event. In addition to that you have the storm characteristics; if I get an 8-inch storm, does that storm hit mostly the lower watershed or the upper watershed and what's the timing of that? Those would be the storm templates. The synthetic storm takes the precipitation volume and scales the storm template up to that volume and then drops it in the historical record to generate the event.

Follow-up Question:

How is this done for something of the temporal distribution of the rainfall?

Answer:

For the storm template, what we have done is pick about 80 of the largest historical events that have happened over the watershed, or nearby, that are more extreme events. We take the pattern of that and transpose it to the watershed of interest. You have both the spatial pattern as well as the temporal pattern of how the storm moves across the watershed. So, it's essentially historical.

Question:

Inaudible.

Answer:

The hydrologic models are not failing. In this case, there are actually a number of failures because of our failure in the rule definition that there are unique cases we did not consider. This put the reservoirs into some odd places that the river model can't solve. We do track those. We are trying to get rid of those failures of the river model. In terms of accounting for those failures and how that impacts the hazard curve, you obviously do not want the failures. But we need to be sure that we are not saying every time that the peak goes above a certain level, then the model fails, and so we're safe. We've tried to account for that and make sure we aren't hitting those, and generally we're not. We're not accounting for them in the modeling otherwise.

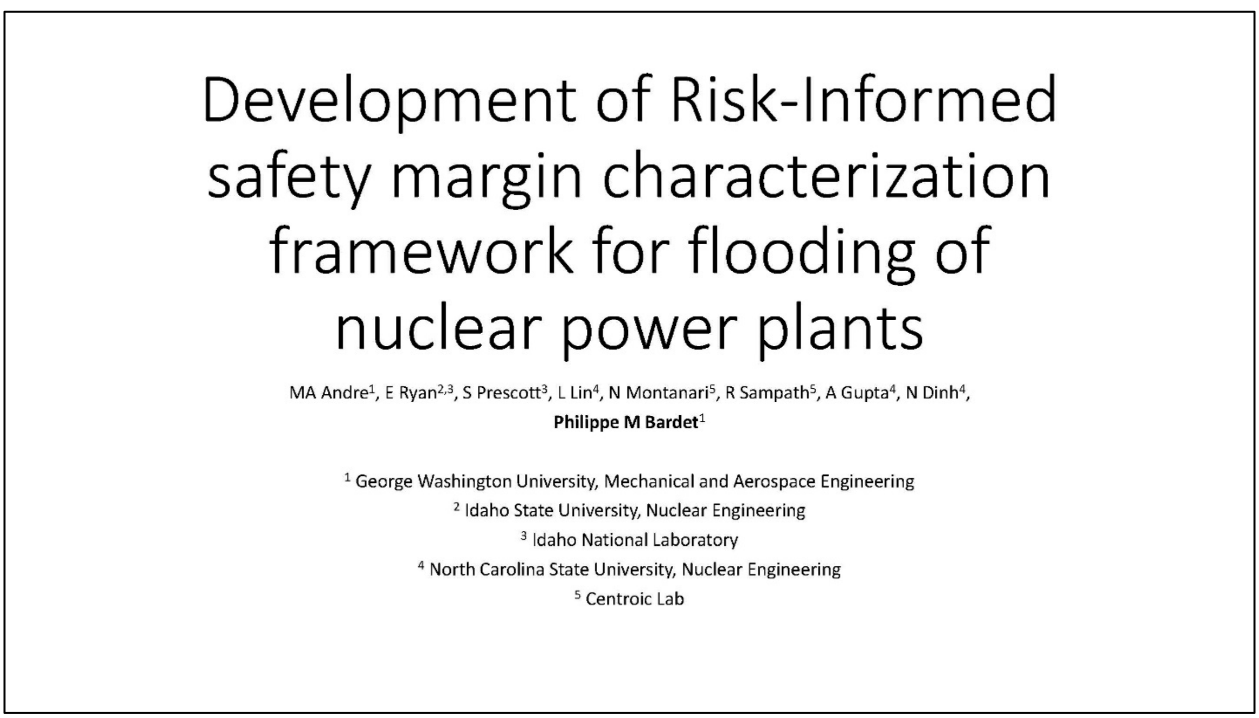
4.3.5.3 Development of Risk-Informed Safety Margin Characterization Framework for Flooding of Nuclear Power Plants.

M.A. Andre, George Washington University; E. Ryan, Idaho State University, Idaho National Laboratory; Steven Prescott, Idaho National Laboratory; N. Montanari, R. Sampath, Centroid Lab; L. Lin, A. Gupta, and N. Dinh, North Carolina State University; and Philippe M. Bardet*, George Washington University (Session 2B-3; ADAMS Accession No. ML19156A469)

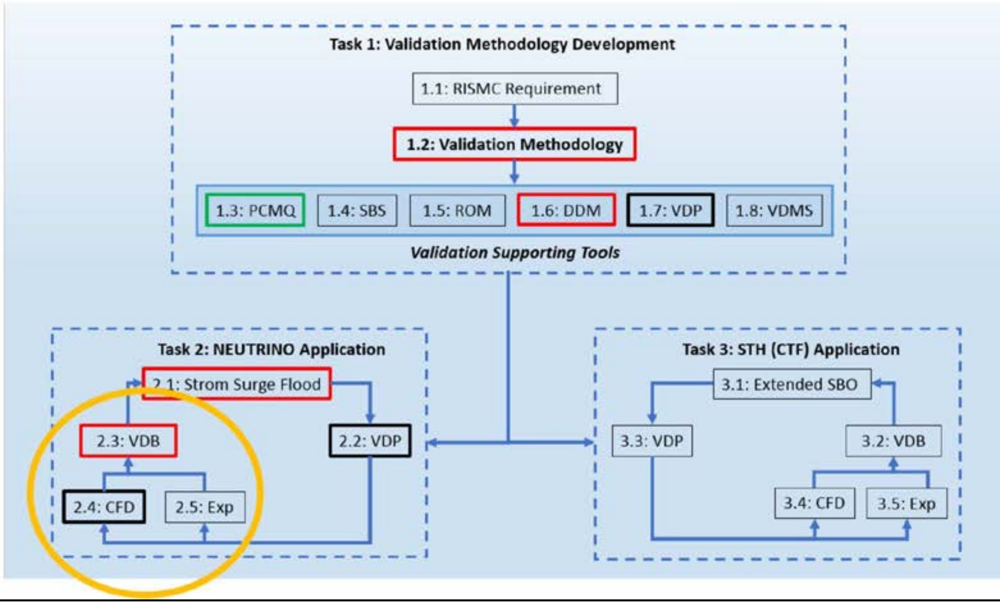
4.3.5.3.1 Abstract

There are six categories of external flooding (XF) listed by the NRC's external flooding documentation Because of site specificities, NPPs have different concerns for flooding. Some flooding mitigation methods, such as temporary or permanent flood walls to guard against storm surge or stream and river flooding, have high uncertainties on their effectiveness due to conditions such as debris and wave overtopping. Thus, flood mitigation systems would benefit from validated Risk-Informed Safety Margin Characterization (RISMC) methodologies. Hence, a computationally efficient and flexible 3-D finite structure interaction, smoothed-particle hydrodynamics (SPH) code, NEUTRINO, is being validated in this context with existing (published) datasets as well as with a dedicated experimental facility. The experimental facility is a large sloshing tank (6 meters x 2.4 meters x 1.2 meters), where a variety of scenarios can be tested. Large impact forces can be generated in a controllable and repeatable manner, and a broad range of diagnostics can be deployed. The code and facility will be presented as well as the organization and collaboration of the numerical and experimental teams, who are closely working to define the experimental and numerical campaigns to validate NEUTRINO and its use in RISMC. Additionally, this work is being used to demonstrate an uncertainty propagation methodology when using multiple sources of data.

4.3.5.3.2 Presentation

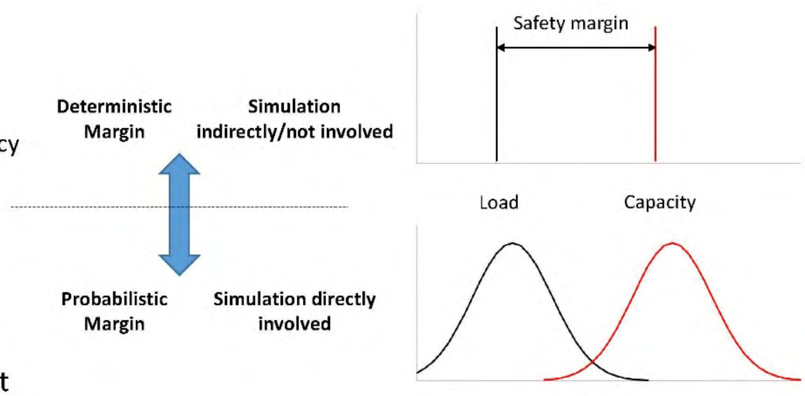


DOE – IRP project overview

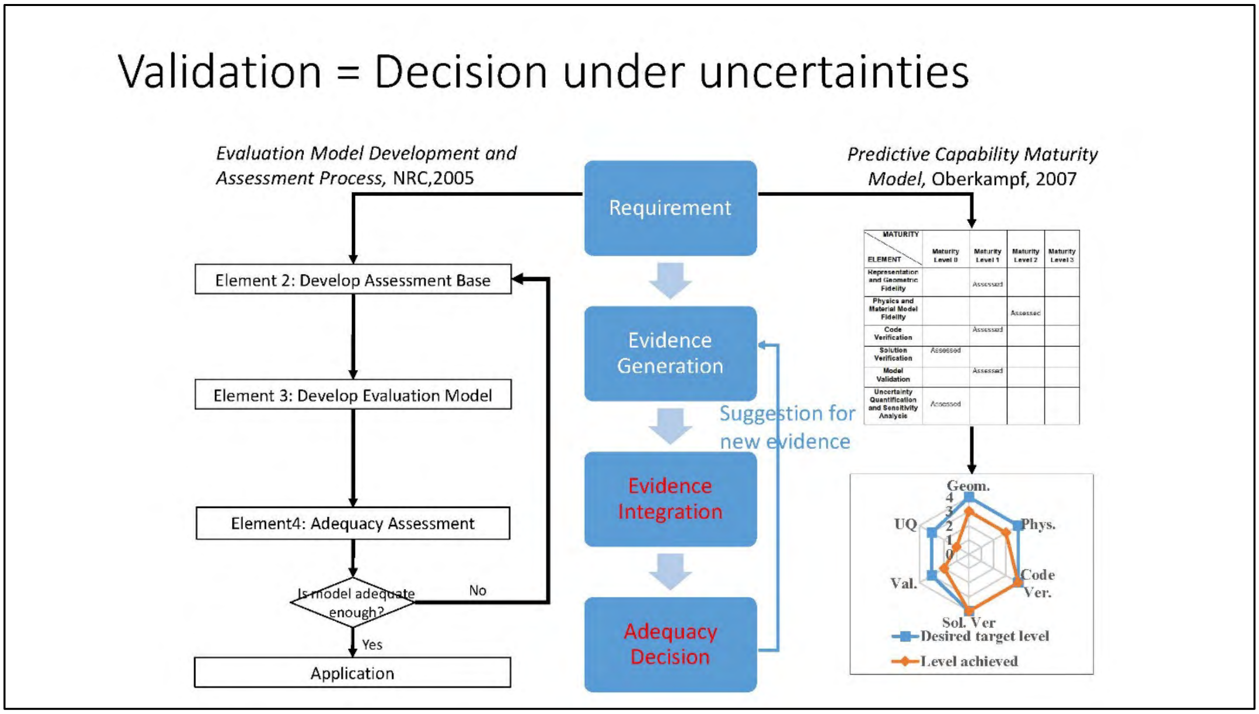


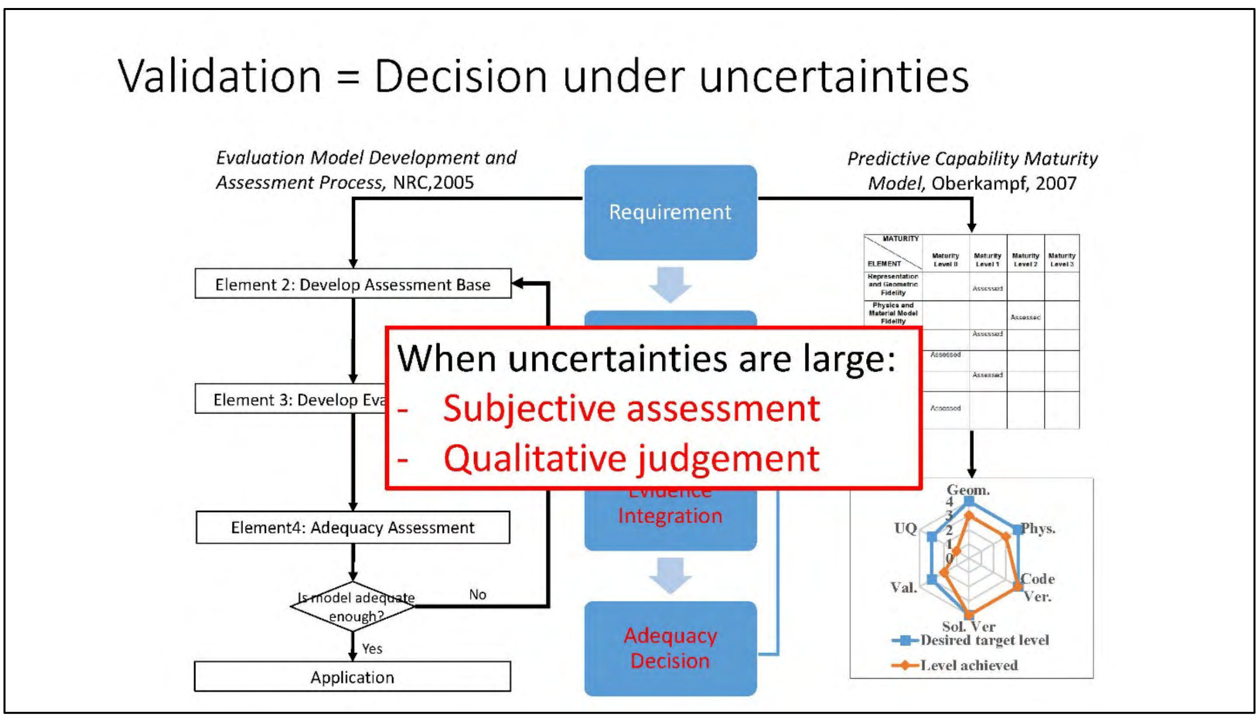
Risk Informed Safety Margin Characterization - RISMC

- Well-Established PRA
  - Statistical analysis
    - Estimate initiating frequency
    - Core damage frequency
- Risk-Informed Safety Margins Characterization
  - Use multi-physics, 3D + t simulations
  - Dynamically monitor event initiation and progression
    - More comprehensive/detailed descriptions
    - More effective and informative for risk management and mitigation purposes
  - Core damage frequency



- How to assess credibility of simulation?
- How does it affect the safety decision?


Validation = Decision under uncertainties
Evaluation Model Development and Assessment Process, NRC,2005
Predictive Capability Maturity Model, Oberkampf, 2007
Requirement
Evidence Generation
Evidence Integration
Adequacy Decision
Suggestion for new evidence
Element 2: Develop Assessment Base
Element 3: Develop Evaluation Model
Element4: Adequacy Assessment
Is model adequate enough?
No
Yes
Application
Geom.
Phys.
Code Ver.
Sol. Ver
Val.
UQ
Desired target level
Level achieved

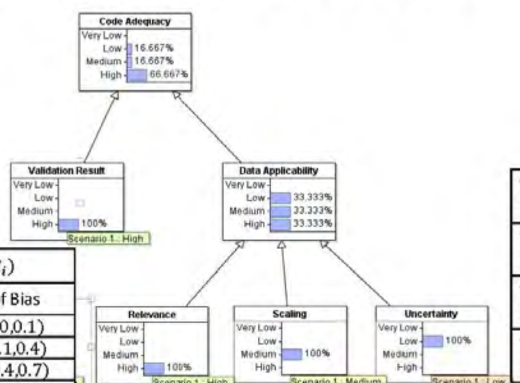

Validation = Decision under uncertainties
Evaluation Model Development and Assessment Process, NRC,2005
Predictive Capability Maturity Model, Oberkampf, 2007
Requirement
Integration
Adequacy Decision
Element 2: Develop Assessment Base
Element 3: Develop Eva
Element4: Adequacy Assessment
Is model adequate enough?
No
Yes
Application
When uncertainties are large:
- Subjective assessment
- Qualitative judgement
Geom.
Phys.
Code Ver.
Sol. Ver
Val.
UQ
Desired target level
Level achieved

Predictive Capability Maturity Quantification by Bayesian Net - PCMQBN

- Motivation
  1. How to formalize and evaluate the subjective component of validation?
     - Subjective assessment
       - Scaling: sufficiency and relevancy of database
       - Physical processes involved
     - Qualitative judgement
       - Model adequacy
  2. How to adapt validation goals/requirements to risk-informed concept?
     - Uncertain scenario
     - Decision-dependent safety goal

- How to make convincing adequacy decision under large uncertainties?
  - Transparent
  - Robust
  - Consistent

Predictive Capability Maturity Quantification by Bayesian Net - PCMQBN



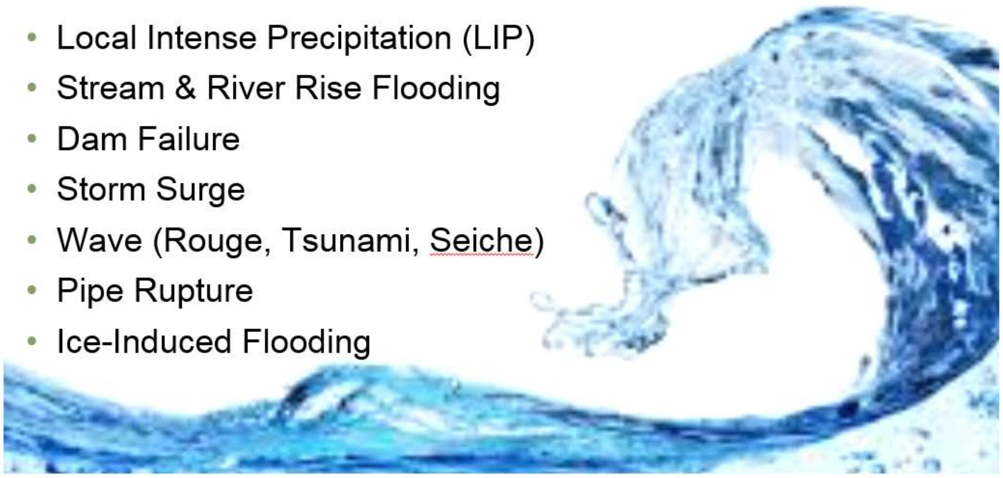
Validation results ($\boldsymbol{VR_i}$)	
Descriptor (i)	Range of Bias
VL	$VR_{VL} \in [0,0.1)$
L	$VR_L \in [0.1,0.4)$
M	$VR_M \in [0.4,0.7)$
H	$VR_H \in [0.7,1]$

Type I data (grade <U> = 1)	Potentially large bias
Type II data (grade <U> = 2)	Single point measurements without uncertainty information
Type III data (grade <U> = 3)	Single uncertainty information (experiments or simulations)
Type IV data (grade <U> = 4)	Both the model prediction and the high-fidelity data has uncertainty information

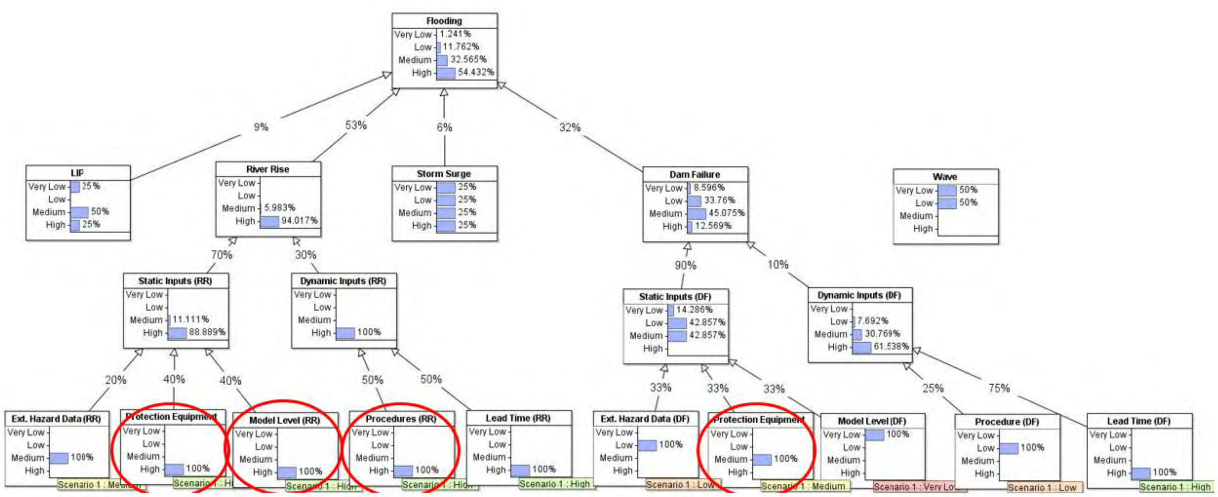
Channel Flow Reynolds number		
Sufficient	Validation database	Application
	$10^5 \sim 10^9$	4×10^6
Insufficient		1×10^4

Flooding scenarios

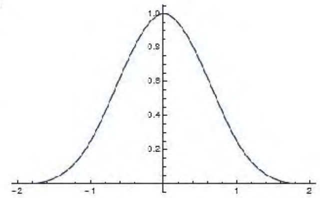
- Local Intense Precipitation (LIP)
- Stream & River Rise Flooding
- Dam Failure
- Storm Surge
- Wave (Rouge, Tsunami, Seiche)
- Pipe Rupture
- Ice-Induced Flooding



RISMC Simulations Confidence Increase



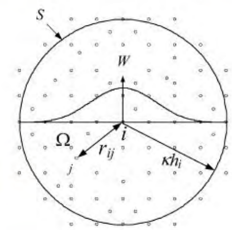
Smoothed Particle Hydrodynamics



- Initially developed by Monaghan in 1977, Smoothed Particle Hydrodynamics method is a computational method for simulating the mechanics of continuum media

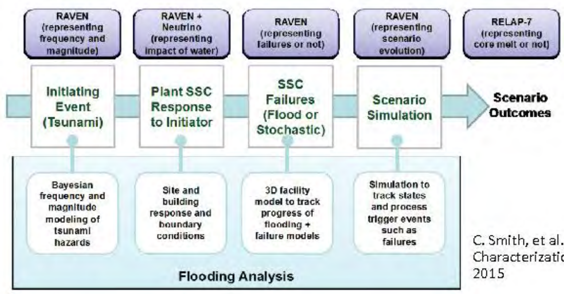
$$f(\vec{r}) = \int f(\vec{r}')W(\vec{r}-\vec{r}',h)d\vec{r}' = \sum_b f(\vec{r}_b)W(\vec{r}-\vec{r}_b,h)\Delta V_b = \sum_b \frac{m_b}{\rho_b} f(\vec{r}_b)W(\vec{r}-\vec{r}_b,h)$$

Smoothing   Discretized   Particle Approximation



- As a mesh-free method, SPH is found to be capable of dealing with complex boundary and interface. It's also found to be naturally conserved and easily parallelizable.

- SPH has been applied in the RISMC analysis as the simulation tool for external floods



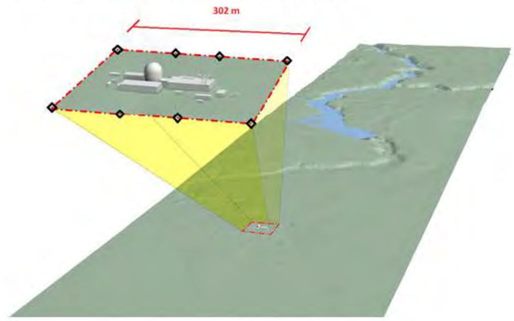
C. Smith, et al., "Risk-Informed Safety Margin Characterization (RISMC) Path Technical Program Plan", 2015

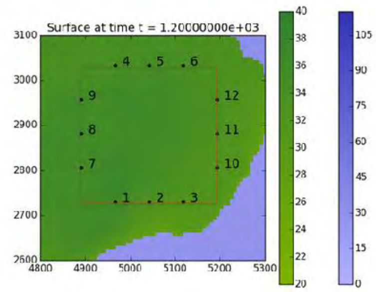
NEUTRINO – SPH code

- Neutrino's Boundary Implicit Incompressible SPH Solver
  - Rest Density based formulation of Incompressibility
  - Iterative Pressure Solver
  - Hydrostatic/Hydrodynamic Coupled Simulation
  - Rigid/Fluid Coupling
- Requirements for flooding
  - Deal with Complex Geometry
  - Robust
  - Fast Realization of Simulations
  - Tracking Interfaces
    - Free Surface (For Measuring Fluid Height)
    - Fluid-Structure. (Computing Forces/Pressure etc)
  - Verification & Validation
  - Ability to couple with PRA Simulations

NEUTRINO – case study: Dam Break

- Couple SPH to shallow water model (GeoClaw)
- Shallow Water model for dam break until region of interest
  - Solve the Navier-Stokes equations with SPH – Flow Structure
  - Couple Domains - In/out flow boundaries
    - Horizontal velocity components + Height.





NEUTRINO – case study: Dam Break

Requirements for Validation Data for Safety Margin Analysis

1. Need data that complement existing validation studies
   - Literature review
2. Need data with high statistical significance
   - Highly repeatable measurements with well characterized boundary condition and initial values
3. Need high quality data with quantified uncertainty

VUQ Quality	Grade			
	4	3	2	1
Relevance [R]	Very High (direct)	High	Medium	Low
Scaling [S]	Prototypic (full-scale)	Adequately scaled	Medium	Inadequately scaled (large distortions)
Uncertainty [U]	Well-Characterized	Characterized	Medium	Poorly-Characterized

Flexible experiment to address specific needs as they are identified

Large scale experiment (can also be adapted for smaller scale tests)
Scaling parameters can also be used (e.g. Froude number)

Measurements performed by trained experimentalists

Quantities of interest

Event Confidence - Scenario Dependent
(high impact scenarios)

	Pressure/Impulse	Duration	Max Height / Splash	Velocity	Turbulence
Door Failure	High	-	-	-	-
Barrier Over-Top	-	High	Med	Med	-
Barrier Failure	High	*Low	-	-	*Med
Penetration	-	High	-	High	-
Exhaust Vent	-	-	High	-	-
Ducting	High	-	-	-	-
Debris Impact	-	-	Low	High	Med

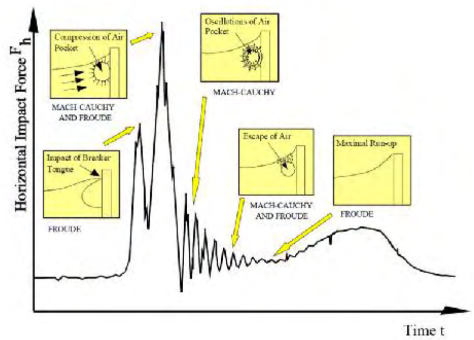
"*" Type Dependent

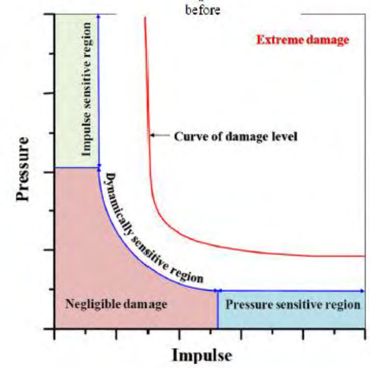
(Example - needs to be developed and approved by a standards committee/NRC)

Quantities of interest

- First phase focuses on wave impacts
- Pressure ~ Force ~ Structural damage
- Also Impulse

$$P(\mathbf{x}) = \int_{\text{before}}^{\text{after}} p(\mathbf{x}, t)\,dt$$





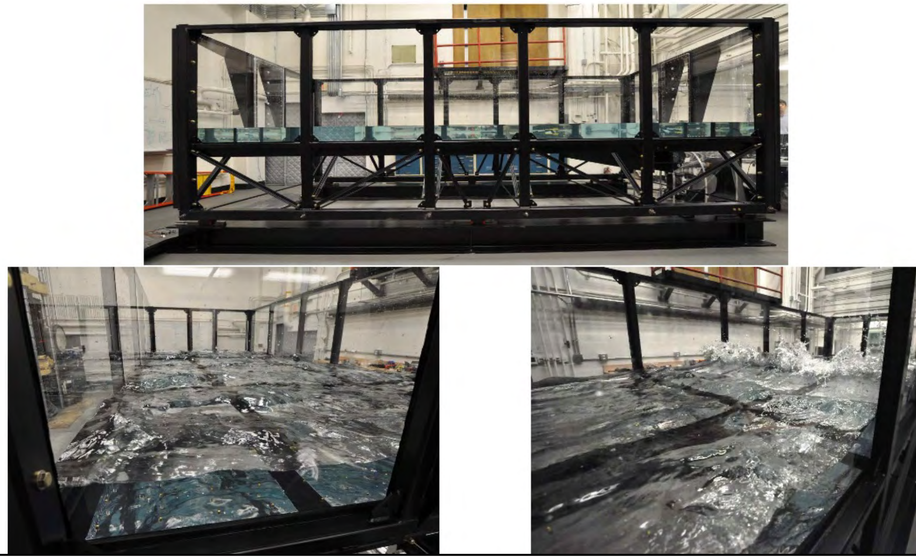
In-house design

<u>By doing the design in-house, and already having access to some of the infrastructure, a large scale facility has been built at modest cost</u>

- Location
  - GWU Tompkins Hall: In a former civil engineering lab, equipped with a strong floor and hydraulic controllers
- Tank
  - 20’ x 8’ x 4’ (6m x 2.4m x 1.2m) L x W x H
  - 10 tons (10 m^3) of water
  - Structural steel frame with acrylic walls
- Forcing
  - Up to 10” (25 cm) amplitude
  - Up to 20”/s (0.5 m/s) velocity
  - Up to 0.5g (5 m/s^2)
  - 22 kips Hydraulic actuator, linear bearings on precision rails

Construction of the facility

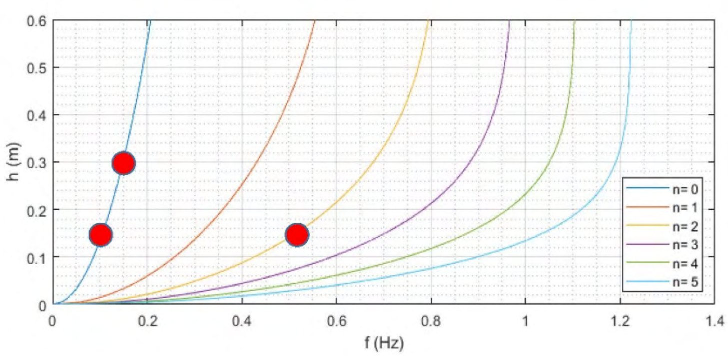
Facility now completed



Shakedown Tests

2D Wave natural frequency

$$f = \sqrt{\frac{(2n+1)g}{4\pi L}\tanh\left(\frac{(2n+1)\pi h}{L}\right)}$$



Shakedown TEsts

6” depth, 4” 0.49 Hz forcing (3rd mode)

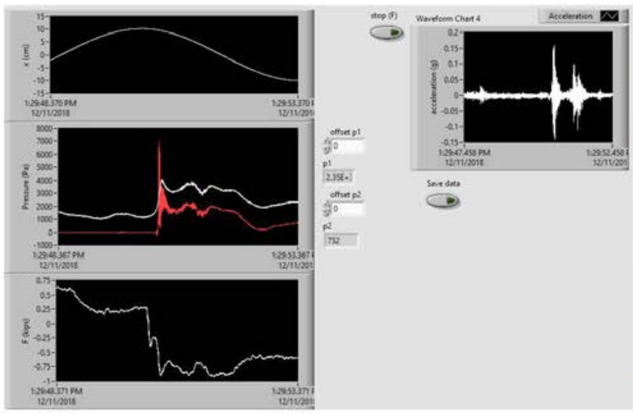
Shakedown TEsts

12” depth, 4” 0.155 Hz forcing (1st mode)

Instrumentation

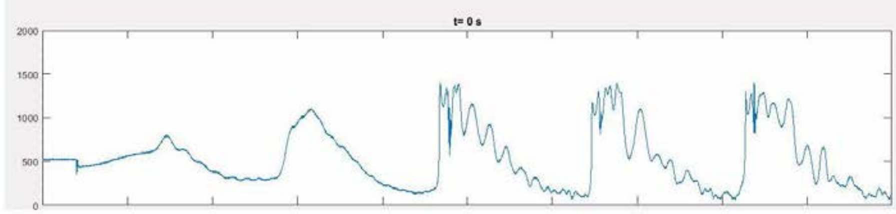
Pressure probes (end wall center, z=4 and 10")
Accelerometer
Forcing data
NI DAQ (2 kHz acquisition)

ε=35 Pa
f_c=1 kHz



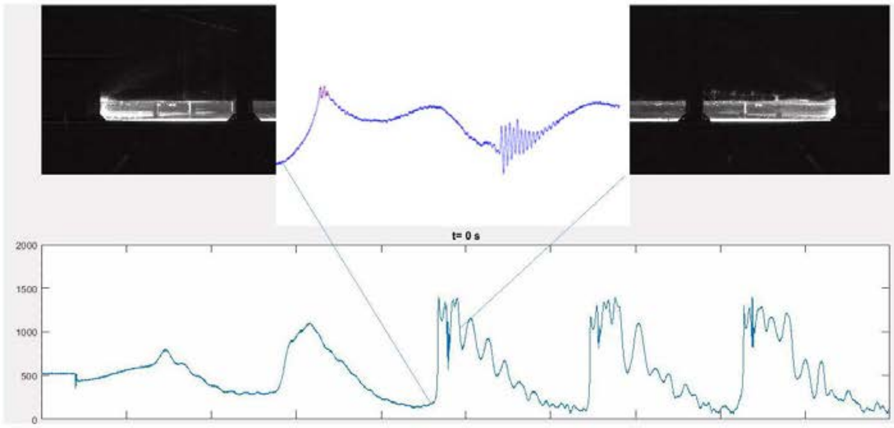
First test case:

6" depth, 4" 0.11 Hz forcing (1st mode)
Pressure measurement at end wall



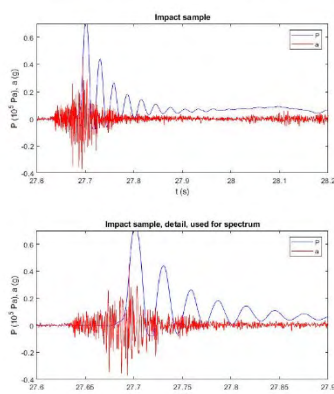
First test case:

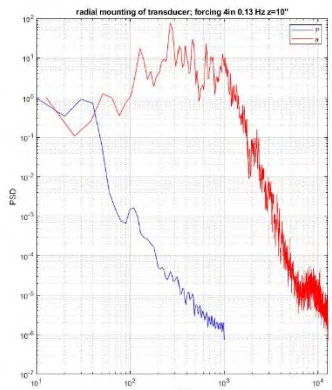
6" depth, 4" 0.11 Hz forcing (1st mode)
Pressure measurement at end wall



Check panels vibrations

Pressure signal shows high frequency during impact.
Could be bubble oscillations, but need to rule out acrylic vibrations



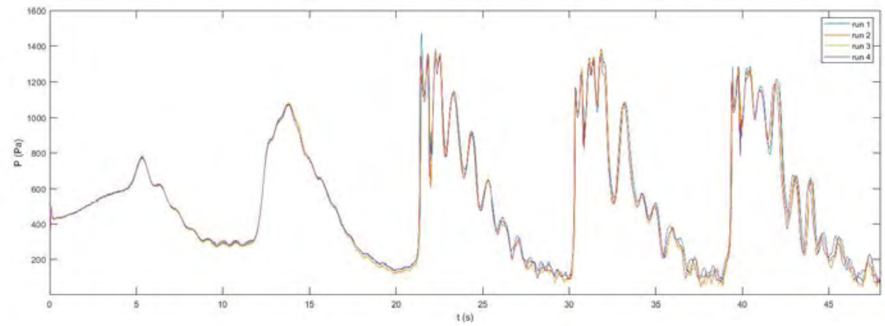


Pressure oscillation not linked to panel vibration
Likely due to bubbles (not modeled in Neutrino)

First test case:

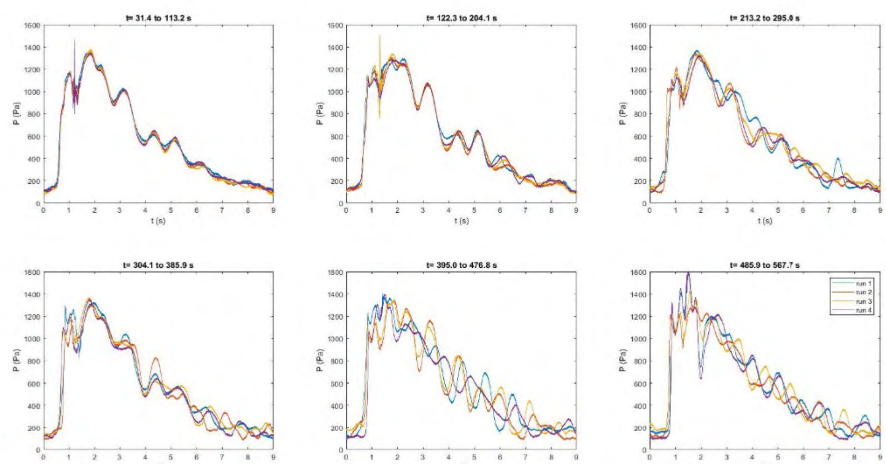
6” depth, 4” 0.11 Hz forcing (1st mode)
Assessment of repeatability

Run	h (mm)	f (Hz)	A (mm)	Comments
1	152.4	0.11	101.6	Reference run
2	152.4	0.11	101.6	Identical to Run 1
3	152.4	0.11	102.108	Change of the forcing amplitude by 1%
4	153.4	0.11	101.6	Change of the water depth by 1 mm



First test case:

6” depth, 4” 0.11 Hz forcing (1st mode)
Assessment of repeatability

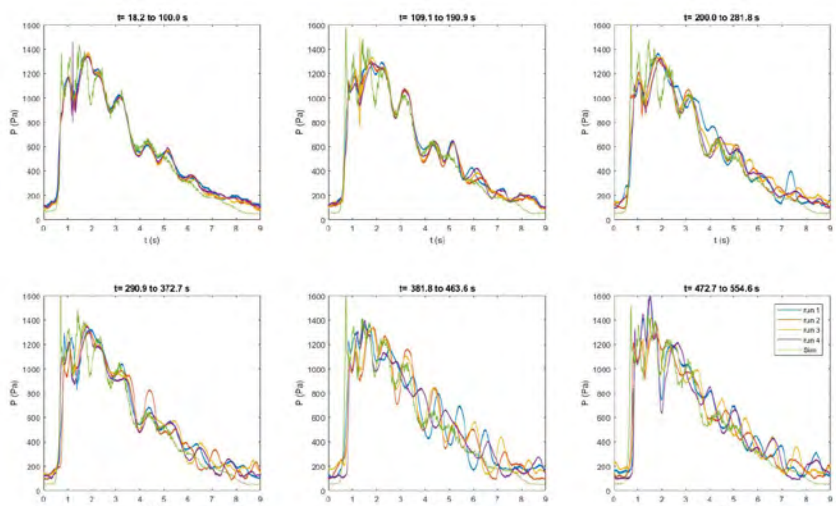


Sloshing Tanks

- Simulation has been performed by Emerald Ryan in Idaho State University
- Simulation Tank width is less than the real facility (0.2m compared to 2.4m)
- Particle size is 0.0125m and the results are acceptable.
- Simulation takes around 10 hours for 30 cycles, and the output frequency is 50Hz

Sloshing Tank

- SPH predicted pressure force are compared against the measurements
- Hard to visualize the quality of SPH predictions, especially when the pressure fluctuations are large
- It's suggested that sophisticated validation metrics should be used for better characterizing the credibility of SPH methods in predicting the sloshing tank phenomenon



Sloshing Tank

- Root mean square error

$$(L_2)_m = \sqrt{\frac{1}{N}\sum_{i=1}^{N}((\bar{P}_i)_m - (\bar{D}_i)_m)^2}$$

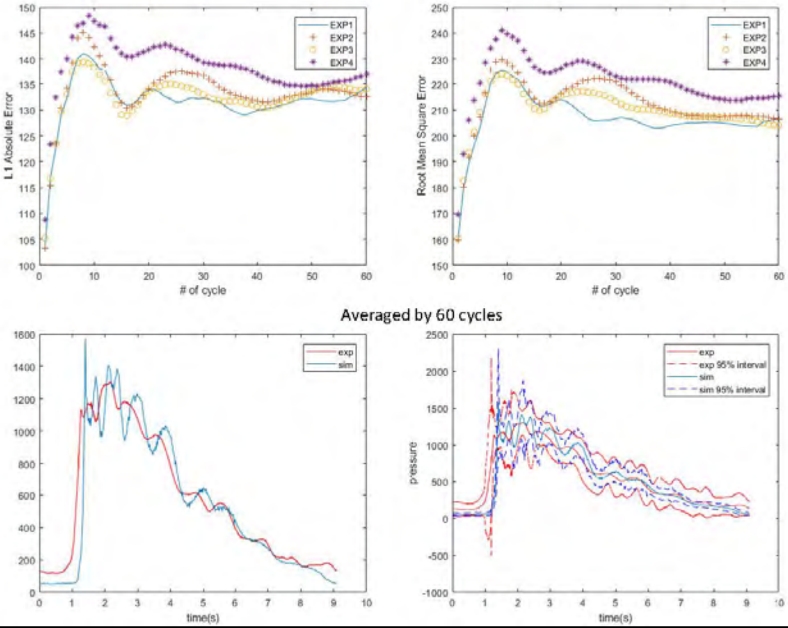
- Absolute Error

$$(L_1)_m = \frac{1}{N}\sum_{i=1}^{N}|(\bar{P}_i)_m - (\bar{D}_i)_m|$$

- Confidence Interval

$$P_{i,m} = \mathbb{N}((\bar{P}_i)_m, \mu_m)$$

- Simulation errors are bounded after 20 cycles
- Absolute distance metrics serve the purpose quite well
- The EXP data band covers the SIM data band, observed phenomena (turbulence, void) are not captured by NEUTRINO simulation



Sloshing Tank

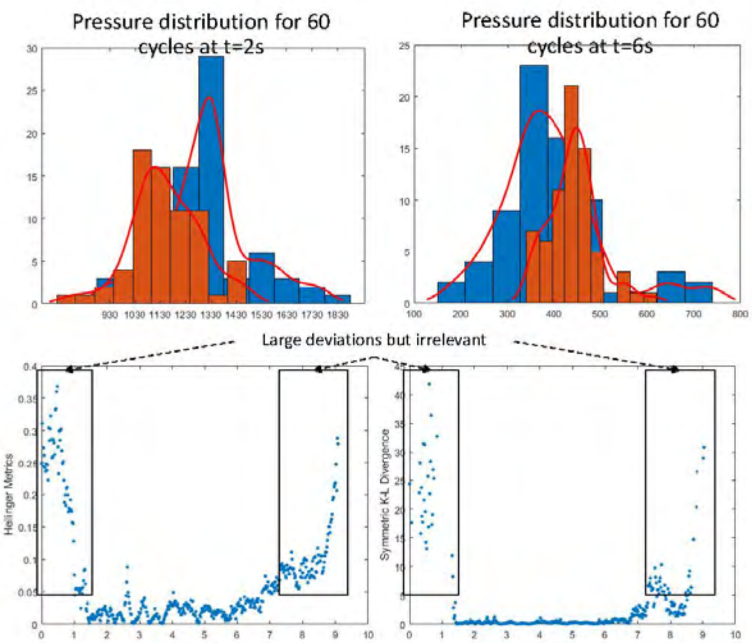
- Probability distributions for both simulation $PDF(P_i)$ and measurement distributions $PDF(D_i)$
- Fit the distribution to Kernel Density Estimation (multi-variant distributions)

$$PDF(P_i) = \frac{1}{Nh_1h_2 \dots h_d}\sum_{i=1}^{N}\prod_{j=1}^{d}k(\frac{x_j - y_{ij}}{h_j})$$

- K-L Divergence and Hellinger metrics for measuring the "similarity" of two distributions

$$D_{KL}(P,D) = \sum_i P(i)\log\left(\frac{P(i)}{D(i)}\right) + D(i)\log\left(\frac{D(i)}{P(i)}\right)$$

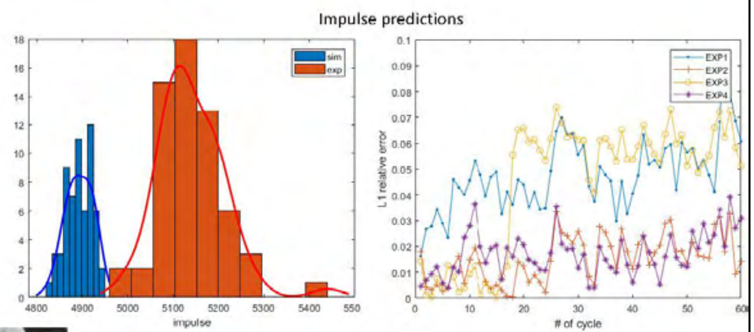
- Ranges with less similarity are found

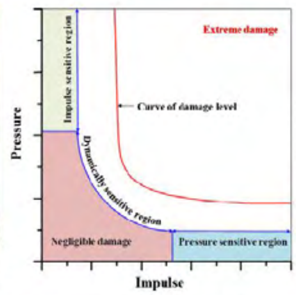


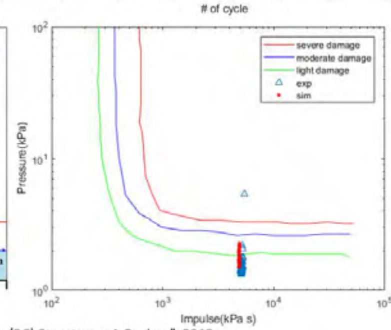
Sloshing Tank

- NEUTRINO has better predictions for impulse than pressure
- P-I curve suggests the limiting surface of SSC structures
- Incorporate model adequacy results into the P-I curve

Damage Level	NEUTRINO	EXP
No	44/60	57/60
Light	16/60	2/60
Moderate	0/60	0/60
Severe	0/60	1/60





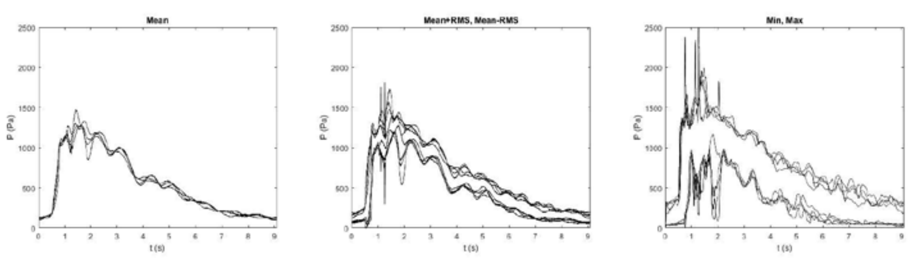


M. Abedini, etc., "Pressure-Impulse (P-I) Diagrams for Reinforced Concrete (RC) Structures: A Review", 2018

First test case:

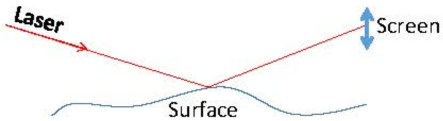
Two ways of comparing experiment and simulations:

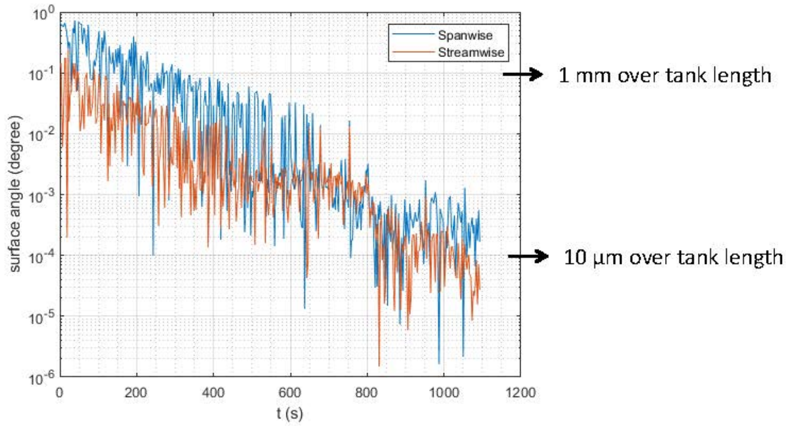
1. Exact temporal evolution of pressure
   a) Useful for single event (tsunami)
   b) Cannot be applied past ~10 cycles (random and chaotic flow)
2. Statistical approach (phase averaged pressure)
   a) Provide better estimation of the accuracy of simulation
   b) Can be used for Bayesian analysis
   c) Computationally more expensive



INSTRUMENTATION development

- Laser-based slope measurement for initial flow conditions

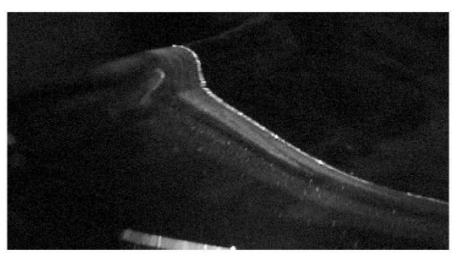




INSTRUMENTATION development

- High Speed stereo-imaging

Wave impact, bubble formation, detailed profilometry

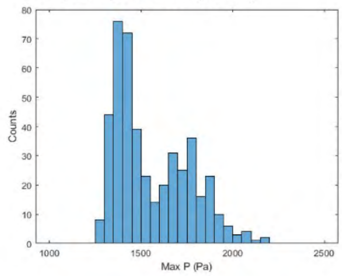


Scaling analysis

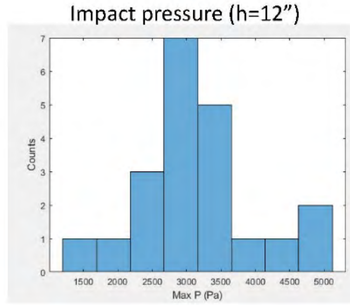
- Scaling with water depth

$$P^* = \frac{P}{\frac{1}{2}\rho V^2} \qquad V = c = \sqrt{gh} \qquad P^* = \frac{P}{\frac{1}{2}\rho g h}$$

Impact pressure (h=6")

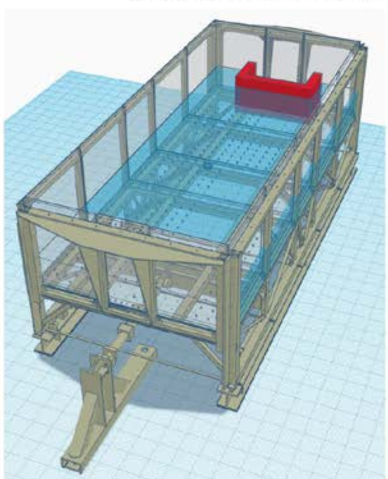


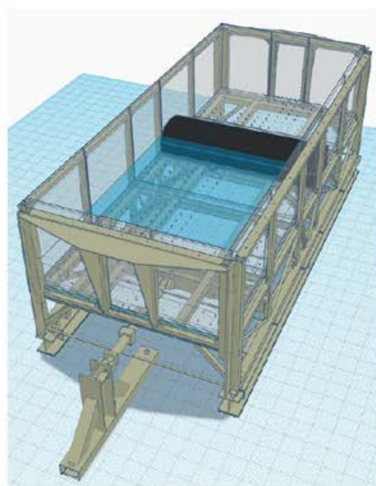
Impact pressure (h=12")



Future tests

- Many types of structures can be mounted to the tank:
  - Dike, barriers, building models





4.3.5.3.3 Questions and Answers

Question:

Will the modeling results be used to assess flood protection assessments and guidance? I think the U.S. Department of Energy (DOE) is funding you in part to look at that issue of flood protection.

