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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 1: *First Annual NRC Probabilistic Flood Hazard Assessment Research Workshop*

Research Information Letter
Research Office of Nuclear Regulatory Research

Disclaimer

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).

1 FIRST ANNUAL NRC PROBABILISTIC FLOOD HAZARD ASSESSMENT RESEARCH WORKSHOP

1.1 Introduction

This chapter details the 1st Annual NRC Probabilistic Flood Hazard Assessment Research Workshop held at U.S. Nuclear Regulatory Commission (NRC) Headquarters in Rockville, MD, on October 14–15, 2015. Participants in this workshop were limited to NRC technical staff and management, NRC contractors, and staff from other Federal agencies..

The first day of the workshop began with presentations from staff in the NRC Office of Nuclear Regulatory Research (RES), Office of New Reactors (NRO), and the Office of Nuclear Reactor Regulation (NRR). The RES presentation gave an overview of the RES Probabilistic Flood Hazard Assessment (PFHA) Research Program. Presentations by NRO and NRR staff provided perspectives on research needs and priorities related to flood hazard assessment and analysis of risks from flooding. The balance of the workshop included presentations from RES contractors describing the individual research projects comprising the PFHA Research Program.

1.1.1 Organization of Conference Proceedings

Section 1.2 provides the agenda for this workshop.

Section 1.3 presents the proceedings from the workshop, including a session summary and presentation slides.

Section 1.4 summarizes the workshop.

Section 1.5 lists the workshop attendees, including remote participants.

1.2 Workshop Agenda

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

AGENDA: OCTOBER 14, 2015

08:30–08:45	Opening Remarks *Richard Correia, Director, Division of Risk Analysis, Office of Nuclear Regulatory Research; William Ott, Chief, Environmental Transport Branch, Division of Risk Analysis*
08:45–09:00	Orientation and Introductions

Session I—Program Overview

09:00–10:15	NRC PFHA Research Program Overview *Joseph Kanney, NRC*
10:15–10:30	Break
10:30–1:15	Office of New Reactors Perspectives on Flooding Research Needs *Michelle Bensi and Christopher Cook, NRC*
11:15–12:00	Office of Nuclear Reactor Regulation Perspectives on Flooding Research Needs *Jeffrey Mitman, NRC*
12:00–13:00	Lunch

Session II – Climate

13:00–13:45	Regional Climate Change Projections—Potential Impacts to Nuclear Facilities *Ruby Leung, Rajiv Prasad and Lance Vail, Pacific Northwest National Laboratory (PNNL)*

Session III – Precipitation

13:45–14:30	Estimating Precipitation—Frequency Relationships in Orographic Regions *David Keeney and Katie Holman, U.S. Bureau of Reclamation (USBR)*
14:30–15:15	Numerical Simulation of Local Intense Precipitation *M. Levent Kavvas, Kei Ishida and Mathieu Mure-Ravaud, University of California at Davis*
15:15–15:30	Break
15:30–16:30	SHAC-F (Local Intense Precipitation) *Rajiv Prasad, Robert Bryce, Philip Meyer and Lance Vail, PNNL; Kevin Coppersmith, CCI*
16:30–17:00	Day 1 Wrap-up

Session IV: Riverine and Coastal Flooding Processes

08:00–08:45	PFHA Technical Basis for Riverine Flooding *Rajiv Prasad and Philip Meyer, PNNL*
08:45–09:30	PFHA Framework for Riverine Flooding *Brian Skahill and Aaron Byrd, US Army Corps of Engineers (USACE)*
09:30–10:15	State of Practice in Flood Frequency Analysis *Timothy Cohn, US Geological Survey (USGS); Joseph Wright, USBR*
10:15–10:30	Break
10:30–11:15	Quantification and Propagation of Uncertainty in Probabilistic Coastal Storm Surge Models *Norberto Nadal-Caraballo, Jeffrey Melby and Victor Gonzalez, USACE*
11:15–12:00	USBR Dam Breach Physical Modeling *Tony Wahl, USBR*

12:00–13:00	Lunch

Session V: Plant Response to Flooding Events

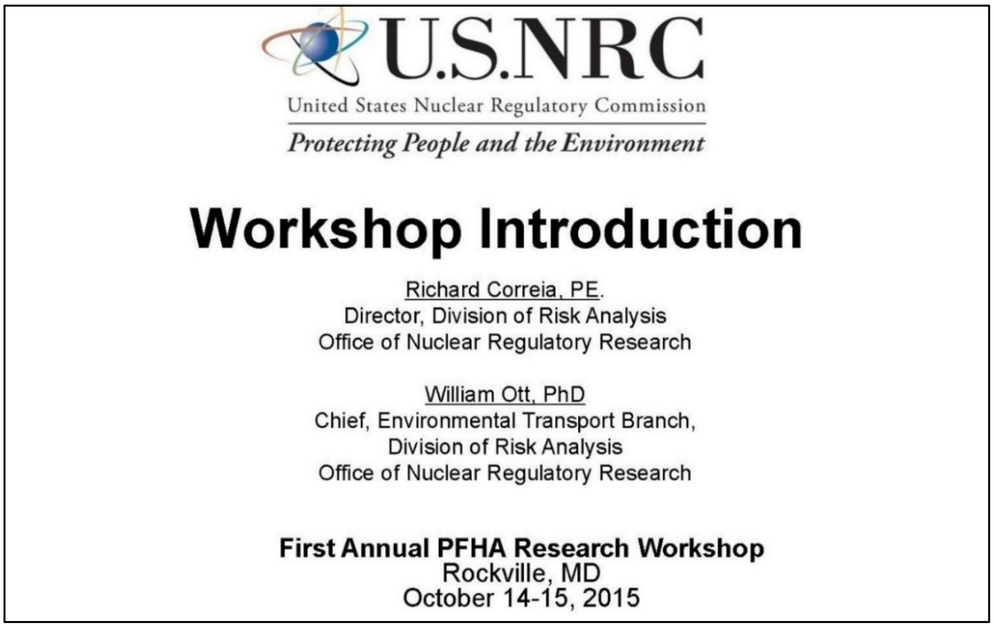
13:00–14:15	Effects of Environmental Factors on Flood Protection and Mitigation Manual Actions *Rajiv Prasad, Garill Coles, Kristi Branch, Angela Dalton and Nancy Kohn, PNNL; Timothy Carter, BCO; and Alvah Bittner, Bittner and Associates (B&A)*
14:15–15:00	Flooding Information Digests *Kellie Kvarfordt and Curtis Smith, Idaho National Laboratory (INL)*
15:00–15:45	Framework for Modeling Total Plant Response to Flooding Events *Zhegang Ma and Curtis Smith, INL*
15:45–16:00	Performance of Penetration Seals *Jacob Philip, NRC*
16:00–16:30	Observations/Comments from NRO/NRR Staff and Management
16:30–1700	Open Discussion