Answer:

I did not mention the latest results we have on assessing the scalability of the code because we are simulating small-scale experiments in the lab and the barriers are going to be on a smaller scale. How do we scale that up? We have a significant effort with Perdue University on understanding the scalability of the experiments in the code. As a caveat, the project is ending in September, so time is short. We are also deploying some of the diagnostics in which we are exploring the velocity and pressure inside the liquid.

Question:

Who is collaborating with you on the experimental design and testing of the model and the physical model?

Answer:

The people doing the simulation all know what to do. We do the simulations ourselves as well. This is all done by one postdoc in my lab. We design everything from scratch ourselves. We are, first and foremost, engineers. We like to do new things. Now we have lasers and cameras moving with the tanks. We have a million dollars' worth of cameras starting to shake with the tank and so far, we didn't break anything. We're going to try to keep it this way.

4.3.5.4 Modeling Frameworks Panel Discussion. (Session 2B-4)

Moderator: Thomas Nicholson, NRC/RES/DRA

Rajiv Prasad, Pacific Northwest National Laboratory
Shaun Carney, RTI International
Philippe M. Bardet, George Washington University
Guest Panelist: Will Lehman, USACE/IWR, Hydrologic Engineering Center
Guest Panelist: Joseph Kanney, NRC/RES

Moderator:

The panel discussion this afternoon is on modeling frameworks. We have asked Will Lehman, who talked this morning on the various HEC models, to be part of a panel. As a guest panelist, we have Joseph Kanney, who works at NRC/RES in hydrology.

I'd like to open the questions by talking in generalities about modeling frameworks. Rajiv Prasad, you heard an attendee point to the discussion of interpreting data from Shaun Carney's presentation as a good reason for you to do, or propose to do, SHAC-F. How difficult would it be to do Levels 2 and 3 of SHAC-F, and what kinds of difficulties do you see? You talked about LIP and riverine flooding, but what about storm surge and other types of flood events?

Rajiv Prasad:

In terms of difficulty, we don't know yet. We have not done any of these assessments yet. The virtual studies that we did provide some information that we used to streamline how the process would look. The study is tailored after the SHAC-F study. In a Level 3 study, the teams would consist of the flood experts and the flooding data experts, and others of that sort. It still involves three workshops and four working meetings. A lot of time that goes into this is related to the time that you need these experts to come in and talk about the data, the model, and how to put it together. In SHAC-F, we are trying to reduce that burden a little bit by making the teams and the topics that you discuss more appropriate for the flooding assessment at the level that we want to run the SHAC-F process for a particular review or assessment. So, while we do not know yet about the cost, hopefully in the near future, when we do some pilot studies, we will sort out some of these thorny questions.

Joseph Kanney:

They actually have a project in place that we will begin, hopefully in the next month or so, by applying SHAC-F ideas to storm surge hazard analysis. This work will be done jointly between the NRC, our colleagues at USACE (Norberto Nadal-Caraballo, Victor Gonzalez, and their group), and PNNL.

Moderator:

One of the dilemmas, not just for SHAC-F, but for the other modeling frameworks we have heard about today, is formulating credible scenarios both now and projected into the future. I would think, especially for TVA, which has dams, NPPs, and coal-fired plants, there are probably a lot of issues that you ought to address in the selection of scenarios. Shaun Carney, could you tell us about the formulation of scenarios that you and your colleagues did?

Shaun Carney:

So far, I've really focused on using precipitation frequency and looking at individual dams that are doing their semiquantitative risk assessments and PRAs. In those cases, we are focused on those specifically. The precipitation frequency analysis was based on historical data. It does not consider climate change or future scenarios. But what is first is looking at this historical precipitation, then incorporating some paleoflood data. We first look back to understand, as best we can, what's happened historically. Then let's start considering what happens if the present frequency is actually shifting. That would be another level of complexity.

Moderator:

Will Lehman, could you comment on how you and John England and others at USACE look at risk? You look at different scenarios, using the full complement of the HEC models, some watershed models, and hydraulic models of the channels. You were talking about, in particular, breach of levees. How does USACE focus on certain locales and issues associated with those locales, how do you then formulate these scenarios, and how rigorously do you test them?

Will Lehman:

First of all, John England showed an f-N diagram (annual probability of failure vs. average life loss) for a hypothetical "cartoon dam." But in terms of our risk assessment, our prioritizing our dams, we assign Dam Safety Action Classification ratings. That's trying to combine the likelihood of failure with the consequences, so that we prioritize our analysis to those that will provide the greatest risk, which could be driven by either one of those two. As Shaun Carney was saying, that's focusing on the current condition and historical data, not on future conditions. In the levee screenings, once we get beyond the levee screening tool, which is used to support a Levee Safety Action Classification rating, the mapping, modeling, and consequence standard operating procedure would look at multiple failure locations along the levee system and identify one of the greatest consequences, and then we would use that to drive the risk assessment. We do this if we are trying to find a conservative estimate of the risk, which is not necessarily a true statement of risk. We need to be cautious about that. That is not done necessarily within the HEC-WAT itself. When we are within the HEC-WAT, aside from the issues associated with linked effects on a levee segment, it is traditional to look at the most probable locations of failure, such as a highway going over a levee and a bridge pier going in, or near a shortened seepage path. You might look at that seepage location as a probable failure location. Other locations might be transition lines between different types of infrastructure. We would assess a geotechnical fragility curve at those locations driven by that failure mechanism. Another one might be the lowest point relative to the water surface, which might be an overtopping location. You would plot your fragility curves there and HEC-RAS would be set to breach based on the proper mechanism for those breaching locations and triggered by the fragility curve. That would allow for, within the HEC-WAT, multiple failures to happen simultaneously depending on the shape of the hydrograph and the timing of the hydrograph magnitude.

Moderator:

How do you formulate these scenarios? In SSHAC and now SHAC-F, are you actually looking at truly different alternative conceptual models or are you just changing the variability on certain parameters? How uniquely different do those scenarios have to be to legitimately look at the full realm, or the center, body, and range? Am I capturing the range properly for the scenario selection and formulation?

Will Lehman:

That's really difficult to answer and outside of my domain. In terms of how that process happens at the Risk Management Center (RMC) associated with a dam or levee, they would have a probable failure modes analysis workshop where they would look at, through expert elicitation, what the probable failure modes were and how significant those might be to load into an event tree analysis where they would be looking at a failure tree that could be used to create a fragility curve that might be input into the HEC-WAT at those locations.

Shaun Carney:

This wasn't necessary for TVA but for another project. With respect to looking at the full range of uncertainty, in particular the epistemic, in terms of the models, we're basically using some multi-objective calibration approaches to develop (based on different objectives) a set of different hydrologic parameters that would be for the historical record, all adequately representative of the simulation quality at the different locations. But then for a more extreme event, TVA is going to produce a different result. It's getting towards what we're talking about. It isn't like taking a Sacramento Soil Moisture Accounting Model, or an HMS model and a 2-D model and running those together to see if the model structure is different between them. But it's at least on the parameterization where we are characterizing the different pieces.

Moderator:

At the NRC, people are saying, “You may have floods, but we can quickly go in and manage the flood using the diverse and flexible mitigation strategies (FLEX) approach and so the flood protection measures are possible, especially if you have early warning of an impending flood.” What are your thoughts with regard to flood protection? You are doing some physical and numerical models; how do you inform DOE on risk-informed safety issues?

Philippe Bardet:

DOE hires me to do these measurements using lasers. While I cannot make the decision on risk, hopefully DOE will use the work we are doing for it and the methodology we are developing, such as working with NEUTRINO, to make informed decisions.

Will Lehman:

I would tend to shy away from the term “flood protection” and maybe speak more to “flood risk reduction.” I’ve learned that we need to always remember that nature is stronger than we are. We should be very cautious about saying that we can go in with “heroic efforts” to mitigate in the event of a storm that might overtop our defenses that currently exist. First, that increases the risk to the people who are doing those heroic efforts. Second, it compromises our ability to react to a situation that is outside of our control. While the preservation of infrastructure is important, so is the preservation of life.

Joseph Kanney:

Philippe Bardet compare what we see in natural wind wave effects versus your slosh tank.

Question: Inaudible.

Philippe Bardet:

That’s the most important question about the design we chose for this project. Hopefully I can convince you of the approach we chose. Currently, we’re measuring the wave profile in 2-D. We are now developing a technique to do it in 3-D plus time. We are getting to a level of resolution that is measuring down to capillary waves, which is way beyond what would be needed, but the tools we have capture that. We started talking to people in oceanography to measure the spectrum. Currently, we have sets of cameras mounted at the tank top, moving with the tank and monitoring the wave form continuously. Do the waves look the same as wind-driven waves? I would most likely say no. However, if NEUTRINO, which is the computational fluid dynamics code the Smoothed Particle Hydrodynamics server is using, can reproduce my wave profile, and it does it fairly well, then we reproduce the wave impact while measuring the right wave profile for wind-driven waves or tsunami-driven waves, and we have confidence with quantified uncertainties that it should capture the right impactful force and peak pressure. This has been our approach. Even if you look into a laboratory-scale setup with a large wave tank, in which they create a big wave—and they can create any pattern they want on this wave—you are still limited with scales because you will not have control of your surface tension of water. To understand the effect of bubbles, which are going to create some compressibility and also dampen the peak pressure you will reach in your system, for example, you will have to accept some distortions coming from that as well. We went with the approach where we could get many events and quantify the initial shape to make sure the server was getting it right; therefore, we'll be more confident that we can capture what will happen in nature.

Moderator:

The major driver for many of these analyses, especially with regard to flooding of dams and NPPs, is the precipitation scenario. We heard a lot of discussion yesterday, especially from Mel Schaefer, about how important it is to partition the precipitation record and look at it with regard to certain characteristics in formulating your scenarios. How important is it to understand the nature of the precipitation record with regard to seasonality and the areas involved? For instance, how do you think about coupling rainfall in the subbasins within the TVA region? For example, for a 1,000-year simulation of the synthetic rainfall, how do the statistical methods do that?

Shaun Carney:

There are a few pieces there. One is the work that Mel Schaefer is focused on, and the other is the 1,000-year simulation. First, there's an extended-period simulation where we are capturing how the system responds. Then we drop individual stochastic events on top of that. With the 1,000-year simulation, we are using an alternating renewal method, where we break up the historical record into chunks of wet and then dry. We repeat that and then the distribution seats and then we reshuffle. We are maintaining the characteristics of real storms but placing them in a different order. For example, the largest storm from one year is combined with the next year, within a given month. That is one piece of it, that continuous record. Then there are the characteristics of the precipitation. Mel Schaefer put a lot of effort into getting the volumes of the whole regional point precipitation frequency right and converting it into watersheds. But then also, using storm templates, these patterns from the largest historical storms are used to capture the spatial and temporal variability across those really large storms. We are trying to get the combination of how events could sequence in time; that's from the long-term simulations that caused the reservoirs to get to some level. That, along with the characteristics of the extreme events, as well, all in one.

Joseph Kanney:

How much spinup time do you need to do that 1,000-year simulation?

Shaun Carney:

For the 1,000-year simulation, we essentially just drop the first year or something. It depends on how much memory there is in the hydrologic model. Usually you'll get over those initial conditions within a month or two on a continuous hydrological model. But we'll just drop one year so that it is actually 999 years. That part of it is less of a concern.

Joseph Kanney:

I thought the spinup might be longer once you have all the reservoirs in the system.

Shaun Carney:

That's a good point, but we try to start the reservoir at a normal elevation. If we are starting the simulation in January, we use whatever the typical level is that we would be starting out at that point in the season.

Will Lehman:

On this point, it's about initial conditions, not the uncertainty in our initial conditions, and when that storm hits. There are multiple ways of achieving that: taking continuous simulation and dropping in storms with a selected date. In general, in the HEC-WAT, we randomize initial conditions. Inside of ResSim, our pool elevations would be based on stratified monthly or seasonally stratified distributions per starting pool. That way we erase the need for having continuous simulation by randomly starting each event. This is okay when speaking about certain parameters like flow frequency. However, if we think about expected annual damage, there are other things within our system that have memory, such as structures, and whether or not it has been rebuilt, or whether or not people have evacuated. There are other pieces in our memory other than just the natural water and reservoir operations. That question is really complex. In terms of storm typing, the best predictor we have for stream flow in a river is stream flow in a river. In some cases, the best way to get around the issue of knowing whether we should do storm typing is to look at how our system has behaved historically. We bundled up a lot of parameters into that. Within the HEC-WAT, we use correlated flow frequency curves within the hydrologic sampler to allow for that. But again, there are things that we've never seen. In order to get out to the 10^{-6} or 10^{-8} range, stochastic hydrology is the best approach. That means weather generation of some sort, and things like SEFM are critical to that. Selecting the wrong types or, if you're stratifying, selecting the wrong parameters for stratification can also lead to inefficient outcomes and inaccurate outcomes. So, a lot of care is needed. As was said earlier, we always need to keep the human in the loop. We can't let the computer do everything. It's only going to do as well as it's told to do.

Moderator:

In a previous workshop, I think was last year, we heard about a storm catalog that USACE is developing that looks at certain significant historical floods on the Missouri, or whatever river system you are concerned about. Then USACE looked at the rainfall that contributed to that flood event. We understand that USACE is developing this catalog now. When will that become available? It goes back to the comment that you have to look at the history and understand when the floods occur on the Missouri, going back in time, and what is the causative mechanism, the rainfall, snowmelt that caused that flooding. How do you decipher that in an understanding on a watershed basis?

John England:

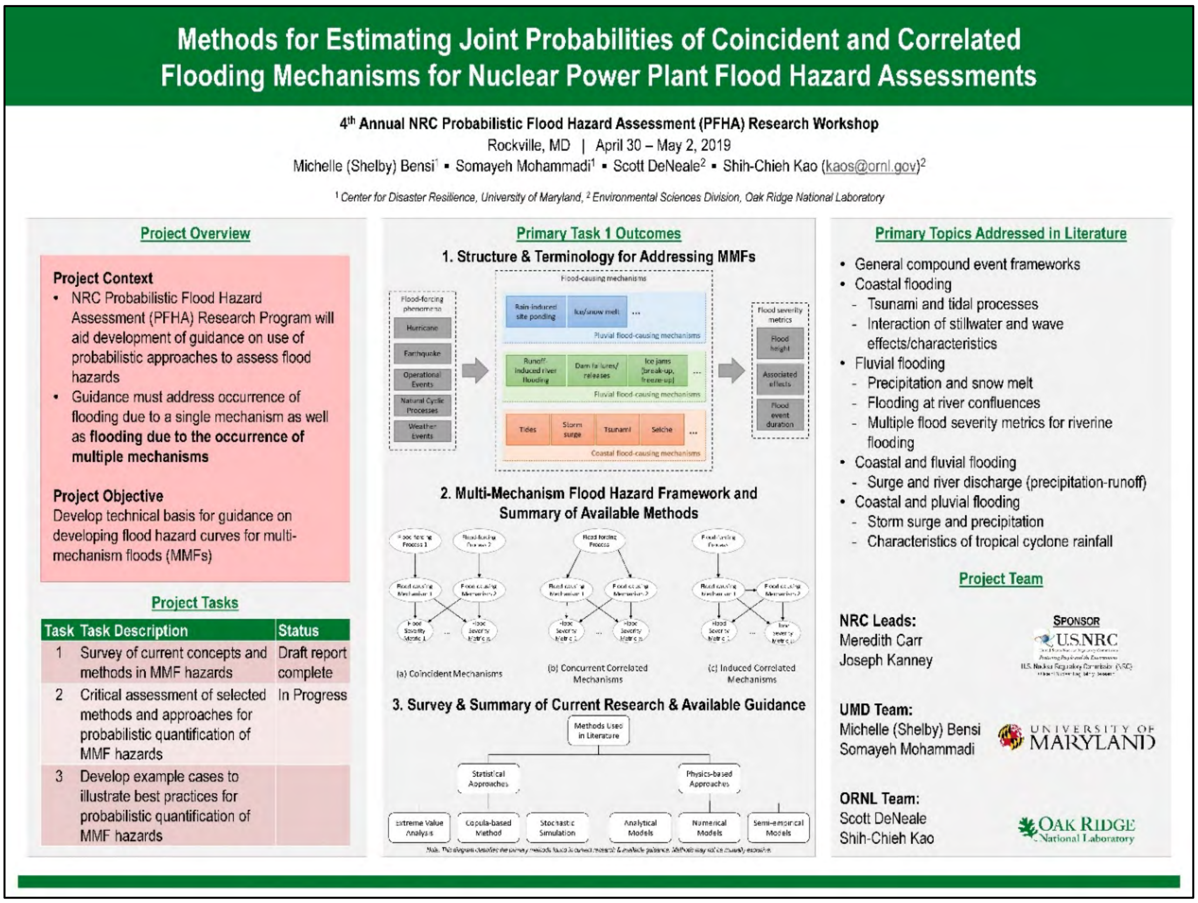
In extreme storms, those spatial temporal patterns are really important. We have a live database internally at USACE. It is under active development and population, and the structure is set. We used to have an open public Web site for anyone to access. It's not accessible currently to the public. We hope that the information technology portion will go through this fall, so that the public can access it just like the National Levee Database or other USACE facilities where you can have a spatial map and search for events and pull down varying levels of information. It could be gridded information, hourly 4-km grids for a storm, or it could be just qualitative information in PDF forms. We are looking at a larger group that Tom Nicholson in our Extreme Storm Work Group has been working on to propagate this information to NOAA. USACE is working internally to develop a database to answer some questions that we have at our facilities and share it as we can.

4.3.6 Day 2: Poster Session 2C

Session Chair: Meredith Carr, NRC/RES/DRA/FXHAB

4.3.6.1 Coastal Storm Surge Assessment using Surrogate Modeling Methods.
Azin Al Kajbaf and Michelle Bensi, Department of Civil and Environmental Engineering, University of Maryland. (Poster 2C-1)—*not included in these proceedings.*

4.3.6.2 Methods for Estimating Joint Probabilities of Coincident and Correlated Flooding Mechanisms for Nuclear Power Plant Flood Hazard Assessments. Michelle Bensi and Somayeh Mohammadi, Center for Disaster Resilience, University of Maryland; Scott DeNeale and Shih-Chieh Kao, Environmental Sciences Division, Oak Ridge National Laboratory. (Poster 2C-2; ADAMS Accession No. ML19156A470)



Methods for Estimating Joint Probabilities of Coincident and Correlated Flooding Mechanisms for Nuclear Power Plant Flood Hazard Assessments

4th Annual NRC Probabilistic Flood Hazard Assessment (PFHA) Research Workshop

Rockville, MD | April 30 – May 2, 2019

Michelle (Shelby) Bensi[1] ▪ Somayeh Mohammadi[1] ▪ Scott DeNeale[2] ▪ Shih-Chieh Kao (kaos@ornl.gov)[2]

[1] Center for Disaster Resilience, University of Maryland, [2] Environmental Sciences Division, Oak Ridge National Laboratory

Project Overview

Project Context

- NRC Probabilistic Flood Hazard Assessment (PFHA) Research Program will aid development of guidance on use of probabilistic approaches to assess flood hazards
- Guidance must address occurrence of flooding due to a single mechanism as well as **flooding due to the occurrence of multiple mechanisms**

Project Objective

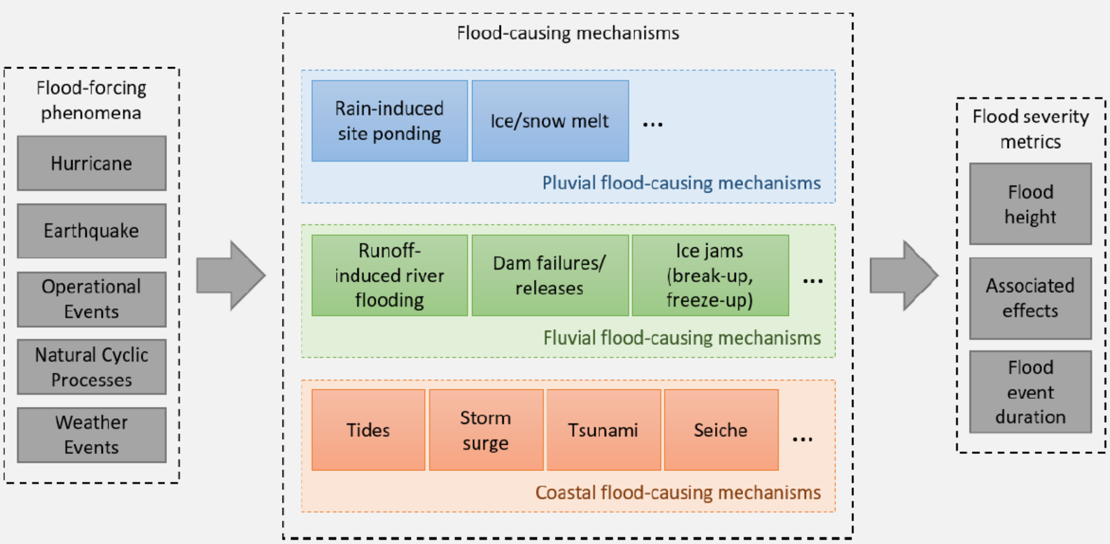
Develop technical basis for guidance on developing flood hazard curves for multi-mechanism floods (MMFs)

Project Tasks

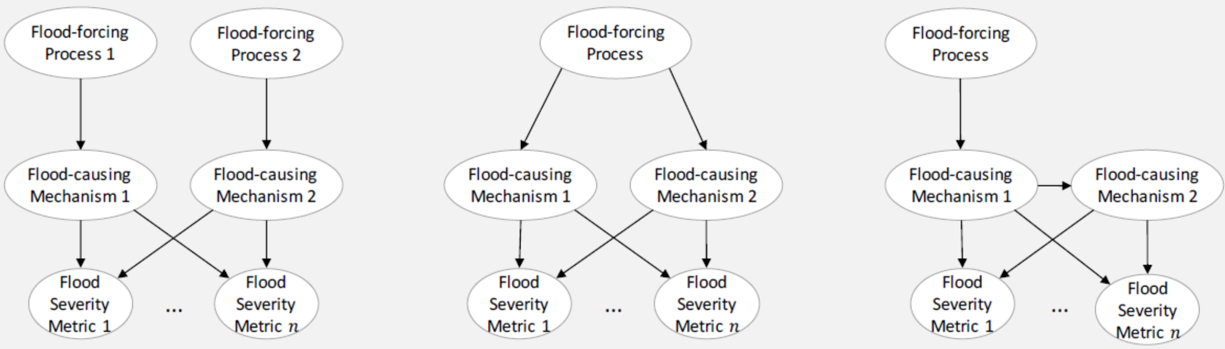
Task	Task Description	Status
1	Survey of current concepts and methods in MMF hazards	Draft report complete
2	Critical assessment of selected methods and approaches for probabilistic quantification of MMF hazards	In Progress
3	Develop example cases to illustrate best practices for probabilistic quantification of MMF hazards	

Primary Task 1 Outcomes

1. Structure & Terminology for Addressing MMFs



2. Multi-Mechanism Flood Hazard Framework and Summary of Available Methods

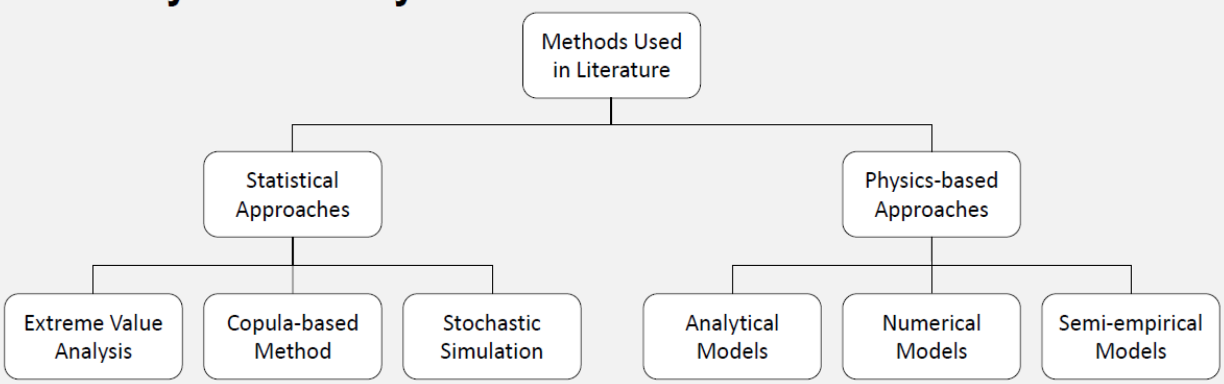


(a) Coincident Mechanisms

(b) Concurrent Correlated Mechanisms

(c) Induced Correlated Mechanisms

3. Survey & Summary of Current Research & Available Guidance



Note: This diagram classifies the primary methods found in current research & available guidance. Methods may not be mutually exclusive.

Primary Topics Addressed in Literature

- General compound event frameworks
- Coastal flooding
  - Tsunami and tidal processes
  - Interaction of stillwater and wave effects/characteristics
- Fluvial flooding
  - Precipitation and snow melt
  - Flooding at river confluences
  - Multiple flood severity metrics for riverine flooding
- Coastal and fluvial flooding
  - Surge and river discharge (precipitation-runoff)
- Coastal and pluvial flooding
  - Storm surge and precipitation
  - Characteristics of tropical cyclone rainfall

Project Team

NRC Leads:
Meredith Carr
Joseph Kanney

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UMD Team:
Michelle (Shelby) Bensi
Somayeh Mohammadi

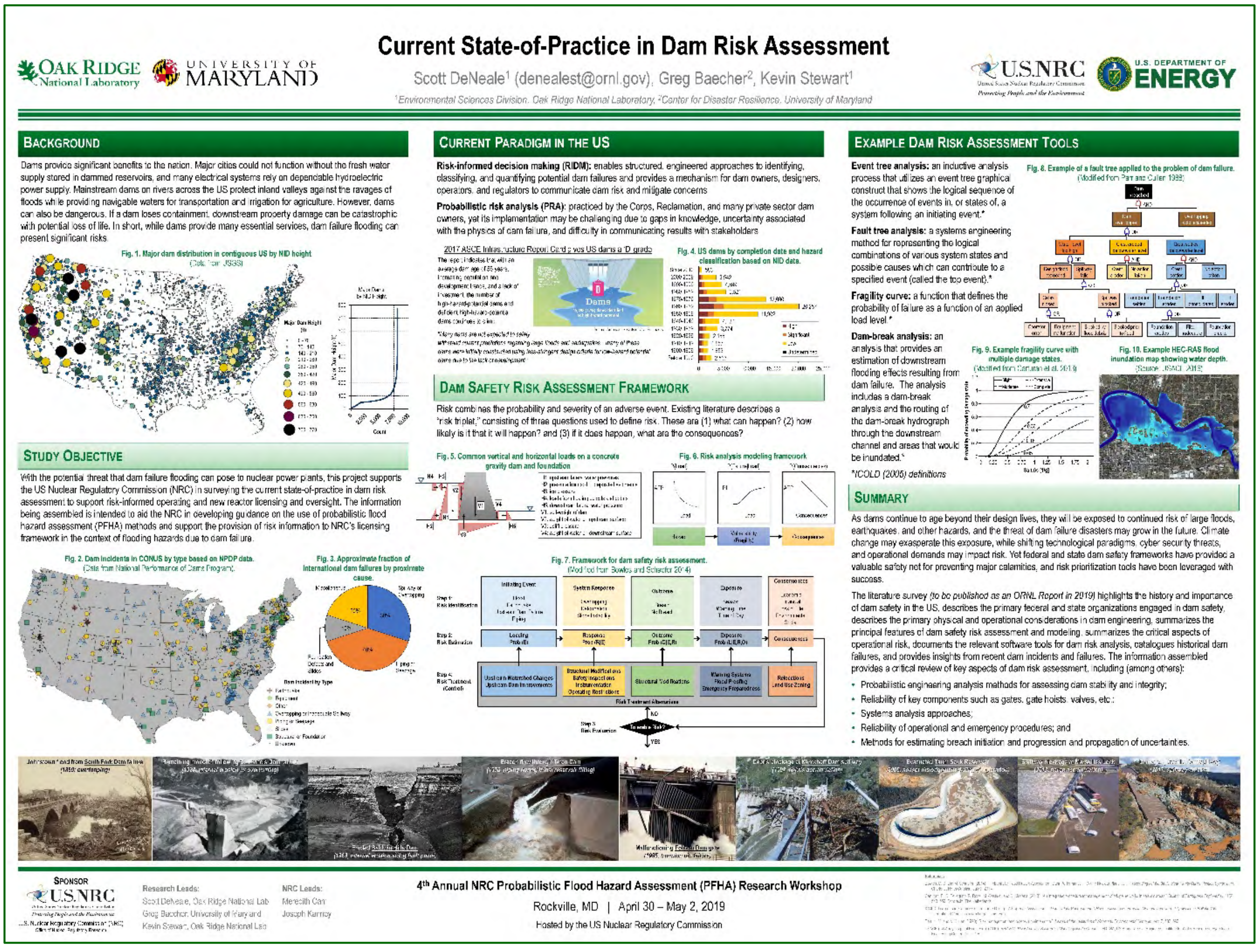
UNIVERSITY OF MARYLAND

ORNL Team:
Scott DeNeale
Shih-Chieh Kao

OAK RIDGE National Laboratory

4.3.6.3 Modelling Dependence and Coincidence of Flooding Phenomena: Methodology and Simplified Case Study in Le Havre in France. A. Ben Daoued, Sorbonne University—Université de Technologie de Compiègne; Y. Hamdi, Institut de Radioprotection et de Sûreté Nucléaire; N. Mouhous-Voyneau, Sorbonne University—Université de Technologie de Compiègne; and P. Sergent, Cerema (Poster 2C-3)—*not included in these proceedings.*

4.3.6.4 Current State-of-Practice in Dam Risk Assessment. Scott DeNeale, Environmental Sciences Division, Oak Ridge National Laboratory; Greg Baecher, Center for Disaster Resilience, University of Maryland; Kevin Stewart, Environmental Sciences Division, Oak Ridge National Laboratory. (Poster 2C-4; ADAMS Accession No. ML19156A471)



Current State-of-Practice in Dam Risk Assessment

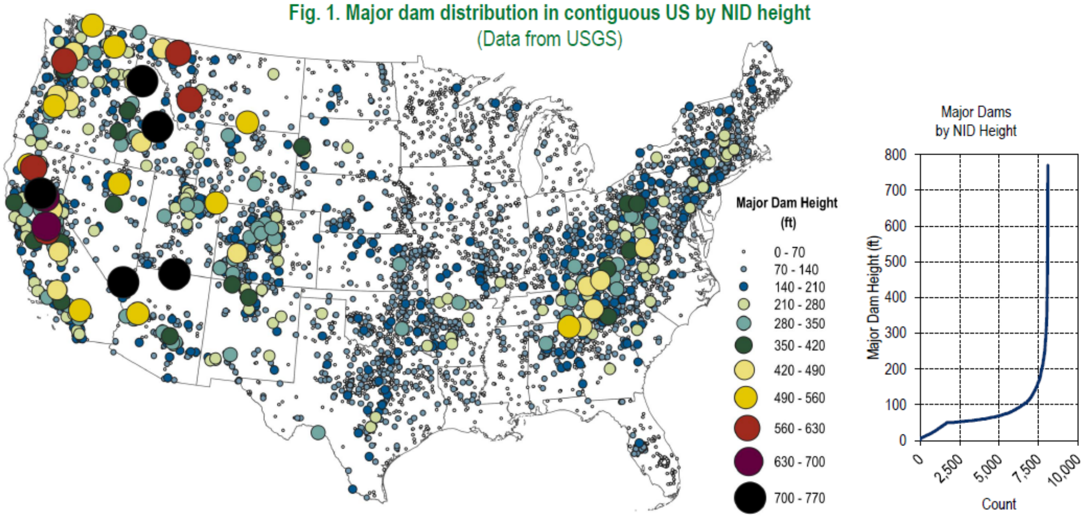
Scott DeNeale[1] (denealest@ornl.gov), Greg Baecher[2], Kevin Stewart[1]

[1]*Environmental Sciences Division, Oak Ridge National Laboratory,* [2]*Center for Disaster Resilience, University of Maryland*

Background

Dams provide significant benefits to the nation. Major cities could not function without the fresh water supply stored in dammed reservoirs, and many electrical systems rely on dependable hydroelectric power supply. Mainstream dams on rivers across the US protect inland valleys against the ravages of floods while providing navigable waters for transportation and irrigation for agriculture. However, dams can also be dangerous. If a dam loses containment, downstream property damage can be catastrophic with potential loss of life. In short, while dams provide many essential services, dam failure flooding can present significant risks.

Fig. 1. Major dam distribution in contiguous US by NID height
(Data from USGS)



Study Objective

With the potential threat that dam failure flooding can pose to nuclear power plants, this project supports the US Nuclear Regulatory Commission (NRC) in surveying the current state-of-practice in dam risk assessment to support risk-informed operating and new reactor licensing and oversight. The information being assembled is intended to aid the NRC in developing guidance on the use of probabilistic flood hazard assessment (PFHA) methods and support the provision of risk information to NRC's licensing framework in the context of flooding hazards due to dam failure.

Fig. 2. Dam incidents in CONUS by type based on NPDP data.
(Data from National Performance of Dams Program).

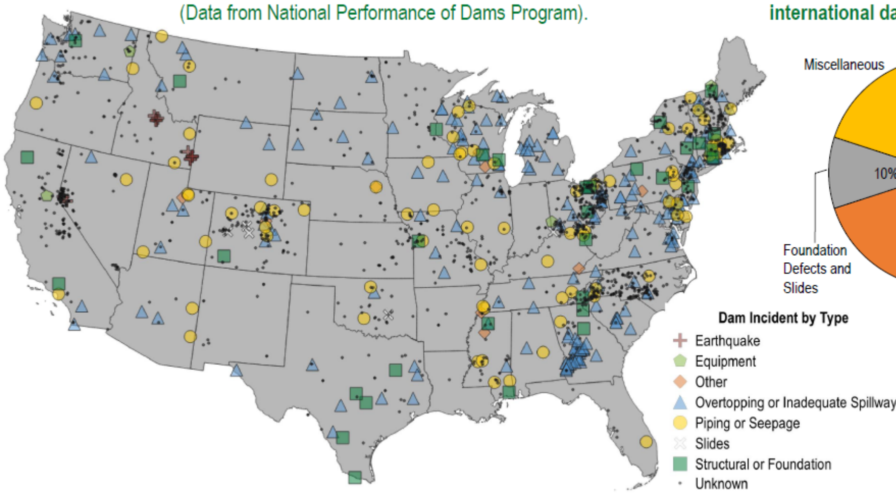
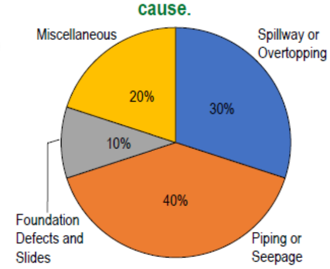


Fig. 3. Approximate fraction of international dam failures by proximate cause.



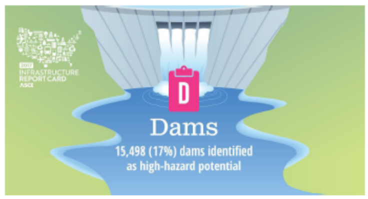
Current Paradigm in the US

Risk-informed decision making (RIDM): enables structured, engineered approaches to identifying, classifying, and quantifying potential dam failures and provides a mechanism for dam owners, designers, operators, and regulators to communicate dam risk and mitigate concerns

Probabilistic risk analysis (PRA): practiced by the Corps, Reclamation, and many private sector dam owners, yet its implementation may be challenging due to gaps in knowledge, uncertainty associated with the physics of dam failure, and difficulty in communicating results with stakeholders

<u>2017 ASCE Infrastructure Report Card gives US dams a 'D' grade</u>

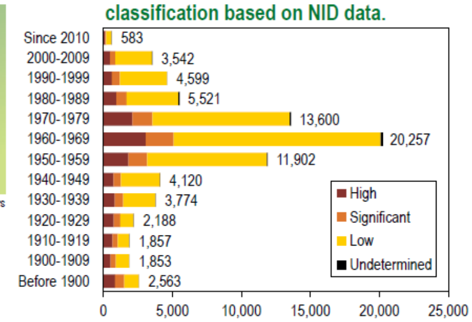
The report indicates that with an average dam age of 56 years, increasing population and development trends, and a lack of investment, the number of high-hazard-potential dams and deficient high-hazard-potential dams continues to climb.



Source: American Society of Civil Engineers

"Many dams are not expected to safely withstand current predictions regarding large floods and earthquakes…many of these dams were initially constructed using less-stringent design criteria for low-hazard potential dams due to the lack of development."

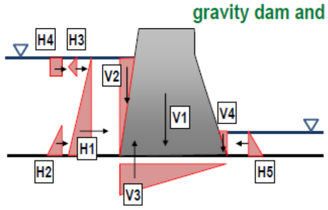
Fig. 4. US dams by completion date and hazard classification based on NID data.



Dam Safety Risk Assessment Framework

Risk combines the probability and severity of an adverse event. Existing literature describes a "risk triplet," consisting of three questions used to define risk. These are (1) what can happen? (2) how likely is it that it will happen? and (3) if it does happen, what are the consequences?

Fig. 5. Common vertical and horizontal loads on a concrete gravity dam and foundation



- H1: upstream lateral water pressures
- H2: pressure from soil or deposited sediments
- H3: ice pressure
- H4: loads from floating objects and debris
- H5: downstream lateral water pressure
- V1: self-weight of dam
- V2: weight of water on upstream surface
- V3: uplift pressure
- V4: weight of water on downstream surface

Fig. 6. Risk analysis modeling framework

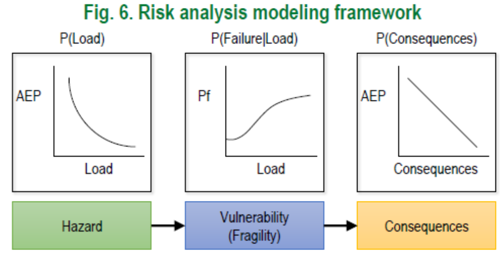
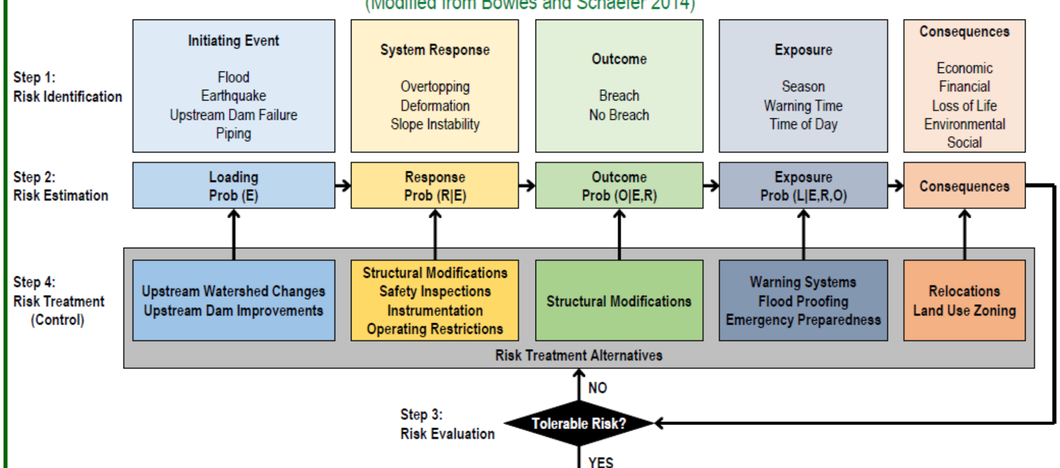


Fig. 7. Framework for dam safety risk assessment.
(Modified from Bowles and Schaefer 2014)



EXAMPLE DAM RISK ASSESSMENT TOOLS

Event tree analysis: an inductive analysis process that utilizes an event tree graphical construct that shows the logical sequence of the occurrence of events in, or states of, a system following an initiating event.*

Fault tree analysis: a systems engineering method for representing the logical combinations of various system states and possible causes which can contribute to a specified event (called the top event).*

Fragility curve: a function that defines the probability of failure as a function of an applied load level.*

Dam-break analysis: an analysis that provides an estimation of downstream flooding effects resulting from dam failure. The analysis includes a dam-break analysis and the routing of the dam-break hydrograph through the downstream channel and areas that would be inundated.*

**ICOLD (2005) definitions*

Fig. 8. Example of a fault tree applied to the problem of dam failure.
(Modified from Parr and Cullen 1988)

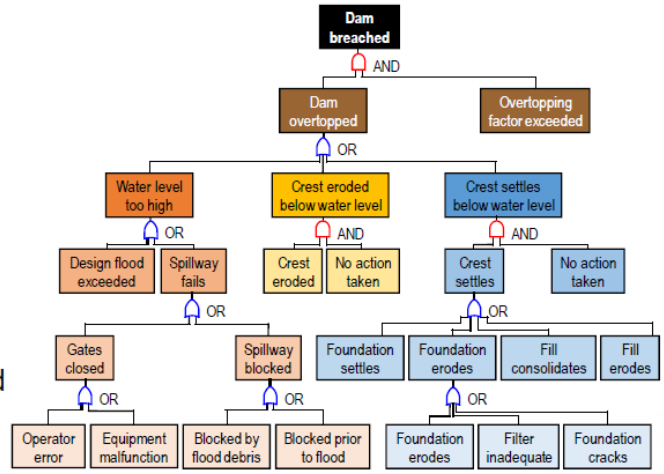


Fig. 9. Example fragility curve with multiple damage states.
(Modified from Carturan et al. 2013)

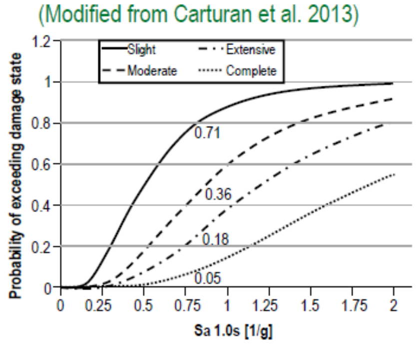
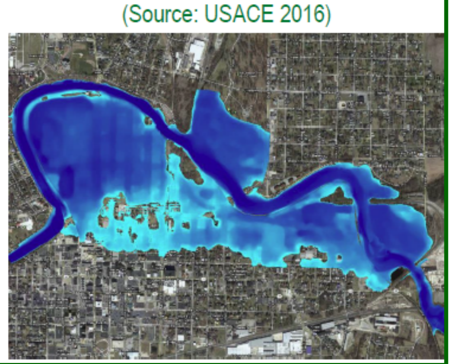
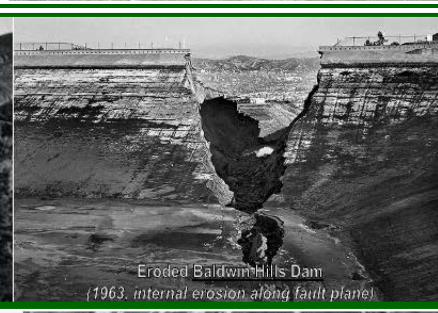
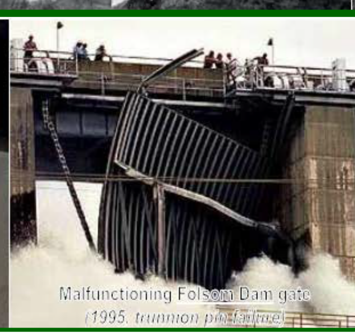


Fig. 10. Example HEC-RAS flood inundation map showing water depth.
(Source: USACE 2016)







Summary

As dams continue to age beyond their design lives, they will be exposed to continued risk of large floods, earthquakes, and other hazards, and the threat of dam failure disasters may grow in the future. Climate change may exasperate this exposure, while shifting technological paradigms, cyber security threats, and operational demands may impact risk. Yet federal and state dam safety frameworks have provided a valuable safety net for preventing major calamities, and risk prioritization tools have been leveraged with success.

The literature survey *(to be published as an ORNL Report in 2019)* highlights the history and importance of dam safety in the US, describes the primary federal and state organizations engaged in dam safety, describes the primary physical and operational considerations in dam engineering, summarizes the principal features of dam safety risk assessment and modeling, summarizes the critical aspects of operational risk, documents the relevant software tools for dam risk analysis, catalogues historical dam failures, and provides insights from recent dam incidents and failures. The information assembled provides a critical review of key aspects of dam risk assessment, including (among others):

- Probabilistic engineering analysis methods for assessing dam stability and integrity;
- Reliability of key components such as gates, gate hoists, valves, etc.;
- Systems analysis approaches;
- Reliability of operational and emergency procedures; and
- Methods for estimating breach initiation and progression and propagation of uncertainties.

4th Annual NRC Probabilistic Flood Hazard Assessment (PFHA) Research Workshop

Rockville, MD | April 30 – May 2, 2019

Hosted by the US Nuclear Regulatory Commission

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Research Leads:
Scott DeNeale, Oak Ridge National Lab
Greg Baecher, University of Maryland
Kevin Stewart, Oak Ridge National Lab

NRC Leads:
Meredith Carr
Joseph Kanney

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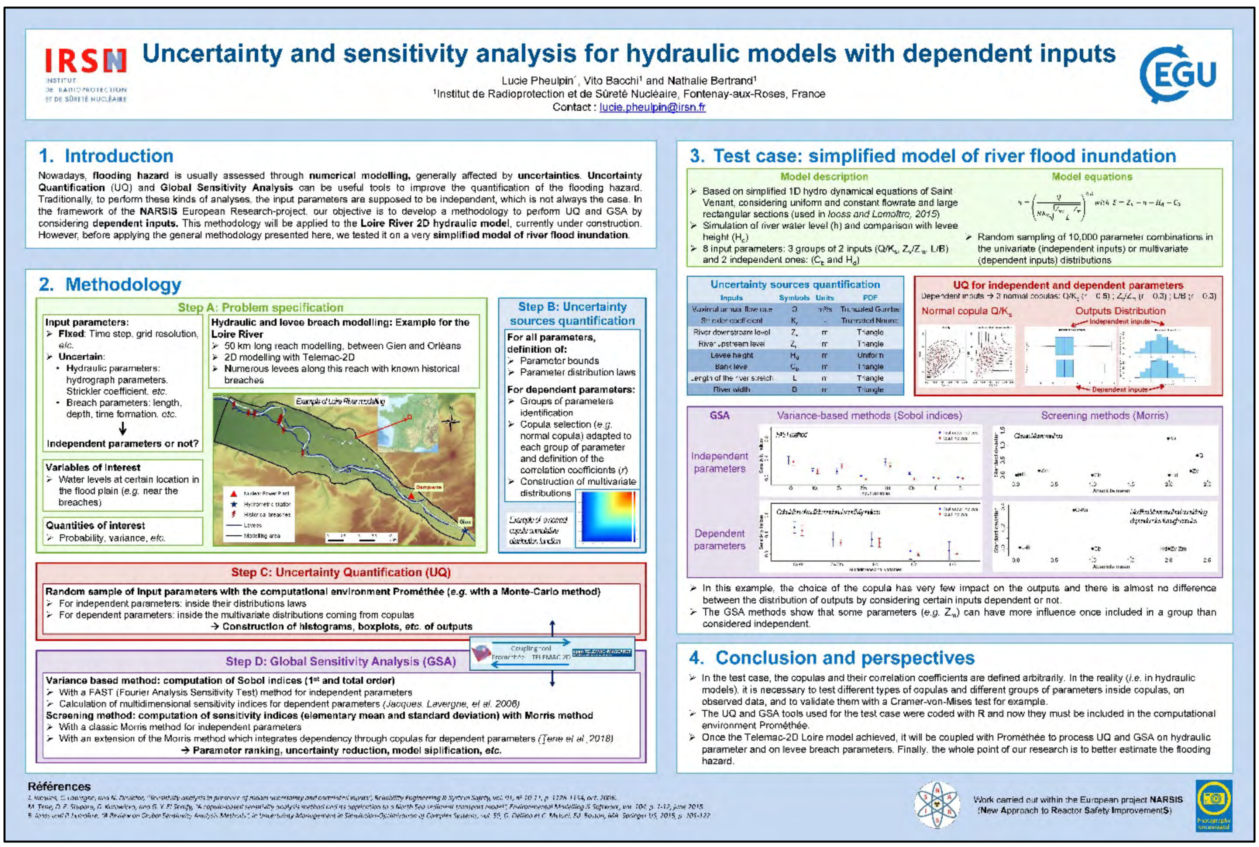
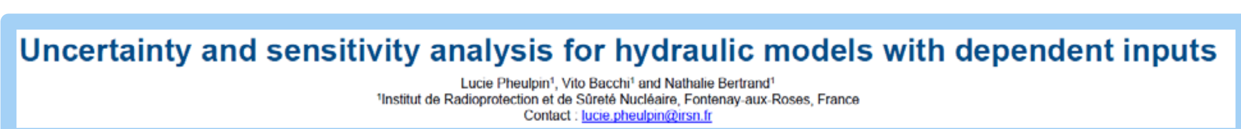
4.3.6.5 Hurricane Harvey Highlights Challenge of Estimating Probable Maximum Precipitation. Shih-Chieh Kao, Scott T. DeNeale and David B. Watson, Environmental Sciences Division, Oak Ridge National Laboratory. (Poster 2C-5)—*not included in these proceedings.*

4.3.6.6 Uncertainty and Sensitivity Analysis for Hydraulic Models with Dependent Inputs. Lucie Pheulpin, Vito Bacchi, Nathalie Bertrand, Institut de Radioprotection et de Sûreté Nucléaire, Fontenay-aux-Roses, France. (Poster 2C-6; ADAMS Accession No. ML19156A473)





1. Introduction

Nowadays, **flooding hazard** is usually assessed through **numerical modelling,** generally affected by **uncertainties**. **Uncertainty Quantification** (UQ) and **Global Sensitivity Analysis** can be useful tools to improve the quantification of the flooding hazard. Traditionally, to perform these kinds of analyses, the input parameters are supposed to be independent, which is not always the case. In the framework of the **NARSIS** European Research-project, our objective is to develop a methodology to perform UQ and GSA by considering **dependent inputs.** This methodology will be applied to the **Loire River 2D hydraulic model**, currently under construction. However, before applying the general methodology presented here, we tested it on a very **simplified model of river flood inundation**.

2. Methodology

Step A: Problem specification

Input parameters:

- **Fixed**: Time step, grid resolution, *etc.*
- **Uncertain**:
  - Hydraulic parameters: hydrograph parameters, Strickler coefficient, *etc.*
  - Breach parameters: length, depth, time formation, *etc.*

↓

Independent parameters or not?

Variables of interest

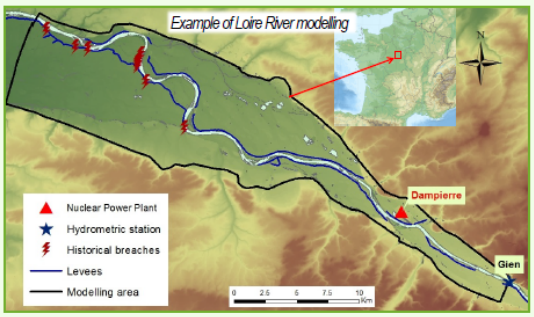
- Water levels at certain location in the flood plain (*e.g.* near the breaches)

Quantities of interest

- Probability, variance, *etc.*

Hydraulic and levee breach modelling: Example for the Loire River

- 50 km-long reach modelling, between Gien and Orléans
- 2D modelling with Telemac-2D
- Numerous levees along this reach with known historical breaches



Step B: Uncertainty sources quantification

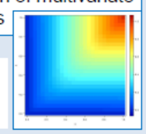
For all parameters, definition of:

- Parameter bounds
- Parameter distribution laws

For dependent parameters:

- Groups of parameters identification
- Copula selection (*e.g.* normal copula) adapted to each group of parameter and definition of the correlation coefficients (*r*)
- Construction of multivariate distributions

Example of a normal copula cumulative distribution function

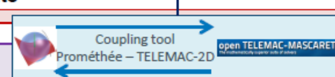


Step C: Uncertainty Quantification (UQ)

Random sample of input parameters with the computational environment Prométhée (*e.g.* with a Monte-Carlo method)

- For independent parameters: inside their distributions laws
- For dependent parameters: inside the multivariate distributions coming from copulas

→ **Construction of histograms, boxplots, *etc.* of outputs**



Step D: Global Sensitivity Analysis (GSA)

Variance based method: computation of Sobol indices (1st and total order)

- With a FAST (Fourier Analysis Sensitivity Test) method for independent parameters
- Calculation of multidimensional sensitivity indices for dependent parameters *(Jacques, Lavergne, et al. 2006)*

Screening method: computation of sensitivity indices (elementary mean and standard deviation) with Morris method

- With a classic Morris method for independent parameters
- With an extension of the Morris method which integrates dependency through copulas for dependent parameters *(Ţene et al.,2018)*

→ **Parameter ranking, uncertainty reduction, model siplification, *etc.***

Références

J. Jacques, C. Lavergne, and N. Devictor, "Sensitivity analysis in presence of model uncertainty and correlated inputs", Reliability Engineering & System Safety, vol. 91, n° 10-11, p. 1126-1134, oct. 2006.

M. Ţene, D. E. Stuparu, D. Kurowicka, and G. Y. El Serafy, "A copula-based sensitivity analysis method and its application to a North Sea sediment transport model", Environmental Modelling & Software, vol. 104, p. 1-12,

B. Iooss and P. Lemaître, "A Review on Global Sensitivity Analysis Methods", in Uncertainty Management in Simulation-Optimization of Complex Systems, vol. 59, G. Dellino et C. Meloni, Éd. Boston, MA: Springer US, 2015

3. Test case: simplified model of river flood inundation

Model description

- Based on simplified 1D hydro-dynamical equations of Saint-Venant, considering uniform and constant flowrate and large rectangular sections (used in *Iooss and Lemaître, 2015*)
- Simulation of river water level (h) and comparison with levee height (H_d)
- 8 input parameters: 3 groups of 2 inputs (Q/K_s, Z_v/Z_m, L/B) and 2 independent ones: (C_b and H_d)

Model equations

$$h = \left(\frac{Q}{BK_s\sqrt{\frac{Z_m - Z_v}{L}}}\right)^{0.6} \quad with \ S = Z_v + h - H_d - C_b$$

- Random sampling of 10,000 parameter combinations in the univariate (independent inputs) or multivariate (dependent inputs) distributions

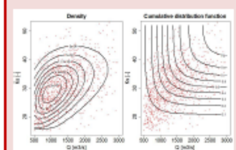
Uncertainty sources quantification

Inputs	Symbols	Units	PDF
Maximal annual flow rate	Q	m³/s	Truncated Gumbel
Strickler coefficient	K_s	-	Truncated Normal
River downstream level	Z_v	m	Triangle
River upstream level	Z_m	m	Triangle
Levee height	H_d	m	Uniform
Bank level	C_b	m	Triangle
Length of the river stretch	L	m	Triangle
River width	B	m	Triangle

UQ for independent and dependent parameters

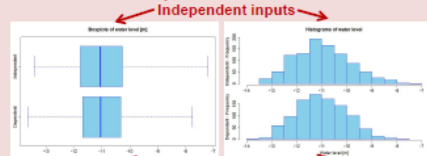
Dependent inputs → 3 normal copulas: Q/K_s (r = 0.5) ; Z_v/Z_m (r = 0.3) ; L/B (r = 0.3)

Normal copula Q/K_s



Outputs Distribution

Independent inputs

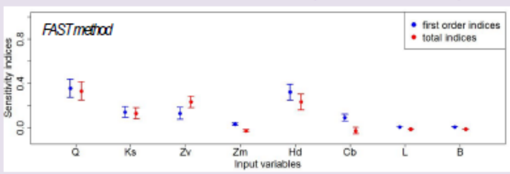


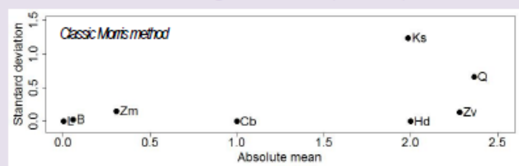
Dependent inputs

GSA

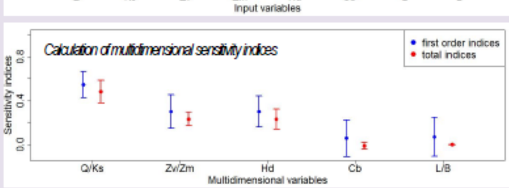
Variance-based methods (Sobol indices) | Screening methods (Morris)

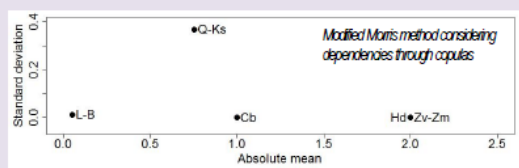
Independent parameters





Dependent parameters





- In this example, the choice of the copula has very few impact on the outputs and there is almost no difference between the distribution of outputs by considering certain inputs dependent or not.
- The GSA methods show that some parameters (*e.g.* Z_m) can have more influence once included in a group than considered independent.

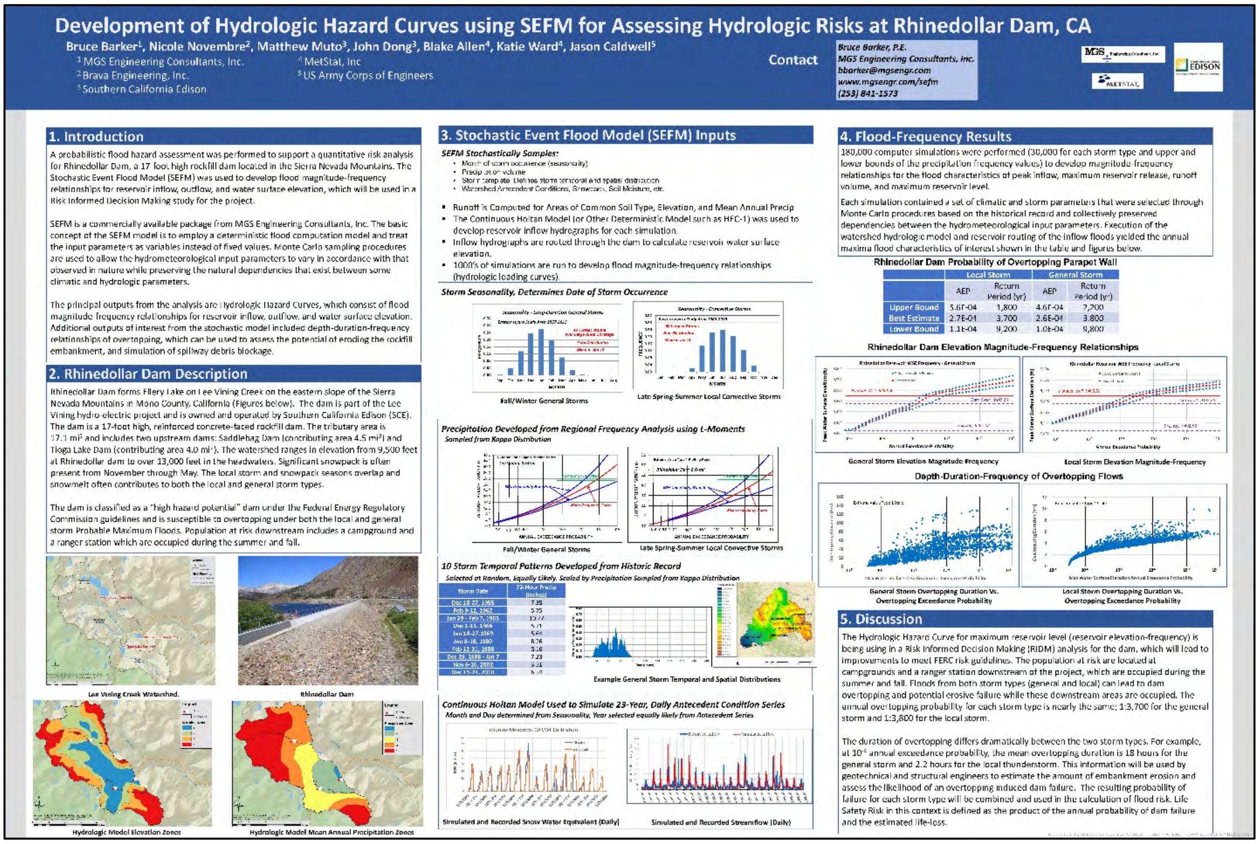
4. Conclusion and perspectives

- In the test case, the copulas and their correlation coefficients are defined arbitrarily. In the reality (*i.e.* in hydraulic models), it is necessary to test different types of copulas and different groups of parameters inside copulas, on observed data, and to validate them with a Cramer-von-Mises test for example.
- The UQ and GSA tools used for the test case were coded with **R** and now they must be included in the computational environment Prométhée.
- Once the Telemac-2D Loire model achieved, it will be coupled with Prométhée to process UQ and GSA on hydraulic parameter and on levee breach parameters. Finally, the whole point of our research is to better estimate the flooding hazard.

Work carried out within the European project **NARSIS** (**N**ew **A**pproach to **R**eactor **S**afety **I**mprovement**S**)

Photography encouraged

4.3.6.7 Development of Hydrologic Hazard Curves Using SEFM for Assessing Hydrologic Risks at Rhinedollar Dam*, *CA. Bruce Barker, MGS Engineering Consultants, Inc.; Nicole Novembre, Brava Engineering, Inc.; Matthew Muto, John Dong, Southern California Edison, Blake Allen, Katie Ward, MetStat, Inc.; and Jason Caldwell, Weather & Water, Inc. (Poster 2C-7; ADAMS Accession No. ML19156A474)



Development of Hydrologic Hazard Curves using SEFM for Assessing Hydrologic Risks at Rhinedollar Dam, CA

Bruce Barker[1], Nicole Novembre[2], Matthew Muto[3], John Dong[3], Blake Allen[4], Katie Ward[4], Jason Caldwell[5]

[1] MGS Engineering Consultants, Inc.
[2] Brava Engineering, Inc.
[3] Southern California Edison
[4] MetStat, Inc
[5] US Army Corps of Engineers

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1. Introduction

A probabilistic flood hazard assessment was performed to support a quantitative risk analysis for Rhinedollar Dam, a 17-foot high rockfill dam located in the Sierra Nevada Mountains. The Stochastic Event Flood Model (SEFM) was used to develop flood magnitude-frequency relationships for reservoir inflow, outflow, and water surface elevation, which will be used in a Risk Informed Decision Making study for the project.

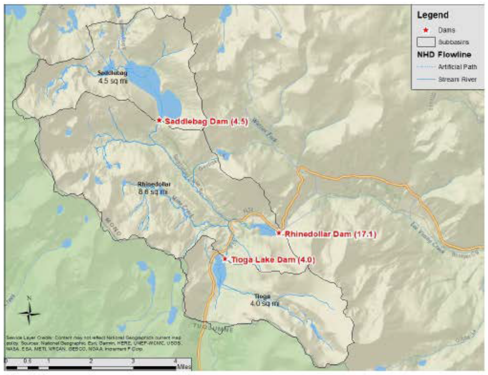
SEFM is a commercially available package from MGS Engineering Consultants, Inc. The basic concept of the SEFM model is to employ a deterministic flood computation model and treat the input parameters as variables instead of fixed values. Monte Carlo sampling procedures are used to allow the hydrometeorological input parameters to vary in accordance with that observed in nature while preserving the natural dependencies that exist between some climatic and hydrologic parameters.

The principal outputs from the analysis are Hydrologic Hazard Curves, which consist of flood magnitude-frequency relationships for reservoir inflow, outflow, and water surface elevation. Additional outputs of interest from the stochastic model included depth-duration-frequency relationships of overtopping, which can be used to assess the potential of eroding the rockfill embankment, and simulation of spillway debris blockage.

2. Rhinedollar Dam Description

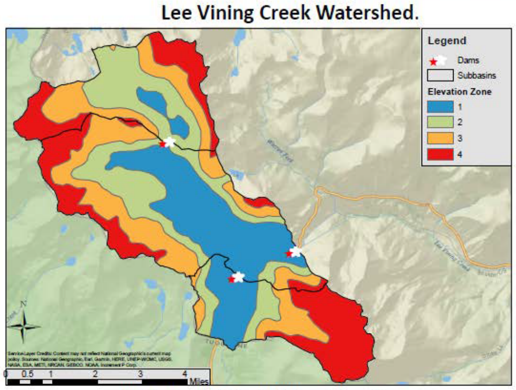
Rhinedollar Dam forms Ellery Lake on Lee Vining Creek on the eastern slope of the Sierra Nevada Mountains in Mono County, California (Figures below). The dam is part of the Lee Vining hydro-electric project and is owned and operated by Southern California Edison (SCE). The dam is a 17-foot high, reinforced concrete-faced rockfill dam. The tributary area is 17.1 mi^2 and includes two upstream dams: Saddlebag Dam (contributing area 4.5 mi^2) and Tioga Lake Dam (contributing area 4.0 mi^2). The watershed ranges in elevation from 9,500 feet at Rhinedollar dam to over 13,000 feet in the headwaters. Significant snowpack is often present from November through May. The local storm and snowpack seasons overlap and snowmelt often contributes to both the local and general storm types.

The dam is classified as a "high hazard potential" dam under the Federal Energy Regulatory Commission guidelines and is susceptible to overtopping under both the local and general storm Probable Maximum Floods. Population at risk downstream includes a campground and a ranger station which are occupied during the summer and fall.

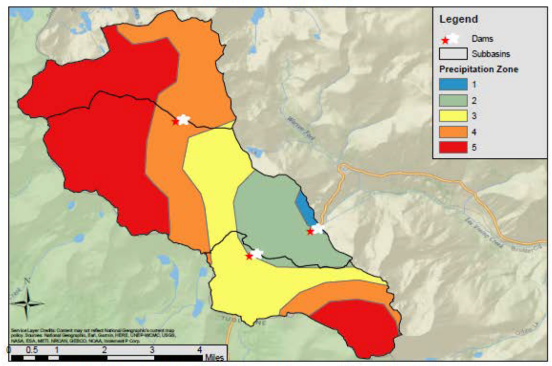


Lee Vining Creek Watershed.

Rhinedollar Dam



Hydrologic Model Elevation Zones



Hydrologic Model Mean Annual Precipitation Zones

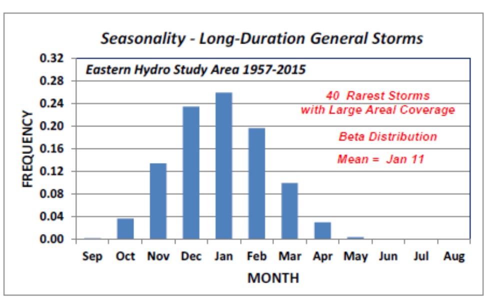
3. Stochastic Event Flood Model (SEFM) Inputs

SEFM Stochastically Samples:

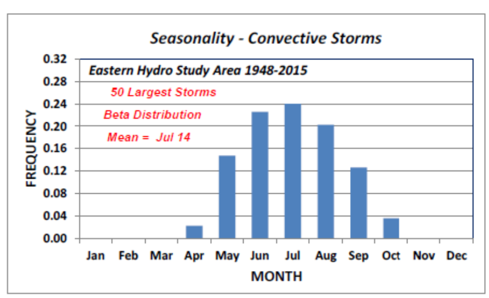
- Month of storm occurrence (seasonality)
- Precipitation volume
- Storm template, Defines storm temporal and spatial distribution
- Watershed Antecedent Conditions, Snowpack, Soil Moisture, etc.

- Runoff is Computed for Areas of Common Soil Type, Elevation, and Mean Annual Precip
- The Continuous Holtan Model (or Other Deterministic Model such as HEC-1) was used to develop reservoir inflow hydrographs for each simulation.
- Inflow hydrographs are routed through the dam to calculate reservoir water surface elevation.
- 1000's of simulations are run to develop flood magnitude-frequency relationships (hydrologic loading curves).

Storm Seasonality, Determines Date of Storm Occurrence



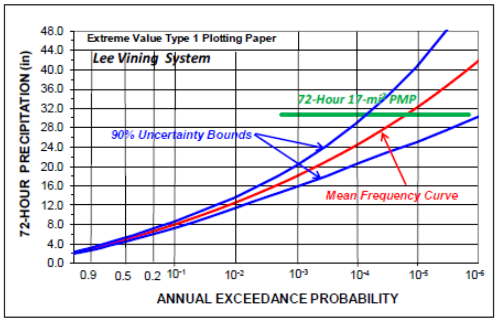
Fall/Winter General Storms



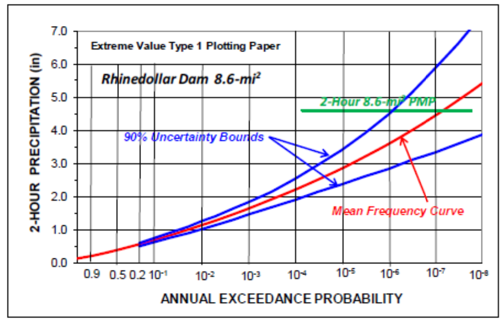
Late Spring-Summer Local Convective Storms

Precipitation Developed from Regional Frequency Analysis using L-Moments

Sampled from Kappa Distribution



Fall/Winter General Storms

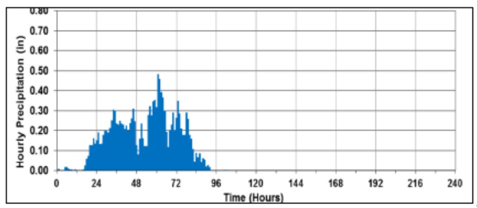


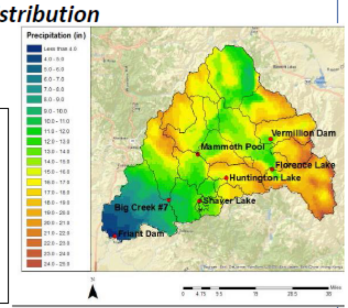
Late Spring-Summer Local Convective Storms

10 Storm Temporal Patterns Developed from Historic Record

Selected at Random, Equally Likely. Scaled by Precipitation Sampled from Kappa Distribution

Storm Date	72-Hour Precip (inches)
Dec 18-27, 1955	7.35
Feb 3-12, 1962	5.75
Jan 29 - Feb 7, 1963	10.77
Dec 1-11, 1966	5.71
Jan 18-27,1969	5.64
Jan 8-18, 1980	8.76
Feb 12-21, 1986	8.16
Dec 29, 1996 - Jan 7	7.23
Nov 6-16, 2002	3.51
Dec 15-24, 2010	6.54

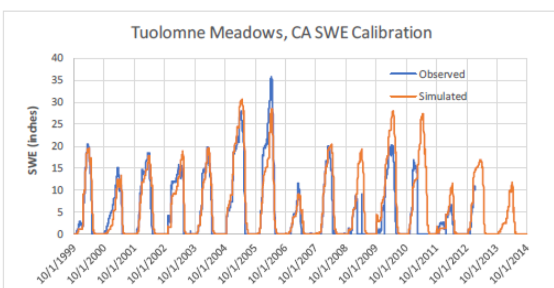




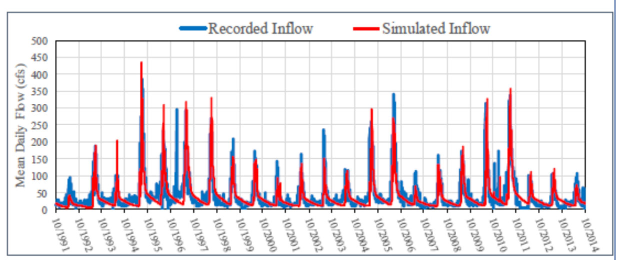
Example General Storm Temporal and Spatial Distributions

Continuous Holtan Model Used to Simulate 23-Year, Daily Antecedent Condition Series

Month and Day determined from Seasonality, Year selected equally likely from Antecedent Series



Simulated and Recorded Snow Water Equivalent (Daily)



Simulated and Recorded Streamflow (Daily)

4. Flood-Frequency Results

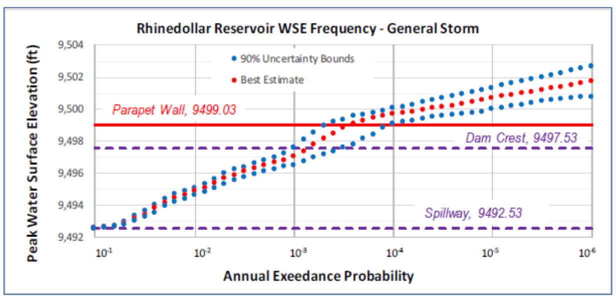
180,000 computer simulations were performed (30,000 for each storm type and upper and lower bounds of the precipitation frequency values) to develop magnitude-frequency relationships for the flood characteristics of peak inflow, maximum reservoir release, runoff volume, and maximum reservoir level.

Each simulation contained a set of climatic and storm parameters that were selected through Monte Carlo procedures based on the historical record and collectively preserved dependencies between the hydrometeorological input parameters. Execution of the watershed hydrologic model and reservoir routing of the inflow floods yielded the annual maxima flood characteristics of interest shown in the table and figures below.

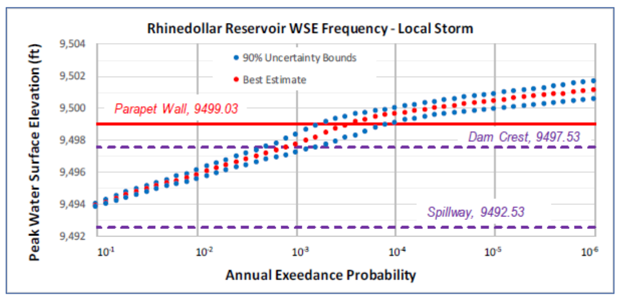
Rhinedollar Dam Probability of Overtopping Parapet Wall

	Local Storm		General Storm	
	AEP	Return Period (yr)	AEP	Return Period (yr)
Upper Bound	5.6E-04	1,800	4.6E-04	2,200
Best Estimate	2.7E-04	3,700	2.6E-04	3,800
Lower Bound	1.1E-04	9,200	1.0E-04	9,800

Rhinedollar Dam Elevation Magnitude-Frequency Relationships

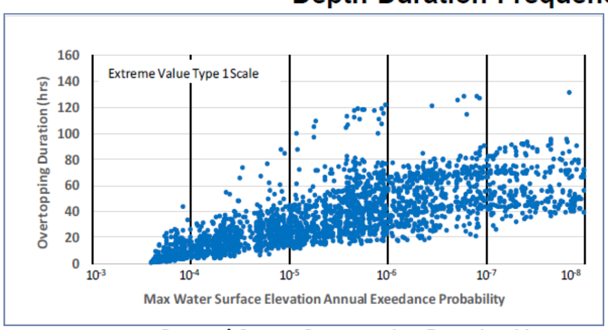


General Storm Elevation Magnitude-Frequency

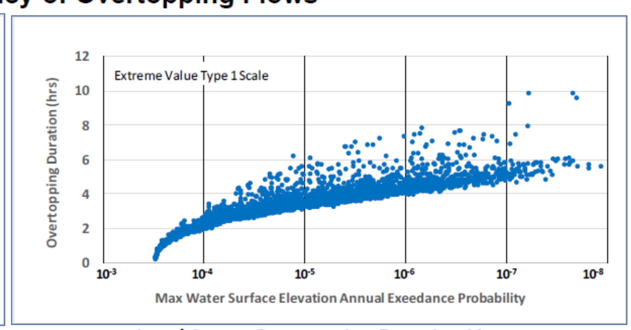


Local Storm Elevation Magnitude-Frequency

Depth-Duration-Frequency of Overtopping Flows



General Storm Overtopping Duration Vs. Overtopping Exceedance Probability



Local Storm Overtopping Duration Vs. Overtopping Exceedance Probability

5. Discussion

The Hydrologic Hazard Curve for maximum reservoir level (reservoir elevation-frequency) is being using in a Risk Informed Decision Making (RIDM) analysis for the dam, which will lead to improvements to meet FERC risk guidelines. The population at risk are located at campgrounds and a ranger station downstream of the project, which are occupied during the summer and fall. Floods from both storm types (general and local) can lead to dam overtopping and potential erosive failure while these downstream areas are occupied. The annual overtopping probability for each storm type is nearly the same; 1:3,700 for the general storm and 1:3,800 for the local storm.

The duration of overtopping differs dramatically between the two storm types. For example, at 10^{-4} annual exceedance probability, the mean overtopping duration is 18 hours for the general storm and 2.2 hours for the local thunderstorm. This information will be used by geotechnical and structural engineers to estimate the amount of embankment erosion and assess the likelihood of an overtopping induced dam failure. The resulting probability of failure for each storm type will be combined and used in the calculation of flood risk. Life Safety Risk in this context is defined as the product of the annual probability of dam failure and the estimated life-loss.

4.3.6.8 Probabilistic Flood Hazard Analysis of Nuclear Power Plant in Korea. Beomjin Kim, Ph.D. Candidate, Kyungpook National University, Korea; Kun-Yeun Han, Professor, Department of Civil Engineering, Kyungpook National University; Minkyu Kim, Principal Researcher, Korea Atomic Energy Institute, Korea. (Poster 2C-8)—*not included in these proceedings.*

4.3.7 Day 3: Session 3A - Climate and Non-Stationarity

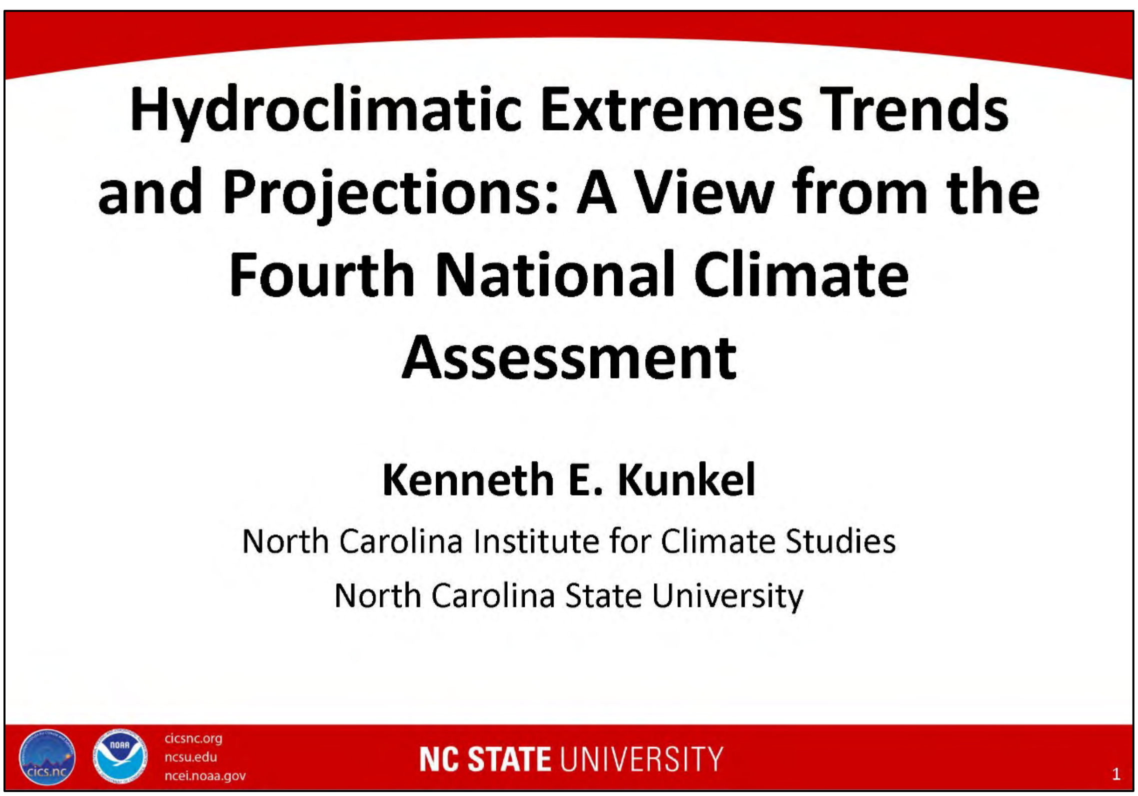
Session Chair: Joseph Kanney, NRC/RES/DRA/FXHAB

4.3.7.1 KEYNOTE: Hydroclimatic Extremes Trends and Projections: A View from the Fourth National Climate Assessment. Kenneth Kunkel*, North Carolina State University (Session 3A-1; ADAMS Accession No. ML19156A475)

4.3.7.1.1 Abstract

This presentation will summarize the findings in the Fourth National Climate Assessment as well as recent work by the presenter. Extreme precipitation has increased overall in the United States. There has been regional variability in the trends, with large increases in the eastern half of the United States and small changes in the far western United States. Future global warming is highly likely to cause further increases in extreme precipitation because atmospheric water vapor concentration will increase as surface ocean waters warm. Analysis of historical precipitation extremes provides a basis for this projection; the magnitude of extreme precipitation events is positively correlated with atmospheric water vapor content. Future changes in floods are much less certain because floods depend on a number of factors in addition to the magnitude of extreme precipitation, such as antecedent soil moisture and flood type.

4.3.7.1.2 Presentation



Outline

- Key findings from the Fourth National Climate Assessment
- Supplementary material from my research

Overarching Question

- How will global warming due to increasing greenhouse gas concentrations change the risk of extreme precipitation events?

The Challenge

- Complex temporal and spatial coherence and variability of extreme precipitation events –
  - Individual thunderstorm cells – hour, a few km
  - Thunderstorm complexes – a few hours, tens-100+ km
  - Spiral rain bands in hurricanes – a few hours, tens-100+ km
  - Low pressure wave – day, 100s of km
  - Hurricanes – day, 100s of km
  - Synoptic low pressure system – days, 1000+ km
  - Hemispheric jet stream wave patterns – weeks, 1000s of km

NCA4

Historical Trends

- Global Historical Climatology Network-Daily (GHCND)
- Long-term stations

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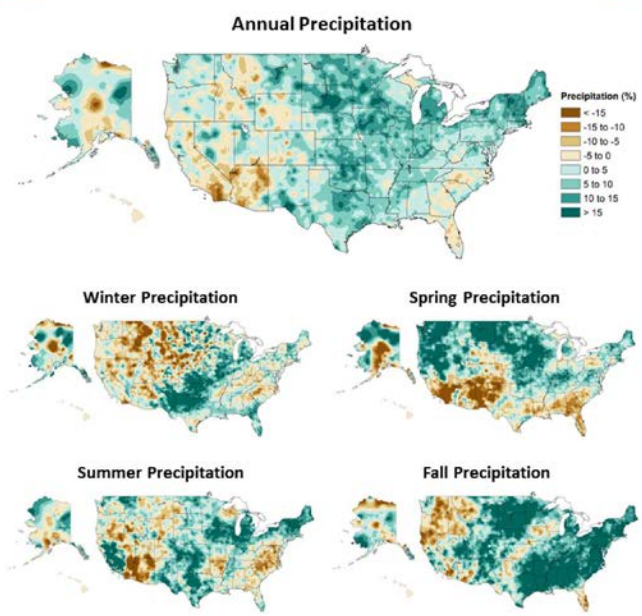
U.S. Mean Precipitation Trends



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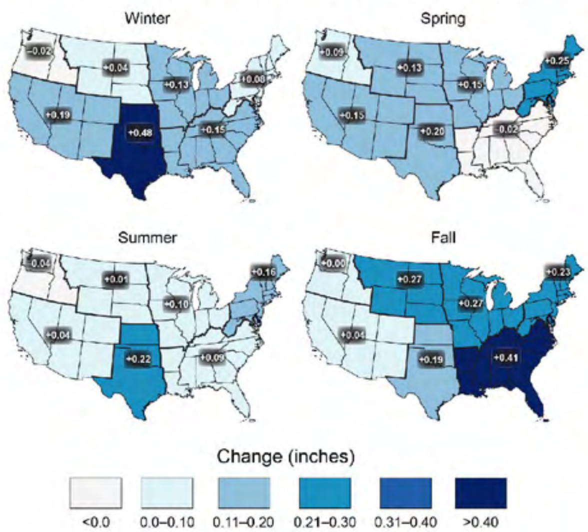
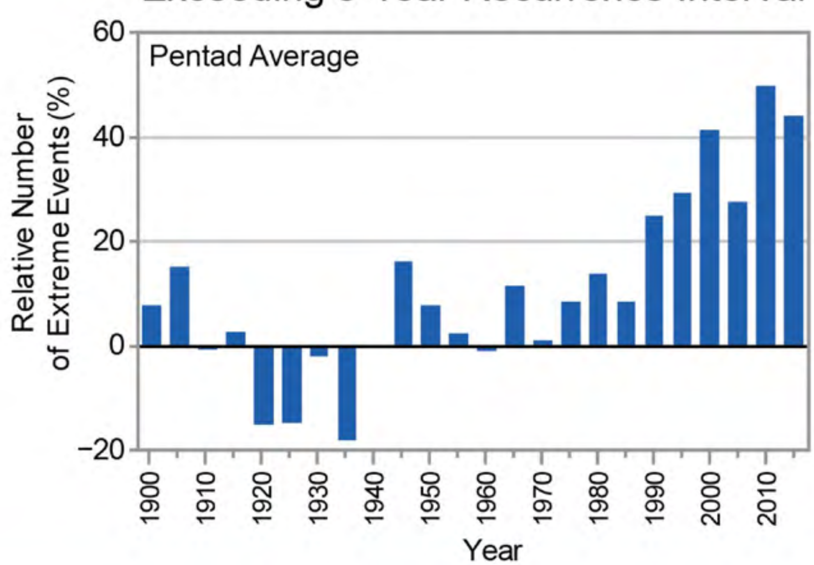
U.S. Extreme Precipitation Trends

Observed Change
in Daily, 20-year Return Level Precipitation

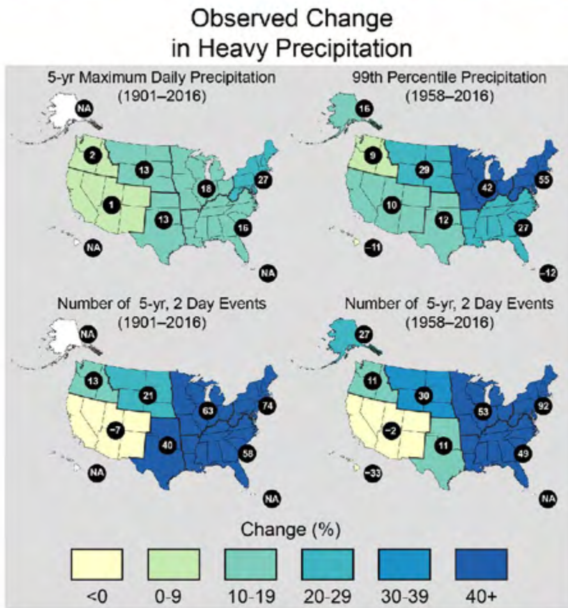


U.S. Extreme Precipitation Trends

2-Day Precipitation Events
Exceeding 5-Year Recurrence Interval



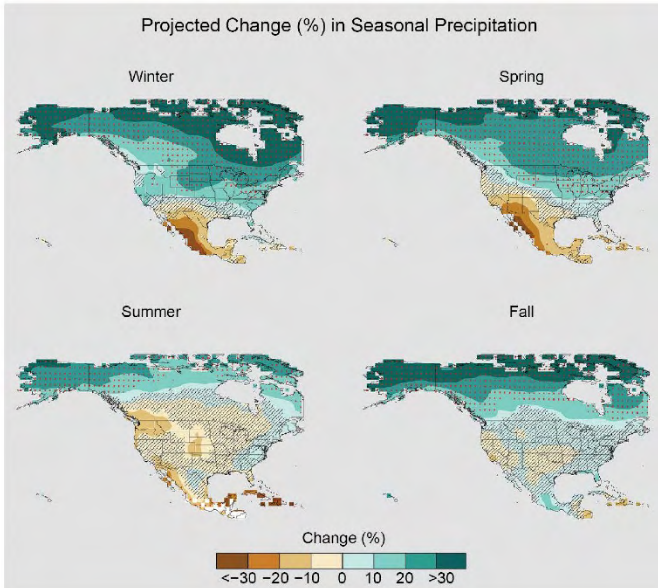
U.S. Extreme Precipitation Trends



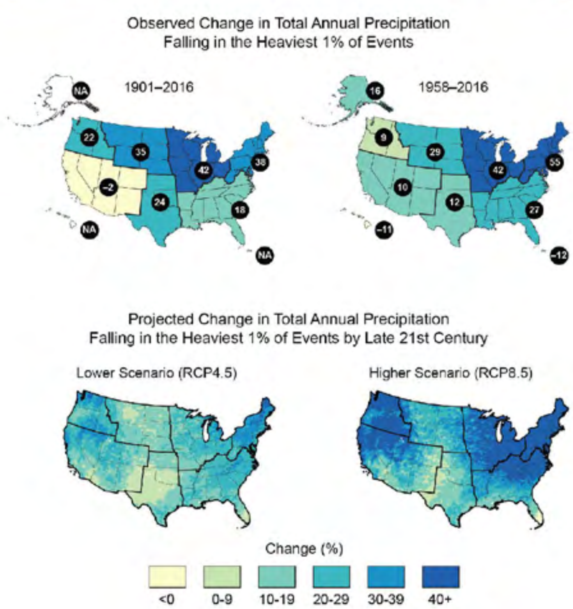
Future Projections

- NCA4 primarily used two future scenarios, RCP4.5 and RCP8.5, to frame the treatment
- Direct output of CMIP5 models
- Statistically downscaled data
  - Localized Constructed Analogs (LOCA)

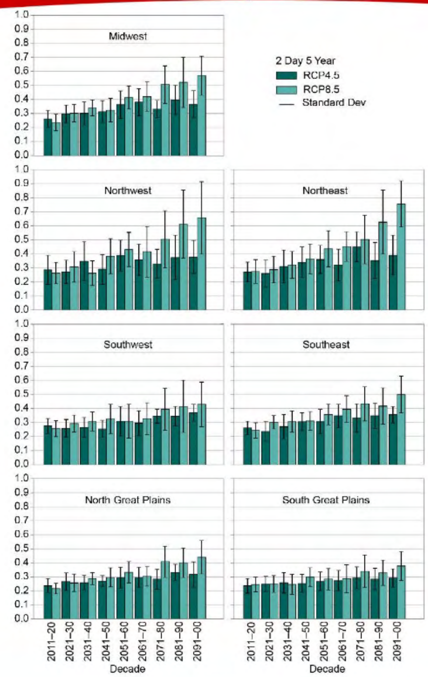
Mean Precipitation Projections



U.S. Extreme Precipitation Trends and Projections



U.S. Extreme Precipitation Projections



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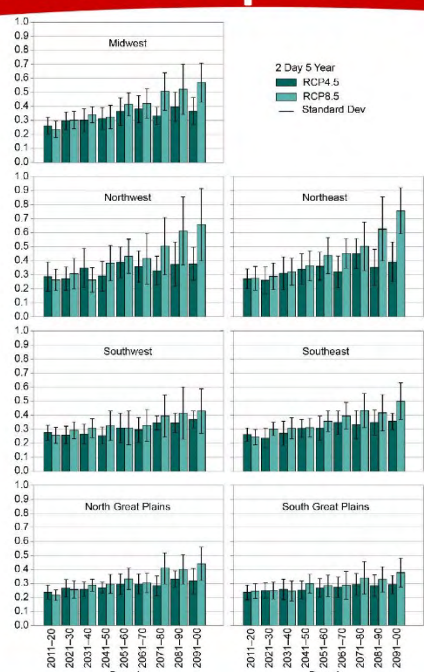
U.S. Extreme Precipitation Projections



Janssen, E., R.L. Shriver, D.J. Wuebbles, and K.E. Kunkel, 2016: Seasonal and regional variations in extreme precipitation event frequency using CMIP5. *Geophys. Res. Lett.*, 43, 5385-5393, doi: 10.1002/2016GL069151

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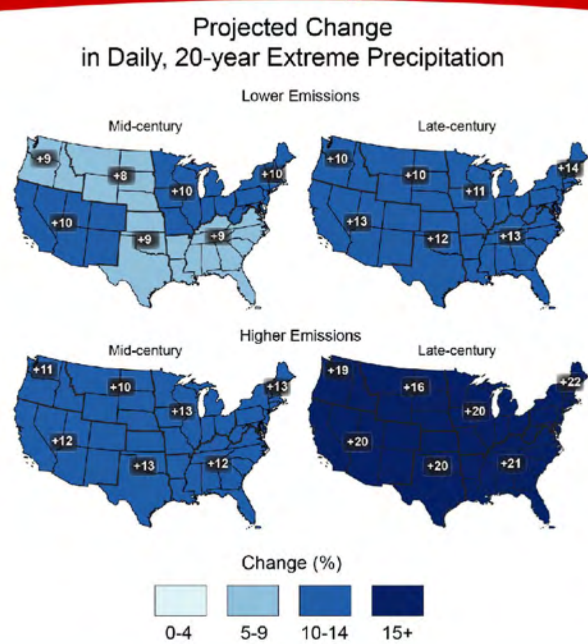
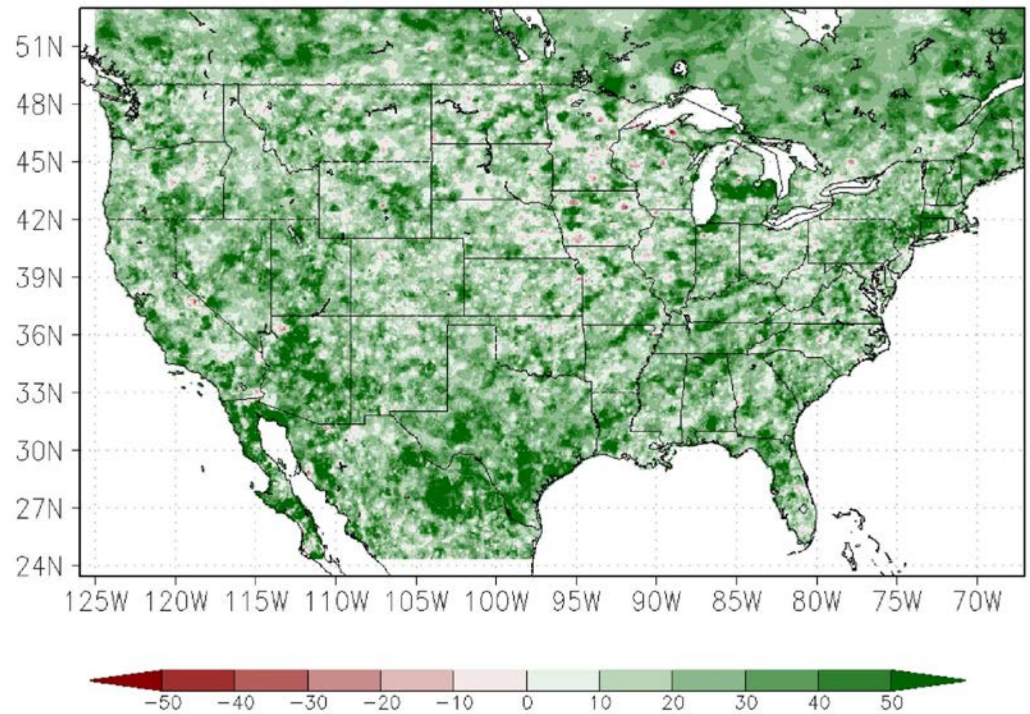
U.S. Extreme Precipitation Projections

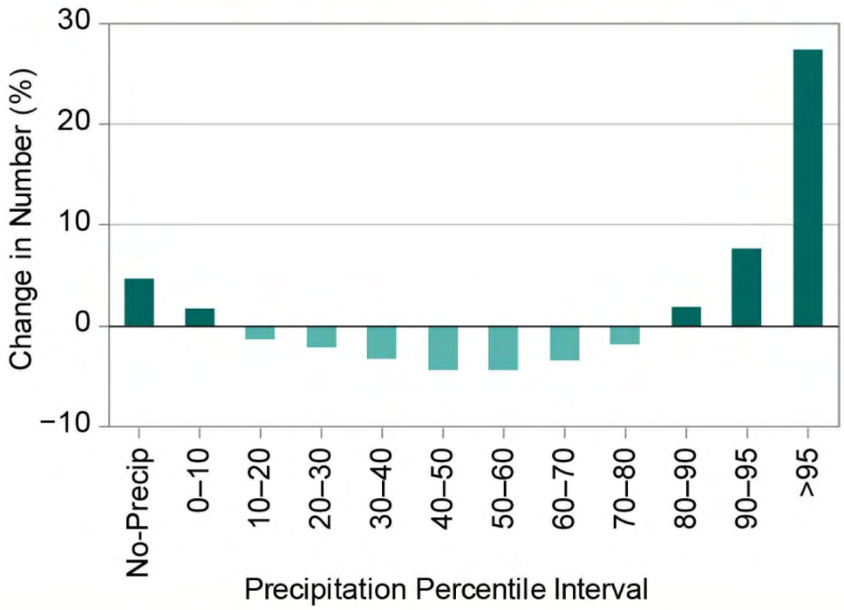
- GEV analysis of daily precipitation
  - Annual Maximum Series of daily precipitation
  - 30-yr time blocks: 1976-2005, 2036-2065, 2070-2099
  - LOCA data

U.S. Extreme Precipitation Trends





U.S. Precipitation Projections



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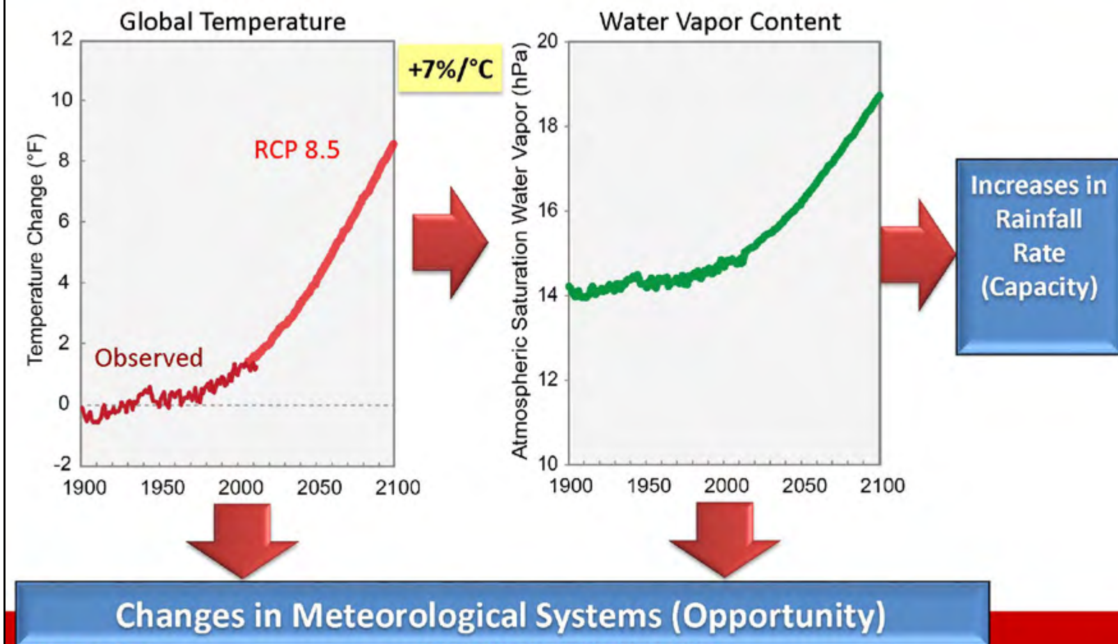
Personal Research Results

Extreme Precipitation Ingredients

- High atmospheric water vapor content
- Upward vertical motion caused by weather systems
  - Extratropical Cyclones
    - Mostly near the fronts of ETCs
  - Tropical Cyclones
  - Intense local convection

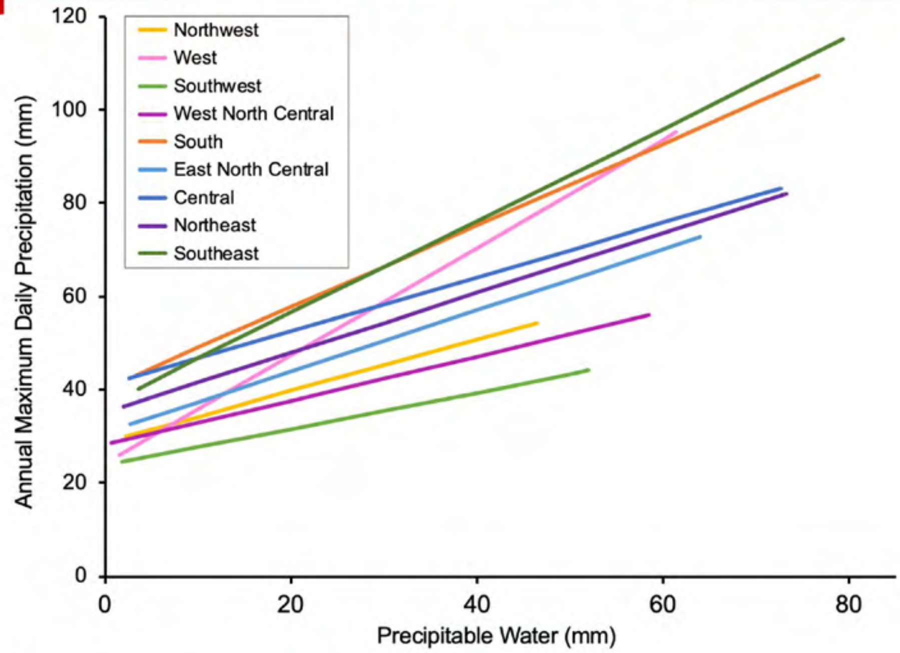
Global Warming->Saturation Water Vapor Increases



Water Vapor-Extreme Precipitation

- Annual maximum daily precipitation (AMS) at 3104 stations
- Relationship of precipitation magnitude with water vapor (precipitable water)
- Relationship of number of extreme precipitation events (1-yr, 1-dy) vs water vapor
- Probability of >25 mm events vs water vapor

Water Vapor and Extreme Precipitation



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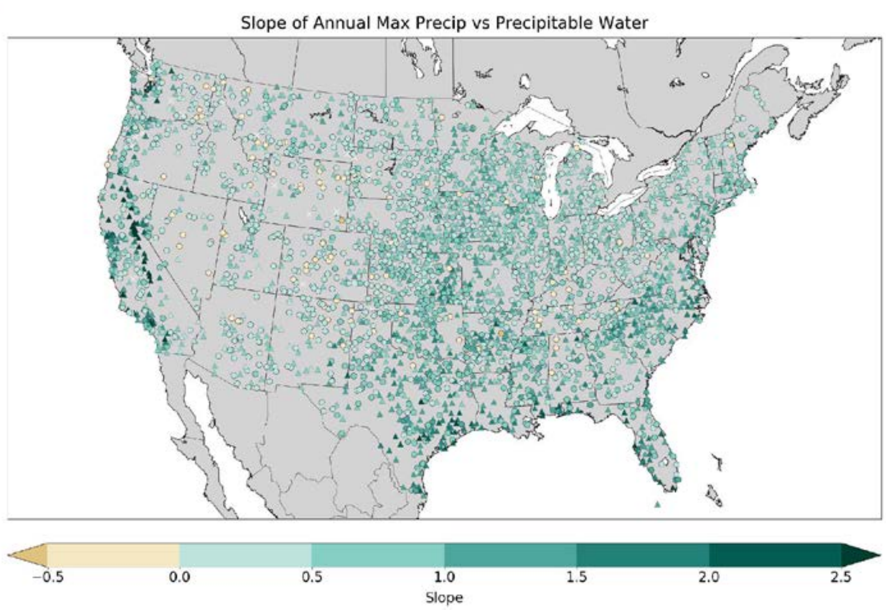
Water Vapor and Extreme Precipitation



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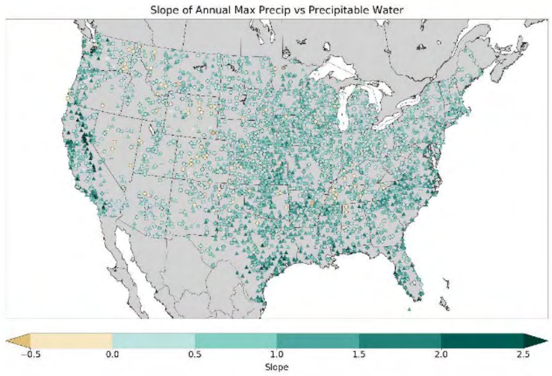
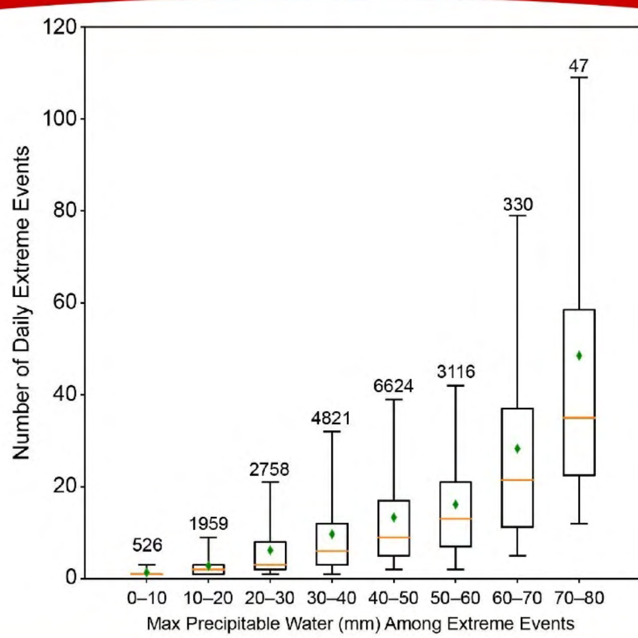
Water Vapor and Extreme Precipitation



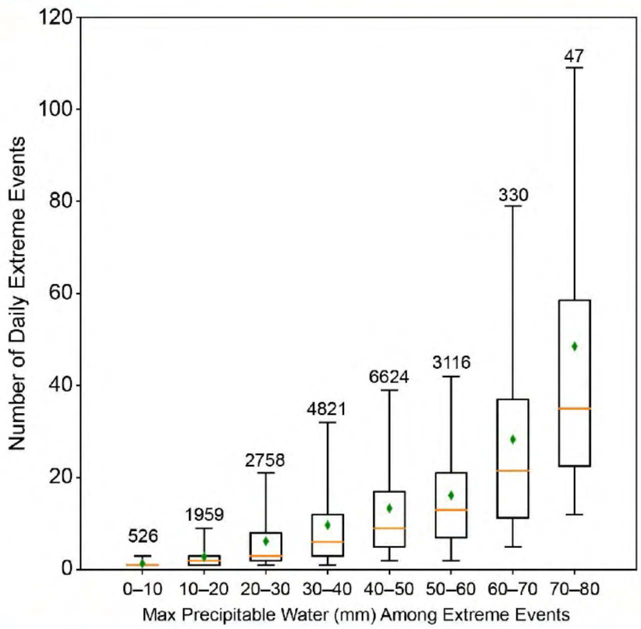
1617 of the 3104 stations have a **statistically significant positive** relationship

0 of the 3104 stations have a **statistically significant negative** relationship

Water Vapor and Extreme Precipitation

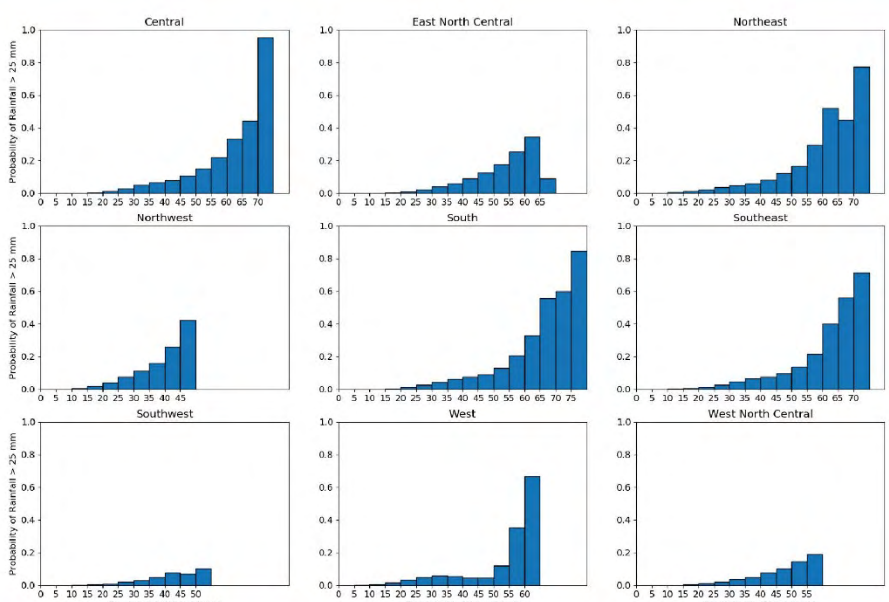


Water Vapor and Extreme Precipitation



Widespread occurrences of extreme precipitation events occur only with high water vapor content

Water Vapor and Extreme Precipitation



Future Projections

- 13 CMIP5 models
- Daily Precipitation
- Highest values of daily precipitation and precipitable water in 30-yr blocks

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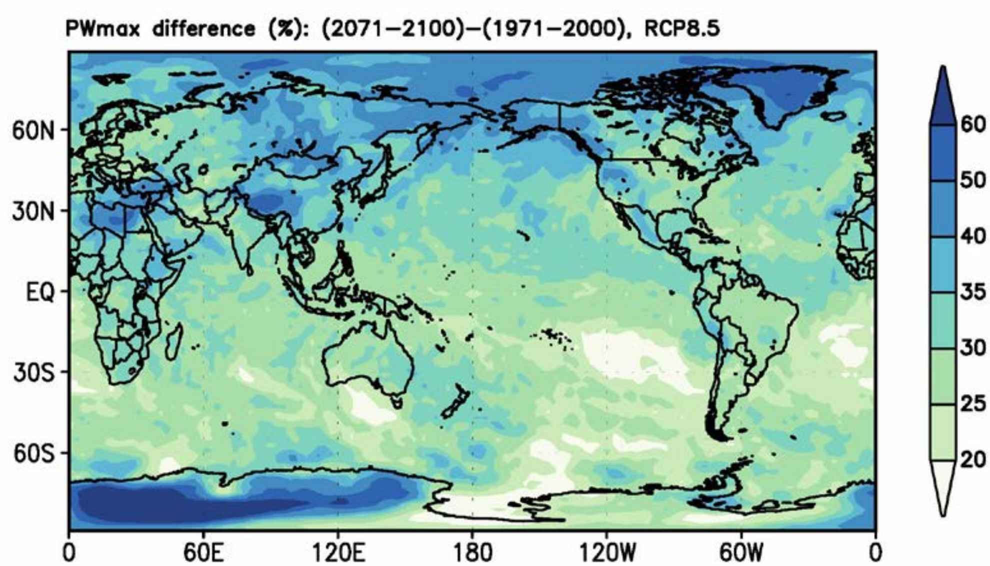
30-yr maximum precipitable water

Projected 100-yr trends



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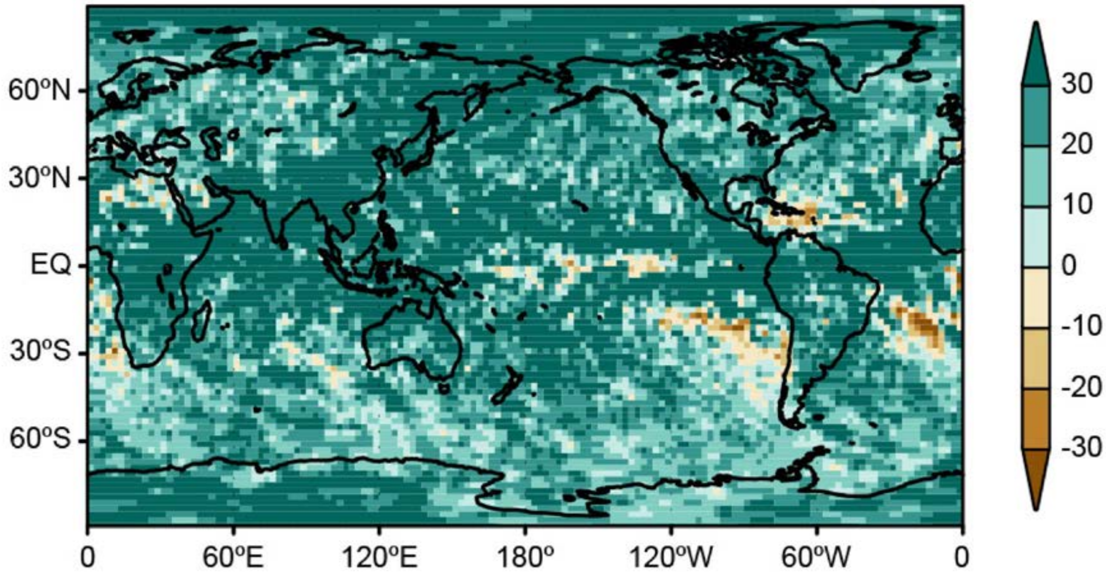
30-yr Maximum Daily Precipitation

Projected 100-yr trends

Maximum Daily Precipitation Difference (%): (2071-2100) - (1971-2000), RCP8.5



Phenomenological Analysis of Weather

- Major **meteorological phenomena** associated with extremes
  - 1-day duration events exceeding threshold for a 1-in-5yr average recurrence interval
  - 1908-2013
  - ~900 stations, > **18,000 events**
  - **Manual analysis**

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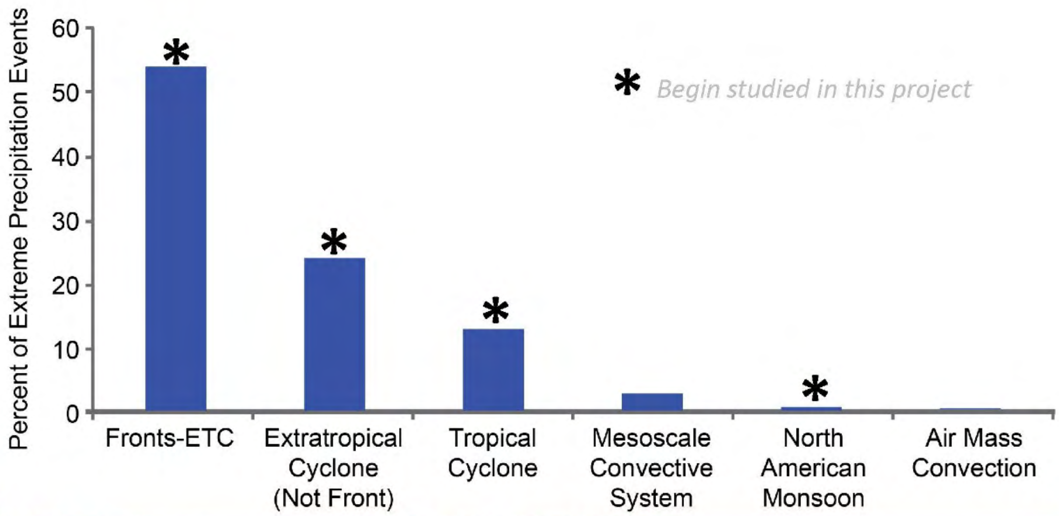
Meteorology Causing Extreme Events

Dominated by Large Systems



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Future Changes in Weather Systems

- Summer fronts may decrease in number
- Extratropical cyclones may also decrease in number but the number of strong ETCs may increase and they may slow down
- Strongest tropical cyclones are projected to increase in number

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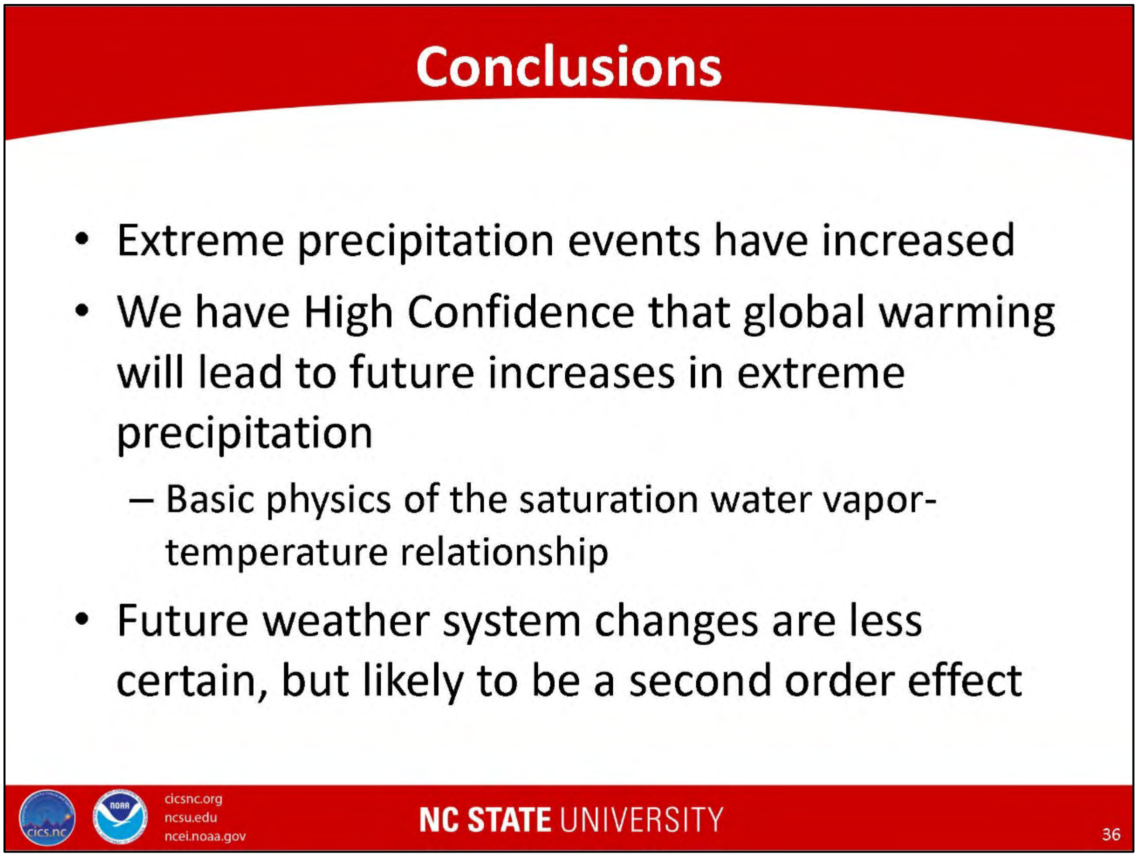


4.3.7.1.3 Questions and Answers

Question:

Inaudible.

Answer:

In terms of total precipitation not changing, in my interpretation of the models, when you have the right ingredients in terms of weather system plus water vapor in the atmosphere, you produce these very heavy rain amounts. You do kind of deplete the atmosphere of water vapor and it has to recharge itself. The recharging or the eventual kind of total precipitation changes in the system are not driven by Clausius-Clapeyron, but rather by changes in the overall energy budget at the surface. Those changes are much more modest, maybe 1 or 2 percent per degree Celsius change in temperature. By virtue of using up the water vapor more efficiently in the storm systems, there's really less available for other systems and that may come along later. You have a greater number of no-precipitation days, which is what the models show.

Question/Comment:

That also implies a smaller number of storms than we expect. What we get is going to be more intense. But a smaller number of storms overall.

Answer:

Generally, one of the things we showed with the models in the assessment was that if you look at a metric of drought, or dry spells, or consecutive dry days, those generally increase in the future; you have longer dry spells in the future. That's one of the counteracting effects in the models.

Question:

What about the issue of multidecadal persistence, and how that affects these trends? From my view of some of the modeling, the models do not handle the longer term, multidecadal persistence particularly well.

Answer:

You have this multidecadal climate mode variability. The Atlantic Decadal Oscillation is an example of one multidecadal oscillation. That's probably a stochastic process that happens in the system. It can happen in some models. But the timing of that, when it happens, is probably largely unpredictable. We have confidence that under this forcing, we should get increases in precipitation. But regionally, there could be modulation by these other factors, such as these kinds of multidecadal oscillations. It's unpredictable. But we could definitely see that in the future. Historically, we have seen some of that; we see no change in the Southwest. It is probably related to some of the changes in the Pacific Decadal Oscillation that have been going on.

Question:

You said you are beginning to look at North American monsoons. What have you discovered in looking at the data? What is causing changes, if there are changes, in the North American monsoons?

Answer:

For the North American monsoon, we have been looking at various metrics that historically are related to occurrence of local extreme precipitation. The one that seems to be the most robust is lower level moisture convergence. It is a larger scale field that models can satisfactorily simulate. When we look at the future, we find that the number of high-convergence days is related to extreme precipitation increase. From that we would expect larger precipitation amounts during North American Monsoon events in the future. Events that would normally be large anyway will become larger. Is that just because of the change in water vapor, or are other dynamic things going on? We are just digging into that now to find out if we can separate the two and how much of it is just purely a water-vapor phenomenon.

Question (from the Webinar):

What is the next step in this research?

Answer:

Right now, we are trying to quantify both the water vapor/thermodynamic part of this and the weather system/dynamic part. Our goal in the research is actually to develop future intensity duration frequency curves for the United States that incorporate the nonstationary process. I hope that we have some results in about a year from now.

4.3.7.2 Regional Climate Change Projections: Potential Impacts to Nuclear Facilities.

L. Ruby Leung* and Rajiv Prasad, Pacific Northwest National Laboratory (Session 3A-2; ADAMS Accession No. ML19156A476)

4.3.7.2.1 Abstract

This project is part of the NRC's PFHA research plan that aims to build upon recent advances in deterministic, probabilistic, and statistical modeling to develop PFHA regulatory tools and guidance. To provide improved understanding of large-scale climate patterns and associated changes in the context of PFHA, this project provides a literature review, focusing on recent studies of the mechanisms of and changes in climate parameters in the future, including discussions of the robust and uncertain aspects of the changes and future directions for reducing uncertainty in projecting those changes. During the first year, the project reviewed various aspects of climatic changes nationwide, the second year focused on more detailed changes in the southeastern United States, and the third year focused on changes in the midwestern United States. The current focus, during the fourth year, is on the northeastern region and on updating the first three years' reports. The Midwest region consists of eight states (Minnesota, Wisconsin, Michigan, Iowa, Missouri, Illinois, Indiana, and Ohio). The third-year report discusses observed historical changes and the projected future changes, drawing on major reports from the National Climate Assessment and peer-reviewed journal papers. Overall, mean and annual 5-day maximum temperatures are projected to increase. With increasing moisture accompanying the warmer temperatures, precipitation is projected to increase in the cool season, but the changes in warm season precipitation are not statistically significant. Despite inconsistency in mean precipitation changes across the seasons, extreme precipitation (99th percentile) is projected to increase by more than 10 and 30 percent by the end of the 21st century under the Representative Concentration Pathway (RCP)4.5 and RCP8.5 emissions scenarios, respectively. Consistent with observational evidence, a regional climate modeling study at 4-km resolution projected more than tripling in the frequency of intense summertime mesoscale convective systems. Lake-effect snow storms are projected to increase as reduction of the surface area of lake ice with warming increases evaporation from the surface; larger warming farther into the future may shift snowfall into rain. The Great Lakes water levels have exhibited large variability historically. Models projected small variations in the lakes' levels with a large range of uncertainty, possibly indicating incomplete understanding of the lakes' water budget. Observational records show strong evidence of increasing flood frequency but limited evidence of increasing flood magnitudes. With the projected increase in extreme precipitation and storm events, flooding is projected to increase notably in the future. Both land use and climate changes affect streamflow with greater effects from the latter. The fourth year report on the northeastern United States is being developed to include literature review on historical and future changes in mean temperature, heat waves, wet bulb temperature, mean and extreme precipitation, extratropical storms, heavy snowfall, severe storms and strong winds (tropical cyclones, severe convective storms, lake effect snow storms), sea level rise, storm surge, nuisance flood, Lake Ontario water level, flood and drought, and stream temperature.

4.3.7.2.2 Presentation

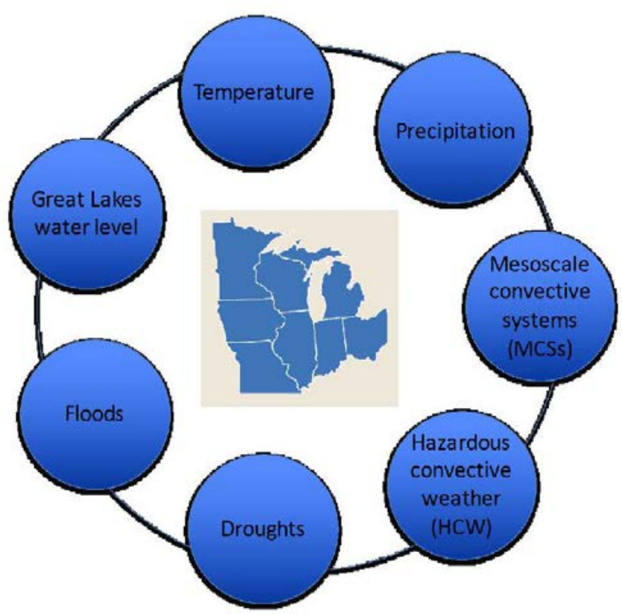
Regional Climate Change Projections - Potential Impacts to Nuclear Facilities

L. Ruby Leung and Rajiv Prasad
Pacific Northwest National Laboratory

4th Annual Probabilistic Flood Hazard Assessment Workshop
NRC Headquarters, Rockville, MD
April 29-May 2, 2019

The Midwest region

- **Midwest Region in NCA3 and NCA4**: Illinois, Indiana, Iowa, Michigan, Minnesota, Missouri, Ohio, Wisconsin
- All states in the Midwest Region except for Indiana, have operating nuclear power plants



NCA4 regions

Observed temperature trends in the Midwest

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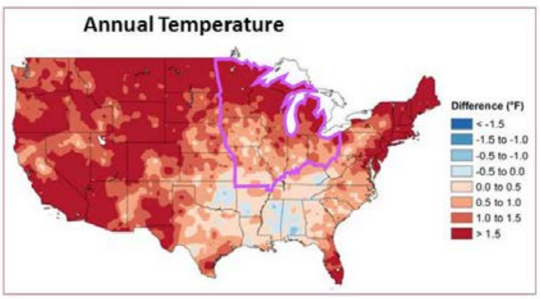
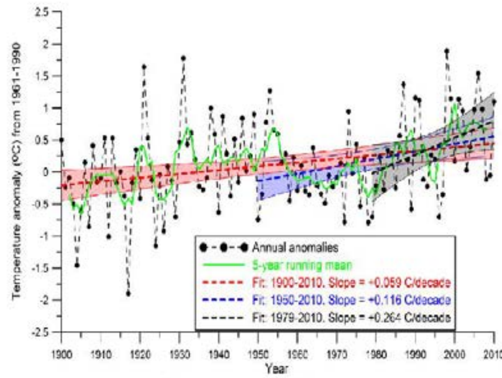
Observed changes between (1986 to 2015) and (1901 to 1960)



(Voss et al. 2017)

Larger rates of warming in more recent decades



(Kunkel et al. 2013)

Future changes in heat waves

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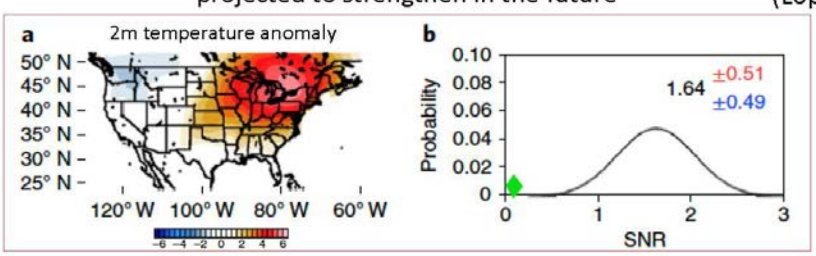
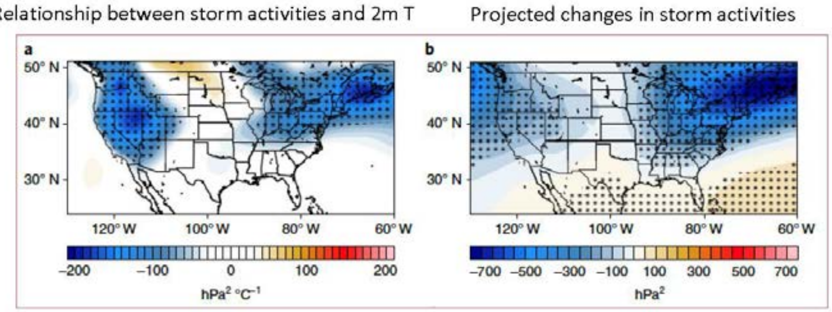
Historically the Great Lakes region is a heat wave cluster, which is projected to strengthen in the future (Lopez et al. 2018)



Projected weakening of storm tracks contribute to increase in heat waves in the Great Lakes region

Relationship between storm activities and 2m T

Projected changes in storm activities



Wet bulb temperature

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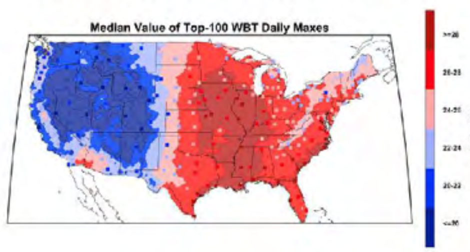
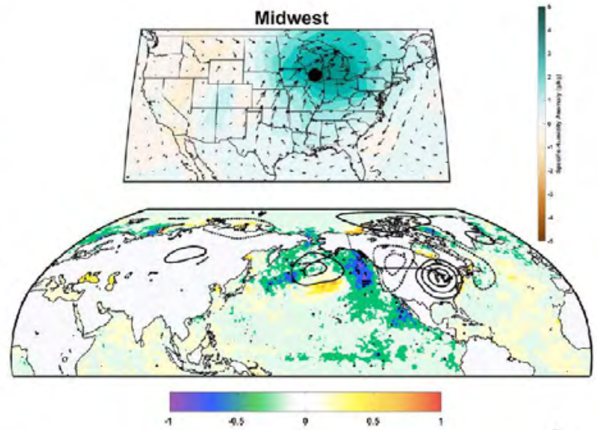
- Humidity anomalies have larger influence on extreme WBT than temperature anomalies
- For the Midwest, extreme WBT is associated with westward expansion of Bermuda high and enhanced southerly moisture transport at the low level and wave train with an upper level ridge

Top-100 WBT daily maximums in the Midwest are between 26°C and 30°C





(Raymond et al. 2017)

Seasonal precipitation changes

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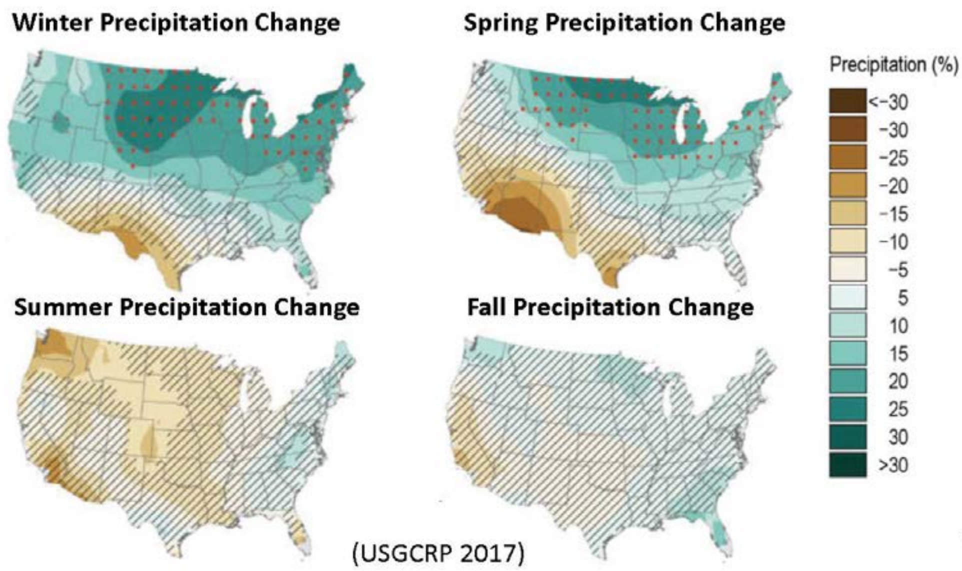
- Annual precipitation in the Midwest has increased by 5% to 15%from 1901–1960 compared to 1986–2015
- Increase in cold season precipitation due to poleward shift of storm tracks



(USGCRP 2017)

Changes in extreme precipitation

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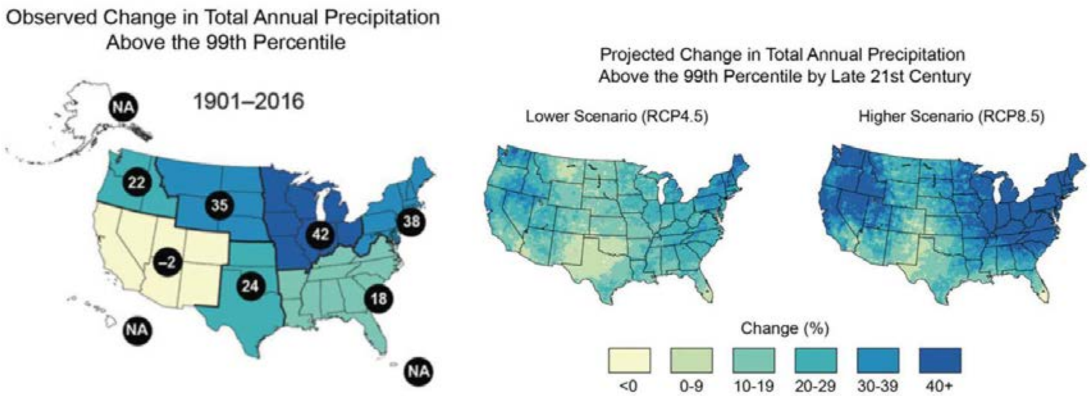
- Observed changes are largest over the Midwest
- Projected changes are largest over the Midwest and western U.S.



(USGCRP 2017)

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Projected changes in precipitation

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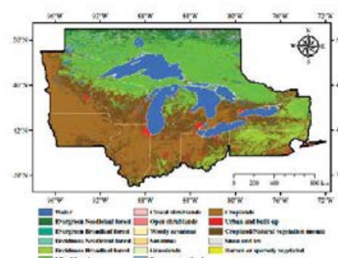
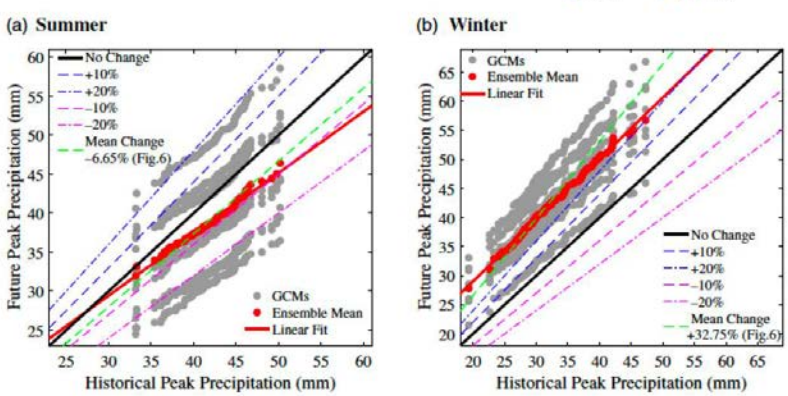
- Select 10 best performing GCMs from 31 CMIP5 models capturing the range of projections
- Use the hybrid delta method to statistically downscaled the 10 GCMs
- Fit GEV and analyze daily peak values





(Byun and Hamlet 2018)

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MCS rainfall increased in the past

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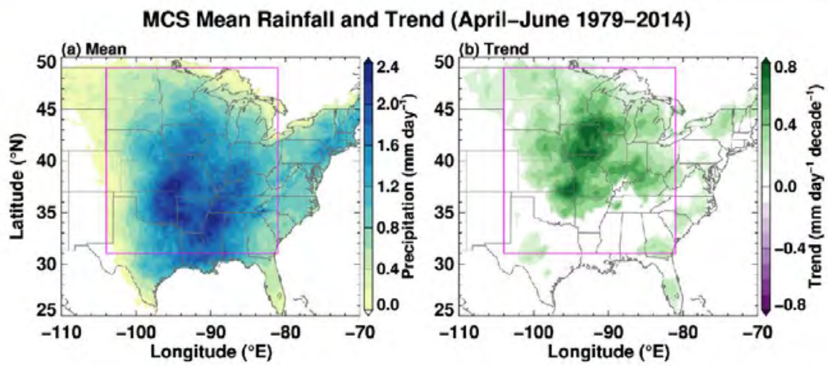
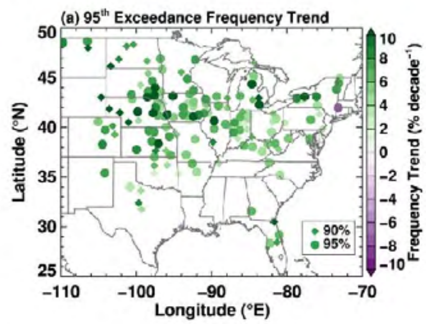


- Some regions in Midwest experienced 0.4-0.8 mm day^{-1} (20-40%) increase in MCS precipitation
- 95th percentile MCS hourly rain-rate increase Moderate to heavy rain-rate (5-30 mm h^{-1}) become more frequent



(Feng et al. 2016 Nature Commun.)

Future changes in MCS precipitation

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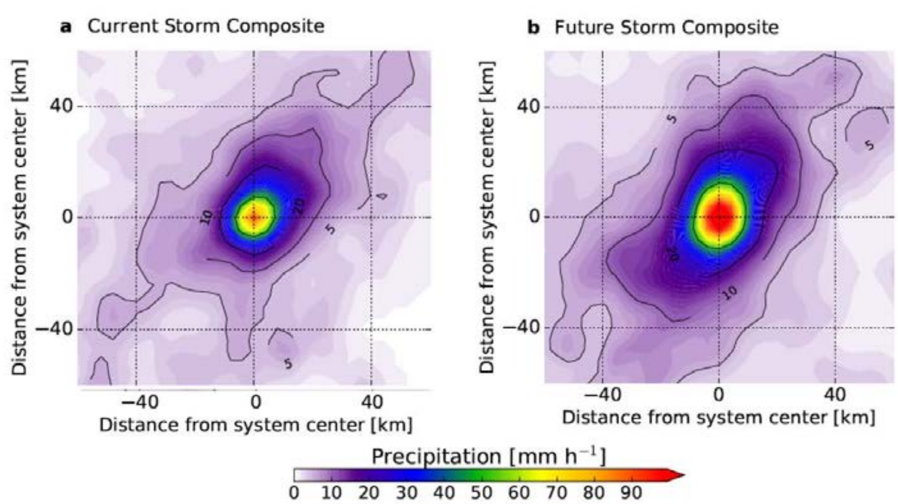
- Intense summertime MCS frequency will more than triple in North America
- MCSs that move slower than 20 kmh^{-1} reduce their speed by up to 20% in the Midwest, Mid-Atlantic, and Canada



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(Prein et al. 2017 Nature Climate Change)

Changes in severe storm environment

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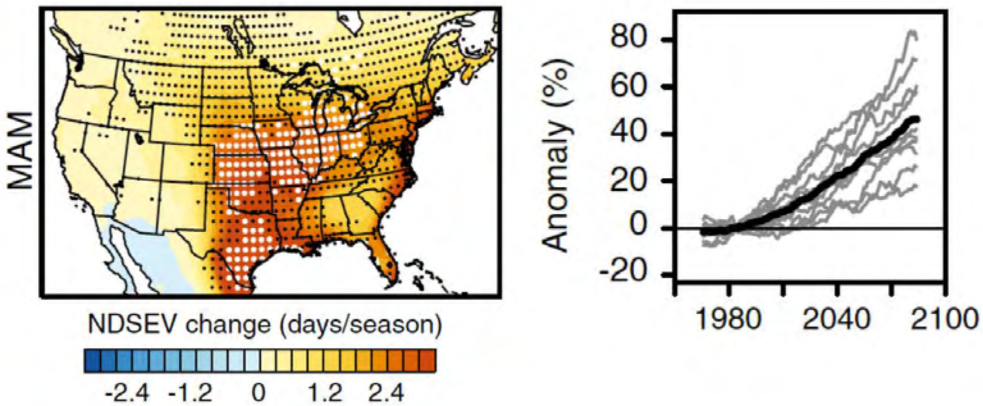
Changes in number of days with spring (March-April-May) severe thunderstorm environment (NDSEV) comparing 2070 to 2099 with 1970 to 1999 from CMIP5 models in the RCP8.5 scenario



(Diffenbaugh et al. 2013)

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Severe weather environment vs. downscaled HCW

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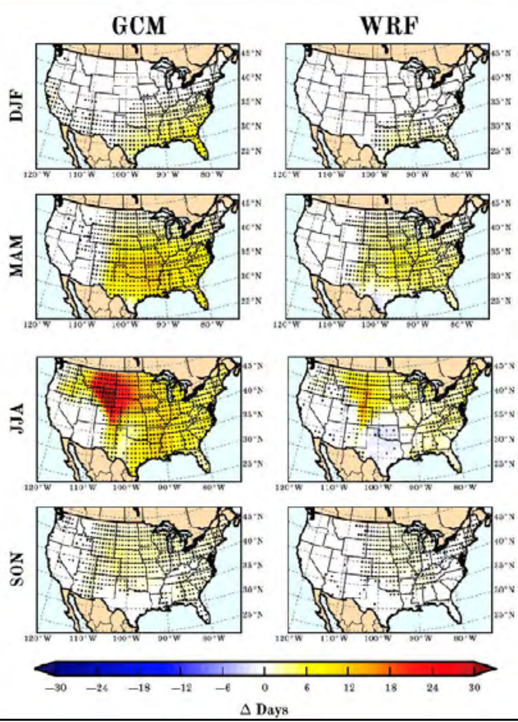
- Larger increase in NDSEV than HCW, particularly in spring and summer
- A ~25% reduction in extratropical cyclone frequency in JJA reduces forced ascent and may be responsible for the smaller change in HCW, despite large change in NDSEV



(Hoogewind et al. 2017)

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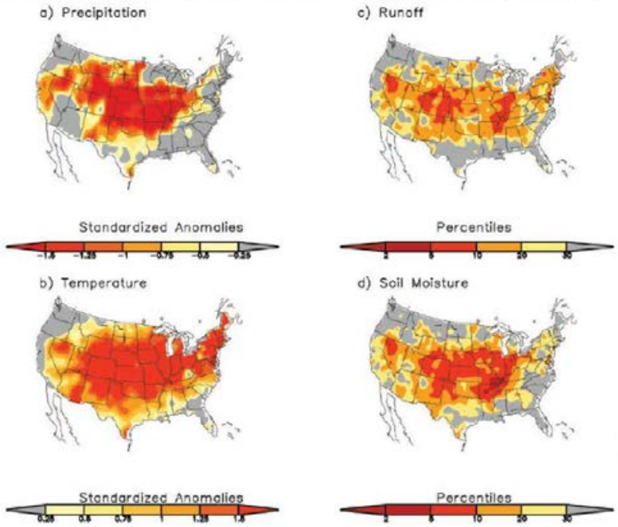
Midwest droughts - historical

- Meteorological (precipitation deficit), Agricultural (soil moisture deficit), and Hydrological (runoff/streamflow deficit)
- 2012 Great Plains/Midwest drought, most severe observed meteorological drought- caused by large-scale meteorology reducing rain during summer (May-August, 2012)

Standardized anomalies over May – Aug 2012 relative to 1979-2011



(Hoerling et al., 2014 BAMS)

13

Midwest droughts - projected

- Increases in temperatures in the future are expected to result in increases in evapotranspiration exceeding increases in precipitation, leading to increased soil moisture deficits and agricultural droughts

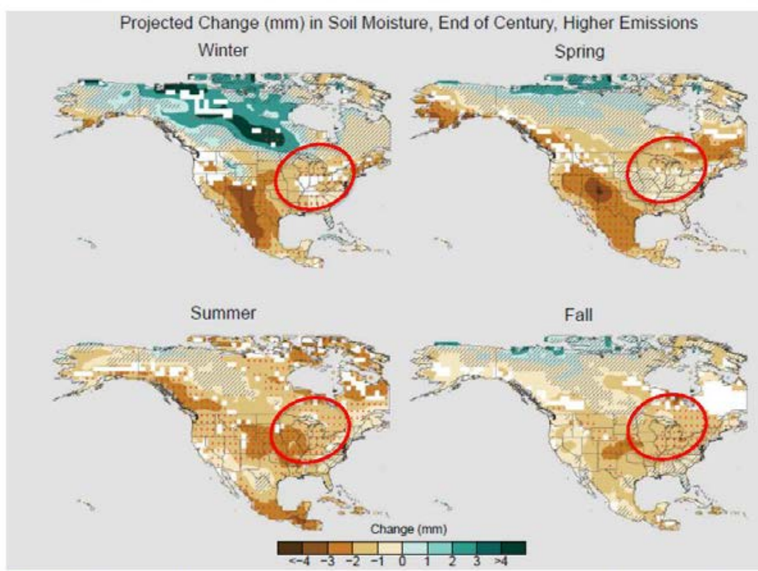


Figure 8.1: Projected end of the 21st century weighted CMIP5 multimodel average percent changes in near surface seasonal soil moisture (mrsos) under the higher scenario (RCP8.5). Stippling indicates that changes are assessed to be large compared to natural variations. Hashing indicates that changes are assessed to be small compared to natural variations. Blank regions (if any) are where projections are assessed to be inconclusive (Appendix B). (Figure source: NOAA NCEI and CICS-NC).

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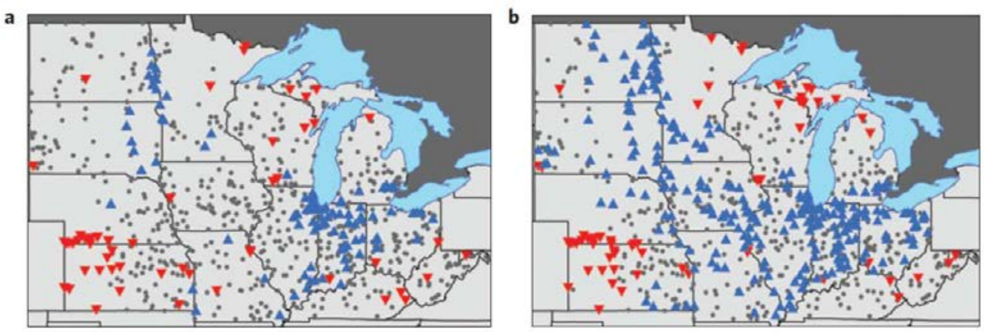
(USGCRP 2017)

Midwest floods - historical

- 2008 floods (USGS Professional Paper 1775)
  - Above-average snowpack, record precipitation, saturated soils, remnants of two hurricanes
- 2011 floods (USGS Professional Paper 1798-B)
  - Large snowpack, near-record spring rainfall, large releases from dams
- Peterson et al. 2013
  - Long-term data from catchments with minimal land-use/water management changes showed peak discharge trend from -10 to +15 percent per decade
- Mallakpour and Villarini, 2015, 2016



Magnitude ▲ Positive trend ▼ Negative trend Frequency

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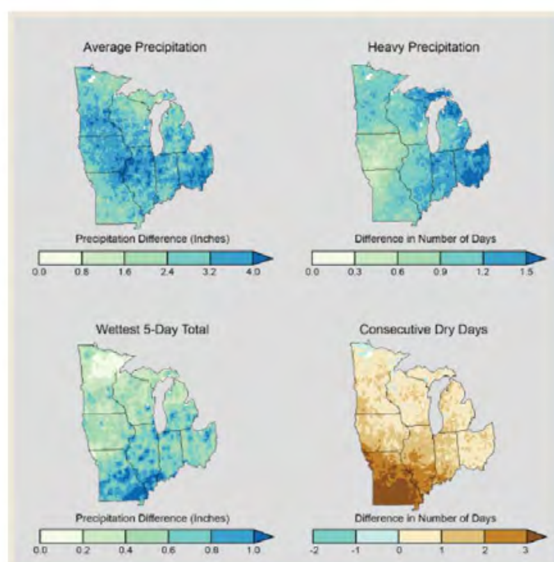
Midwest floods - projected

- Projected future floods
  - NCA3: Increases in rainfall and flooding are expected to continue in the future
    - Total amount of precipitation to increase
    - Number of days with top 2% of rainfalls to increase
    - Wettest 5 -day total precipitation to increase
    - Consecutive dry days to increase (related to droughts)
    - Warm-season precipitation to increase
  - NCA4:
    - Frequency and intensity of heavy precipitation events to increase (high confidence); based on physical reasoning local flooding in some catchments or regions would increase (medium confidence)



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Midwest floods - projected

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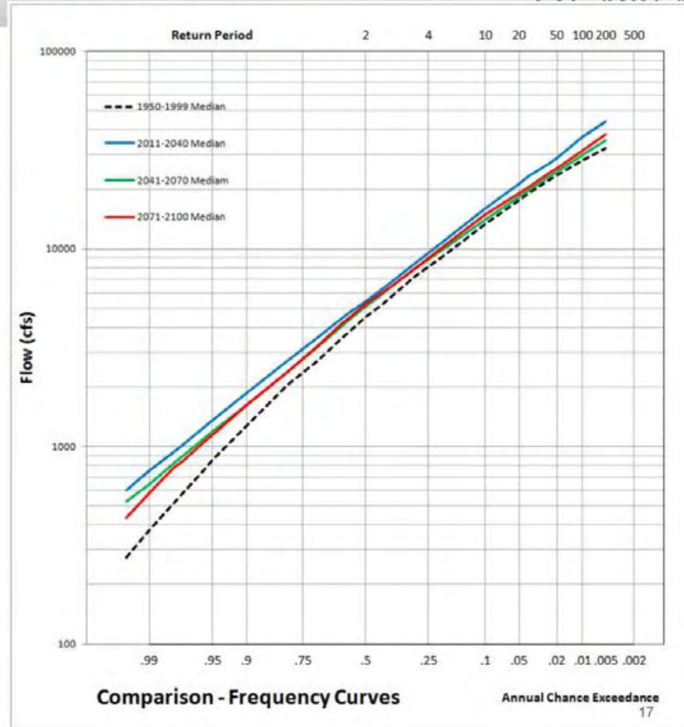
- Projected future floods
  - USACE 2015 – Pilot Study, Impacts of Climate Change on Flood Frequency Curve
    - Red River of the North at Fargo, North Dakota



Midwest floods - projected

Pacific Northwest NATIONAL LABORATORY

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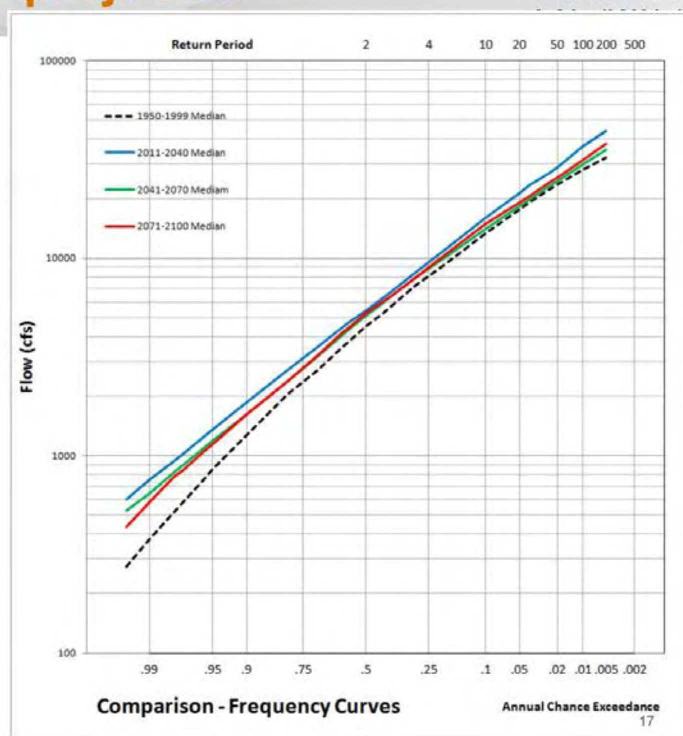

Midwest floods - projected

Pacific Northwest NATIONAL LABORATORY

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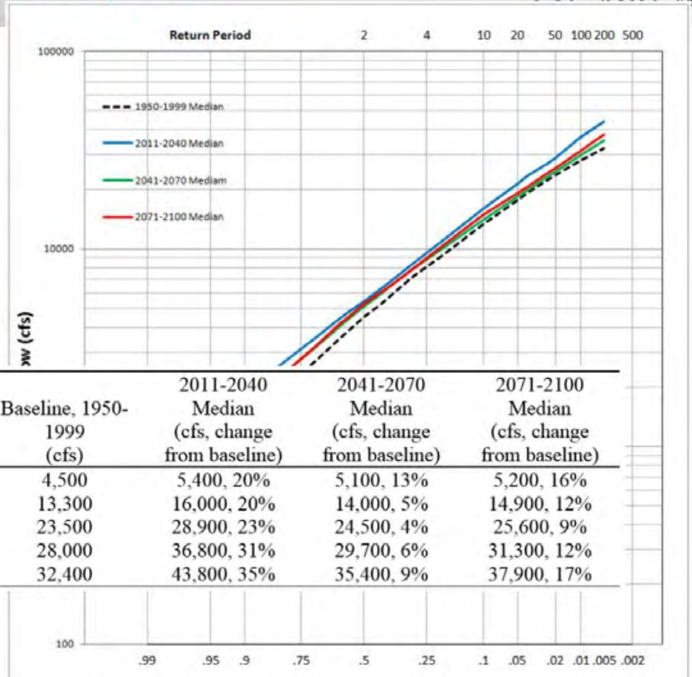

Annual Exceedance Probability	Return Period (yr)	Baseline, 1950-1999 (cfs)	2011-2040 Median (cfs, change from baseline)	2041-2070 Median (cfs, change from baseline)	2071-2100 Median (cfs, change from baseline)
0.5	2	4,500	5,400, 20%	5,100, 13%	5,200, 16%
0.1	10	13,300	16,000, 20%	14,000, 5%	14,900, 12%
0.02	50	23,500	28,900, 23%	24,500, 4%	25,600, 9%
0.01	100	28,000	36,800, 31%	29,700, 6%	31,300, 12%
0.005	200	32,400	43,800, 35%	35,400, 9%	37,900, 17%

Comparison - Frequency Curves

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Great Lakes water levels - historical

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- Historical water levels
  - GLERL's Seasonal and Inter-Annual Water Supply Forecasting Project
    - Uses a suite of hydrologic and hydraulic models
  - Large Lake Statistical Water Balance Model
    - Treats water balance components as random variables; estimates prior probability distributions using historical data; estimates posterior probability distributions using Bayesian approach
    - Was used to explain the record rate of rise in Lakes Superior and Michigan-Huron between January 2013 and December 2014

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Great Lakes water levels - historical

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- Historica'
  - GLERL's Annual Project
    - Uses mod
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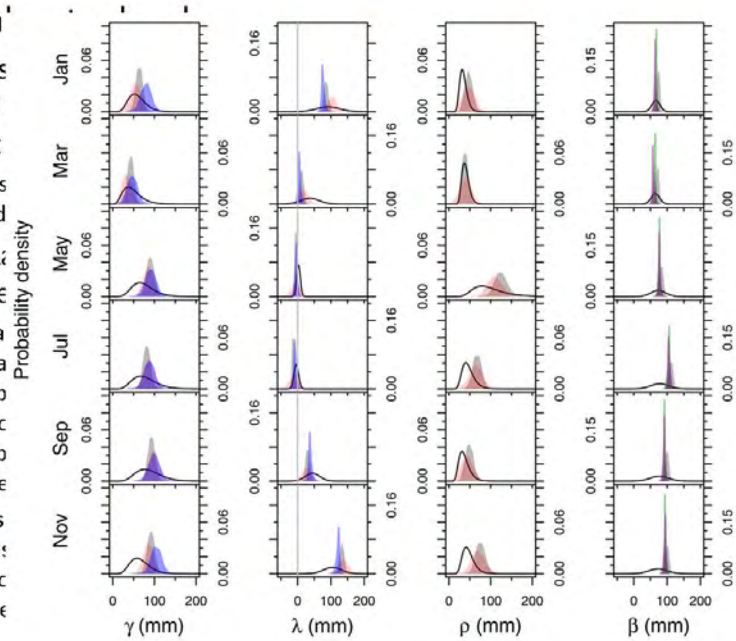

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Great Lakes water levels - historical

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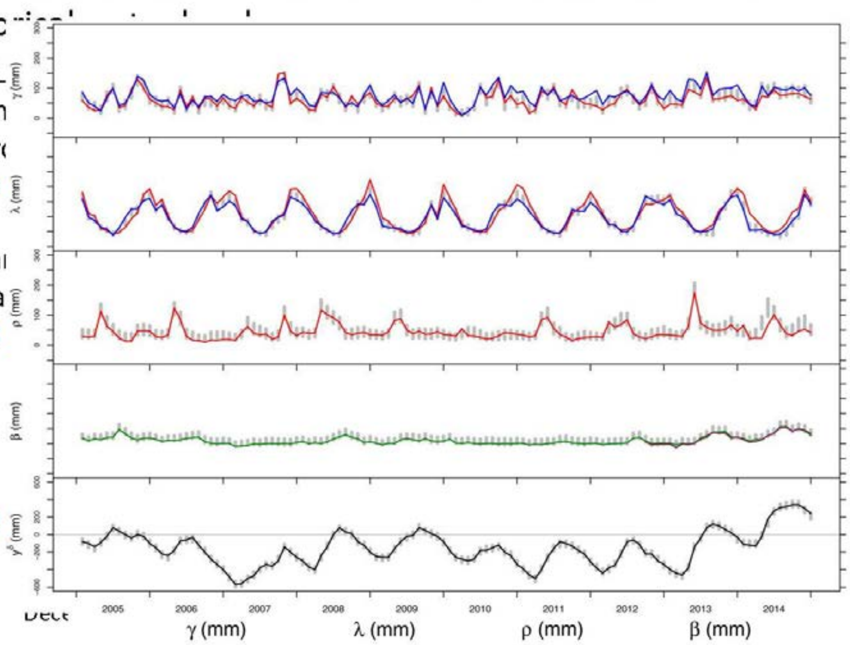

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Great Lakes water levels - projected

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- Projected future water levels
  - International Upper Great Lakes Study, 2012
  - NCA3: Angel and Kunkel, 2010; MacKay and Seglenieks, 2012
  - Notaro et al. 2015
  - Lofgren et al. 2011; Lofgren and Rouhana 2016

Table 4-3: Estimated Lake Level Changes for Lake Michigan-Huron at the 5th, 50th and 95th percentiles

Year	5th	50th	95th
B1 Emission Scenario			
2020	-0.60	-0.18	0.28
2050	-0.79	-0.23	0.15
2080	-0.87	-0.25	0.31
A1B Emission Scenario			
2020	-0.55	-0.07	0.46
2050	-0.91	-0.24	0.40
2080	-1.43	-0.28	0.83
A2 Emission Scenario			
2020	-0.63	-0.18	0.20
2050	-0.94	-0.23	0.42
2080	-1.81	-0.41	0.88

Source: Angel and Kunkel (2010)

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Great Lakes water levels - projected

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- Projected future water levels
  - International Upper Great Lakes Study, 2012
  - NCA3: Angel and Kunkel, 2010; MacKay and Seglenieks, 2012
  - Notaro et al. 2015
  - Lofgren et al. 2011; Lofgren and Rouhana 2016

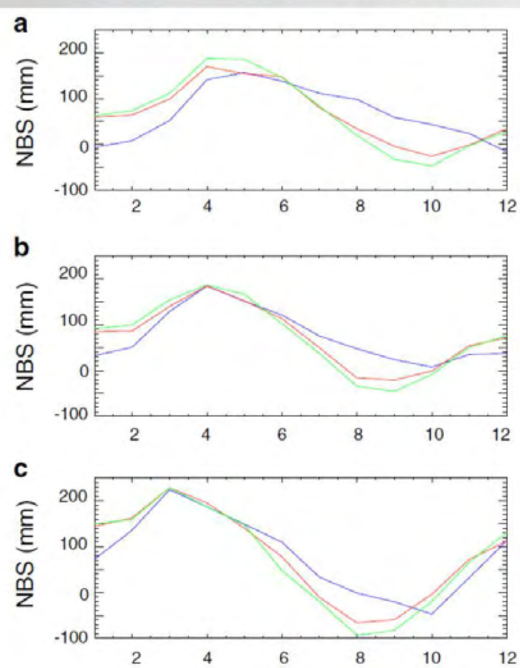

Fig. 3 NBS mean seasonal cycle for: **a** Lake Superior; **b** Lake Michigan – Huron; **c** Lake Erie. blue-observed (EC residual method); red-GLRCM 1962–1990; green-GLRCM 2021–2050. Units are mm over lake surface area

23

Great Lakes water levels - projected

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- Projected future water levels
  - International Upper Great Lakes Study, 2012
  - NCA3: Angel and Kunkel, 2010; MacKay and Seglenieks, 2012
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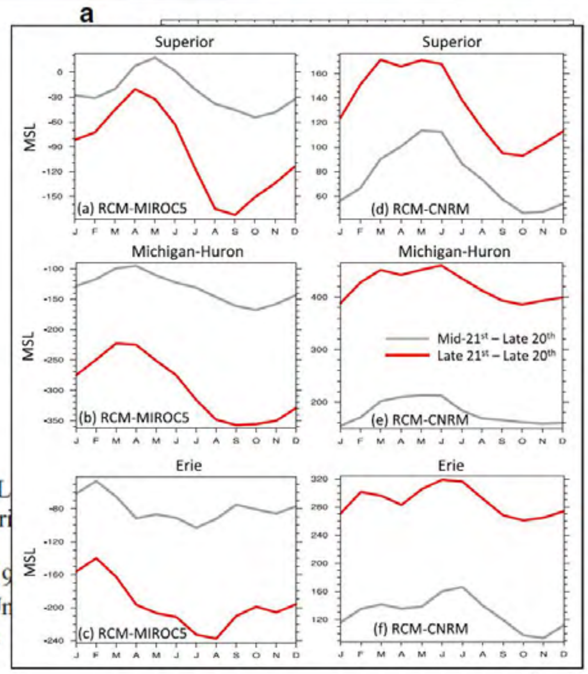

Fig. 3 NBS mean seasonal cycle for: **a** Lake Superior; **b** L Michigan – Huron; **c** Lake Eri blue-observed (EC residual method); red-GLRCM 1962–19 green-GLRCM 2021–2050. Ur are mm over lake surface area

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Summary

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- The Midwest has seen warming and larger increase in precipitation in the past compared to other US states
- Hot days and extreme precipitation are projected to increase in the future
- Convection permitting modeling is becoming viable for projecting changes in MCSs and HCW
  - MCS precipitation has increased in the past and is projected to increase in the future
  - HCW and its large-scale environment are projected to be more frequent in the future
- Droughts are projected to be more intense and last longer due to earlier snowmelt and increase in summer ET
- Floods may increase as extreme precipitation increases
- Great Lakes water level may become lower in the future

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4.3.7.2.3 Questions and Answers

Question (from the webinar):

Slide 3 has no observed temperature data for the period from 1961 to 1985. Why is that?

Answer (Ruby Leung):

There are observed data. This figure is just comparing two time periods, and the study selected to have a comparable time period for 16 years, versus 18. It's not a problem of not having data, it is just that the way they chose to select two time periods to do the comparison.

Question:

The title of your presentation included potential impacts to nuclear facilities. Did you perform any climate change projections related to any particular nuclear facilities?

Answer (Ruby Leung):

No, this project is mainly about reviewing the literature that we find about climate projections or hydrological projections. We are not specifically looking at nuclear facilities. The type of extreme discussed in the literature, that exceedance probability, is not really similar to what the NRC is concerned about in terms of safety.

Joseph Kanney:

The project was designed to look into the climate science literature to find out if there is useful information for nuclear safety. We found that there is a gap in terms of what is considered extreme in the dam safety and nuclear safety worlds, versus what is typically referred to as extreme in the climate sciences. There is a difference in terminology. But we think that understanding what the climate trends are, seeing what the climate projections are, informs our work. But this project is not collecting data that we can put into an analysis at present.

Question (John England):

Rajiv Prasad, USBR has a long history doing downscale analyses and propagating them through VIC, a hydrological model. I want to point out a gap and see if you found any areas in your research or in your literature review, particularly around the flows. We have had problems with model calibration. What I showed yesterday was to include rainfall runoff models for extreme flood prediction. We want those variances of those estimates. One of the slides you showed earlier had statistical analysis of the flows for a time window of perhaps 90 days. In my estimation, those models perform absolutely poorly. They do bias correction at a monthly timescale. If we are not able to get the monthly flows right, and we correct them after we run the models, what can we say about the tails? Have you found anything? We are searching the climate literature with regard to this gap, such as 3-day flows, the flood, and the runoff response side.

Answer (Rajiv Prasad):

You are right that bias correction is a major issue. As far as I remember, in the study we showed, the bias correction was not done on the flows but on the climate projections, and then there wasn't that much of a rigorous calibration. It was mostly visual, trying to determine whether the spread, using those 90 realizations of daily sequences, could actually bracket what the history was doing, looking at the historical period of 3 months. That was the basis for determining that the models were performing well for the historical timeframe and then using PRISM. But I have not seen bias correction, particularly at the frequencies or annual exceedance probabilities used in licensing.

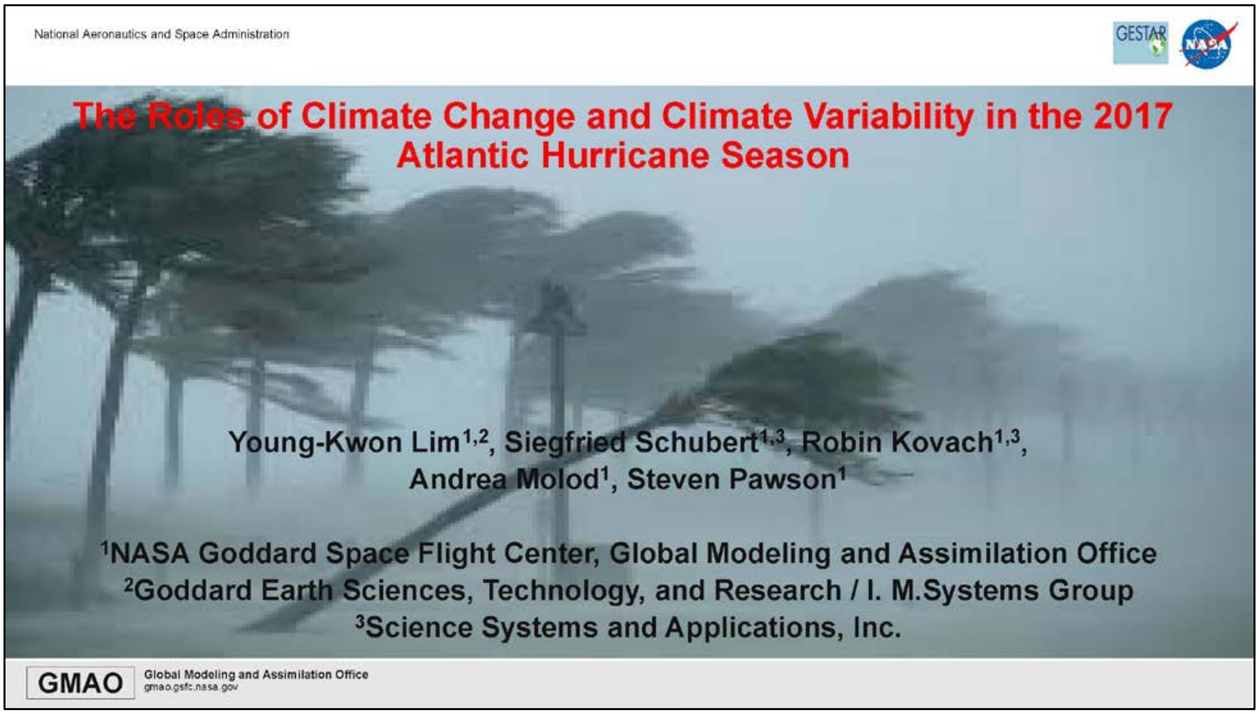
4.3.7.3 Role of Climate Change/Variability in the 2017 Atlantic Hurricane Season. Young-Kwon Lim*, NASA/GSFC, Global Modeling and Assimilation Office and Goddard Earth Sciences, Technology, and Research/I.M. Systems Group; Siegfried Schubert and Robin Kovach, NASA/GSFC, Global Modeling and Assimilation Office and Science Systems and Applications, Inc.; Andrea Molod and Steven Pawson, NASA/GSFC, Global Modeling and Assimilation Office (Session 3A-3; ADAMS Accession No. ML19156A477)

4.3.7.3.1 Abstract

The 2017 Atlantic hurricane season was extremely active with six major hurricanes, the third most on record. The sea-surface temperatures (SSTs) over the eastern Main Development Region (EMDR), where many tropical cyclones (TCs) developed during active months of August and September, were ~0.96 degree Celsius above the 1901–2017 average (warmest on record): about ~0.42 degree Celsius from a long-term upward trend and the rest (~80 percent) attributed to the Atlantic Meridional Mode (AMM). The contribution to the SST from the North Atlantic Oscillation (NAO) over the EMDR was a weak warming, while that from El Niño–Southern Oscillation (ENSO) was negligible. Nevertheless, ENSO, the NAO, and the AMM all contributed to favorable wind shear conditions, while the AMM also produced enhanced atmospheric instability.

Compared with the strong hurricane years of 2005 and 2010, the ocean heat content (OHC) during 2017 was larger across the tropics, with higher SST anomalies over the EMDR and Caribbean Sea. On the other hand, the dynamical and thermodynamical atmospheric conditions, while favorable for enhanced TC activity, were less prominent than in 2005 and 2010 across the tropics. The results suggest that unusually warm SST in the EMDR, together with the long fetch of the resulting storms in the presence of record-breaking OHC, may be key factors in driving the strong TC activity in 2017.

4.3.7.3.2 Presentation



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Extremely active Atlantic hurricane season in August/September 2017

1. **Six major hurricanes** (two of them Category 5 (Irma and Maria)).
2. **The third highest number of major hurricanes** (exceeded only by the 1961 and 2005).
3. **10 consecutive named storms have strengthened into hurricanes.**
4. **Quick growth to hurricane level** and **long life times** (Harvey, Irma, Jose, and Maria).
5. **The fourth largest total accumulated cyclone energy (ACE)** since 1950.
6. **The ACE for September 2017: the largest ACE in a single month** in the Atlantic basin.

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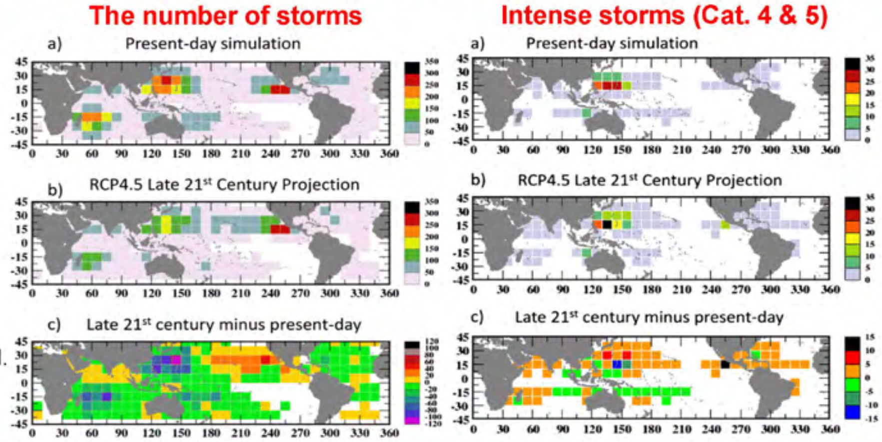
Tropical cyclone activity under climate change (previous study)

The number of storms | **Intense storms (Cat. 4 & 5)**



Present (P)

Climate change (CC)

CC minus P

Knutson et al. (2015) J. Climate

Fewer TCs in a warmer climate, but also an increase in the number and occurrence days of very intense TCs.

Large consumption of the evaporating moisture → more possibility of intense TCs → large cooling effect over ocean → less TC genesis

Wind current slowed down by climate change → slowly moving TCs

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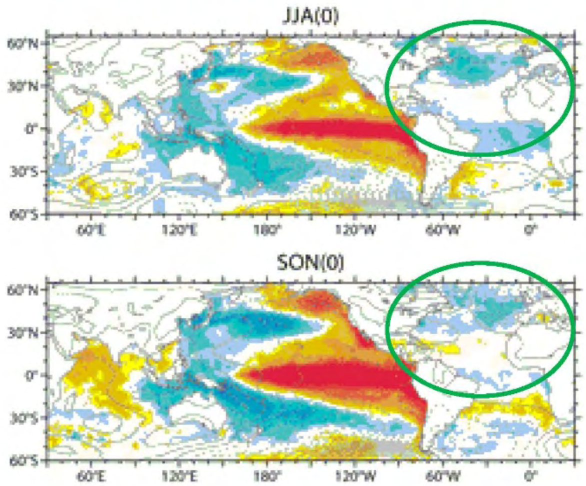
The leading climate variability that impacts the North Atlantic TC activity



Deser et al. (2010) Annu. Rev. Mar. Sci.

ENSO

The positive phase of the ENSO (El Niño) during the Atlantic hurricane season (June – November) : positive SST anomalies over the tropical eastern Pacific, with near zero or negative anomalies across the Main development region, indicating unfavorable conditions for the TC genesis over the North Atlantic, and vice versa for the negative phase of the ENSO (La Niña).

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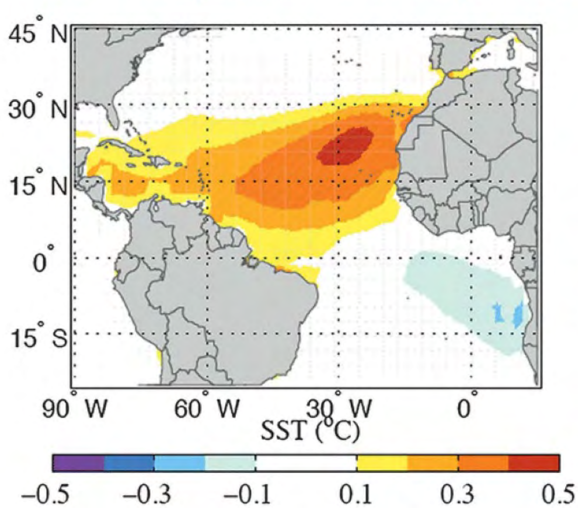
The leading climate variability that impacts the North Atlantic TC activity



Smirnov and Vimont (2011) J. Climate

Atlantic Meridional Mode

The positive phase of the AMM is characterized by positive SST anomalies over most of the Northern Atlantic covering the Main Development Region, indicating favorable conditions for the TC genesis over the North Atlantic, and vice versa for the negative phase of the AMM.

Atlantic Multidecadal Oscillation (AMO), representative of the North Atlantic SST condition, similar to the AMM, also impacts the North Atlantic TC activity significantly on decadal time scale.

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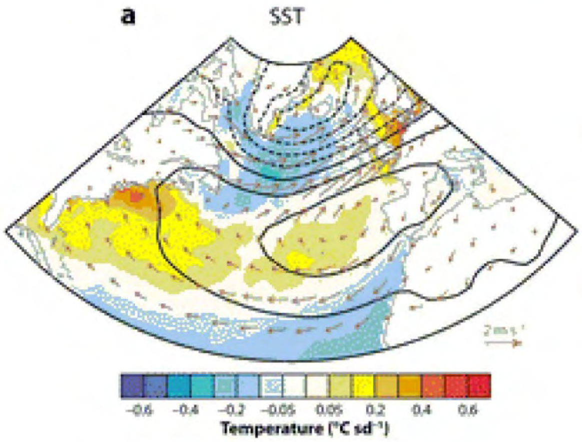
The leading climate variability that impacts the North Atlantic TC activity



Deser et al. (2010) Annu. Rev. Mar. Sci.

North Atlantic Oscillation

The positive phase of the NAO : includes the well-known North-South tripole structure over the extra-tropical Atlantic. A negative SST anomaly (shaded) dominates the Main Development Region (MDR), which is not favorable for strong TC activity. The negative phase of the NAO is known to be more favorable for TC genesis over the MDR.

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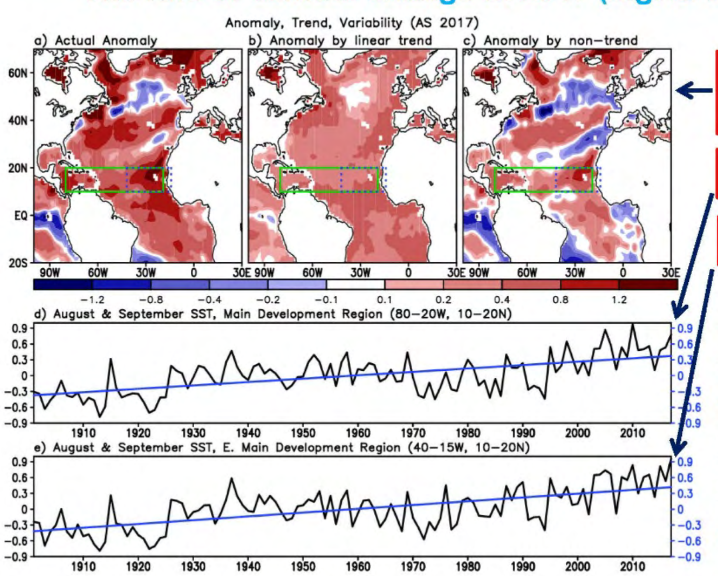
The role of climate change in 2017 (signal in sea surface temperature)



North Atlantic SST anomalies (actual, trend, non-trend) in Aug/Sep 2017

Main Development Region (MDR)

Eastern MDR

The long-term trend (climate change signal): ~0.37 (MDR) and ~0.42°C (EMDR).

Non-trend: ~0.41 (MDR) and ~0.54°C (EMDR).

The third highest MDR SST, following 2010 and 2005. SST anomaly in the EMDR, where tropical disturbances developed and grew to be major hurricanes during AS 2017 (e.g., Harvey, Irma, Jose, Lee, and Maria), is the highest on record (~0.96°C).

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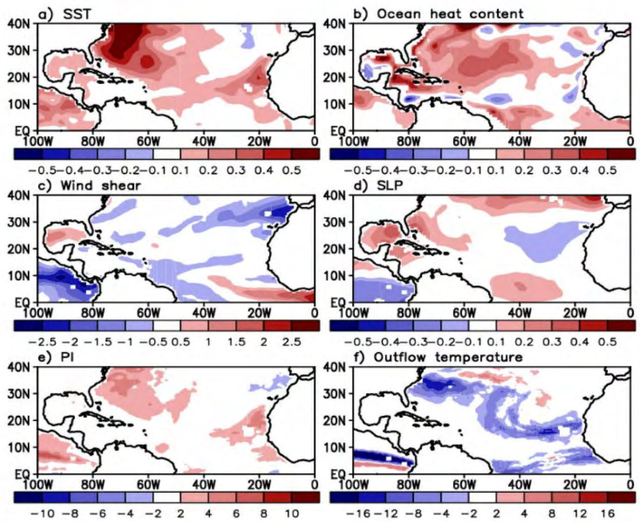
The role of climate change

Trend distributions of SST & ocean heat content (ocean), wind shear & sea level pressure (dynamical impact), and potential intensity and outflow temperature (thermodynamical impact)



Ocean (SST&OHC) shows larger trend than atmosphere. Wind shear and outflow T is getting weaker and cooler.

The upward trend in the OHC is primarily observed over the western-central North Atlantic, associated with maintaining warm ocean surface and strengthening of hurricanes as they traverse the Atlantic.

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REOFs for capturing the leading modes of climate variability

In order to assess the contributions of the leading modes of climate variability to the SST anomalies, we decompose the SST anomalies in terms of Rotated Empirical Orthogonal Functions (REOFs) for the August/September months over the period 1982-2017.

The climate change signal has been first removed for the period 1901–2017 to solely investigate the climate variability, and the resulting SST for the period 1982–2017 is applied to the REOF analysis.

We extract the spatial patterns of the leading climate modes (left panel on the next page) and corresponding time series (right panel, called Principal Component time series) that present interannual variation of each climate mode.

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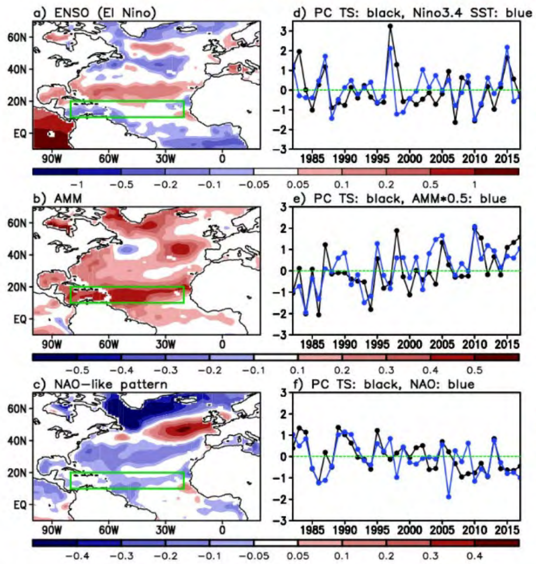
The role of climate variability (the three leading climate modes)

ENSO

AMM

NAO



ENSO: The weak La Niña (or near neutral) conditions in 2017 are manifested in the small amplitude of this PC.

AMM: SST in 2017 is characterized by a large positive phase of the AMM that contributed to a favorable environment for TC activity, but the magnitude is a little smaller than those for 2005 and 2010.

NAO: The modest amplitude negative NAO in 2017 indicates that the NAO is likely to have had a positive impact on the TC activity.

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Reconstruction of the anomaly explained by each leading mode

We assess quantitatively how much of the detrended anomaly of SST and other key variables in 2017 is explained by a combination of ENSO, the AMM, and the NAO modes.

For example, the reconstructed
SST_{ENSO} (x, y, t) anomaly determined by the ENSO mode at (x, y) and time t is

$$SST_{ENSO}(x, y, t) = REOF\_ENSO(x, y) \cdot PC\_ENSO(t)$$

where REOF_ENSO (x, y) is the unnormalized REOF SSTs for the ENSO mode and PC_ENSO (t) is the normalized (detrended) PC time series.

This calculation is repeated for the other two modes over 1982–2017. This procedure helps quantify the effectiveness of the leading modes in reconstructing the observed anomaly each year.

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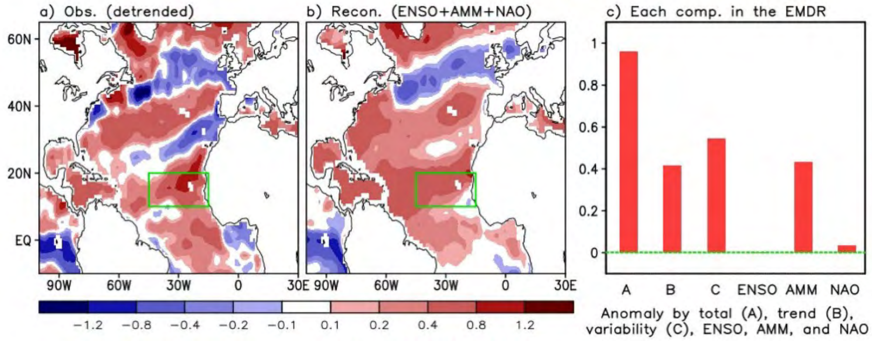
The role of climate variability (SST anomaly)



non-trend comp. ENSO+AMM+NAO

EMDR SST contributed by total, trend, non-trend, and each mode

The SST anomaly over the Eastern Main Development Region (EMDR) in AS 2017

0.96 (total) (A) = 0.42 (by trend) (B) + 0.54 (by non-trend) (C)

Contribution by the leading climate modes over the EMDR (reconstructed from the individual modes)
Non-trend SST anomaly explained by the AMM is ~0.43 (of the 0.54 by non-trend). ENSO impact on the EMDR SST is very weak, and there is a weak positive contribution of the NAO.

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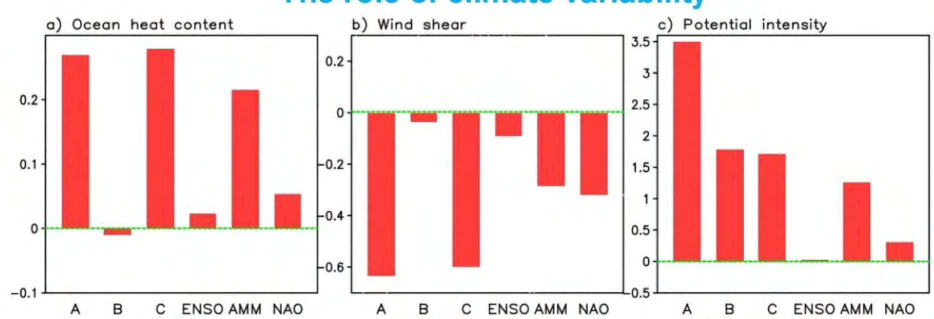
The role of climate variability



Ocean heat content (Ocean) **Vertical wind shear (Dynamics)** **Potential intensity (Thermodynamics)**

a) Three climate modes have a positive impact on OHC. The OHC is important as it acts to maintain the warm ocean surface and facilitates the strengthening of the TCs as they traversed the Atlantic.

b) and **c)**: The leading climate modes drive weaker wind shear and unstable atmosphere.

The AMM is the key factor driving the ocean and thermodynamic impacts (a,c). In contrast, the wind shear linked to the jet, pressure, and circulation associated with the ENSO & NAO is influenced by all three climate modes.

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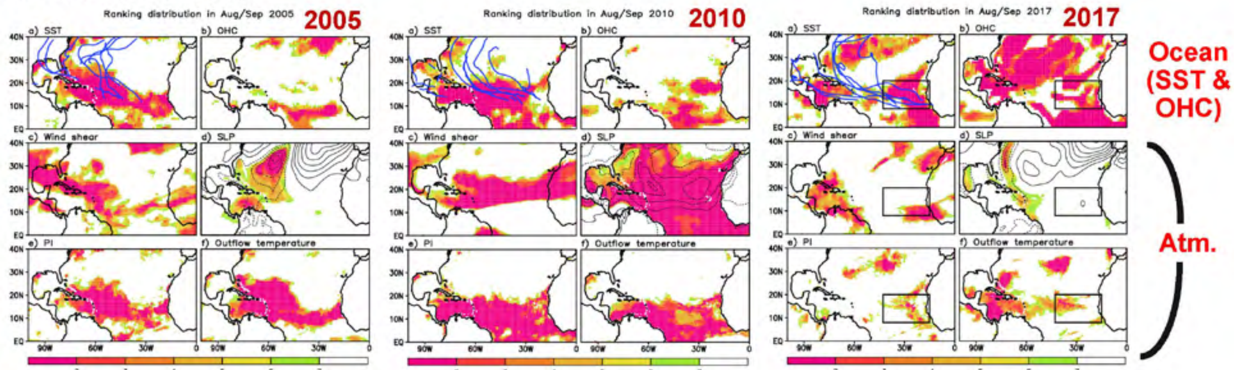
Comparison with other extremely active seasons (2005 and 2010) (Climate change + Climate variability)

Ranking value distributions of the key quantities. Ranking values closer to 1,2,3 (red shaded region) indicate very favorable condition for tropical cyclone activity.



Ocean plays more key role in 2017. Warm sub-surface keep the SST warm : strong & long life time hurricanes

Atmosphere is also favorable for hurricane activity, but less prominent than 2005/2010. Smaller magnitude of the Atlantic Meridional Mode (climate variability) than 2005/2010 is the main reason

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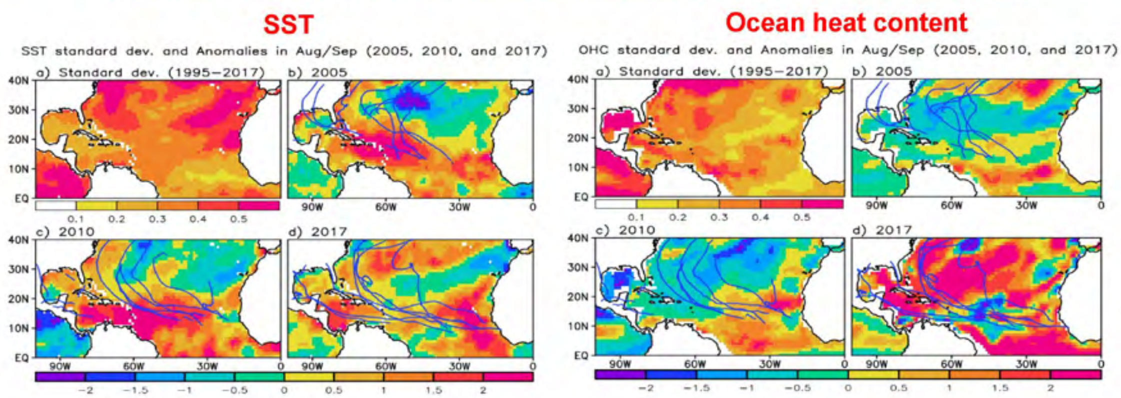
SST and Ocean heat content anomalies (2005, 2010, and 2017)



The largest SST anomalies are confined to the west in 2005 and to the east in 2017, while 2010 shows large SST anomalies over much of the MDR. Similarly standardized OHC anomalies match well the rankings shown in previous slides, supporting that the three years have unique OHC distributions, causing different impacts on TC activity.

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Conclusions

The record-setting warm SST was found over the EMDR in AS 2017, driven primarily by the climate change signal (~0.42 °C above the 1901–2017 average) and the AMM that accounted for 80% of the additional (beyond the trend) warming of ~0.54 °C.

ENSO, the NAO, and the AMM all contributed to favorable wind shear conditions, while the AMM also produced enhanced atmospheric instability.

Compared with 2005/2010, the ocean heat content (OHC) during 2017 was larger across the tropics, with higher SST anomalies over the EMDR and Caribbean Sea.

On the other hand, the dynamical/thermodynamical atmospheric conditions, while favorable for enhanced TC activity, were less prominent than in 2005/2010 across the tropics.

The results suggest that both climate change (warm SST with the long fetch of the resulting storms in the presence of record breaking OHC) and variability (three climate modes of variability) play a role in driving the strong TC activity in 2017.

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Discussions

Even in the presence of climate change characterized by increasing SST, it is the leading modes of climate variability that largely determine the extremes in seasonal TC activity, in that they are associated with both the thermodynamical and dynamical conditions favorable (or unfavorable) for TC development (e.g., strong TC seasons in 2005 and 2010, and weak TC seasons in 2013 (NAO), 2014 and 2015 (ENSO))

Nevertheless, we can expect that climate change will play an increasingly important role in determining extremely active years in that it provides an increasingly warmer baseline in SST from which the major modes of climate variability deviate.

The 2005 and 2017 TC seasons (both characterized by a positive AMM, and weak NAO and ENSO) appear to be consistent with such an interpretation. During those years, the tropical Atlantic SSTs and the major hurricane counts are comparable, despite a relatively smaller magnitude of the positive phase of the AMM in 2017 than in 2005, indicating an increasingly greater role for climate change.

For more information:
Lim, Y.-K., S. D. Schubert, R. Kovach, A. M. Molod, and S. Pawson, 2018: The roles of climate change and climate variability in the 2017 Atlantic hurricane season. *Scientific Reports,* 8, doi:10.1038/s41598-018-34343-5

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4.3.7.3.3 Questions and Answers

Because of time limitations, questions for Session 3A-3 were moved to the panel discussion (see Section 5.3.7.4).

4.3.7.4 Climate Panel Discussion. (Session 3A-4)

Moderator: Joseph Kanney, NRC/RES

Kenneth Kunkel, North Carolina Institute for Climate Studies, North Carolina State University
L. Ruby Leung, Pacific Northwest National Laboratory
Young-Kwon Lim, NASA/GSFC
Guest Panelist: Kevin Quinlan, NRC/NRO

Question (from the Webinar):

Young-Kwon Lim, you focused on years with a lot of TCs. Did you look at years with fewer TCs?

Young-Kwon Lim:

I looked at the 2013, 2014, and 2015 hurricane years. I also investigated the 2006 TC season, which was a very inactive hurricane year. The conclusion was that the climate variability was not so favorable in those years. There were very negative impacts on the TCs.

Question:

I'm a hydrologist. On the hurricane and TC activity, can you apply it to, for example, nuclear hazard questions, to refine it to particular locations? For example, if you look at the 1999 hurricane season in North Carolina, the interesting story that would provide big impacts is Dennis in August and Floyd in September. We are most interested in the clustering of hurricanes and their landfall locations and subsequent impacts. Are there ways you can use the Rotated Empirical Orthogonal Functions (REOF) work you did to get some favorable conditions, particularly in the Gulf at Texas, as opposed to parts of the southern Atlantic coast? That refinement would be really helpful.

Young-Kwon Lim:

On the seasonal timescale, this analysis technique can provide what the TC track on the seasonal timescale can be, for example, more toward the Texas area or just the north Atlantic Ocean region without much landfall. The analysis technique can provide that useful information. But even if there is a seasonal characteristic, individual storms are influenced not only by the seasonal climate characteristics, but also on the mesoscale and synoptic-scale features. So, individual storms can have some exception to the seasonal trend results from the REOF analysis technique.

Question (Ray Schneider):

We're having this meeting at the NRC, so we want to understand what the impact is going forward for the NPPs. We want to know how this information will be used. The title of the second presentation indicated that it would cover how we are using the information that we are collecting about climate change. It was not that long ago that we in the industry prepared the flood hazard reevaluation reports (FHRRs) for all the plants in the United States. You have expanded that discussion to talk about the temperature changes, which may be related to ultimate heat sink and also the potential for precipitation and ice/snow loads. From the point of view of a nuclear industry practitioner point of view, which is probably unique among people here, we are confronted about how to screen out events and how to analyze and get quantitative information on events. We are identifying that there may be thicker tails at the 2-percent AEP and such. But we can't really wait until you get to the 10^{-6} AEP level to start figuring out how to use that information. How would we start feeding some of this information back into the modeling, procedures, or guidance to make sure that we have the proper protections? How do we make sure that we are understanding what's important and what's not, rather than just saying things are changing?

Ruby Leung:

When we look at the climate science literature, it includes literature that looks at climate models and climate data but also include studies that look at hydrologic modeling. As we mentioned before, almost all of the studies look at extreme events only at a scale of around 10^{-2} AEP. There is a lot of interannual variability, or noise, in the climate system as well as the hydrological system. We currently lack two things to be able to look at that AEP range of 10^{-3} or 10^{-4}. We do not have a long enough record of data for projecting into the future. We do not have enough ensemble members to look at the 10^{-3} to 10^{-4} uncertainty range. The community is moving slowly towards that, but I think the gap is still very significant. Also, the information that we provide is not local yet. Determining whether a specific location of an NPP might be experiencing more flooding, or similar, will require a lot more regional information, which is not quite available.

Follow-up Question (Ray Schneider):

But the fact is, we are operating and working with the information that we have available now, with the understanding of what's changing, going forward. If we are supposed to be integrating that into our thinking, is there a process? Does the NRC plan on having a process? Or is it just basically: There's a lot of information out there and we have to think about it. Is it going to be turned into practice in any practical way within our timescale of the life of the industry?

Moderator:

You are entirely correct. This is a challenge. We are working to try to understand how we can incorporate some of the information from the climate science community along with what we know about hydrologic engineering practicalities. It's a struggle, and I can't give you a timeline for when we will have specific guidance on what you need to do about climate change in the next year.

Andy Campbell:

I can answer some of that question. I'm Andy Campbell, the Deputy Director in the NRC/NRO Division of Siting, Licensing, and Environmental Analysis (DSLE). The External Hazards Center of Expertise (EHCOE) comes under my purview. We have a process that was approved by the Commission called the Process for Ongoing Assessment of Natural Hazard Information (POANHI). We do get frequent questions about sea level rise and climate change impacts. POANHI takes information from this. It is an internal staff process. The PFHA research is part of that. So, the NRC staff will use POANHI if an issue of the significance that could challenge the capabilities of the plants arises. In other words, the current design basis, the plants' flood protection, their FLEX strategies, and their mitigating strategies, similar to what we did for the response to the accident at the Fukushima Dai-ichi NPP in Japan. As we look at that, we, with the help of a technical advisory committee, will make a decision. For example, does the issue need to go into the generic issues program or is it very specific to one plant, or maybe a couple of plants?

The POANHI is being finalized. I am currently reviewing an office instruction as well as informing the Commission about this process. So, we do have a process for dealing with climate change as new information comes our way. I will note that in the Commission memorandum and order approving the license application for Turkey Point Units 6 and 7, the Commission specifically dealt with sea level rise (on pages 25 to 28). The applicant used deterministic models to come up with a storm surge level, which included some sea level rise. If sea level rises higher in the future, and it significantly changes our decision, then we would then look at that in more detail. The Commission did not believe that, given all the conservative decisions built into that deterministic analysis, that the sea level rise in and of itself would change our decision. But we will monitor the situation. That is the answer the Commission gave a year ago. That is the answer I give whenever I get a letter asking about how climate change impacts this or how sea level rise impacts that. We are aware. We're cognizant. We look at the new information that comes along. But does it really change the likelihood of occurrence? A lot of what you see on sea level rise in the public has to do with the most extreme curve from the NOAA projections out to 100 years. There are enormous uncertainties associated with those. We have to consider the uncertainties associated with that. The entire agency is going through what we call a transformative process. We are becoming more risk informed. We are now capable of reviewing probabilistic storm surge analyses. The staff went through a steep learning curve on that. We have been looking at frequency-based analyses so we can incorporate any new information that comes along, if it would significantly change and have a significant impact on the plant's ability to basically keep the core cool, and to stay safe. I think that's the best way to answer that. I don't know what the ultimate answer is. Some of those most extreme projections require 30 percent of the Greenland ice sheet to be in the North Atlantic to melt. That will take a while. If that happens, then we're going to be paying attention to it. But that's not currently what the best estimates are. Those are the most extreme. We consider the best estimates, the median from probabilistic analysis when we start looking at a risk-informed approach.

Moderator:

Kenneth Kunkel and Ruby Leung, can you fill in a bit of the background on the National Climate Assessment (NCA) to explain how the NCA is developed? Different research groups have their models. The models get put together in the Coupled Model Intercomparison Project (CMIP) collection that becomes a de facto basis. Could you lay out how that process works?

Kenneth Kunkel:

The NCA is mandated by the Global Change Research Act of 1990. It's supposed to be put out every 4 years. I've been involved in the last two of these. The U.S. Global Change Research Program (GCRP) has developed a process to nominate authors, and then GCRP selects authors for various report chapters. I've been part of a committee on the climate science side of it to develop the approaches that are used to produce foundational climate science material from climate model simulations and other derived products. Generally, this consists of people from the GCRP agencies that contribute and make recommendations. The foundational climate science material has come out of the CMIP process of the World Meteorological Organization (WMO). We are always trying to connect to these global efforts to produce these climate model simulations. For the rest of the report, the sectoral and regional chapter authors are selected through this nomination process. Then we go through a very intensive review process that involves a public comment period of review by the GCRP government agencies. For both the third and fourth NCAs, the report was reviewed by the National Academies of Science, Engineering and Medicine. The National Academies performed two reviews for the third NCA.

Moderator:

This workshop is focused mainly on flooding. However, there are a lot of other factors and parameters when performing safety reviews. Kevin Quinlan, could you talk a little bit about some of those other things, beyond flooding, that you look at?

Kevin Quinlan:

As part of the safety reviews and environmental reviews, we really look at most hazards that could occur at the site. Speaking from a meteorology perspective, we look at things like tornadoes and tornado wind speeds, and hurricanes and potential missiles. We look at the high and low temperatures and humidity. We do look at different recurrence intervals for low and high temperature and humidity, looking at 100-year return periods. For winds, it's out to 10^{-6}, generally. So usually, there is enough margin to account for the limited period of record that we have. We take into account the climate at the site to see what kind of changes have occurred. However, a weakness, I think, in our guidance right now is how we actually account for climate change in the different site characteristics. Currently, we are dealing with the climate record and trying to build in some safety margin for either a highest occurrence of hazards that we see in a site region, trying to project it out so that we have some idea of margin there, that, during the life of the plant, won't be exceeded. Or if it is exceeded, how it is dealt with in the actual design of the plant.

Follow-up Comment/Question (from Kevin Quinlan):

One thing I was hoping to get some of you to comment on is PMP. Kenneth Kunkel and I worked together on the Colorado-New Mexico statewide PMP study. Later this year, hopefully later this spring or early summer, we are putting out for public comment a document of considerations for site-specific PMP estimates at NPPs. It has a section on long-term climate change. With site-specific PMPs, the assumption has been, up to this point, if climate change is being taken into consideration, if the climate is changing, it will show up in the storm record. It will be accounted for that way. It's never been a terribly satisfying answer to any of us (that we'll just see it in the storm record) because it doesn't account for future climate change or going out in the next hundred years during the life of the plant. So, based on the presentations that we just saw, what is a reasonable way to account for climate change on precipitation in a site-specific PMP study, an analysis that is generally deterministic, based on the historical storm record and then maximized for moisture and location? I think part of the problem is we do not really have a grasp on what is a reasonable way to account for it. I think we all agree that it should be accounted for, but we don't really know how. Even this guidance document that we will be putting out for public comment states, "Future site-specific PMP studies should account for the effects of climate change, especially in consideration of precipitable water." So, we're really putting the onus back on the industry. It's kind of an open-ended question. What would be a reasonable way to go about considering this?

Ray Schneider:

I was very interested in the presentation that Kenneth Kunkel from North Carolina State gave because you have the extrapolations. We have the data. To some extent, we have processes, we have good methods, and we have design methods. Now we have a little bit more information that, for example, the tails are getting a little thicker. With that information, and we know approximately the size of the tail thickness (for example, either 20 or 40 percent on a local basis), it seems like we should be able to come up with a reasonably comfortable way of dealing with that and not leave it up to the individual to basically say, "I believe climate change could do this or I believe climate change can do that." It seems like enough information is available without having to go to 10^{-6} and get that data. Use the concepts of what we've learned combined with some overlay of extreme value statistics to get an idea of where we should be ending up.

Kenneth Kunkel:

The process of the radiative imbalance in the energy budget of the atmosphere that's being driven by increasing greenhouse gas concentrations is a very fundamental aspect of what's going on in the climate system. It's warming the earth. More specifically, it's warming the ocean, and the ocean is serving as a reservoir of that heat. That will continue. You can't stop it. The other thing you can't stop is the increase in water vapor over the ocean driven by this Clausius-Clapeyron relationship between temperature and saturation vapor pressure. That's not going to be what the past has been. It will continue. The degree to which it continues depends entirely on how fast we increase greenhouse gas concentrations in the atmosphere. We are virtually certain that the magnitude of that increase in water vapor depends on the pathway of greenhouse gas concentrations. But it seems like the worst assumption one can make is that it is not going to happen in the future, so we will rely on the historical record to tell us when it has happened. There's only one direction it is going to go in. It seems short sighted to rely on historical records to tell us what's happening when we are as close to 100-percent certain what direction things will go in. We can discuss the magnitude, but there's only one direction it will go in. These really big storms seem to be controlled by water vapor concentration. We know what direction that is going in. Could the meteorology change with these systems in ways that would offset that? Perhaps, but I'm skeptical that these really, really big storms wouldn't increase in direct proportion to the water vapor concentration or water vapor availability.

4.3.8 Day 3: Session 3B - Flood Protection and Plant Response

Session Chair: Thomas Aird, NRC/RES/DRA/FXHAB

4.3.8.1 **External Flood Seal Risk-Ranking Process*.*** Ray Schneider*, Westinghouse; and Marko Randelovic*, EPRI (Session 3B-1; ADAMS Accession No. ML19156A478)

4.3.8.1.1 Abstract

Preventing water from entering into areas of NPPs that contain significant safety components is the function that various flood-protection components serve across the industry. Several types of flood barriers, both permanent and temporary, are used at NPPs. These barriers include external walls, flood doors, and flood barrier penetration seals (FBPSs) that allow cables, conduits, cable trays, pipes, ducts, and other items to pass between different areas in the plant. A comprehensive guidance on the design, inspection, and maintenance of flood-protection components has been assembled in EPRI's technical report, "Flood Protection System Guide."[12] This document includes information related to these topics for a variety of flood-protection components, while focusing specifically on FBPSs. NRC/RES has initiated a project to develop testing standards and protocols to evaluate the effectiveness and performance of seals for penetrations in flood-rated

[12] Nov. 2015, no cost to members https://www.epri.com/#/pages/product/3002005423/?lang=en-US

barriers at NPPs. EPRI is currently developing a qualitative risk-ranking process for the plants to categorize, or “risk-rank,” installed penetration seals according to the likelihood and consequence of seal failure(s) considering the various metrics regarding seal condition, design, and location. In addition to identifying potentially risk-significant FBPS for prioritization of surveillance and/or replacement, plants performing an external flood PRA may use this process to identify which penetrations may need to be explicitly modeled in the PRA. The intent of this guidance is to provide a process to categorize and rank penetration seals with regard to the likelihood of failure and the significance of a loss of the penetration sealing capability.

4.3.8.1.2 Presentation

Risk Ranking of External Flood Penetration Seals

- Plants include several hundred penetration seals which provide in-leakage protection from external flood. Experience shows that the quality, condition and capability of these seals is variable.
- Project prioritizes which of the many flood seals are potentially important to plant flooding risk
  - Process should focus on important characteristics of flood seals and what they protect in order to focus resources on risk significant items
  - Process should make use of information expected to be readily available to utility to the maximum extent practical

Failure of Cable opening

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Scope

- Develop practical process to "Risk" Rank External Penetration Seals in Response to External Flood risks. The overall process is intended to:
  - Be practical (does not require External Flood PRA)
  - Capture plant knowledge of challenges, plant layout passive flood barriers and active mitigation strategies
  - Explicitly consider seal design features, and location

- Process builds upon deterministic information available from plant post-Fukushima Hazard Re-evaluation Reports (HRRs) and External Flood Integrated Assessments (IAs) along with Deterministic and Probabilistic Internal Flood Studies
- Process to integrate insights from available information on available industry seal tests and EPRI Flood Protection Systems Guide

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Key Elements Considered in External Flood Penetration Binning Process
Two Phase Process

- Phase 1: Ranking of Flood Penetration Seals based on Seal Failure Probabilities and Seal Leak Rates
- Focuses on Flood Hazard, Seal Characteristics, Leakage Removal Strategies.
  - Characterization of the Flood Challenge
    - Extent of hazard (flood depth, duration)
  - Seal Capability
    - Type
    - Condition/Failure Mode
    - Seal Leak Rates
  - Means of Barrier protection
    - Floor drains
    - Sump pumps

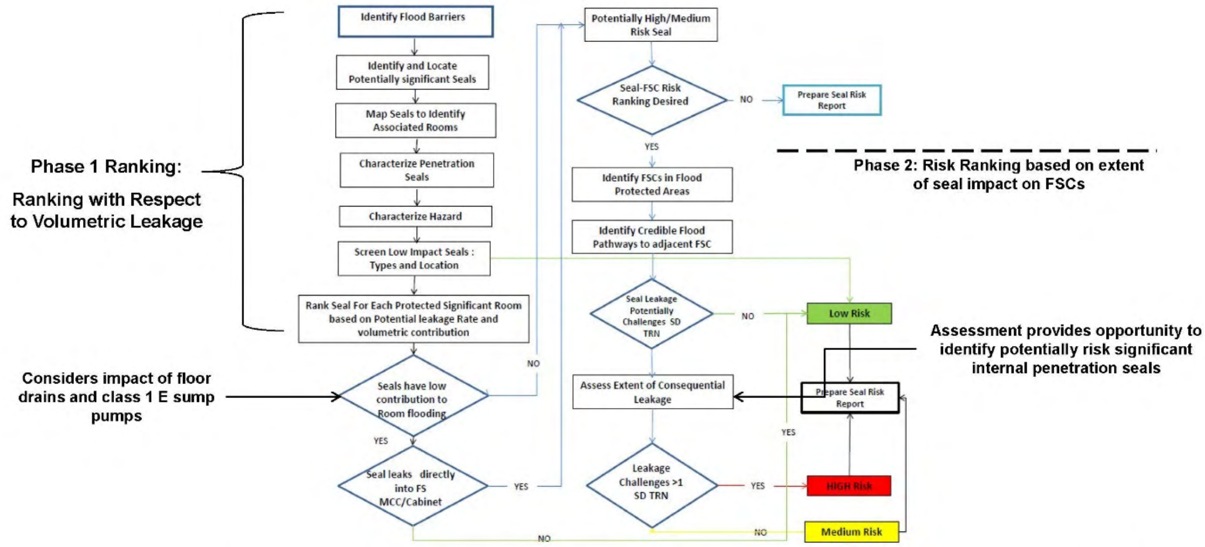
Phase 1 Results: High level screening of the external flood seals

Key Elements Considered in External Flood Penetration Binning Process
Two Phase Process: Phase 2

- Phase 2: Ranking of Flood Penetration Seals based on Potential Risk Impact of Flood Significant Components
  - Uses leakage information generated in Phase 1
  - Extends impact assessment to directly Map potentially risk significant seals with Flood Significant Components (FSCs)
  - Characterizes FSC Water-Induced Failure Conditions
  - Establishes room specific volumetric inflows considering
    - Hazard related inflows (not related to penetration seals)
    - Room related water removal features
    - FSC water-protection/ placement
  - Room flood calculations used to identify potential for flood significant internal penetration seals
  - Seals ultimately ranked/binned by their potential impact on operation of flood significant components

Phase 2 Results: Ranking/ Binning using three bins (H,M, L for risk significance)

Preliminary Overview of Seal Risk Ranking Process



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Flood Seal Risk Ranking Approach

Expected Benefits

- Task provides a proactive means to provide a plant-specific assessment of the importance of flood seals
- Structured "Risk-Informed" classification provides a reasonable basis for graded treatment of seals.
- Prioritizes actions important to surveilling and maintaining seals
- Focuses on those seal penetrations as well as internal flood barriers that may be significant to plant risk
- Provides basis for identifying Risk Important seals for treatment in an external flood PRA

Known Limitations

- Binning process limits resolution in seal characterization within "buckets". More refined categorization may be needed
- Process does not establish fragilities for seals, instead focuses on their importance to risk should they fail. However, it does identify those seals where a fragility assessment would be beneficial, and does credit experimentally observed seal type performance in seal flood/leak assessments, where available.

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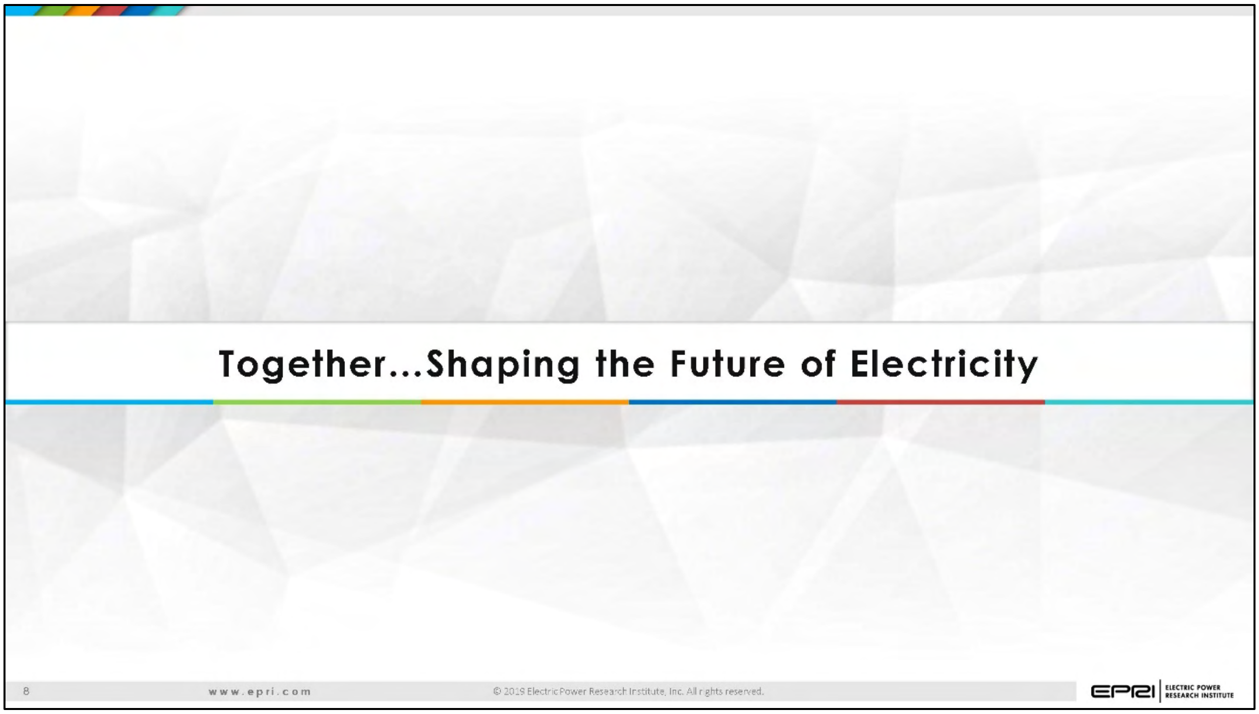
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4.3.8.1.3 Questions and Answers

Question:

I am very interested on the other side of the wall, not in the plant, but out where the backfill is. I am very interested in learning about causative mechanisms for those significant seals that are important to risk. You showed on the second slide the Blayais site in France, where some of those seals failed. Have you thought about how you can go back to EDF and ask how we could understand better what caused those seals to fail? It is not just the water level, you talked about hydrostatic load. But perched water systems could be created, and obviously subsurface condensation and local pockets of water. Could you get EDF and its contractors to say something about the causative mechanisms that caused them to fail? Could you use special geophysical methods, like electric probes, that could be associated with those seals? For example, when it does get to a certain water level or a certain condition, you would then want to have a closer inspection of these significant seals that make a difference in risk. Have you talked to the French?

Ray Schneider:

We have not talked to the French. Blayais was designed as a dry site. There was never any intention for the seals to be fully waterproof, other than for minor rain events. We can find more information for them. But we have talked to utilities that have tested different seal types. We have actually started to evaluate those data and found that certain seal types can take up to 80 pounds of hydrostatic head with just weeping. We also see the other kinds of leakage modes, of peripheral leaks around the outer periphery of the seal penetration, where it is connected to the wall and is basically the size of the surface roughness plus a few millimeters, which seems to be consistent with the data. Another set of certain seals will actually lose traction and, with enough pressure, could actually be pushed out of the gap. We are trying to identify which groups they fall in and figure out what the exact pressure levels will be when you actually get the dislodgement activity. We think this will be enough information to basically make that kind of judgment. You can use that information to determine how leakage is going to drive the water levels inside the plant. We have also looked at the cable issues and the impact on equipment. We will look at the ability of leakage through the cable-to-cable penetrations if they pass over equipment, and we will give that as a potentially risk-significant item if the leakage is passing over an important running motor. Those things are kind of built in or buried into the process; we did not want to get into that level of detail, although we are collecting some of that information. There is also a lot of anecdotal information out there, but EDF can't release it to us because third-party companies have done some of this work.

Marko Randelovic:

The information we are getting is for the test performance of new seals; the aging effects are extremely hard to quantify. I think the NRC's contractor performed the tests on new seals as well. There is an effort among the NRC, the INL, and EPRI to potentially harvest the seals in the field and characterize the aging effects on the performance of the seals. So, this project will not look into that. This is just a risk-ranking process at a high level to eliminate most of the seals from the plants.

Question:

Could you give some more information about the seals in the station in France, and especially the Blayais site, as it was the dry set concept? The seals we saw that failed are mainly fire seals that were, in fact, designed only for fire. Then the water coming into the installation had water pressure sufficient to push the seals. This could be another aspect about the French feedback. After the Blayais event, there was a large review for all the NPPs, and EDF developed the concept of volumetric protection to identify what was the polling, what should be protected, and then close all the penetrations around this volume just to limit the number of cells to be controlled or improved. Did you have you some feedback from that type of method?

Ray Schneider:

I have heard about the volumetric closure process but was not sure how EDF implemented it. I think to some extent it is the same. It sounds like what you described is similar to what we are recommending in terms of identifying the important seals; you'll look at your components that you are protecting that are important, in our case, to the flood risk. We would be evaluating the seals for maintenance. We would not necessarily require replacement of, for example, an elastomer seal with a concrete ground seal. But clearly that kind of understanding of which seals are important will help with the ability to mitigate the event, and there are multiple ways of trying to mitigate a flood event.

Question:

It is really important to be doing this sort of situational awareness in the field and thinking about it from a system's perspective. This process is very much based on having information and knowledge about the system. How are you envisioning this process to be used potentially to identify where you need to look for unsealed penetrations? We know that can be a potential challenge. Can you prioritize what areas you might want to search for unsealed penetrations? My second question is, what are you thinking with regard to inaccessible seals hidden behind something, hard to get to, or certain seals with properties that are hard to understand once they are installed? With a mechanical seal, we can see what kind of seal it is and understand it, but what are you thinking with regard to elastomer seals with the development? Third, will the process consider unknown propagation pathways, such as something that may not be an external floodwall but that may suddenly become more important if there is an unknown propagation path on the other side.

Ray Schneider:

For the propagation pathways, we will look at the ability for new sources of water, such as around walls that are assumed to wall off water. We will look at some submerged penetration seals that are internal to the plant. We would look at those to basically rank those. The last phase would be to determine whether there are penetration seals that are internal seals, not external seals, that could create new pathways that would cause an issue, and we would tag and identify those, although there is more of a standard PRA process to deal with it. For your other question, the unsealed penetrations are interesting, but we have not thought about that in particular. You want to look at where the penetrations are going through and determine what the potential impact would be. What are the seal sizes supposed to be? If we're really unsure about a penetration (we don't have that in the process yet), we could assume that it has a total flow area through it and know which areas it's going to propagate through, and then the process is the same. We would need to determine whether that an important area in terms of the amount of water. For penetrations you can't reach to see them or repair them or their properties are unclear, then you have to know their importance.

Question Clarification:

For example, a lot of these seals need to have a certain amount of length of the seal around the penetration to have resistance against blowout if you don't necessarily know how or if it's been injected to 6 inches.

Ray Schneider:

We are looking at the test data, but if the seal is injected and is basically in place and you have a leakage pathway around it, that will be a function of the length of the seal. We could do some sensitivity studies on installation designs to determine how important that is, but you don't need that much installation length in order to keep the leakage rates low enough to basically indicate that. Of more concern is the adhesion to the outside surface.

Marko Randelovic:

The process is designed assuming you have the seals, because we can't build a process for every single case where you have to assume that there is no seal. When they do the walkdown, they will look at those hundreds of seals and will eliminate most of them. They will have to spend more time looking into some of the more important ones and seeing if there is a seal or what kind of design is there. We did a tabletop exercise for one specific plant, and that information is available although not easy to get to.

4.3.8.2 Results of Performance of Flood-Rated Penetration Seals Tests.

William (Mark) Cummings, Fisher Engineering, Inc. (Session 3B-2; ADAMS Accession No. ML19156A479)

4.3.8.2.1 Abstract

Overall risk analyses of NPPs include the need for protection against potential flooding events, both internal and external events. Typically, a primary means to mitigate the effects of a flooding event are to construct flood-rated barriers to isolate areas of the plant to prevent the intrusion or spread of flood waters. Any penetrations through flood-rated barriers to facilitate piping, cabling, and similar items 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. In fiscal year 2016, the NRC 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. Although this presentation represents a summary of the project, which was completed in September 2018, its primary focus is the results of testing of candidate seal assemblies using the draft test protocol that was performed in August 2018. The test results were used to evaluate if potential changes/updates to the test protocol were needed.

4.3.8.2.2 Presentation

1

PERFORMANCE OF FLOOD RATED PENETRATION SEALS

W. Mark Cummings, P.E.

Fisher Engineering, Inc.

FISHER ENGINEERING

Flood Penetration Seal Performance Evaluation

2

NRC PROJECT TITLE: Flood Penetration Seal Performance at NPPs

Project Team: Fire Risk Management, Inc. (*now Fisher Eng.*)
Nuvia US

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, Performance Based 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, performance based criteria and protocols for testing effectiveness and performance of FPSs.

Task 2: Testing of Selected Flood Penetration Seal Types and Designs

- Designed to "test the test protocol"
- Use observations to determine if mods to Test Protocol are warranted

Flood Penetration Seal Performance Evaluation

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TASK 1.1 OVERVIEW

- Researched publicly-available information regarding installed Flood-rated Penetration Seals
  - ADAMS database
  - NPP responses to NRC 50.54 Letter (54)
  - NRC Audit Reports
  - LERs, NUREGs, INs. IRs (relevant info noted in 28/-/15/13)
- 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

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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
- Summary Report Developed: "*Flood Penetration Seal Assemblies at Existing Nuclear Power Plants*" (08/2016)

Flood Penetration Seal Performance Evaluation

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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)
- 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

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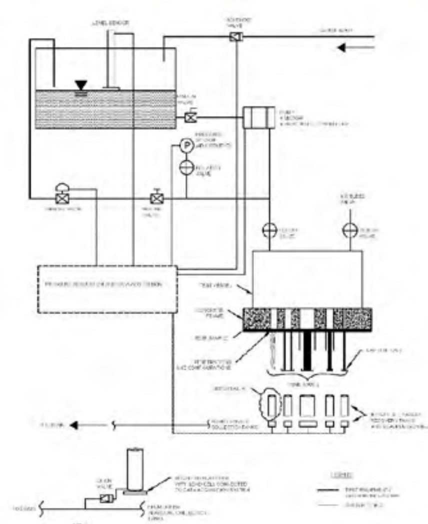
TASK 1.2 OVERVIEW (Cont'd)

- Development of draft Procedure complete – ready for use in Phase II
  - Provides "guidance" and standardized methodology for testing flood-rated penetration seals
    - Test apparatus design; including data acquisition
    - Performance-based approach to metrics (no specific pass/fail criteria)
  - Manufacturers will need to specify limitations of their products
  - Phase II testing may identify potential short-comings with the p-based approach



Flood Penetration Seal Performance Evaluation

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TASK 1.2 OVERVIEW (Cont'd)

- Development of draft Protocol complete – ready for use in Phase II
  - Provided "guidance" and standardized methodology for testing flood-rated penetration seals
    - Test apparatus design; including data acquisition
    - Performance-based approach to metrics (no specific pass/fail criteria)
  - Manufacturers will need to specify limitations of their products
  - Use Task 2 testing to assess Protocol flexibility with the p-based approach
  - NRC Issued Draft for public review/comment 02/2018 – "*Draft Methodology for Testing and Evaluating the Performance of Flood Penetration Seals*"

Flood Penetration Seal Performance Evaluation

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TASK 2 OVERVIEW

- Updated Draft Test Methodology
  - Updates based on public comment
  - Final draft developed for use during Task 2 testing series; 06/2018
- Development of Test Plan
  - Selection of candidate FPSs; types and numbers to be tested
  - Final design for Test Decks (Installed Penetrations & Seal Assemblies)
  - Location for testing (Framatome Lab in Lynchburg, VA)
  - Inclusive of Test Matrix
    - Range of seal assemblies/materials
    - Greater emphasis on "formed in place" (including configurations noted during Task 1)
    - Specific penetrations assigned to participating Mfgrs
  - Final Test Plan submitted to NRC 07/2018; "*Test Plan for Flood-rated Penetration Seal Performance Testing*"
- Test Objective(s)
  - Exercise & evaluate Flood Test Procedure ("test the test")
  - Research/Evaluation of specific FPS assemblies/materials noted as installed at NPPs

Flood Penetration Seal Performance Evaluation

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TASK 2 – Test Series

- Candidate Test Decks
  - General design/configuration predicated on Framatome Test Apparatus
  - 12" concrete "slabs"
  - 5 Sample Decks included in Test Series
  - Variety of circular & rectangular/square penetrations
  - Sleeved & core drilled
  - "blanks" & variety of penetrants: pipe (PVC), cable, cable & cable trays, conduit
  - Low & High density foam & silicone materials
  - Mechanical seals; boot & link types
  - Restrained & unrestrained penetrants
  - Penetrants sealed to prevent leakage "through" penetrating item

Flood Penetration Seal Performance Evaluation

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TASK 2 – Test Series

- Candidate Test Decks – Pre-test Preparation

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Flood Penetration Seal Performance Evaluation

TASK 2 – Test Series

- Candidate Test Decks – Pre-test Preparation

Sealed Cable Penetrant

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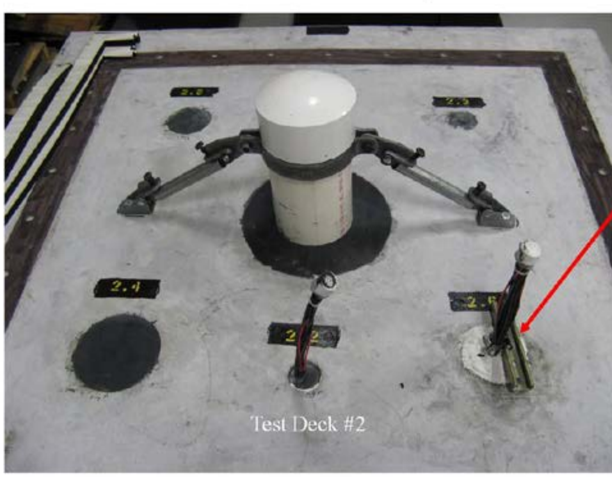
Flood Penetration Seal Performance Evaluation

TASK 2 – Test Series

- Candidate Test Decks – Pre-test Preparation



Restrained Cable

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Flood Penetration Seal Performance Evaluation

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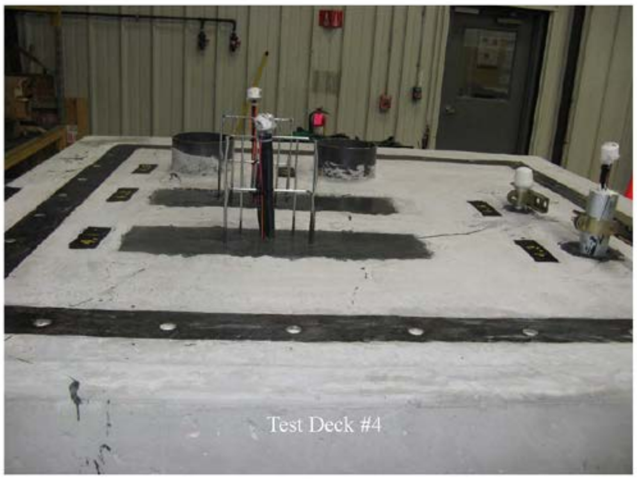
TASK 2 – Test Series

- Candidate Test Decks – Pre-test Preparation



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Flood Penetration Seal Performance Evaluation

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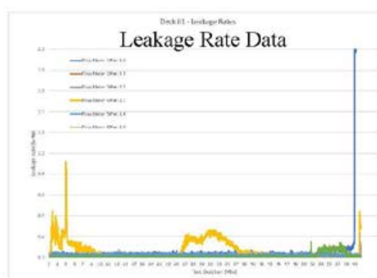
TASK 2 RESULTS

- Candidate Test Decks – Post-test Results



Flood Penetration Seal Performance Evaluation

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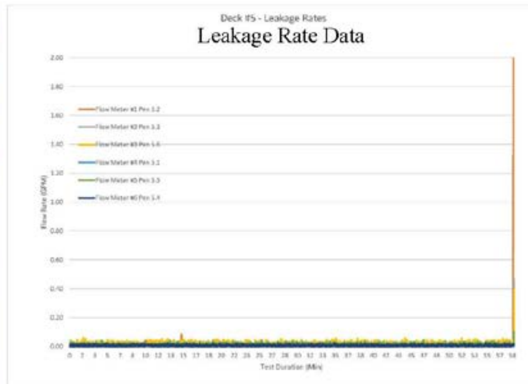
TASK 2 RESULTS

- Candidate Test Decks – Post-test Results



Flood Penetration Seal Performance Evaluation

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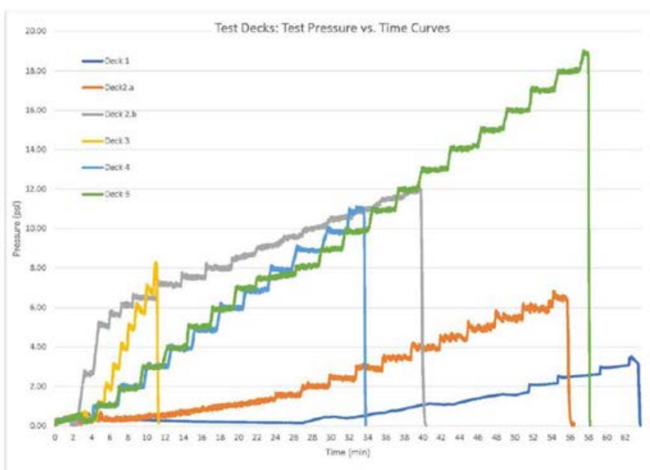
TASK 2 RESULTS

- Candidate Test Decks – Post-test Results



Flood Penetration Seal Performance Evaluation

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TASK 2 RESULTS

- Candidate Test Decks – Post-test Results
  - Lessons Learned
    - Mechanical Seals performed well (link & boot seals ≥ 19 psig)
    - Performance of low density foam dependant on numerous variables
      - Number/type of penetrant(s)
      - Sleeved vs. unsleeved and sleeve material
      - Small "free area" to circumference ratio (higher density fill ratio)
    - Silicone elastomer did not adhere well to PVC penetrant or sleeve
    - Better performance with restrained penetrant(s) (low density foams/high density elastomers)
  - Test Methodology Appears Adequate and Flexible to Support Seal Performance Data
- Final Task 2 Testing (Summary) Report Submitted
  - "*Flood-Rated Penetration Seal Performance Testing*" (09/2018)

Flood Penetration Seal Performance Evaluation

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PATH FORWARD

- Promulgation of Test Methodology for Industry Use
  - Issued via NUREG (NRC action)
    - 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

FISHER ENGINEERING **Flood Penetration Seal Performance Evaluation**

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Presenter Info

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4.3.8.2.3 Questions and Answers

Question:

Fire barrier penetration seals are pretty robust because they have to be tested with a fire test and then subsequent hose stream tests. Can we assume that they will remain intact during an internal flood event?

Answer:

It depends on the material. There are many fire barrier seals for which you will use a low-density material that may not have the adhesion properties—the friction properties. It can easily stop a fire. Your question does get to other parameters that are not covered by this test methodology. That's an impact issue that is primarily an external issue, although it can also be an internal issue since you can still have material flying around in there. You could calculate the dynamic pressure of a hose stream against the seal. I do not know if that has ever been done. Even then, if you have ever watched Underwriters Laboratories run a hose test, the tester is just spraying the item to see whether the materials in their contract and cause a failure. The same kind of analogy could apply to how seals exposed to salt water perform. Is there a compatibility issue there versus a freshwater scenario? A lot of this will come down to the manufacturers stating the specific uses of these materials. For example, if you have to do a seal through bare concrete, and it does not adhere well to the concrete, you will need to apply a layer of paint or similar substance that would prove the adhesion properties. Ultimately, the manufacturers will have to define the performance parameters at least for new seals and how they believe the seals will perform and then run a test.

Question:

Why are fire barriers and fire dampers not on your list of tested material?

Answer:

Again, we are only talking about flood penetrations. You could have dual-rated flood and fire penetrations. We know fire dampers have been modified to basically become smoke dampers. In many cases, a gasket is added to prevent the migration of smoke when that damper is closed. I don't know of any tests that look at the fire or flood rating on a fire damper. This goes back to why the whole intent is to be performance based. Leakage through a seal is not necessarily failure. What is on the other side to suck out or drain the water? If I can quantify to some degree the leakage through a flood seal based on a certain pressure parameter, at least it gives those doing the PRA a quantifiable number.

Question:

Have you tested anything else other than the polyvinyl chloride (PVC)? What was the rationale for using the PVC?

Answer:

The main rationale was ease of availability. However, some of the sleeve materials were steel. Unfortunately, the lab had problems getting big steel pipe. Since we were "testing the test," we were not specifically looking at material compatibility, although we know that's a factor. We wanted to have different materials that we could at least address and look at to see if anything obvious was evident. In this case, the elastomer did not like the PVC. It adhered much better to bare concrete than with PVC. It did fine with the steel pipe. Issues such as what you are penetrating through and what the penetrations consist of, whether it's sleeved or not will need to be accounted for in terms of your performance when you try to qualify and quantify what material to use or what is in the hole.

Question:

When do you plan to release the test report?

Answer (NRC):

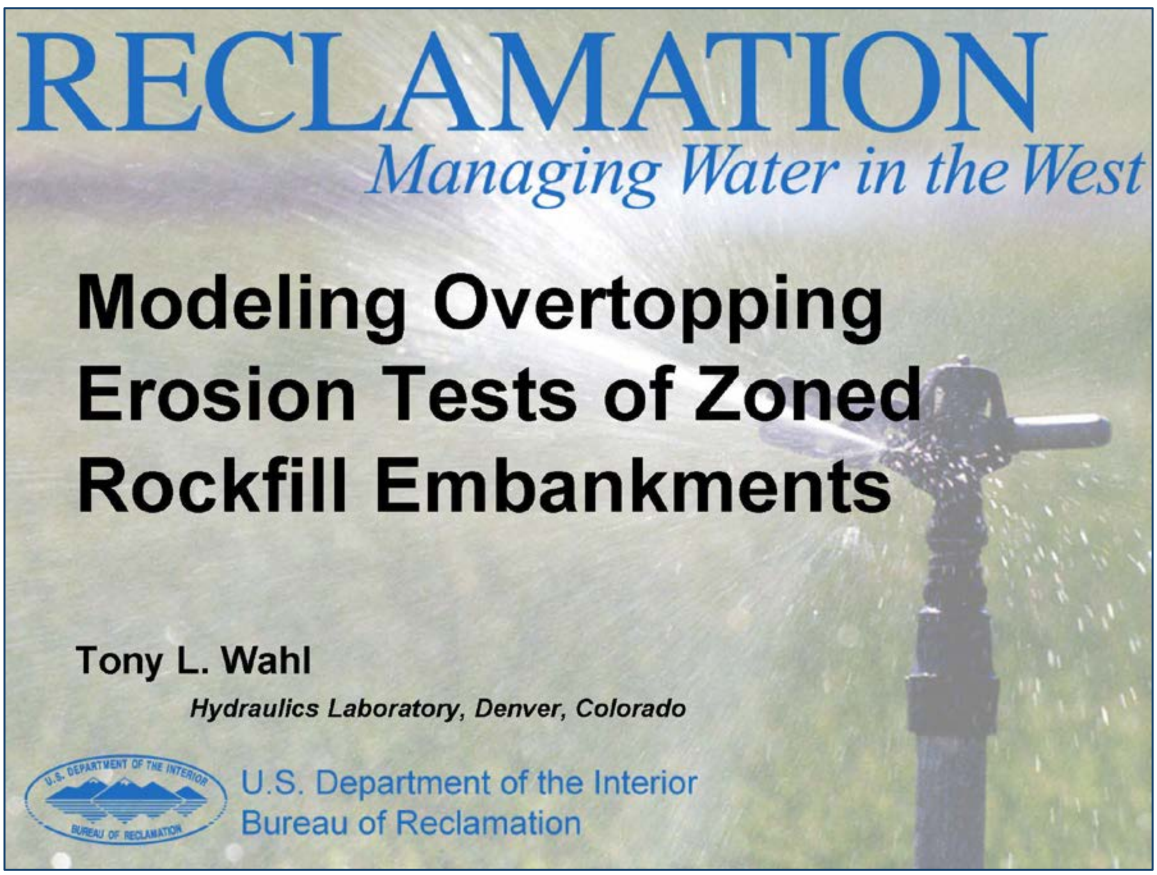
A draft report has been completed. We have received Mark Cummings' comments on it. NRC/RES will perform an internal review before sending it to the Office of Nuclear Reactor Regulation and NRO for their comments.

4.3.8.3 Modeling Overtopping Erosion Tests of Zoned Rockfill Embankments. Tony Wahl^, U.S. Bureau of Reclamation (Session 3B-3; ADAMS Accession No. ML19156A480)

4.3.8.3.1 Abstract

A 3-foot-high physical model of a zoned rockfill embankment dam was tested in the USBR hydraulics laboratory to gain a better understanding of erosion and dam breach processes associated with overtopping flow. Erosion rates of the model embankments were evaluated from visual records, and erodibility parameters of the soils were compared to small-scale submerged jet erosion tests performed on the test embankments and other compacted soil samples. This presentation discusses attempts to simulate the test using two computational dam breach models, WinDAM C and DL Breach. The idealized erosion process frameworks of each model are presented and compared to one another and to the erosion processes observed in the physical model test.

4.3.8.3.2 Presentation



Overview

- Previously reported on three dam breach physical model tests performed for NRC by Reclamation's Hydraulics Lab
- Today: Focus on an overtopping flow test from that project
  - Discuss computational modeling of that test using two dam breach models
    - WinDAM C
    - DL Breach

RECLAMATION

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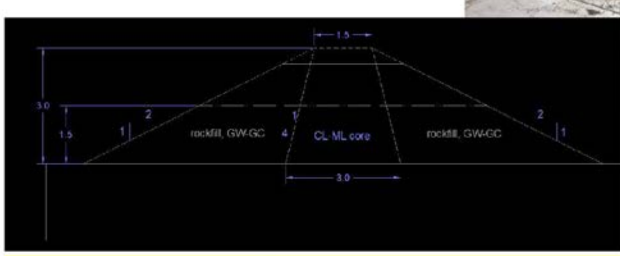
Dam Breach Test Facility

- 13-ft wide, 3-ft high embankment
- Silty clay core (CL-ML)
- Upstream and downstream "rockfill" zones (Well-graded gravel with clay) (a GW-GC roadbase soil)



RECLAMATION

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Embankment under construction

4

Objectives

- Observe erosion and breach development mechanics
- Study relationships between applied stress, erosion resistance of embankment materials, and observed erosion rates

$$\varepsilon_r = k_d(\tau - \tau_c)$$

- Compare to numerical dam breach models

RECLAMATION

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Overtopping Test – 3 minutes

6

Overtopping Test – 5 minutes

7

Overtopping Test – 7 minutes

8

Overtopping Test – 14 minutes

9

Overtopping Test – 19 minutes

10

Overtopping Test – 26 minutes

11

Overtopping Test – 33 minutes

12

Overtopping Test – 37 minutes

13

Overtopping Test – 47 minutes

14

Overtopping Test – 77 minutes

15

Overtopping Test – 120 minutes

16

Overtopping Test – 180 minutes

End of Test

17

End of Test

Material Behavior - cohesive

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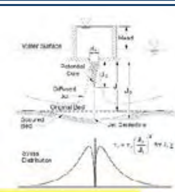
Observations

- Despite cohesive behavior (near-vertical sidewalls), a headcut "step" did not develop. Dominant process was surface erosion of the breach channel invert.
  - Why no headcut?
    - Lack of tailwater pool to recirculate and erode toe
    - Erodible crest did not allow establishment of a free overfall

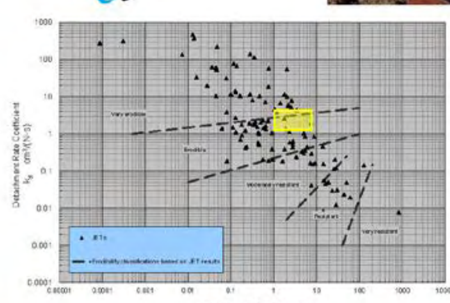
Examples of headcutting (USDA-ARS tests)

Post-Test Analysis



- Estimated erosion rates and hydraulic stresses from photo records and used these to estimate values of k_d and τ_c

$$\varepsilon_r = k_d(\tau - \tau_c)$$



- Compared to JET tests
- Core and rockfill zones had similar erodibility $k_d \approx 0.7$ to 2.5 ft/hr/psf

Applying Dam Breach Models

- **WinDAM C – Model developed by USDA**
  - **Available since 2011**
- **DL Breach – Model developed by Dr. Weiming Wu (Clarkson University)**
  - **Available since about 2013**
  - **Algorithms being added to next HEC-RAS**

RECLAMATION

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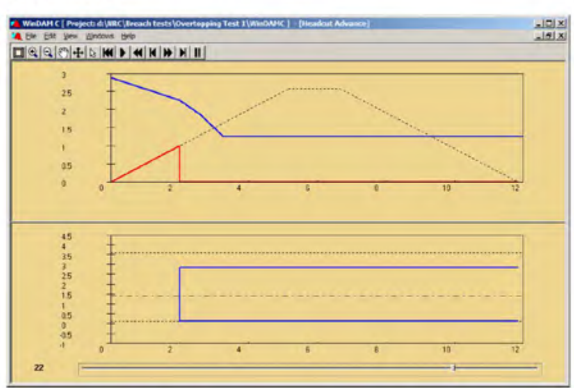
WinDAM C (2011-2016)

- **WinDAM C simulates overtopping and internal erosion failures of <u>homogeneous</u>, <u>cohesive</u> embankments**
- **For overtopping failures, breach development is by headcutting**
- **No surface erosion of crest**



RECLAMATION

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WinDAM C Modeling Results

- For this application, because the crest does not erode down and there is a constant upstream reservoir level, the model predicts no increase in discharge until the headcut advances into the reservoir, then a rapid spike
- In contrast, in the lab experiment there was no headcut development or headcut advance. Instead, we observed significant surface erosion and lowering of the crest…with gradually increasing outflow

RECLAMATION

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WinDAM C Modeling Results

- WinDAM C did not accurately model our overtopping test
- *WinDAM C was developed for USDA dams, which tend to have enough initial erosion resistance of the crest (τ_c) that they consistently develop headcuts.*

RECLAMATION

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DL Breach

- **DL Breach – dam and levee (DL) breach model** https://adweb.clarkson.edu/~wwu/DLBreach.html
- **Many options:**
  - **Overtopping and internal erosion**
  - **Homogeneous and zoned embankments**
  - **Surface erosion, headcut erosion, and mass wasting mechanisms**
  - **Erosion models for cohesive and granular soils**

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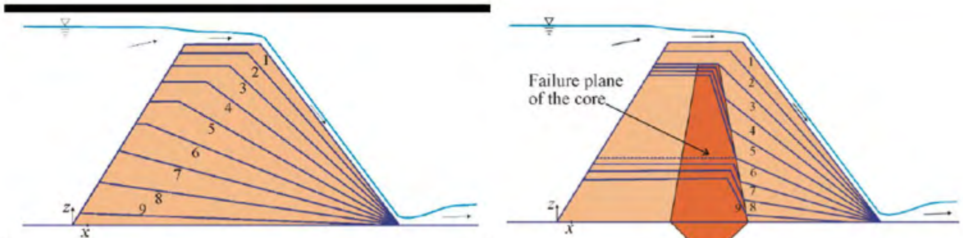
DL Breach – Surface Erosion



[redacted]

- **Erosion of crest surface and downstream slope are both possible**
- **With an erosion-resistant core this can give the appearance of headcutting, but mechanism is different**
- **May choose surface erosion models for either cohesive soil or granular soil (by zone)**

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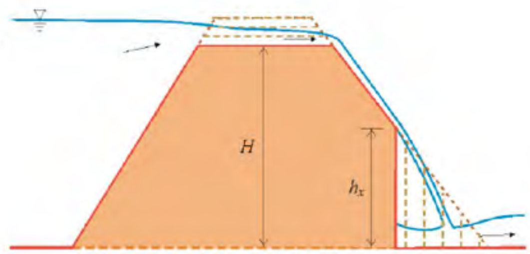
DL Breach – Headcut Erosion

- **Can only be used for a homogeneous embankment**
- **Surface erosion of crest can also occur (cohesive or granular equations)**
  - **There is no surface erosion of downstream slope**
- **Three headcut model options:**
  1. **SITES model that uses headcut erodibility index K_h**
  2. **Temple (1992) model (the suggested option)**
  3. **Temple et al. (2005)**
     - **Similar to WinDAM C's energy-based model**



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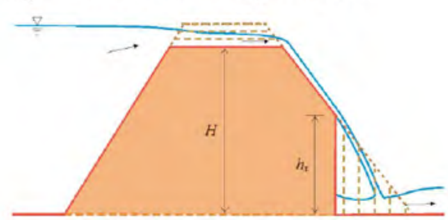
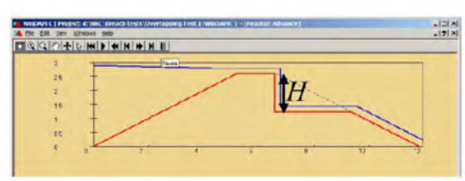
RECLAMATION

Headcut Models - Comparison

- **Although DL Breach option 3 and WinDAM C Energy-Based headcut appear outwardly "the same", there are important differences.**
  - **Different initiation locations**
  - **Different head definitions (*H*)**
  - **Crest lowering**
  - **DL Breach uses multiplier (H/h_x) to accelerate initial headcut advance**





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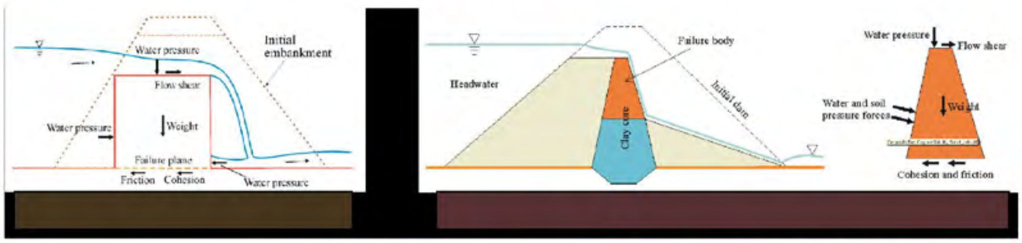
RECLAMATION

DL Breach Mass Wasting

- In headcut mode (a), sliding failure of whole dam body is possible
- In surface erosion of zoned embankment (b), sliding failure through core is possible
- Slope failure of breach-channel sides is also possible – geotechnical force balance



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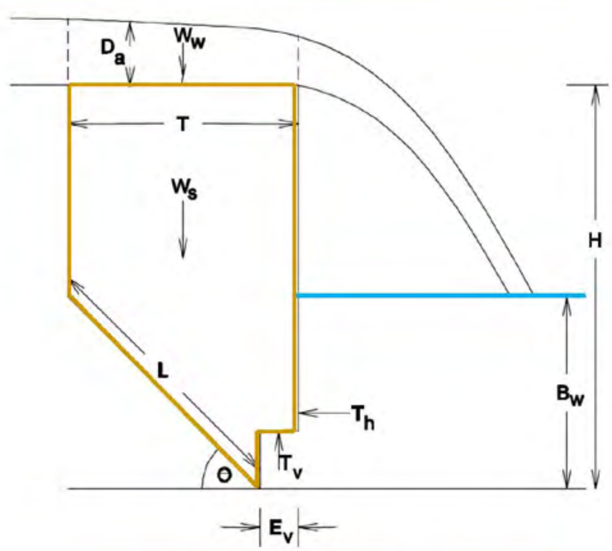
Mass Wasting – WinDAM C

- Headcut advance is a continuous mass wasting process at the headcut face, with rate of advance determined from force-balance
- No method for sliding of whole embankment or top section like DL Breach
- Breach channel widens in proportion to headcut advance rate



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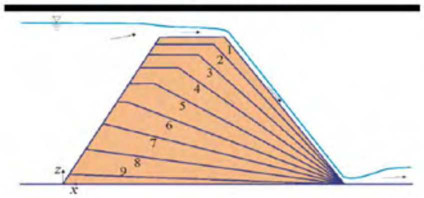
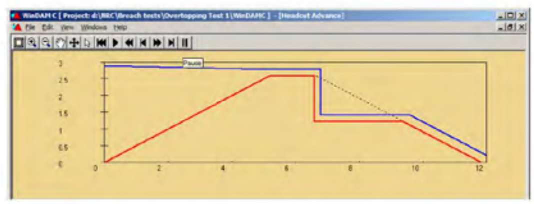
Erosion Equations Comparison

- **DL Breach**
  - Non-cohesive (granular) sediment transport equation
  - Cohesive sediment erosion by excess stress equation
- **WinDAM C**
  - Excess stress equation for initial erosion of downstream slope and deepening of headcuts





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RECLAMATION

DL Breach – Granular Sediment

- Total transport capacity is the sum of suspended load (Zhang 1961) and bed-load (Wu et al. 2000) capacities
- Bed load transport rate is a function of "grain shear stress"

$$\tau_b' = \left(\frac{n'}{n}\right)^{3/2} \tau_b$$

τ_b is total bed shear stress

n' is Manning's n of sediment grains, n is Manning's n of whole channel

- The ratio $(n'/n)^{3/2}$ "partitions" the stress into the part that actively causes transport of soil grains vs. the part that acts upon bed forms

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RECLAMATION

DL Breach – Cohesive Sediment

- **Does not partition the stress…total bed stress is used to calculate detachment rates using the linear excess stress equation**

$$\varepsilon_r = k_d(\tau_b - \tau_c)$$

- **In contrast, WinDAM C uses "erosionally effective stress" to develop and deepen headcuts**

$$\tau_b' = \left(\frac{n'}{n}\right)^2 \tau_b$$

$$\varepsilon_r = k_d(\tau_b' - \tau_c)$$

RECLAMATION

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Applying DL Breach to the NRC zoned embankment overtopping test

- **Zoned embankment with surface erosion, using cohesive soil erosion equations for all zones**
  - **Seemed like good match to observed soil behavior**
- **Zoned embankment with surface erosion, using granular sediment transport equations**
  - **Because this might be more appropriate for gravel zones**
- **Homogeneous embankment with surface erosion**
  - **(Cohesive equations)**

A real challenge is no graphical output, only time series of breach bottom elevation and width, upstream and downstream slope, and breach outflow…hard to visualize what is happening

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Results

- **Zoned embankment with surface erosion, using cohesive soil erosion equations**
  - **Initial runs made using erodibility parameters estimated from test results did not match well**
  - **Problem was that test results were analyzed with effective stress methods (WinDAM approach), but DL Breach uses total stress**
  - **Significant reduction of erodibility coefficients (k_d) was needed**

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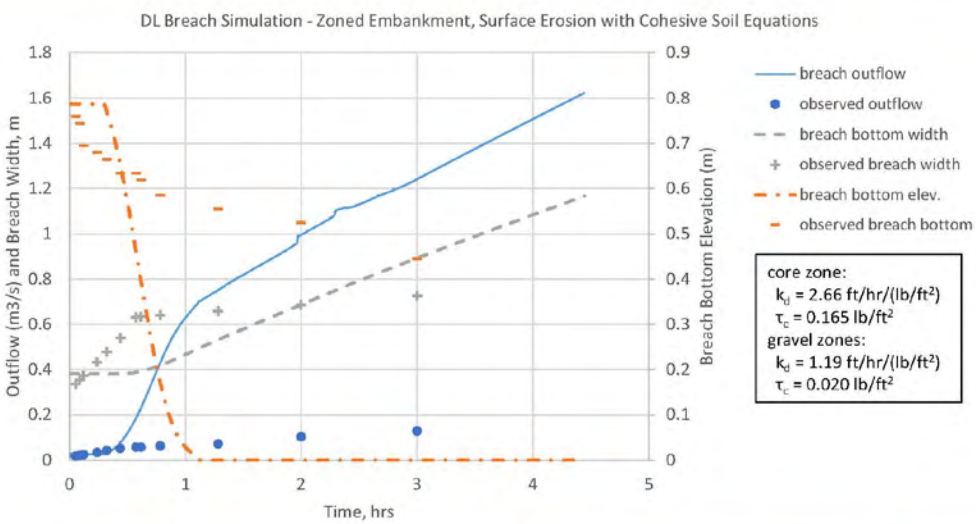
Poor Result – breach forms too quickly and grows too large, too fast



RECLAMATION

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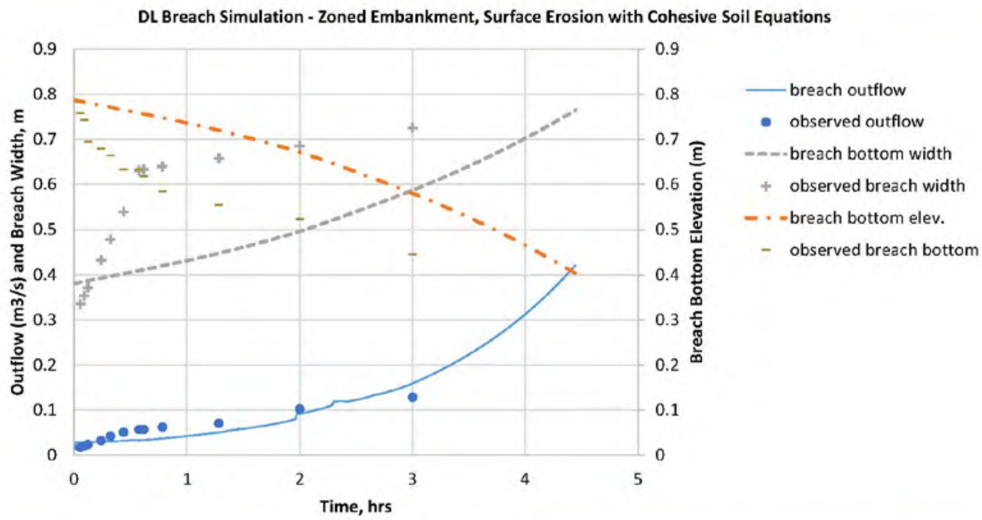
Better Result



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Results

- Zoned embankment with surface erosion, using granular sediment transport equations
  - No suitable combination of inputs could be found that produced a realistic result
  - A large mass-wasting event seemed to be occurring in some runs (big change in outflow), but was difficult to interpret from limited output

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Results

- **Homogeneous embankment, surface erosion**
  - Similar result as zoned embankment with surface erosion of cohesive soils
  - In this experiment the different zones had similar erodibility (even though much different soil types), so zoned vs. homogeneous did not make much difference.

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Model Comparison Summary

- **Some obvious differences, plus some significant differences even in parts that seem outwardly similar**
- **Crucial for modeler to know algorithm details and how erosion mechanisms interact**
- **Ability to "see" intermediate stages of breach development is important for knowing what the models are doing**
  - This is difficult in DL Breach…better in WinDAM C
    - HEC-RAS implementation may improve this

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4.3.8.3.3 Questions and Answers

Specific audience questions were included in the panel discussion immediately following the presentation.

4.3.8.4 Flood Protection and Plant Response Panel Discussion. (Session 3B-4)

Moderator: Thomas Aird, NRC/RES/DRA/FXHAB

Ray Schneider, Westinghouse
William (Mark) Cummings, Fisher Engineering, Inc.
Tony Wahl, U.S. Bureau of Reclamation
Guest Panelist: Jacob Philip, NRC/RES/DE

Moderator:

We added one new member in addition to our three speakers to this panel. His name is Jacob Philip, a senior geotechnical engineer at NRC/RES.

Question:

The erosion process is very important in calculating the dam breach hydrograph. The hydrograph will be influenced by the submergence effect immediately downstream of the dam. Tony Wahl, did you consider this aspect in your experiment?

Tony Wahl:

I agree that submergence of the downstream side of the embankment can be important. Our intention in the way we set up our lab experiment was to try to maximize the volume of water that we could release through the embankment before we completely submerged the downstream side. We elevated the embankment somewhat above the downstream channel. In retrospect, since we did not see development of a head cut there, I wish we hadn’t done that, although I don’t know for certain that it would have changed what we saw. I wish we could have run it both ways, but we did not have the opportunity to do that.

Question:

Mark Cummings, did you take into consideration the jacket material of the cables that you used in your test?

William (Mark) Cummings:

In a broad sense, yes, although we didn’t specifically request a particular type of jacket material. A lot of this was just spare material, or we got it from a hardware store, to try to formulate the bundles. However, we see that it can be an issue, whether it’s the jacket material for the cables themselves, the material for sleeving, or the penetrant. All of that needs to be factored in.

Follow-up Question:

A lot of balance-of-plant cabling will have PVC jacketing and so adherence is an issue. You did not talk much about the internal seals, although you considered them and are testing them. Will the testing methodology that you are developing be applied to manufacturers of the internal seals as well?

William (Mark) Cummings:

We actually did have some conduit with cable that had some internal seals. I was just showing a few representatives. When the NUREG comes out, you'll get the full matrix and see all the different penetrations that were part of the series. It wasn't exhaustive, but certainly items like internal conduit seals are all things that can be tested. Those are things that in terms of the test apparatus are what you see in the methodology, as an example. A wide range of designs could be used. You could have a test apparatus specific to internal conduit seals, which would be much simpler in configuration if that was your focus, depending on whether it's a plant or manufacturer.

Question (from the Webinar):

The question concerns the time duration, in particular. One of the instances we may be looking at is tsunami-induced flooding. With tsunamis, there's a lot of uncertainty about the full wave driveup and the maximum head height and the maximum hydrostatic pressures those seals could see before it starts to taper down, as the wave recedes. Is there any developed methodology behind how we can look at reasonable time durations using a graded approach with applied pressures?

William (Mark) Cummings:

We did not take any of the tests for long durations. It depends on the flood curve, or hazard curve, for your plant. We could have run these tests for 2, 3, or 4 days at a time. Obviously, we were time constrained and trying to look at as many different aspects of the methodology as we could. So, we used a step function to take it up to a maximum pressure. Some we held for minutes on end or much longer, in terms of each step, to try and see any changes in any of the seals or leakage rates that we were measuring. During a specific timestep and others, we ramped up the pressure. That will be a function of whatever flood scenario you are trying to mimic and that those seals you are testing would be exposed to.

NRC Response:

We designed the test procedure to be flexible enough so that you could design whatever pressure regime you wanted. It did not specify some kind of 1- or 2-hour pressure event.

Question:

You have a test facility that is able to look at a number of different seal concepts and combinations. From industry, we have seen that a lot of these concepts basically fit into classifying groups: foams behave one way, elastomers behave another way, and they behave differently with and without cables. If you have one source of testing, it could provide useful information in terms of how the seal leakage occurs and the size of the leak. We have estimates of what we are getting now, which is basically just leakage around the edges in gaps as they partially dislodge, as to how the partial displacement actually resulted. You are looking for a protocol to make everyone do this individually. Why didn't you try to answer some of those fundamental questions that might be helpful in reducing the scope of what everyone's will have to do?

William (Mark) Cummings:

Although we were there to test the test, we certainly were trying to, within the parameters that we had to work with, obtain lessons learned, and the report will include some of those. For example, some of the lower density foams actually perform better in some cases than we expected. In some of those tests, you will actually see where there was leakage, especially with the elastomer around the PVC. But as we increased pressure, as if you have some plumbing plugs, where there was a bowl through two washers, it expanded radially. We think something like that was occurring with this, because as we increased pressure, the leakage actually slowed, and then finally stopped and held it until it basically wasn't leaking and until, in this particular case, the seal ejected. There will be a wide range of leakage pathways or reasons for leakage to occur. A lot of that relates to material compatibility, and some is just the function of the material itself, not necessarily the compatibility of it and its surroundings. Ideally, we would have a large research effort to test all of these aspects, but that was not the case here. Hopefully, as more tests occur and the data are made publicly available to all plants as different plants test, we can begin to develop a database, and maybe some of the manufacturers will have more knowledge of how their products perform. The proprietary nature of this is a problem. When we are trying to assess how a seal penetration will perform under certain pressures, hopefully, there is a range of pressures that, regardless of who makes the seal, it performs within that range. We can build a database and begin to assess, and those insights could be very useful and could minimize the scope in terms of what other people have to do under the protocol. One of the subjects we discussed with manufacturers was having them come up with this because they know their products. That is, we would ask the manufacturer to develop a test using a standardized methodology that is acceptable to the NRC, so we are not testing every single seal assembly in every single configuration. Instead, based on these tests that found the issue and then performing engineering evaluations in the middle, the manufacturer can generally tell how the seal will react and perform.

Joseph Kanney:

It's important to keep in mind that our project was based upon one fundamental observation: there wasn't any protocol for testing.

Jacob Philip:

When we started this project, we did not know the types of seals in these areas, and therefore we made the first task to look at all the NRC documents and to determine what the seals are like, how many there are, the shapes and sizes of the openings, and how many go through those penetrations. These considerations and the seal materials to be used were very important for us starting at the beginning. We were not going to actually test a seal and say that it is bad or not good. We wanted to have a protocol on testing because there wasn't any such available in the literature. We felt that we needed to have some type of methodology to test the seals that could be applied in the lab, rather than at a site, but that can replicate a site test. At some stage, we also want to standardize the test, potentially working with an organization like the American Society for Testing and Materials (ASTM).

William (Mark) Cummings:

As part of Task 1, we tried to get as much information as possible on the types of seal materials currently in use when the plants originally responded to the NRC request for information on flood seals. Some were low-density foams that were there for fire, where the plant had installed a silicone caulk on the top just to make it waterproof. We did test a configuration such as that to see how it performed. One had just the low-density foam and one had the same configuration but with the silicone caulk, and we did see an improvement. We did try to look at some of the configurations that might be nonstandard, which some plants had been trying to use to develop their flood mitigation strategies. But these are all things that we will look into more.

Question:

When the project is over, have you considered turning over the testing procedure and your information to ASTM and finding out if there is enough interest in the industry to pick up on what you started and to actually do an ASTM standard? I'm sure others are worried about cable integrity and seals. Here in Washington, the organization that operates the Metrorail system is worried about this. By starting an ASTM standard, based upon the work you began, other groups and industry might contribute and decide to think about testing procedures.

William (Mark) Cummings:

Yes, I think that is one of the NRC's goals for the protocol/methodology.

Moderator:

It wouldn't be unprecedented. It has been done for other research projects.

Jacob Philip:

We have done that before. When we were working on the high-level waste repository, we developed a lot of guides for issues related to rock mechanics and high pressures and high temperatures that were not available in the literature at the time. We worked with ASTM to develop some of those guides. There is a precedent, and we can actually do that for this particular function if there is really interest in it.

William (Mark) Cummings:

We tried not to make the protocol and the test apparatus very specific. They are simply one of many ways to do it. Organizations like ASTM and Underwriters Laboratories do like to have set protocols. If we move that way, I hope they can develop something that would be flexible enough to roll out a range of test apparatus that could be more flexible and test certain penetrations, hopefully in a more cost-effective manner.

Comment from Andy Campbell (NRC):

This is Andy Campbell, NRC/NRO DLSE. Remember that this project originated when the NRC accompanied the industry on a walkdown of the plants. We found a lot of issues with seals—seals degraded, seals not there. There was also the St. Lucie Plant video that went viral after the walkdowns had taken place. Seals are a focus of importance for a variety of reasons. Ultimately, it is up to the licensees to ensure that their systems are appropriate. I think this provides important information. But in and of itself, research reports are not regulatory requirements; they can become that through a process, but they are not necessarily regulatory requirements. So again, I think this is great information for the industry. I believe the industry has an ongoing effort to come back to the NRC with how they will approach seals for the future. But it is ultimately their responsibility and they have the flexibility to show how their seals will continue to hold up.

4.3.9 Day 3: Session 3C - Towards External Flooding PRA

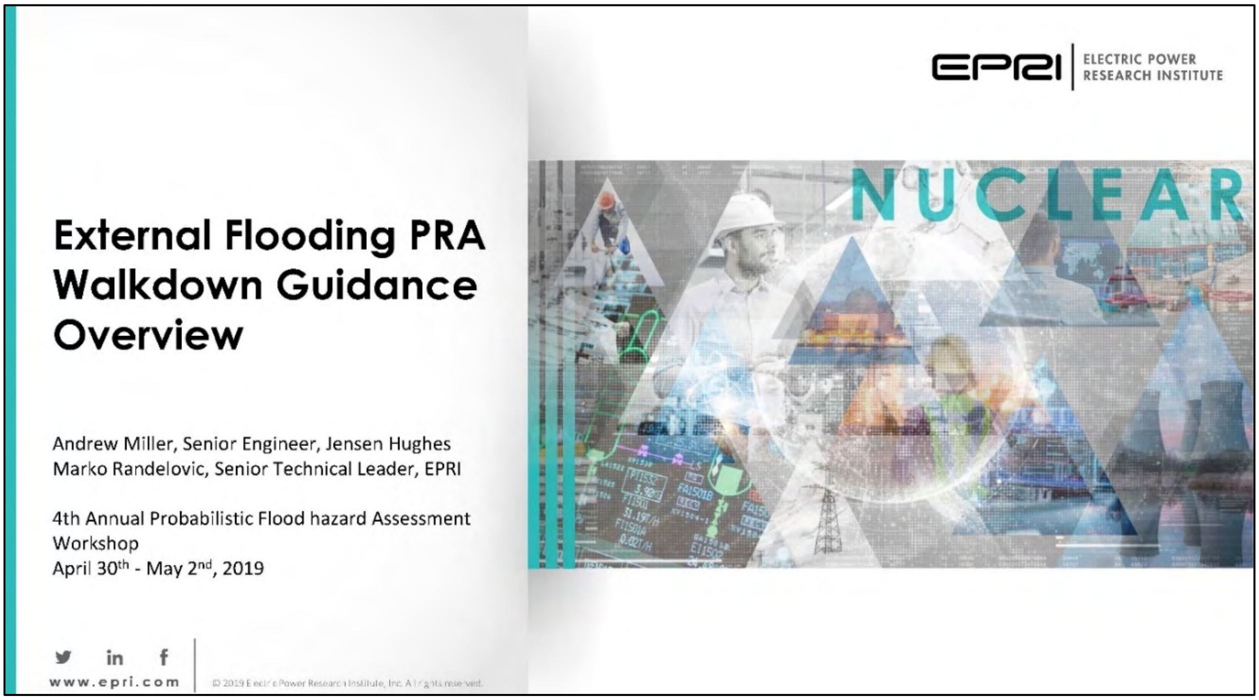
Session Chair: Joseph Kanney, NRC/RES/DRA/FXHAB

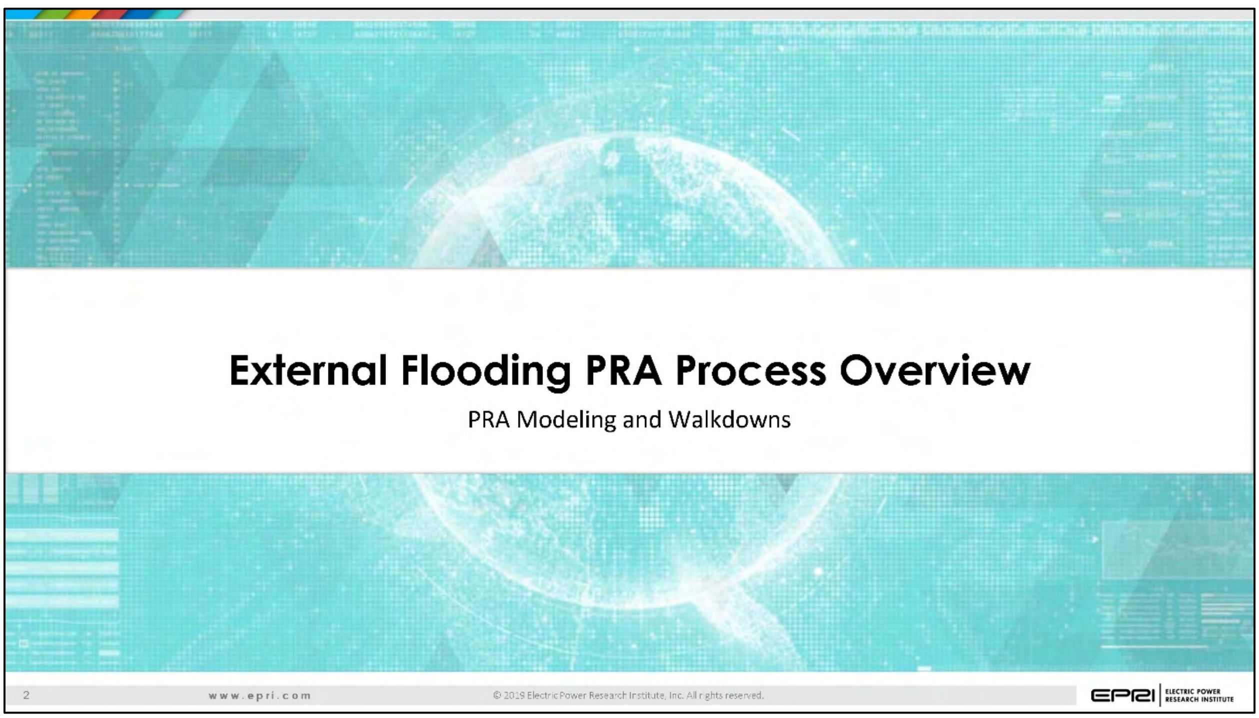
4.3.9.1 External Flooding PRA Walkdown Guidance. Andrew Miller*, Jensen Hughes; Marko Randelovic*, EPRI (Session 3C-1; ADAMS Accession No. ML19156A481)

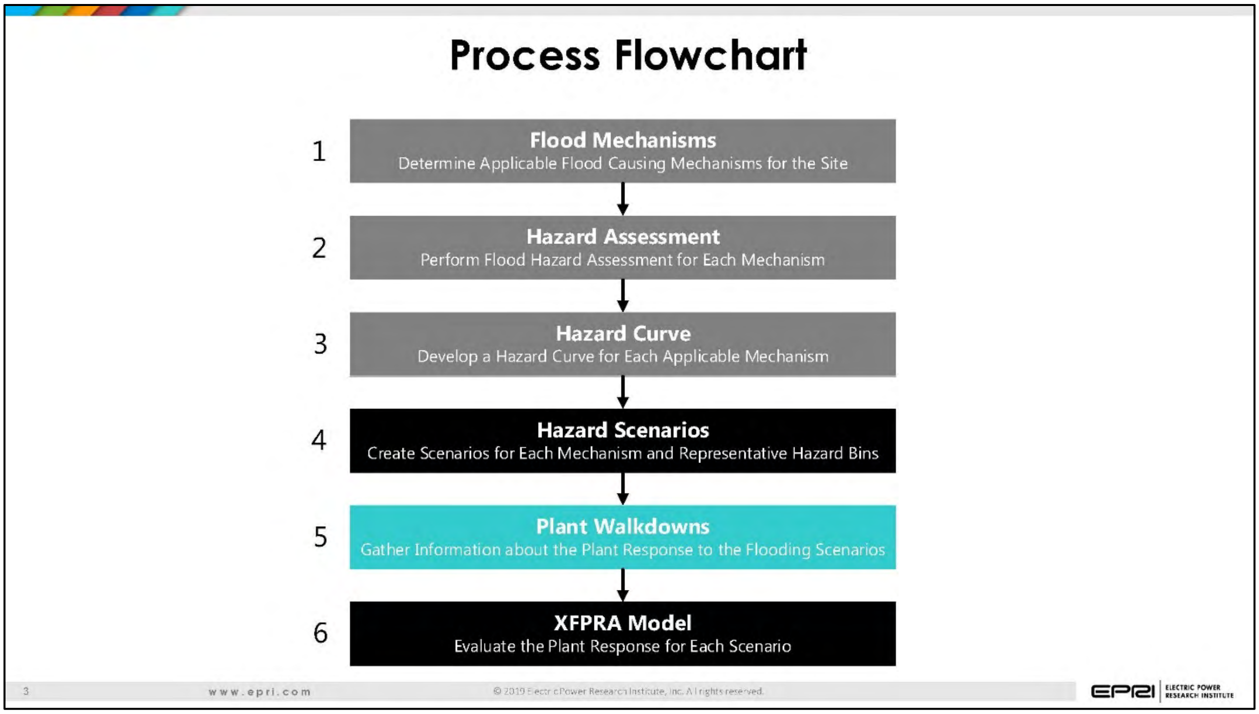
4.3.9.1.1 Abstract

As a result of the accident at Fukushima Dai-ichi, the need to understand and account for external hazards (both natural and manmade) has become more important to the industry. A major cause of loss of alternating current power at Fukushima Dai-ichi was a seismically induced tsunami that inundated the plant's safety-related SSCs with flood water. As a result, many NPPs have reevaluated their XF hazards to be consistent with current regulations and methodologies. As with all new information obtained from updating previous assumptions, inputs, and methods, the desire exists to understand the changes in the characterization of the XF hazard and the potential impact to the plant's overall risk profile. This has led to an increased need to develop a comprehensive external flooding probabilistic risk assessment (XFPRA) for more NPPs. One of the steps for developing XFPRA is the plant walkdown, which is the central focus of the research. This research provides guidance on preparing for and conducting XF walkdowns to gather the necessary information to better inform the XFPRA process. Major topics that will be addressed include defining key flood characteristics, preparing for the pre-walkdown, performing the initial walkdown, identifying the need for refined assessments or walkdowns, and documenting the findings in a notebook. This guidance also addresses walkdown team composition, guidance on useful plant drawings, and utilizing previous walkdowns or PRAs to inform the XF walkdown process.

4.3.9.1.2 Presentation






Process Flowchart
1
Flood Mechanisms
Determine Applicable Flood Causing Mechanisms for the Site
2
Hazard Assessment
Perform Flood Hazard Assessment for Each Mechanism
3
Hazard Curve
Develop a Hazard Curve for Each Applicable Mechanism
4
Hazard Scenarios
Create Scenarios for Each Mechanism and Representative Hazard Bins
5
Plant Walkdowns
Gather Information about the Plant Response to the Flooding Scenarios
6
XFPRA Model
Evaluate the Plant Response for Each Scenario
3
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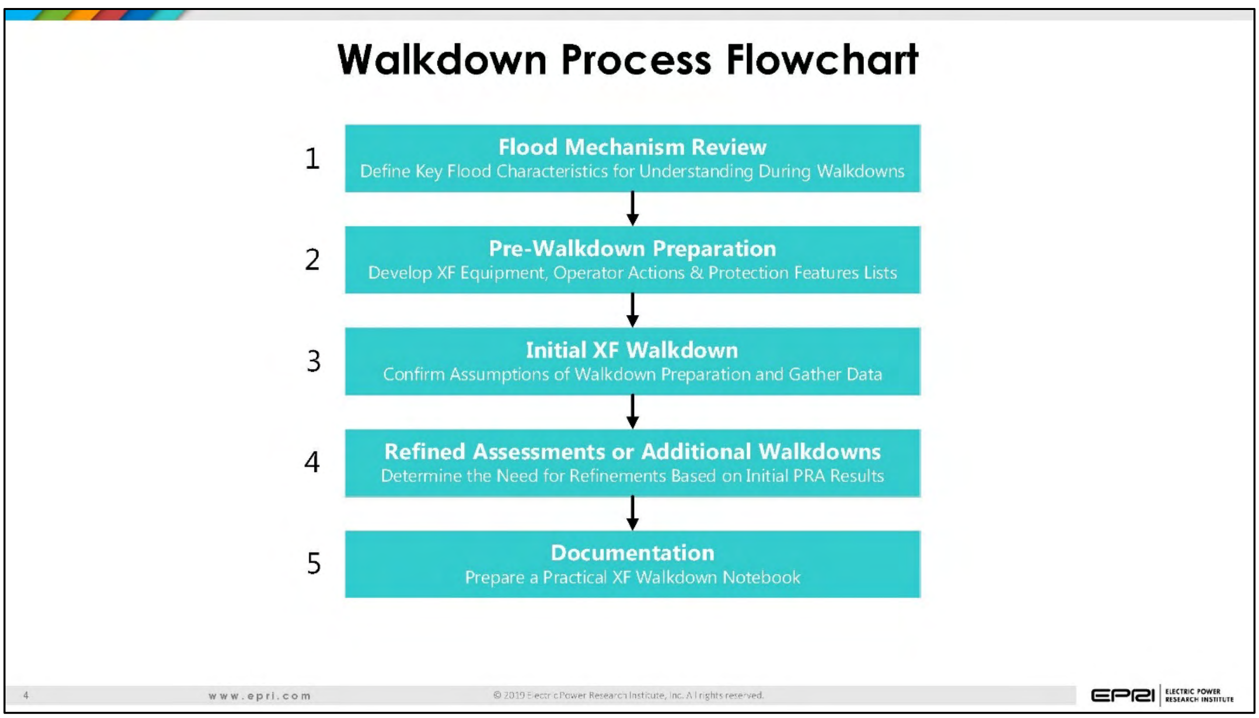
Walkdown Process Flowchart
1
Flood Mechanism Review
Define Key Flood Characteristics for Understanding During Walkdowns
2
Pre-Walkdown Preparation
Develop XF Equipment, Operator Actions & Protection Features Lists
3
Initial XF Walkdown
Confirm Assumptions of Walkdown Preparation and Gather Data
4
Refined Assessments or Additional Walkdowns
Determine the Need for Refinements Based on Initial PRA Results
5
Documentation
Prepare a Practical XF Walkdown Notebook
4
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Understanding Flooding Scenarios

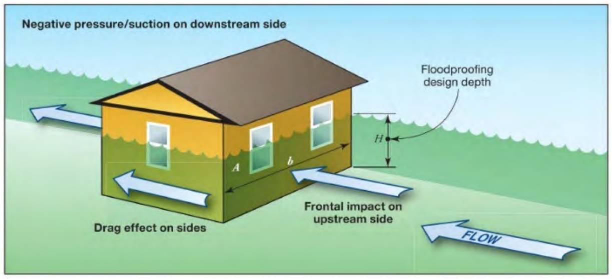
Key Flood Parameters

Define Mechanisms Applicable to Site

- Local Intense Precipitation
- Flooding in Streams and Rivers
- Dam Failure
- Storm Surge
- Seiche
- Tsunami
- Ice-Induced Flooding
- Channel Migration
- Combined Effects

Understanding Key Flood Parameters

- Sources for Flood Analysis
- Defining and Interpreting Key Flood Parameters
- Characterizing Associated Effects
- Developing Flood Scenarios



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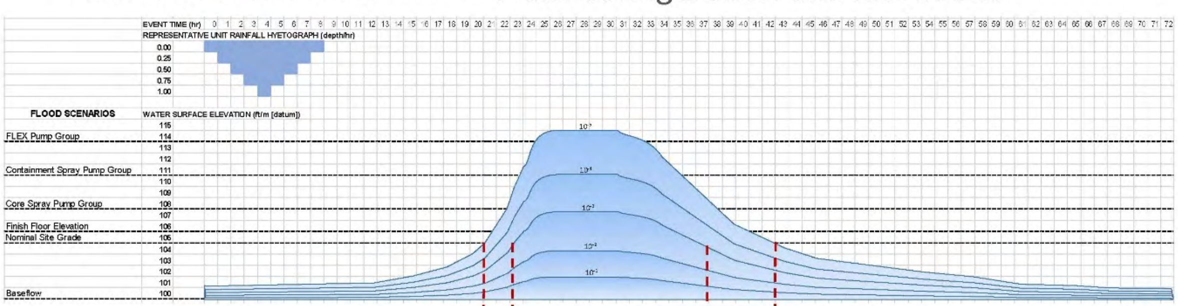
Importance of Understanding Scenarios

- Guidance provided for translating parameters into scenarios
- Things for consideration
  - Warning Time
  - Flood Progression
  - Period of Inundation
  - Propagation Pathways
  - Period of Recession
  - Plant Configuration and Elevations



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Pre-Walkdown Preparation

Information for a Successful Walkdown

Process Flowchart

1. **XF Equipment List**
   Develop the XFEL and Associated Buildings External Flood Boundries
2. **Parameters from Challenging Floods**
   Determine the Key Flood Parameters for the Buildings External Boundries
3. **Propagation Pathways**
   Identify Pathways Water may Flow from the Exterior Through the Interior
4. **Impacted Equipment**
   Create the List of Equipment Potentially Impacted by Flood Water Egress
5. **XF Response Strategy**
   Review the Existing or Planned XF Response Strategy
6. **Protection for XF Equipment**
   Correlate SSCs on the XFEL with XF Protection Features or OAs

Utilizing Previously Completed Walkdowns

- Rec. 2.3 Walkdowns
  - Provides information on Flood Protection Features
  - Location, critical height and condition of seals
  - Available Physical Margin Assessment for all FPF
- Considerations Before Using
  - Focused on confirming design/licensing basis commitments
  - Limited walkdowns to design/licensing basis flood heights
  - Did not consider failure modes or collect data for PRA model development

Detailed Guidance

- Utilizing Previous Analyses
  - Internal Flooding PRA, IPEEE, MSA, FHRR, Focused Evaluation, etc
- Developing the XFEL
  - Determine risk-significant SSCs, their location and desired state
  - Identify XF boundaries and propagation pathways to determine SSCs susceptible to flooding

Example of XFEL Entries

Equipment ID	Equipment Description	Associated Flood Mechanism	OSP Dependent?	Flood Susceptible?	Building/ Elevation (ft or m)	SSC Elevation (ft or m)	Room or Row/ Column	Normal Position	PRA Desired Position	MOV/AOV Failed Position	Permanently Installed?
IA-001	IA Compressor Outlet Valve	LIP	Yes	Yes	Turbine/ 240	244	TH/12	Open	Open	N/A	Yes
SW-P01A	Service Water Pump A	LIP	No	No	Intake/200	207	IA/14	On	On	N/A	Yes
MFW-P01B	Main Feedwater Pump B	LIP/Riverine Flood	Yes	Yes	Turbine/ 219	222	TC/8	On	On	N/A	Yes

Reviewing XF Response Strategy

- Identifying appropriate procedures for each scenario
- Determining XF operator actions required
- Creating an XF Operator Action List

Example of Operator Action Feasibility Walkdown Notes

Operator Action/ HFE BE	Description	Governing Procedure/ Step	Included in IE HRA?	Action Performance Location	Accessible Location and Environmental Factors	Alternate Paths	Extra Timing Required?
HRAOPER1	Failure to manually isolate Service Water to Turbine Building	EOP-001/4.2	Yes	CCW Room	No effects on action due to High Winds. Access path will remain clear.	Multiple	No
HRAOPER2	Failure to provide alternate cooling to AFW Pumps	EOP-001/6.3	Yes	AFW Pump Room and Turbine Building	Part of this action is performed in the Turbine Building, so access path may be blocked due to debris or action may be hindered due to building or component damage.	Multiple paths through Turbine Building, only one path into AFW Pump Room	Yes
Install Flood Barrier to Aux. Building	Operator fails to install temporary flood gate for Aux Building	FSG-001/3.4	No	Turbine Building door leading to Aux Building	Pump will be staged in a protected location. Pathway should be free of flooding and debris if performed according to procedure during warning time period.	Two paths identified in FSG	No

Guidelines for External Flooding Walkdowns

Guidance for Performing Walkdowns

- Assembling a knowledgeable team
- Performing an exterior site walkdown
- Confirming building ingress pathways
- Performing a detailed walkdown of the protection features
- Confirming interior flood propagation pathways
- Performing a confirmatory walkdown of affected equipment

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Guidance for Performing Refined Walkdowns

- Determining when refined walkdowns are necessary
- Identifying the types of refinements available
  - Detailed inundation/propagation modeling
  - New or modified operator actions
  - Detailed fragility/stability analysis
  - PRA Model updates/changes
- Performing walkdowns to support or confirm differences from refinements

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Guidelines for Preparing Walkdown Notebook

Notebook Organization and Overview

- Purpose and Scope
- Walkdown Team Composition
- Summary of Walkdown Findings
- Applicable Flood Mechanisms
- Results of Pre-Walkdown Preparation
- Results of the Walkdown
- Results of Additional Walkdowns

External Flooding PRA Walkdown Forms

- Summary Form
- Applicable flood causing mechanisms
- Flooding effects
- Visual Inspections
- Functional Testing/Periodic Monitoring
- Activity or Procedure Walk-through/reasonable simulation

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4.3.9.1.3 Questions and Answers

Question:

Are there any plans for pilots for the walkdown and the other guidance?

Answer:

We did try to pilot the walkdown guidance, but the interest in flooding in the United States and internationally is fading—it is very low. We were unable to find anyone who would be willing to actually pilot either the walkdown guidance or the penetration seal project. EDF actually reviewed the document and provided very valuable comments. But we do not have a pilot plant.

Question:

How does the guidance consider combined effects, such as a high wind with storm surge or heavy rain?

Answer:

The guidance is not intended to tell you what to evaluate. It lists the things that need to be evaluated or verified that they were evaluated. For example, in the United States, the combined hazards would have been included in the FHRR. The walkdown guidance says to find your scenarios based on what is in that guidance already and what is required to be evaluated. There is always some wind speed attributed during flooding events, and that would need to be included in the FHRR that is included during the PRA review.

Question (Suzanne Dennis, NRC):

In your slides, you had a bullet on defining risk-significant SSCs before you do the walkdown. Is that based on your internal events PRA? Does the guidance include a methodology for determining those?

Answer:

The guidance talked about different methods. People have different ways to do this. One of the ways is to go into your internal events model and strip out the event tree branches or initiators that don't matter, and then set off a "power to true" and items are shown as being important. For sites that will do a flood PRA, they already know that they have a problem. They have done a lot of work already to identify which pieces of equipment are considered critical. That's the other part of what this guidance is saying: look at the mitigating strategies assessment (MSA) and the focused evaluation and see what's identified as necessary during the flood.

Question:

Would the walkdown identify potential pathways related to FLEX? Would the walkdown also look at external flood-related manual actions?

Answer:

Yes. The MSAs were done back in 2014–2015. Some are not yet finished. But the MSA should have been reviewed. If part of your strategy is that you have FLEX—the need to mitigate a flood and the effects of flood—then yes, it would identify those penetration fields that should be reviewed. Make sure there are no pathways that would defeat implementing FLEX during a flooding event. For operator actions, the guidance does talk about taking environmental factors and inundation pathways into account and making sure that those operator actions are not impacted from the effects of the flood.

Question:

We have two regional response facilities around the United States, and some of these sites will be inundated for 7 days. However, they need the ability to get that equipment from the regional response facilities to support sites. Do your PRA walkdowns account for that? Or how are you accounting for it? The roads and bridges will not be available.

Answer:

That is far beyond the walkdown scope, but I will answer anyway based on my involvement in writing the guidance for focus evaluation and MSA. Essentially, every site needed to look at what their coping capability is during and after a flood. You have to have a safe, stable end-state for the focus evaluation and grade assessment. I believe that term is indefinitely or at least long enough to let the flood recede. When preparing for the walkdown, you create a scenario; you should have already looked at what you are using to mitigate a flood, whether that is on site or not. Everyone has capability for FLEX on site as well, according to the MSA. Everyone has already evaluated that they have at least one train of system available on site that can be implemented during the reevaluated floods, whether that's LIP, storm surge, dam break, or some other event. The regional response would only be required if the plant did not have an installed capability or an onsite portable capability. The guidance does not explicitly talk about regional response for FLEX. But if that is something that the plant would rely on, and it is part of its strategy, then the plant would have to consider that.

4.3.9.2 Updates on the Revision and Expansion of the External Flooding PRA Standard.

Michelle Bensi*, University of Maryland (Session 3C-2; ADAMS Accession No. ML19156A482)

4.3.9.2.1 Abstract

Recently, a significant effort has been undertaken to revise the American Nuclear Society/American Society of Mechanical Engineers (ANS/ASME) XFPRA standard. The draft standard is currently in the process of being reviewed and revised through the standards development process. The proposed revision is significantly more detailed than the existing standard, reflects recent lessons learned since the last revision, and recognizes the current state of practice. This presentation with share insights from the development of the proposed revision as well as other recent experience with various aspects of XFPRA.

4.3.9.2.2 Presentation

UPDATES ON THE REVISION AND EXPANSION OF ASME/ANS EXTERNAL FLOODING PRA STANDARD

Michelle (Shelby) Bensi, Ph.D.*
University of Maryland, College Park

2019 NRC PFHA Workshop
May 2, 2019

*Presenting on activities of the JCNRM Part 8 Project Team.

1

Background and Context

ASME/ANS PRA Standard for Level 1/Large Early Release Frequency Probabilistic Risk Assessment (PRA) for Nuclear Power Plant (NPP) Applications

Purpose

- Sets forth requirements for probabilistic risk assessments (PRAs) used to support risk-informed decisions for commercial nuclear power plants
- Prescribes a method for applying these requirements for specific applications

2

Background and Context

ASME/ANS PRA Standard for Level 1/Large Early Release Frequency Probabilistic Risk Assessment (PRA) for Nuclear Power Plant (NPP) Applications

Structure

- Parts (Hazard Groups)
- Technical Requirements
- High-level Requirements
- Supporting Requirements
- Capability Categories
- Commentary/Non-Mandatory Appendices

Background and Context

ASME/ANS PRA Standard for Level 1/Large Early Release Frequency Probabilistic Risk Assessment (PRA) for Nuclear Power Plant (NPP) Applications

Key notes

- Consensus Standard
- "What to do" not "how to do"
- Reflects current state of practice
- Periodically revised

Structure of XFPRA Standard

Uses three technical elements (like other external hazard groups)

1. Hazard Analysis Technical Element
2. Fragility Technical Element
3. Plant Response Technical Element

*XFPRA = External Flooding Probabilistic Risk Assessment.

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Structure of XFPRA Standard

1. Hazard Analysis Technical Element

- Screening
- Data collection, site characterization, and walkdowns
- Hazard severity characterization
- PFHA and development of hazard curves

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Structure of XFPRA Standard

3. Fragility Technical Element

- Identification of SSCs for which evaluation is needed (in conjunction with plant response)
- Walkdowns
- Identification of local hazard conditions (demands placed on SSCs)
- Fragility evaluation

Structure of XFPRA Standard

3. Plant Response Technical Element

- Scenario identification and mission times
- Initiating events, accident sequences, and accident progression sequences
- Walkdowns, exercises, and simulations
- Human action identification and reliability assessment
- Quantification of CDF and LERF

Revision of Standard

Standard (all parts) currently being updated
- Modification, deletion, and creation of requirements
- Varying degrees of revision between Parts
- Consistency efforts (particularly between Parts)

Significant effort undertaken by Project Team 8 to revise Part 8

Current version of Part 8
- Limited in detail
- Judged external flooding to be of low significance
- Allowed aggressive screening

Revised version of Part 8
- Significantly more detailed

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Revision of XFPRA Standard

Revision recognizes current knowledge and recent lessons-learned
- Understanding of flooding hazards and risks
- Operating experience
- Hazard and plant response insights from Post-Fukushima activities

Revision recognizes limitations in current state of practice
- Uses many non-prescriptive requirements
- Provides significant flexibility in addressing requirements

Developed extensive non-mandatory appendix
- Provides commentary, clarifications, and insights

*XFPRA: External flood probabilistic risk assessment

10

Challenges Encountered During Revision of XFPRA Standard

Nature of flooding hazards

- Diverse flooding hazards
- Diverse characteristics of flooding events

Plant Impacts From Flooding Hazards

- Diverse ways flood hazards may affect site
- Diverse strategies that may be employed to protect against or mitigate
- Warning time and (potentially) extensive human actions

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Challenges Encountered During Revision of XFPRA Standard

Limited state of practice of NPPs

- Unique relative to other applications

Other issues

- Define scope
- Assign responsibility between hazard groups
- Offer flexibility while avoiding ambiguity
- "To screen or not to screen... that is [one key] question"

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Challenges: Nature Of Flooding Hazards

Multiple and diverse phenomena may lead to flooding at NPP sites
- Natural (weather, geo-hazards)
- Man-made

Combinations of flood-causing mechanisms
- Independent events
- Common cause events
- Induced events

Coexistent hazards
- Events involving multiple hazard groups
- Identifying which hazard "leads the analysis"

Challenges: Nature Of Flooding Hazards

Flooding events are complex
- Temporally and spatially dynamic
- Multiple measures of severity (e.g., flood height and associated effects)
- Warning time and (potentially extended) duration of inundation

Challenges: Plant Impacts From Flooding Hazards

Plant response strategies differ across sites and flooding mechanisms

- Protection approaches
  - Passive/active
  - Permanent/temporary
  - Different strategies for different hazards
- Mitigation approaches
  - Unconventional strategies (particular for hazards not considered in original design)
- Manual actions
- Equipment that are not modeled in the baseline PRA

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Challenges: Plant Impacts From Flooding Hazards

Warning time may be available

- Changes in operating mode
- Plant re-configurations
- Installation of plant protective features

Duration of event may be days to weeks (or longer)

- Differs from conventional PRA mission times

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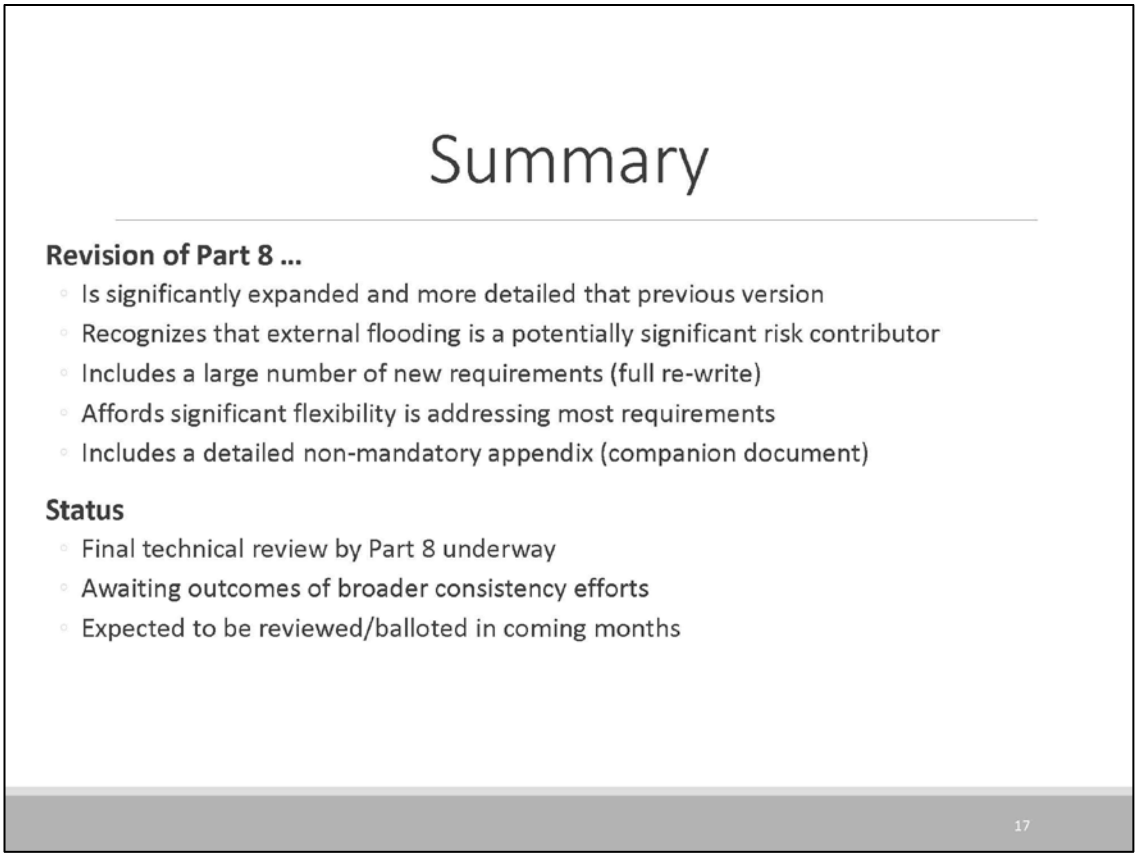


4.3.9.2.3 Questions and Answers

Question:

There is probably a delicate balance between the screening that should be done during the hazard analysis and the PRA team that is taking that hazard analysis on board. I think there needs to be some thought about how the screening duties may be divided between those two groups.

Answer:

There is an entire technical element that is done on the hazard. It does not matter if the hazard was done before or if the hazard was done fresh for the PRA, the requirements have to be met. Within that hazard technical element, there are requirements for screening. If you are using analysis, and you have done screening, it needs to meet those requirements, even if it was done 5 years ago.

Question:

The NRC is in a transformative era, an era of risk-informed decisionmaking. All the probabilistic approaches and dealing with uncertainty are incredibly important now. People are now bringing in much smaller reactor designs or even looking at microreactor designs. All the reviews need a graded approach. We have to have an approach that considers what can go wrong, how likely is it, and what are the consequences? I think this PRA standard is timely. We've received reviews under Title 10 of the *Code of Federal Regulations* 50.69, "Risk-Informed Categorization and

Treatment of Structures, Systems and Components for Nuclear Power Reactors," and are going through a process for storm surge. We are seeing a variety of risk-informed, performance-based approaches. My question, does the geology part of this consider volcanic hazards?

Answer:

I believe volcanic hazards will go under Part 9 of the guidance. If it is landslides, it might go under Part 5, but probably under Part 9 because Part 9 is a catchall. It could also be screened under Part 6.

Question:

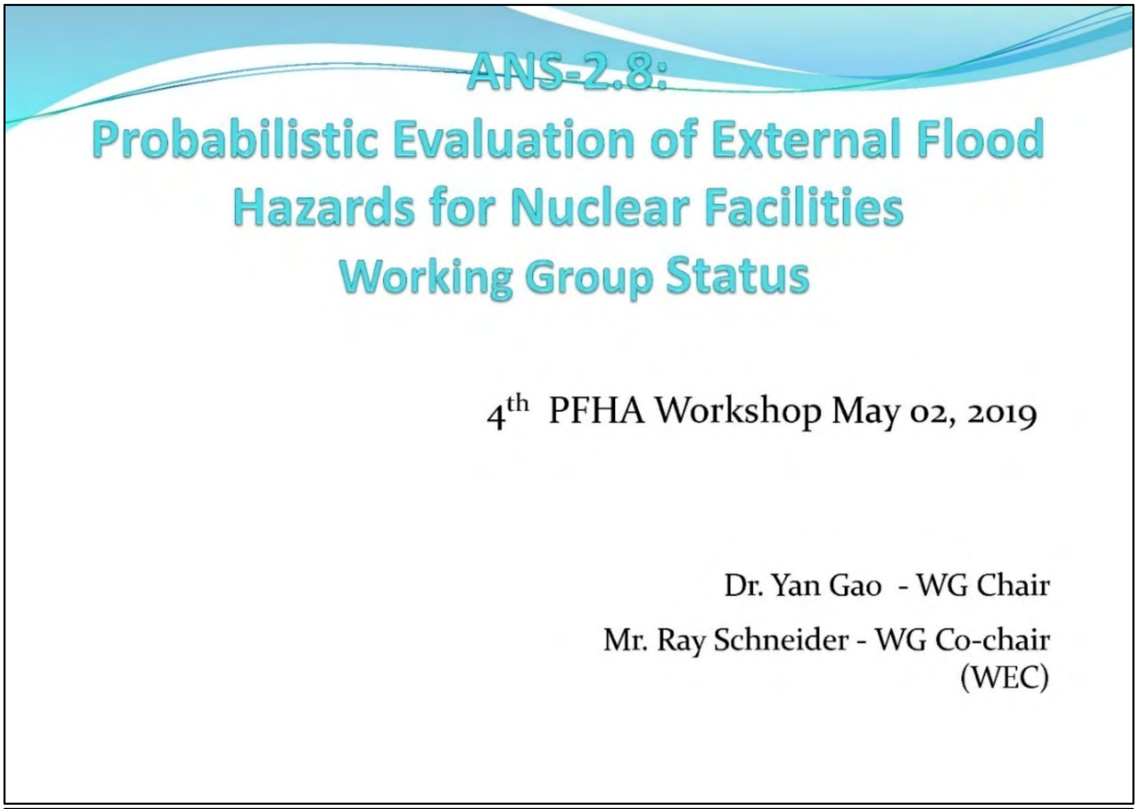
What do you consider to be within the scope and outside the scope of your PRA standard? For instance, do you consider ground water flooding or combined events? How do you determine what is fair to include? You said one of the dilemmas is that certain groups have to assume responsibility because they are combined events. How do you determine what is within the scope and what is outside the scope? I hope that you do not just use screening to determine what is in and out of the scope.

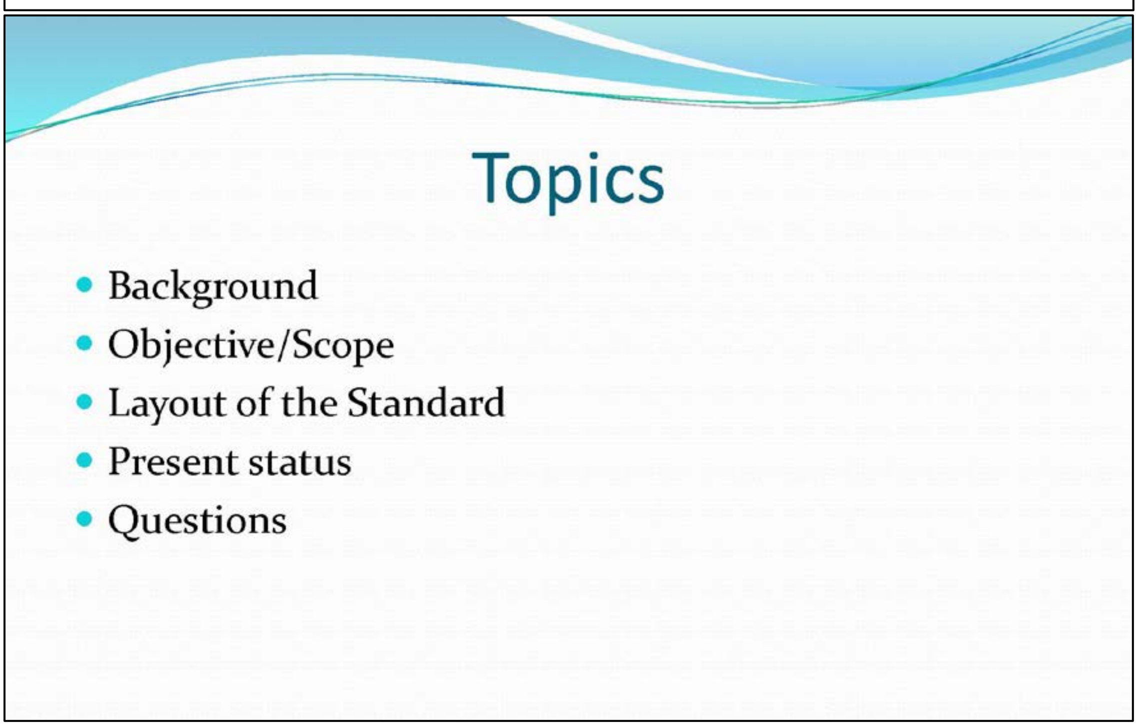
Answer:

This is not a valid standard yet; we are still revising it. A combination, such as a hurricane that can induce a storm surge event, LIP, and a river flood, because you happen to be located in an estuary, would fall under Part 8 because it's all inside flooding. If it crosses between hazard groups, such as a seismic event that induces a flood, then we have to worry about that assignment of responsibility. Right now, if the seismic event is affecting the plant and also causing a flood, it is considered within the seismic period because the seismic event is affecting the site. But if it is a seismic event that happens to fail a dam 500 miles away and it does not also affect the plant, then that is within the scope of flooding. With regard to high winds: we are still making sure we know when winds happen. In practice, the scope will be defined by whoever gets that PRA done first. But I think that's the pragmatic aspect of how it will be done. If you never did a flooding PRA, then you are not going to deal with high winds in your flooding PRA. The guidance does have a note to think about other hazards that we didn't catch. We do not have specific requirements directed specifically at ground water; we do have specific requirements directed at storm surge. But that is not to say that a hazard that doesn't have a specific technical requirement is out of scope in terms of analysis.

4.3.9.3 Update on ANS 2.8: Probabilistic Evaluation of External Flood Hazards for Nuclear Facilities Working Group Status. Ray Schneider*, Westinghouse (Session 3C-3; ADAMS Accession No. ML19156A483)

4.3.9.3.1 Presentation





Background

- ANSI / ANS-2.8 1992 "Determining design basis flooding at Nuclear Power sites"
  - Intent to establish a methodology for a design basis flood hazard with "virtually no risk of exceedance" (e.g probable maximum Floods (PMFs), Probable maximum Hurricanes (PMH), etc.) .
  - Standard covered external flooding hazard with the exception of tsunami
  - Design Basis Flood based on a deterministic process with assumptions intended to produce low probability flood hazard elevations
  - Appendix B (estimated expected frequencies of recommended combinations)
  - Standard withdrawn in 2002 and not subsequently updated
- ANSI/ANS-2.8-XXXX being developed to fill an important gap in standard
  - Standard to reflect lessons learned from nuclear site flooding events from 1992
    - Insights from Katrina, record floods in mid-west, combined flood events at European coastal site and Fukushima
  - Establish hazard based on a probabilistic/statistical approaches
    - Reflect State of the art enhancements in technology in computation methods and capabilities in fluid dynamics/hydrology
    - Extend application to all nuclear facilities
  - Consider Tsunami
  - Integrate consideration of "climate change"

Objective

- **Upgrade ANSI/ANS Standard for determining external flood hazards**
- **Establish a probabilistic framework for modeling external flood hazard parameters considering the aleatory variability uncertainties associated with natural phenomena and epistemic uncertainties in estimating the frequency of occurrence and magnitude of hazards**
- **Hazard characterized by site-wide Water Surface Level (WSL), Wind – Wave Runup, water flowrates**
- **Consider present state-of-knowledge using scientific and engineering modeling capabilities to describe the hazard.**
-

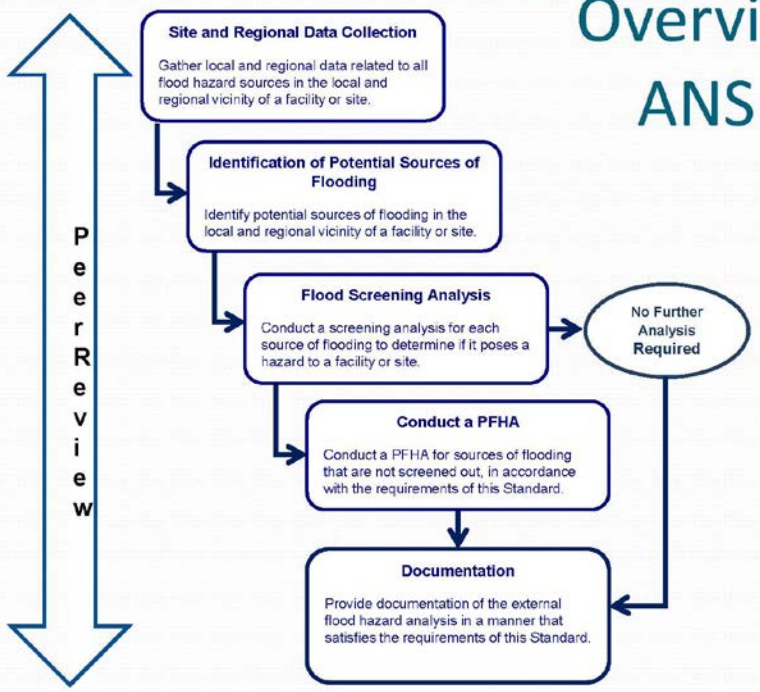
Scope of ANS2.8

- **Local Intense Precipitation**
- **Riverine flooding**
- **Upstream dam failure**
  - **Hydrologic**
  - **Non-hydrologic (seismic, intrinsic, other)**
- **Hurricane induced storm surge**
- **Seiche (wind and earthquake generated)**
- **Tsunami (seismic and landslide initiated)**

Not in Scope

- Low water
- Dispersion, dilution and travel time of accident release of effluents
- Groundwater
- Channel diversions
- Internal or external flooding from failure of pipes or tanks
- Combined Events assessments
- Hydrodynamic loadings on plant structures associated with flood.
- Standard does not specify:
  - any requirement regarding the acceptability of any particular hazard frequency or hazard profile
  - nor does the Standard provide guidance on the appropriateness of facility flood protection or mitigation systems

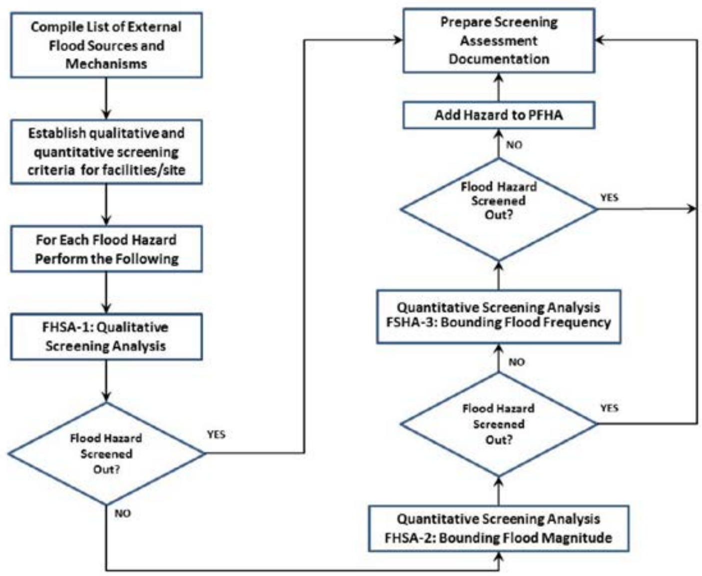
Overview of ANS 2.8



Site and Regional Data Collection and Identification of Potential Sources of Flooding

- Use of consistent datum
- Site and facility description
- Location of main hydrologic features nearby to the facility (streams, rivers, gages etc.) and relevant information regarding the surrounding watershed.
- Location and flood protections of SSCs important to safety
- Site topography and drainage
- Site and regional climatology, meteorology and hydrology (and associated history)

Flood Hazard Screening Analysis



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Probabilistic Flood Hazard Analysis

- PFHA performed on all non-screened flood hazards
- Standard provides specific requirements for performing the PFHA
- Overall PFHA process provides for a structured hierarchical approach based on facility risk and hazard complexity

Safety Category per ANS 58.16-2014	Overall Site Flood Hazard Complexity	Recommended PFHA Level
SC-3 (High Consequence)	High	3,4
	Low	3
SC-2 (Intermediate Consequence)	High	3,4
	Low	2
SC-1 (Low Consequence)	High	2
	Low	1

ANS-2.8

10

Probabilistic Flood Hazard Analysis

Regardless of Level PFHA Process is a hazard evaluation and integration process which includes the following:

- Formation of PFHA team with specific objectives
- Data Collection commensurate with Level of PFHA
- Evaluate and select physically based stochastic models for the assessment of the flood hazard; including consideration of treatment of aleatory variability and epistemic model uncertainty (to the extent warranted by the PFHA Level)
- Integrate models into a probabilistic framework considering sources of uncertainty
- Propagate hazard scenarios to produce a family of site-specific hazard curves

Specific requirements based on meeting high level and subordinate Supporting requirements

ANS-2.8

11

High Level Requirements for Performing a PFHA

No.	Requirement
HLR-PFHA-A	The project organization shall be clearly established including roles and responsibilities of the project participants, shall be identified.
HLR-PFHA-B	The PFHA level of analysis shall be identified and used as the basis for determination of analysis detail.
HLR-PFHA-C	The inputs to the PFHA shall be based on comprehensive up-to-date data.
HLR-PFHA-D	A structured process shall be used for the identification and evaluation of the sources of aleatory and epistemic uncertainty. Where expert elicitation is used, a structured elicitation process shall be implemented.
HLR-PFHA-E	For each flooding source or mechanism (and applicable combinations) an aleatory flood hazard model shall be developed. The aleatory model shall include all elements of the flooding process (meteorological, hydrologic, hydraulic, etc.).
HLR-PFHA-F	For each element of the flooding process, sources of epistemic uncertainty shall be identified, evaluated and modeled using a structured process.
HLR-PFHA-G	The flood hazard shall be characterized in a manner that supports the intended application of the PFHA results.
HLR-PFHA-H	Aleatory and epistemic uncertainties in each step of the hazard analysis shall be propagated and displayed in the final quantification of the flood hazard for each non-screened flooding source and mechanism.
HLR-PFHA-I	A peer review shall be performed whose level of effort is commensurate with the level of the PFHA. (See Section 8)
HLR-PFHA-J	The PFHA shall be documented in a manner that facilitates application of the results, peer review, (and analysis upgrades, where applicable).

ANS-2.8

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PFHA: Presentation of Results

Result	Description
Fractile hazard curves	For flood hazard measure (e.g., peak flood elevation), the flood hazard is quantified in terms of fractile hazard curves. Fractiles that are typically reported are the 5, 15, 50, 85 and 95 percentiles.
Mean hazard curves	The arithmetic mean flood hazard curve is computed from the entire uncertainty distribution of the estimated of the frequency of exceedance generated in the PFHA. The mean is the arithmetic mean estimate of the frequency of exceedance.
Intermediate Results	The type of intermediate results that are provided in a PFHA depends on the source of flooding and the type of flood hazards are being evaluated (e.g., riverine flooding, storm surge). The PFHA analyst shall provide intermediate results of the quantification that provide insight to elements of the analysis. For instance, in the case of riverine flooding, hazard curves could be provided for peak river discharge at a selected river cross-section, in addition to flood hazard curves for peak flood elevation at the same location.
Sensitivity Analysis	Results of sensitivity studies shall be provided that show the effect that different models or parameters have on the PFHA aleatory results as well the uncertainty.
Diagnostic Results	Diagnostic methods such as tornado plots and analysis of variance shall be used to demonstrate the effect that uncertain models and parameters have on the uncertainty in the PFHA result.

ANS-2.8

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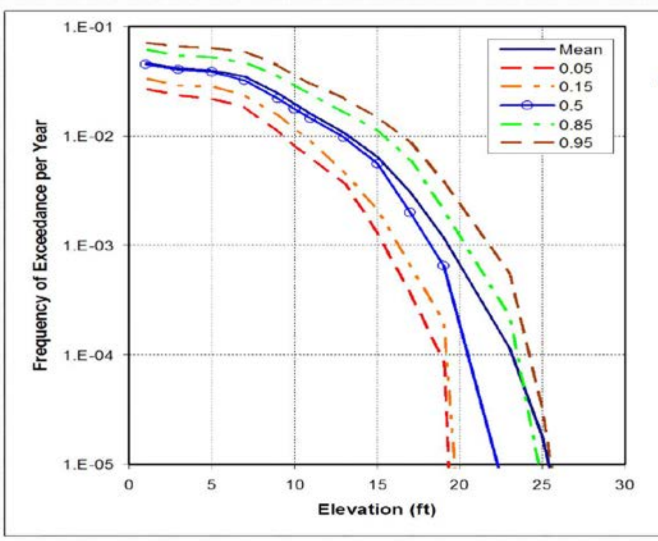
Example Results of Probabilistic Approach: Riverine Flood



- *Example external flood hazard curve*

ANS-2.8

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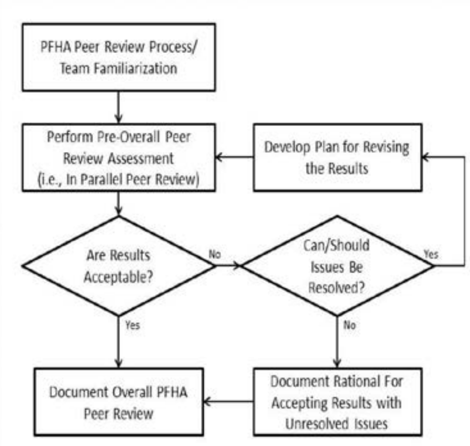
Documentation

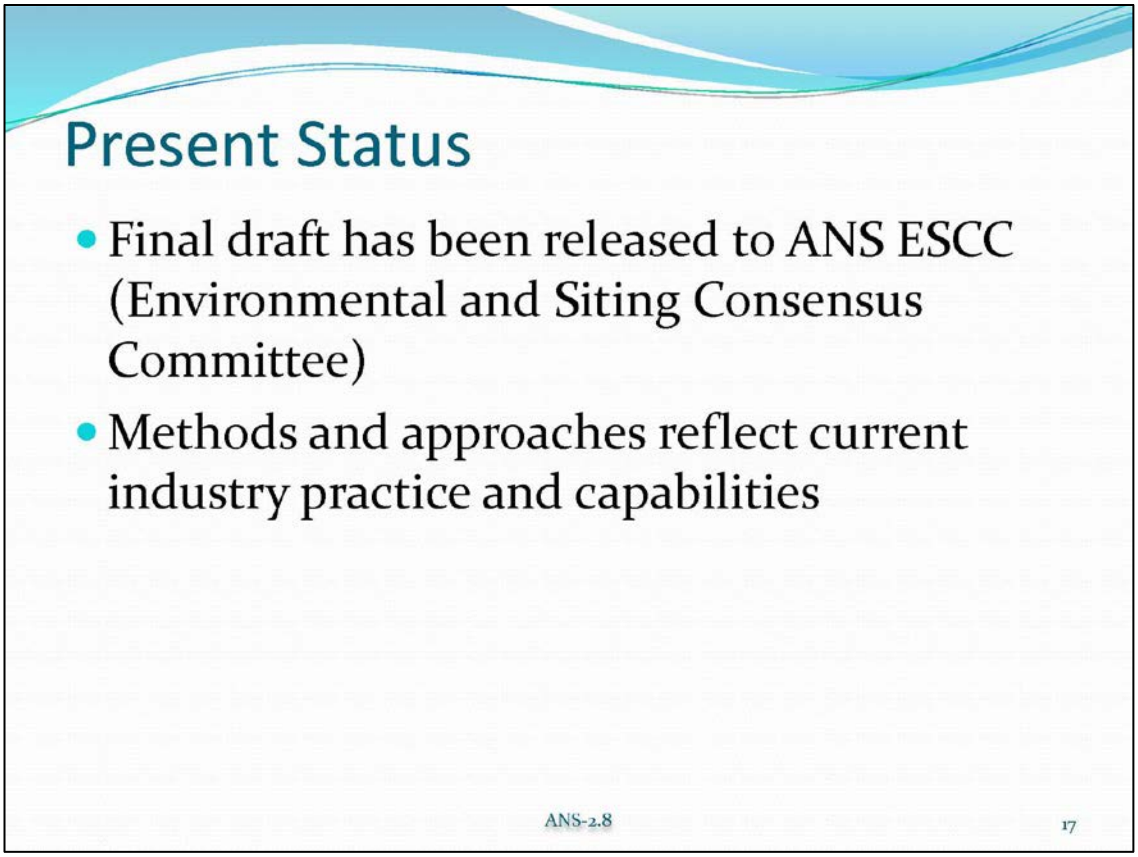
- Documentation process is to cover all aspects of the analysis and support peer review.
- Documentation will be commensurate with PFHA Level and facilitate Peer Review and applications of the PFHA

Peer Review

- Peer Review is an integral part of the revised ANS 2.8 Process
- Overall process is modeled after Seismic Peer Review Process (ANS 2.29)
  - Late Stage Peer Review
  - Participatory Peer Review (required for Level 3 / Level 4 PFHA)

Participatory Peer Review Process





4.3.9.3.2 Questions and Answers

Question:

You say that ANS 2.8, "Determining Design Basis Flooding at Power Reactor Sites," is now being expanded to all nuclear facilities because DOE wanted you to look at other nuclear facilities. Will fuel fabrication facilities, in situ leach mining, waste storage, the Hanford Site with to tanks, and similar facilities be included in the scope? If the scope really includes all nuclear facilities, that changes the objective of why a flood may have consequences.

Answer:

What we are looking at is the frequency, or the frequency and the hazard. If it is a lower risk facility, and you could justify it, you still could just have a much simpler PFHA. You can still go through the process, and then determining what the issues are becomes a Level 1 analysis, and maybe you pick your criteria as 10^{-2} or 10^{-3} and then the analysis does not have to use any of the extreme value methods. You do not necessarily have to make everything 10^{-6} if they are different levels of facilities.

Follow-up Question:

The issue is that, with nuclear power sites, the emphasis was always on safety, not environmental considerations. If you expand the standard to cover all nuclear facilities, depending upon what happens, the flood may cause consequences that have both safety and environmental impacts. It changes the scope of a PRA dramatically with regard to consequences.

Answer:

This is not a PRA. It is meant to identify your hazard at the site and for you to take the appropriate protective measures for the level of site. It is not necessarily tied to the PRA, but you can use it for a nuclear site PRA.

Comment (Joseph Kanney, NRC):

To provide some clarification: this is not meant to support environmental reviews. We do environmental reviews for NPPs anyway; we do that with different processes. This is to support safety analysis. With regard to different types of facilities, that is why the matrix is there, so that when you are deciding what level of analysis you need to perform, it will be based upon the safety category of the facility. But that safety category is based upon the consequences of an unmitigated release from that facility. Then that safety category is borrowed from other American National Standards Institute standards, and then couple that with the complexity of the hazard that you are looking at, and that provides some guidance about what level of analysis you need to do for the facility in question. That matrix was developed to provide some way to choose what level you need for different types of facilities. Obviously, an NPP is always going to fall into the highest level of safety category.

Question:

Will the standard give any guidance, in relation to making a distinction between aleatory and epistemic uncertainty? There are those who will argue that epistemic uncertainty does not really exist but is an actual artifact of the limitations of our phenomenological knowledge, and therefore we use it. At the other end of the scale, I can build a model and I can basically, depending on how I partition the model, put the boundary within the model between aleatory and epistemic. Since the two things work through the risk analysis differently, you can get different answers, depending on how you define the boundary between aleatory and epistemic. Will that be sorted out?

Answer:

That will depend on the models and the hazards that you are dealing with. I don't think there's really detailed guidance on that.

Comment (Joseph Kanney, NRC):

For the purposes of using the standard, we do define what we consider aleatory and epistemic with respect to the standard. Your comment is correct, that in some sense, how you partition actually depends upon what modeling tools or analysis tools you are using. But we considered that you will have a fixed set. You can use the definitions that are in the standard to chunk it into aleatory or epistemic. Although your comment is well taken, I don't think that's an issue that we could solve in the standard, although we did spend hours talking about it.

Question/Comment (Andy Campbell, NRC):

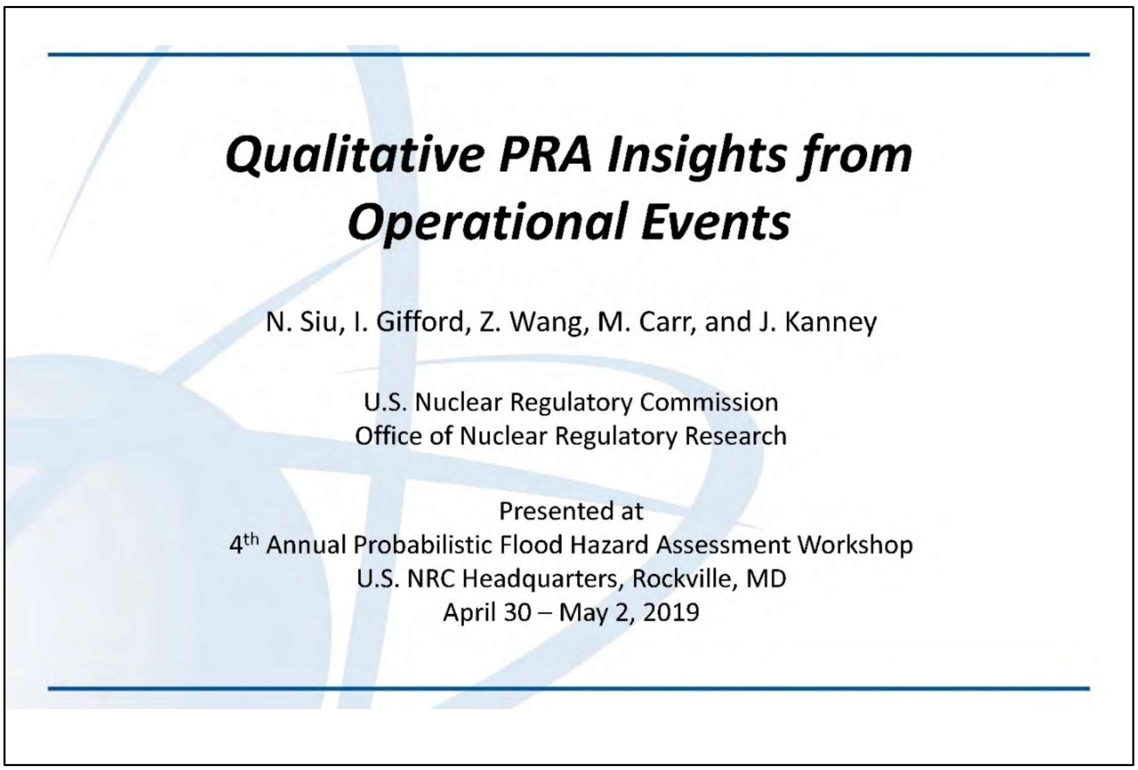
We have provided comments and we will provide more comments on this standard. When you talk about a SHAC process for seismic, most people think seismic SHAC, Level 3, which is a very involved process. We now have guidance, NUREG-2213, "Updated Implementation Guidelines for SSHAC Hazard Studies," issued October 2018, for SHAC Level 1 and Level 2 processes. In our minds, we are thinking SHAC Level 2 is the upper limit for a flooding type of analysis. You have to consider the uncertainties and the competing models. For flooding, that's a narrower field then for seismic, generally.

Answer:

That comment would be very useful as a review comment on the issue. These are consensus standards, and we certainly want to consider that.

4.3.9.4 Qualitative PRA Insights from Operational Events of External Floods and Other Storm-Related Hazards. Nathan Siu, Ian Gifford*, Zeechung (Gary) Wang, Meredith Carr and Joseph Kanney, NRC/RES (Session 3C-4; ADAMS Accession No. ML19156A484)

4.3.9.4.1 Presentation



Background

- Part of the PRA process involves ***searching*** for potential scenarios (What can go wrong?)
- Empirical evidence (operating experience) helps stimulate and temper imagination
- Example: 1975 Browns Ferry fire incident reviews (NUREG/CR-6738)
- Hypothesis - analogous reviews of other incidents could be valuable to:
  - PRA developers and analysts
  - Broader NRC efforts to increase/improve the use of risk information

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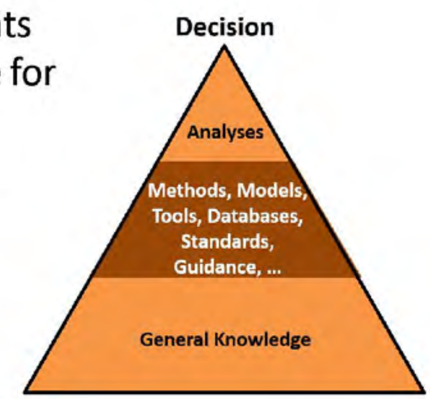
Project Objectives and Scope

- Objectives
  - Identify PRA technology* insights
  - Provide educational experience for risk-informed decisionmaking support
  - Identify lessons for intelligent search tool development
- Scope
  - Exploratory, qualitative study
  - Limited number of incidents



* "Technology" = Methods, models, tools, data

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Approach

- <u>General</u>
  - Review team with varied PRA experience levels and areas of interest
  - Informal event selection, considering:
    - Safety challenge indications (e.g., INES level, CCDP, LOOP, LOUHS)
    - Information availability
    - Personal interest
  - Review structure
    - Chronological
    - Hazard, fragility, plant response
- <u>Principal data sources</u>
  - Publicly available (e.g., LERs, papers, technical reports)
  - IAEA Incident Reporting System

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Incidents Reviewed

External Floods*

- Hinkley Point, 1981
- Dresden, 1982
- Blayais, 1999
- Cruas, 2009
- St. Lucie, 2014

Storms*

- Turkey Point, 1992
- Maanshan, 2001
- Browns Ferry, 2011
- Pilgrim, 2013
- LaSalle, 2013

*Categories are not exclusive.

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Example: Chronological Review

Date/Time	Event or Step Description
August 17	Turkey Point staff began tracking Tropical Storm Andrew in the control room.
August 21	Plant staff began implementing the Emergency Plan Implementing Procedure (EPIP), including moving equipment inside, tying down equipment, and preparing for storm surge. Equipment was moved from the Unit 3 diesel fuel oil tank, which did not have missile protection.
August 23	An Unusual Event was declared due to hurricane warning issued by the National Hurricane Center.
1800	Unit 3 began shutting down. Turkey Point operators estimated that it would take 8 hours to complete an orderly shutdown and wanted to stagger the shutdown on each unit by 2 hours. There was concern over the main turbines and balance of plant supporting equipment being located on an open air deck (risking personnel if they needed to be outside). Unit 3 reached Mode 3 at 1940 and Mode 4 at 0213 on Aug 24th.
2000	Unit 4 began shutting down. Both units were kept in Mode 4, rather than Mode 5, to retain steam-driven auxiliary feedwater pumps as an option for removing decay heat. Unit 4 reached Mode 3 at 2245 and Mode 4 at 0405 on Aug. 24th.
August 24 0400	Hurricane Andrew passed directly over Turkey Point, with sustained winds of 145 mph and gusts of at least 175 mph. Spurious alarms received for the spent fuel pool low level and instrument air pressure low.
...	...

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Example: PRA-Oriented Review

Category	Sub-Category	Summary
Hazard	Conditions	Exceptionally strong storm (985 hPa; 180-200 km/h); high tide, storm surge, wind-driven waves at site.
	Protection	Dikes (5.7 m) insufficient height and inadequate shape, upgrade suggested by earlier study not done. Also, problems with detection and warning systems.
	Onsite Impact	...
Fragility	Safe Shutdown SSCs Exposed	...
	Safe Shutdown SSCs Affected	...
	Barrier SSCs Affected	...
Response	Functions Lost	...
	Safe Shutdown Path	...
	Recovery	...
	Operator Actions	...
	Other Incident Management	...
	Offsite Impact	...
Long-Term	Post-Event Changes (Plant)	...
	Post-Event Changes (Fleet)	...

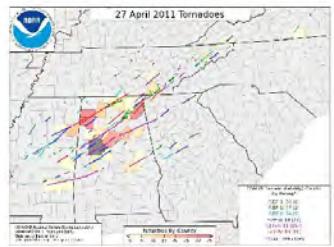
Observations: PRA Technology

Confirmatory

- Multiple hazards
- Asymmetrical multi-unit impacts
- Less-than-extreme hazards
- Hazard persistence
- Failure of mitigation SSCs
- Failure of implicitly considered SSCs
- Warning times and precautionary measures
- HRA and emergency response complexities

Less-Discussed

- Multiple shocks
- Scenario dynamics
- Geographical extent and potential for multi-site impacts



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Observations: Knowledge Management and Engineering

- <u>Educational benefits</u>
  - Improved understanding of specific events and mechanisms
  - Improved understanding of external hazards PRA modeling challenges
- <u>Challenges for intelligent search tools</u>
  - Limitations with current event significance measures
  - Limitations with analytics-based approaches
  - Database concerns (e.g., errors, multiple sources, evolution over time, volatility)
  - Need for multidisciplinary interpretation and analysis

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Concluding Remarks

- Limited scope, exploratory study achieved project objectives
- "Old" events can still provide useful lessons
- Conservative PRA analysis assumptions can "bound" many observed complexities, but
  - might mask important risk contributors
  - might not motivate useful risk management activities (e.g., preparation for asymmetrical impacts)
- Follow-on activities (additional PRA-oriented incident reviews, event catalogs) are underway

Questions?

Additional information about the project can be found here:

http://psam14.org/proceedings/paper/paper_164_1.pdf

NRC Agencywide Documents Access and Management System (ADAMS) Accession No. ML18135A109

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4.3.9.4.2 Questions and Answers

Question:

Given the unique nature of some of these, the current PRAs are not set up to deal with losses of offsite power (LOOPs). Do you have any comments on how well you think the current suite of PRA tools is adapted to capturing these risk contributions from these types of events or making sure that the insights we get out of a PRA are going to point us to these types of potential issues?

Answer:

This is something we talked about a lot as a group. We had a lot of discussions, specifically on LOOP; your PRA model is not going to be able to model that scenario. But does what you are modeling bound all other conditions? We were trying to think of an example when you have already had a LOOP, and you have recovered power, is a second LOOP in a short time after that worse than being in the original LOOP? We were playing around with those ideas and determining what would be most limiting. Our team could not think of an example where the subsequent LOOP would necessarily challenge the plant. We did find some issues with the reliability of power coming on during a multi-LOOP scenario. You have the power recoveries, especially when you have your PRA data and you are looking at the mean recovery times. There was some confusion, occasionally, on the definition of when power is recovered. If you are having continuous LOOPs, technically, you have recovered power in order to have another LOOP, but is the power reliable? Can you count on that power supply? We did not come up with an elegant answer for how to analyze that. But it did beg the question, are the data actually limiting enough to rely on for a realistic PRA?

Question:

Whenever there is a LOOP event, EPRI has its own reevaluation, the NRC has its evaluation. Often, they do not agree because of the instability of the power. Did you look at both of those to see if following this guidance would mean that it is a longer LOOP or longer duration? I think some of that is there, but the only way it really affects the PRA models is how you estimate recovery time.

Answer:

No, we did not directly look at that. But we did look into the significance of some of these findings and thought, let’s assume that we could not use this recovery time. Let’s use a longer recovery time in the model. Does it significantly impact our result enough that it will be worthy? We did not find evidence that it was worth digging into for this project, but we had it noted as something for the future. We were also interested in looking at where the data come from. But when plants are reporting the recovery time of these offsite power recoveries, what guidance do they have? When can they call it recovered? But we did not go in and look at different tables.

Follow-up Answer (Suzanne Dennis, NRC):

The NRC and EPRI are collaborating on our LOOP and LOOP recovery data. This will be covered in a joint report, so you won’t have to worry about any of those decisions.

Question:

Ian Gifford combined flood with electrical systems. I can't help but think of Benjamin Franklin; they're always dangerous together. You talked about a PRA bounding analysis. I'm familiar with a deterministic approach in which you have a conservative bounding analysis, but what do you mean in the PRA world? Because usually, SHAC-F is to look at the full complement of alternative conceptual models, and they determine through that analysis the significant processes and consequences. Bounding often implies worst case, and I do that analysis. If I clear that, then everything else is okay. What do you mean by PRA bounding analysis?

Answer:

When we have LOOP after LOOP after LOOP, is there any initial plant condition? If you have 100 percent power and you have a LOOP, and then you recover power 30 minutes later, is there any reason that would be a more dangerous initial condition for the plant to be in then at 100 percent power? Our focus is on identifying whether there is anything worse than being at full power when you have a LOOP, and is there any reason why having 30 minutes of decay heat taken off the core will put you in a worst case scenario? Our group could not think of a reason. That is what I meant by bounding.

Follow-up Answer (Joseph Kanney, NRC):

We also made observations with some of the high-wind events, related to the risk of a tornado striking a plant. But when you actually look at many of the events, they were actually tornado outbreaks, which could have potentially affected facilities that you might be relying upon in the wider area around the plant that might have some implications for how the plant responds.

Follow-up Answer (Ian Gifford, NRC):

I think that was the Browns Ferry Nuclear Plant in 2011. We talked a little bit more in the paper about that, but it was more of a cluster and so you had simultaneous or near-simultaneous tornadoes across multiple States. That had interesting offsite consequences, and you could actually envision a scenario where multiple sites with multiple units are affected.

4.3.9.5 Towards External Flooding PRA Discussion Panel. (Session 3C-5)

Moderator: Joseph Kanney, NRC/RES/DRA/FXHAB

Andrew Miller, Jensen Hughes
Michelle (Shelby) Bensi, University of Maryland
Ray Schneider, Westinghouse
Ian Gifford, NRC/RES
Guest Panelist: Suzanne Denis, NRC/RES
Guest Panelist: Jeremy Gaudron, EDF

Moderator:

For the panel discussion for this session, we have two guest panelists. Jeremy Gaudron from EDF is a hazards probabilistic safety analysis engineer. Suzanne Denis is a risk analyst in our PRA branch in RES.

Question (from the Webinar):

In updating ANS 2.8 1992 for guidance on performing flooding PRAs, there was not any mention of NUREG/CR-7046, "Design-Basis Flood Estimation for Site Characterization at Nuclear Power Plants in the United States of America," issued November 2011[13], which was the guidance used to develop the FHRRs. NUREG/CR-7046 appears to be a lot of carryover from ANS 2.8 1992. Will it be used in updating the ANS standard? Also, other guidance documents were used during Fukushima flooding, such as Nuclear Energy Institute (NEI)-1605 (External Flood Assessment Guidelines, Rev.1[14]). It appears this would be vital information for screening processes, as a similar screening process was used in the focused evaluations or integrated assessments, as required, in accordance with NEI-1605. This was not mentioned in the presentation. Would the completed Fukushima flooding reports be used as leverage in moving forward for the PRA as well as consulting with those folks who were involved in developing those reports as needed, as a lot of work went into developing them? It would appear this work would also carry over into the PRA.

Ray Schneider:

It varies. In terms of the PRA, everything you just said will be considered. The new ANS 2.8 does not specifically reference NUREG/CR-7046. That would be the follow-on to ANS 2.8 1992.

However, in the new ANS 2.8, we shift the methodology to move towards a probabilistic hazard approach, and that would be more of an extension of the existing standards. The goal was to turn it into a probabilistic environment. However, when you deal with the PRA, everything is included. Michelle Bensi will confirm, we will look at all the information that's available because it has the human factors, the integrated assessment, all the protective equipment, and all of that information. That would be in the PRA itself. But ANS 2.8 is just for the hazard.

[13] NUREG/CR-7046, "Design-Basis Flood Estimation for Site Characterization at Nuclear Power Plants in the United States of America," issued November 2011, ADAMS Accession No. ML11321A195

[14] Nuclear Energy Institute (NEI)-1605 (External Flood Assessment Guidelines, Rev.1, ADAMS Accession No. ML16165A178

Joseph Kanney:

NUREG/CR-7046 is a document that was used as guidance in the post-Fukushima flood hazard reevaluations. But that document addresses deterministic methods. The new ANS 2.8 is probabilistic, so NUREG/CR-7046 isn't really applicable. Some of the other documents produced during the post-Fukushima process address some risk and probability and to that extent they will be relevant.

Michelle Bensi:

Maybe the screening input?

Joseph Kanney:

Yes, there was a part in NUREG/CR-7046 about screening.

Question:

Two of the talks today were about the Blayais site. It suffered through a flood. We saw that there was subsurface flooding. There was talk about failures. But EDF made corrections. They evaluated the consequences of that flood and they made repairs. They did things to lower the flood hazard at that site. The next time there was a flooding condition, the plant survived that, and everything was fine. Vincent Rebour told us about guidance that was put forward after that flood. Could you give us some insight as to EDF's approach with regard to mitigation of flood hazard at that site?

Jeremy Gaudron:

Following Blayais, EDF defined a lot of different flood mechanisms and tried to put some mitigation means in front of each of them. We have some riverine flooding, we have some waves with storm surge, we have a lot of things. As Vincent Rebour already said, we put some big protection in place. For the volumetric protection, that's all the buildings within safety SSCs. We protect them up to 10^{-4} water level so that water cannot come in up to this floor. We also have some peripheric protections, so that almost all the plants are like a bathtub. After the accident at the Fukushima Dai-ichi NPP, we added some more protections. We added some lower protections in front of all building entrances to protect from LIP. We will have some higher protection to cover 10^{-5} water level on sites.

Moderator:

How did the experience at Blayais translate into changes in how probabilistic safety assessments (PSAs) are performed? Are there insights or actual changes to how they're performed at EDF or France in general? Are there significant changes that came from that?

Jeremy Gaudron:

We are just beginning to consider PSA so that's quite new for us. Blayais did not change anything because we did not have any external flooding PSAs beforehand. The first PSAs were released last year, 20 years after the Blayais event. After Blayais, we also improved onsite procedures and guidance to train and enhance how people react to such events. For the first PSA we performed last year, Blayais was not the focus. We integrate all our knowledge in the PSA, and Blayais was just part of the knowledge.

Moderator:

Over the last few days, we have looked at several different types of flooding hazards. We have talked a little bit about coincident or correlated processes or flooding events. We have talked a little bit about the fact that for flooding, there may be a very significant component of manual actions or procedures. What do the panelists think about which one of these we tackle first? Since risk assessment is about trying to find the most risk-significant thing and work on that, in terms of balance between analyzing this extended use of procedures and manual actions versus getting the probability right on a particular flooding event, what do you think is the most important in terms of safety?

Michelle Bensi:

I don't necessarily think getting the probabilities right is most important. I think it is much more important to really understand how the hazards are affecting the plants and being very realistic about the operating experience with regard to the potential for water, where you don't want it from unsealed penetrations, and some of the human action challenges. I think it is important to understand those things and not assume that everything will work the way you wanted it; work with an understanding that things will go wrong. Working through that thought process is the most important thing. That being said, when it comes to the numbers, my biggest concern is how they might be used for screening. I think they become most important when the numerical frequency of exceedance arguments is being used to screen out a hazard, because then we don't get any of those insights with regard to how does the hazard affect the plant? What could go wrong? So as much as I spend my whole life calculating frequencies on floods, I think that it's most important that things don't get screened out improperly because we really just need to understand how these things affect the plants.

Ray Schneider:

Yes, screening is one issue. Human factors and organizational responses are also important. Floods encompass a whole variety or spectrum of events, and you have human actions that deal with them. For example, putting up the floodgates, making the plant less vulnerable to the hazard that's coming, and knowing when to establish your triggers are important. When we did a flood analysis for one of the plants, having to deal with an event that they knew was coming, the highest risk scenario that we came up with involved the plant resources and not being able to put all the flood protections in place because of other reasons. This then caused some vulnerabilities that should not have existed. Had we maybe started earlier and had proper organizational behavior, we would have a lower risk, and that portion of it could diminish. I think we should focus on the organizational behavior, the human hazards—not so much the response, but a lot of the preparatory actions that can be taken in advance. I'm also concerned that we overestimate the fact of the numbers, if they are too low, like at Blayais. For example, you assume you have a 10^{-3} site and put in a wall. Now it's a 10^{-4} site, or maybe it's a 10^{-5} site. But what happens to the event that occurs beyond that? Have you hardened the facilities? Do I still have, for example, fire seals in the area of the electrical penetrations or do I now have flood seals there? Those are the kinds of things that provide the protection that you need. I think these are some of the insights to carry forward.

Andrew Miller:

I've given up waiting for consensus on how to do frequency analysis for any type of flood. I gave up that maybe 7 years ago. I decided we need to move on and think of another way to do it. I couldn't agree more with Ray Schneider about operator actions and procedures, if that's something that your plant relies on. Inappropriate screening and losing the insights is certainly a good topic to address. But since the accident at Fukushima Dai-ichi, we've gotten a better grasp of our hazards. A lot of sites have upgraded their strategies and maybe are able to handle their PMF, which I'm going to say, presumably, would be a low frequency. PRA should really be focused on how we get benefit and what insights do we learn in order to increase actual safety. If it's a human action or organizational response, I think that is definitely where it is important—doing reasonable simulations. Every time we talk with operators, they say that having clear procedural guidance and having training seems to be the most important thing. I would agree: to know what to do when floods come.

Jeremy Gaudron:

I also agree with that. One of the main lessons learned in our first external flooding PSA is that whatever the hazard curve is, whatever your protection heights are, at the end you always find a level where there is a cliff edge effect. So what matters is how you prepare for such events, all the ways to protect your plants, and how you train people to be as well prepared as they can be.

Ian Gifford:

When we were doing the project covered in the presentation, one of the events that I paid particular attention to was Turkey Point Nuclear Generating during Hurricane Andrew. Although this is a 1992 event, I think some of the things we saw are still relevant today. One of the most important things they had was early notification of a hazard, so they could begin preparations. I think early notification is really key. We also saw the issues with human factors, which people have already mentioned. I think it's important to have as many of the features designed into the plant before the hazard occurs. Turkey Point was without offsite power for 5 days. They had a lot of plans on actions that operators would be able to take during the LOOP. It turned out that there was such wide-scale damage at the plant. A lot of the plant operators at that point are also concerned about their homes and their families; there's no communication. Relying on them to follow procedures as they normally would is a bit unrealistic. Also, so much of the equipment that they use for mitigating strategies was damaged in the event. They did not even have trucks because many of them had been wiped away, and there were downed power lines all over the plant. They ended up using large chains to throw across the power lines to see if they were energized or not. These are the things that I'm not sure are always considered when you're saying, "Well, if this happens, we're going to take out this procedure and do this." I mean, they ran a food drive to feed the first responders. So, although that was 1992, I think a lot of those lessons still apply to today.

Suzanne Denis:

Your original question is, "What should we do first?" I think we have the benefit of things happening first, whether or not we think we have made a decision. Human reliability is important. We are already looking at ex-control-room actions, and so that's an area that's being explored outside of flooding. We will be able to pull those insights into the flooding world without necessarily needing to be the initiator. I think some things are just going to happen that aren't flooding specific.

Moderator:

Could you say a little bit more about those other ex-control-room activities that are being analyzed that might be useful for flooding?

Suzanne Denis:

NRC/RES is currently doing a study to look at how to model human reliability for ex-control-room actions. The PRA looks at a lot of things as to what's going on in the control room; you have a heating, ventilation, and air conditioning system, you have a floor. Things that you might not necessarily have especially in some of these more extreme events.

Moderator:

Andrew Miller, you mentioned that in preparing for the walkdown, looking at the mitigating strategies assessments could be valuable. What value, what particular elements have you seen?

Andrew Miller:

In a deterministic world, maybe mitigating strategies are not part of your flood strategy that you would take credit for. But in a PRA, you can certainly include additional capability regardless of whether or not it fits into a design basis or a licensing basis. So, with mitigating strategies, since everyone had to do an MSA, the first place we'll look if there are some issues with current flood protection is the mitigating strategies. When we do those walkdowns, can we reasonably get the equipment where it needs to go? Can it be hooked up? Are there procedures? I can't stress the importance of conducting reasonable simulations, where folks go out and actually do it and you watch them do it. Those types of things are invaluable to all PRA analysts, especially for human reliability analysis (HRA). That's what we would be looking for; going through the MSA to understand and confirm that those assumptions are still valid even in a probabilistic framework, not just our deterministic box that stops here.

Moderator:

In terms of incorporating the flood hazard information into the PRA itself, we talked a lot for the last several days about the need to incorporate the uncertainty in your flood hazard. When it comes to inserting that into the PRA, I think it's probably a lot simpler if you are using mean values. If the hazard analysts are giving you this full family of hazard curves with the epistemic uncertainties as well as the aleatory uncertainty, one of the first things that the PRA analysts are probably going to do is try to simplify it. How would you simplify that, because I think in some cases, the hazard analyst maybe giving you too much?

Andrew Miller:

To my knowledge, no one has actually run a full external flooding PRA with the uncertainties propagated, but the parallel to seismic would be to run your uncertainty analysis with whatever parameters they are, and then you find that the hazard dominates the uncertainty. Are those uncertainties acceptable? From what I've seen, most people are not quite sure what to do with that. Then the uncertainties in the hazard curve get stripped out to look at other things, like are we sensitive to, or do we have high uncertainties with, operator actions? Or do we have high uncertainties? A lot of times to simplify it, the hazard gets removed to get the insights because it usually dominates the entire uncertainty analysis. So, you sometimes can mask those other things if you don't know how to take those out and relook at them.

Ray Schneider:

We actually did an external flood analysis for a plant that's no longer operating. But the issue with this case was dam failures. There are two issues: the frequency and the frequency has uncertainty, and then the elevation and the type of hazard that drives the event. In this case, a riverine event that could be the result of opening floodgates that could be caused by a dam failure. What you had to do is identify and map the hazard profiles (and Andrew Miller showed examples of types of hazard profiles), and those drove different human actions, and those drove different abilities to mitigate the event. You are propagating mainly the uncertainty, especially with the frequency of that event, but you have to also have enough precision or granularity to identify that not all dam floods are going to occur the same way. Some of them come with a lot of pre-flooding on the site, some will occur very rapidly and then totally inundate the site. You have to break it into pieces. It's like anything else; it becomes essentially different hazards with different frequencies. That's the way I try to estimate how you propagate it through. We can understand that these kinds of events are important, because I only have a given amount of time. But if I don't meet my deadline in a certain amount of time, my flood's going to be 3 feet on the site and I can't get my staff to do anything at that point. I have actions that are taken with equipment that is underwater at this point. So, you have to basically do this mapping, although that's a complicated aspect of it.

Suzanne Denis:

I think that I heard earlier this week that we can develop all sorts of uncertainties, but what's the end result? What are decisionmakers going to do with that information? I think sometimes the question is not how do we propagate and get this very detailed uncertainty analysis, but both the hazard community and the risk community struggle with what do decisionmakers do with that information? The bigger question might be what do we do with that information once we have it, rather than how do we do it?

Michelle Bensi:

From a decisionmaking perspective, if you understand the conditional response to these, essentially a plant fragility curve, although it's not quite that simple because it's not just one dimension on the axis. I think it's a key piece of information. Because once you have that sort of understanding, the sensitivity to the hazards and the quantification for decisionmaking purposes is a bit more straightforward. But then again, I think a lot of decisionmaking is made on the mean hazard. So, if it's not made on the mean, estimate.

Andrew Miller:

The main point is we have to be okay with the mean estimate. Even though the uncertainties may be orders of magnitude on the range we care about, in seismic we're okay with the mean now. Flooding needs to be there too to make decisions.

Michelle Bensi:

I think the key thing about understanding the epistemic is also just getting away from the point estimate. I think a lot of what has been done in practice is you come up with a point estimate, which yields one hazard curve. If you do not necessarily know whether that point estimate is near the mean, you do not necessarily know whether you have the right decision point. I think it's understanding where the mean is and not just doing one analysis when you get just one point estimate of the parameters and one hazard curve.

Comment (Andy Campbell):

The NRC has done a review of a PFHA that is very similar to a PSHA. It's in process, so I can't talk in detail about it. But we have looked at that. We have a way of reviewing those. You end up with a hazard curve. You make a decision based upon their hazard curve and what your own analysis does, very similar to what we do routinely for PSHA. So, we do have at least one example that we will eventually publish.

Comment (Des Hartford, BCHydro):

I'm coming from the hydropower perspective and what to do with the results. If you look at what USACE and USBR do with the results, they actually compare the quantitative results from their event tree analysis, the numerical values, without much consideration of these uncertainties because the methods available for us sometimes do not allow us to capture that to any significant degree. So, it's on the rough scale, compared to where we really need to be. It's compared with an acceptable risk guideline. We saw a little bit of that from John England the other day. But that whole process is fraught with difficulty. What the dam owner's going to do, and the same will apply the nuclear power operator, with these risk numbers will not necessarily be compared with a tolerable risk value. In fact, there are very good reasons not to compare with these f-N curves that they've been using. There are good reasons why things must move on. So, the whole area of what to do with these risk numbers is going to take a huge amount of policy work. Much more than is been done for the dams, even though they're making decisions, not basically prioritizing all the work now. A lot will then relate to the policy principles, the actual values of the society or the values of the authorities that are driving the decisionmaking process. How are they going to be factored in to what you do with the numbers? That's a whole new area that needs to be reconsidered for the 21st century, given public perceptions today, compared with what Farmer[15] said back in 1967, for the sighting of nuclear reactors. Now, concerning what Farmer said back in the 1967 seminal paper, and in relation to screening, fundamentally, screening is nonconservative. The second one to deal with is the fact that when you are screening, and you can screen deterministically, up to a point, because you can't cover everything deterministically. If you're screening in a probabilistic sense, you resort to credibility, which is actually a binary decision based on a degree of belief—it's either credible or it's not credible; it's in relation to the physical possibility of whether it can be done. If you screen on the basis of probability, you are faced with the problem that you have assigned the probability to this, it might be 10^{-10}, but you can't be surprised if it happens. The 10^{-10} event will happen because, as Farmer sagely pointed out, the credible event can have an incredibly low probability, whereas the incredible event can be made up of the combination of very credible events, but the combination is unusual. What we recently had to grapple with on the dam side is unusual combinations of usual conditions. We concluded, looking at a small hydropower plant (not very complicated), 10^{27} different system states. Which ones do you screen out? How do you know? You don't. There's a whole raft of things to be done in relation to screening on the one hand, and what to do with the numbers on

[15] Farmer, F.R. (1967). Siting Criteria - A New Approach. In Containment and Siting of Nuclear Power Plants: Proceedings of a Symposium held by the International Atomic Energy Agency (IAEA), Vienna ,3-7 April 1967: IAEA. P. 303-318.

the other, which I think needs to be revamped. Copying what was done in the 1970s, 1980s, and 1990s is not fit for purposes today in relationship to what to do with the results.

Moderator:

There is this idea of PRA capability. You can have a PRA, and it can have different levels of capability. How would you characterize our capability level today, in terms of an external flooding PRA? What capability level do you think we can get to in the near future? What capability level do you think we ultimately need?

Ray Schneider:

Historically, we ended up with three capability categories. The first one, Capability Category I, was basically saying. “This is what we know now. This is the state of knowledge now.” That was 25 years ago. That became the basis to say that this is our state of knowledge; this is good enough to make reasonable decisions. The second capability category, Capability Category II, is what we’d like to be able to do, what we think we should be doing. The third, Capability Category III, was almost aspirational—we can do this, we have enough knowledge, but it’s a lot of work, and is it really worth it? But if you do it, we want to give you credit for it, we want to say that’s really good. Nowadays, I think Capability Category II is where everyone should be. But in some cases, we know that still may be overkill. In certain specific areas, you may want Capability Category I if you can justify a conservative frequency. If you can say, “I’m doing it bounding, I've done the analysis, and I’ve made so many assumptions that I know it's a bounding frequency, but it saves me a lot of work,” then you can get away with Capability Category I. But I’m not really doing the state of the art at that point. But if you do Capability Category II, you can get maybe lower results and more realistic calculations. So, Capability Category I is probably okay if you can do it conservatively and you can justify the conservatism, and Capability Category II is really probably where we should be for the industry. It’s basically right, it’s a realistic mean. But again, if the cost of that realistic mean is enormous and you can live with the Capability Category I, stay there.

Michelle Bensi:

To clarify: it used to be three capability categories, in the current PRA standard revision that’s coming out, it’s going to just be those two (I and II). Capability Category I PRAs have different pedigrees in terms of regulatory decisionmaking. If you submit one of these (Category I), the NRC may respond differently. But the one challenge also with some of the Capability Category I PRAs is that when you start making these conservative assumptions, you may be masking important risk insights. So, it’s a tradeoff. Not just because the answer might be higher in terms of whatever risk metrics, but that you might actually lose some risk insights coming out of that activity.

Ray Schneider:

It’s a balance. If you are using Capability Category I, you do not want to lose those insights in the process.

Andrew Miller:

To answer the question of where we are now, we are not very far. Then where can we get to? I think it’s going to get harder with regard to some of the participatory peer reviews that you have to do; an additional level of rigor that would be state of practice these days. I think there are only a few sites for which the cost would justify having that tool capable. That's the other balance: how much effort does the utility or a site want to put in? A lot of sites are very high up and do not have flood problems, or not nearly as many flood problems. I think the sample set of people who are interested in doing a flood PRA is much, much smaller than all other hazards, period. It's going to take a while to get there, I think.

Moderator:

Jeremy Gaudron, is this capability model process used in France or in Europe?

Jeremy Gaudron:

We don't have such capability categories. But then we have just begun on the subject. It's not quite mature.

Suzanne Denis:

I don't think anyone has done a really full-scope, external flooding PRA. So, we're Capability Category 0 right now, and hopefully moving to something more than that.

Meredith Carr:

We've talked a lot about trying to assign numbers to things: hazards, fragility, human actions. We have not talked much about forecasts and warnings, which are really out of the control of the plant itself. Is there any thought of trying to include the reliability of forecast, either spatial or temporal, in there? Do you think it's a significant issue when you're putting all those numbers together?

Andrew Miller:

That's going to vary organizationally. Some utilities, some sites that I've been to have onsite meteorologists, where they can more directly control how they monitor and when they get forecasts. Others rely on NWS. I think the general trend, since the accident at Fukushima Dai-ichi, that we've seen has been utilities adding time and steps along the way. It is difficult to assign a reliability to that. We are still waiting on a reliability number for just putting up a sandbag wall, let alone how well NWS is going to perform. But I do think that it's warranted to look at that. I think a lot of sites did upgrade their forecasting capabilities. What does that look like post-Fukushima, especially? I know for a few of the sites we worked with after NTTF Recommendation 2.3, those procedures got a lot better: more set points, more defined actions that were not ambiguous. For example, you need to start shutting down if it gets to this level, not merely consider doing this. To me, that's more beneficial to safety than trying to put a reliability number on the forecasts.

Ray Schneider:

From the point of view of the standard, there's no intent for a standard to basically try to do that prediction better. But from the point of view of the response, the key things are the triggers. If you have triggers and good organization, and that defines your organizational behavior, you will be able to respond. The key to that is the plants that have those triggers actually should use them; before the hazard comes upon them. In a couple of instances, people actually start taking out the floodgates when events occur far away because they know that if they wait too long, they would not have enough time. That is one way of getting confidence that the organizational behaviors will be okay.

Michelle Bensi:

I don't think it's necessary to quantify the reliability of forecasts. I think the key message is that you have to understand what the uncertainty is. You know, 24 hours out, you really still might not know where landfall is going to happen on the hurricane. Recognizing that, I think, probably more so before all the NTTF Recommendation 2.1 and 2.3 activities were put in place, some of those procedures were pretty optimistic about how much confidence, or how much warning time, we really have. We think that we wouldn't miss the fact that there's a hurricane making landfall, but maybe not recognizing that, these things track change really late in the game. Or that you can have these large-scale participation events fall on top of the weather center, and they didn't see it coming. These things can happen. I think the key message is to understand the limitations of the forecasting capabilities so that the procedures are not taking advantage of the best case. For example, you know 72 hours out where the flood stage is going to be and you take 72 hours to do the procedure. You can account for those potential cases where things change more than expected, in terms of the forecast, and you don't end up waiting too long because you think you have more time than you actually do.

Suzanne Denis:

I think that we've made a lot of advances just in the last decade. When I started at the NRC, we had a potential licensee say that they'll know there's a flood when the water comes on the site. They literally said, "Well, when our feet get wet." I think we're far beyond that, just in the last 10 years. I think we're probably not quite at quantifying any sort of reliability in forecasts, but there's a much broader recognition for those kinds of things.

Joseph Kanney:

As part of the post-Fukushima flood hazard reassessment process, the NRC asked all the power reactor licensees to reevaluate their flooding hazards. If their reevaluated flooding hazard was higher than their current design basis, then that tipped them into a process called an integrated assessment. In the discussions with NEI and licensees on what should be put into an integrated assessment, there was a specific focus on warning time. NEI developed a white paper[16] on warning that provides basic information on the types of warnings and forecasts that are routinely provided by NWS. It had some guidance about considerations for developing your trigger. So, with respect to that, I think there has been some considerable improvements. I think that's one of the things we had a question about: what sorts of things from the post-Fukushima flooding reevaluations should be rolled into external flooding PRAs? I think that white paper is probably one example of something that developed out of that post-Fukushima process that would be a valuable input.

Andy Campbell:

The NRC did endorse the NEI white paper. We reviewed it thoroughly and endorsed it as one of the things they would do for LIP. A lot of the sites were able to close out their LIP analyses with simple things like sandbags being available, procedures, and warning times. You don't want to be overly optimistic about warning. But I'm a liaison director in the NRC Operations Center, and we had Hurricane Florence coming in last summer. At the NRC Operations Center and NRC Region II, eight plants were already going through their procedures 24 hours beforehand, knowing the hurricane was going to hit somewhere in the Carolinas. They were already going through their

[16] NEI 15-05, Rev 6, Warning Time for Local Intense Precipitation Events, ADAMS Accession No. ML18005A076.

procedures, doing lockdowns, removing loose stops that could become missiles, a variety of different things. In the end, none of the plants was threatened. The storm surge was well below what Brunswick Steam Electric Plant had for its site grade. The rainfall events did not exceed what they already had protection for. But the plants do all of this. We are right there with them, watching and monitoring. Our resident inspectors are in the plant. They hunker down with the plant personnel. So that's a difference, I think.

Meredith Carr:

In a risk-informed space, we have a lot of forecasts where the event doesn't happen. Maryland, Virginia, and Washington, DC, were all under a tornado warning recently. There is different reliability in different places. But it sounds like the approach has been deterministic and conservative, for how to respond to it.

Andrew Miller:

Yes, that is the way it has been approached thus far. There are definitely set points along the way for every site that has that as a hazard to remove the ambiguity as much as possible.

4.4 Summary

This report documents the 4th Annual NRC Probabilistic Flood Hazard Assessment Research Workshop held at NRC Headquarters in Rockville, MD, on April 29–May 2, 2019. These proceedings included the following:

- Section 5.2: Workshop Agenda (in the program (ADAMS Accession No. ML17355A081)
- Section 5.3: Proceedings (abstracts at ADAMS Accession No. ML17355A081 and complete workshop presentation package, including slides and questions and answers, at ADAMS Accession No. ML17355A071)
- Section 5.4: Summary
- Section 5.5: Workshop Participants

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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.

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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

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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 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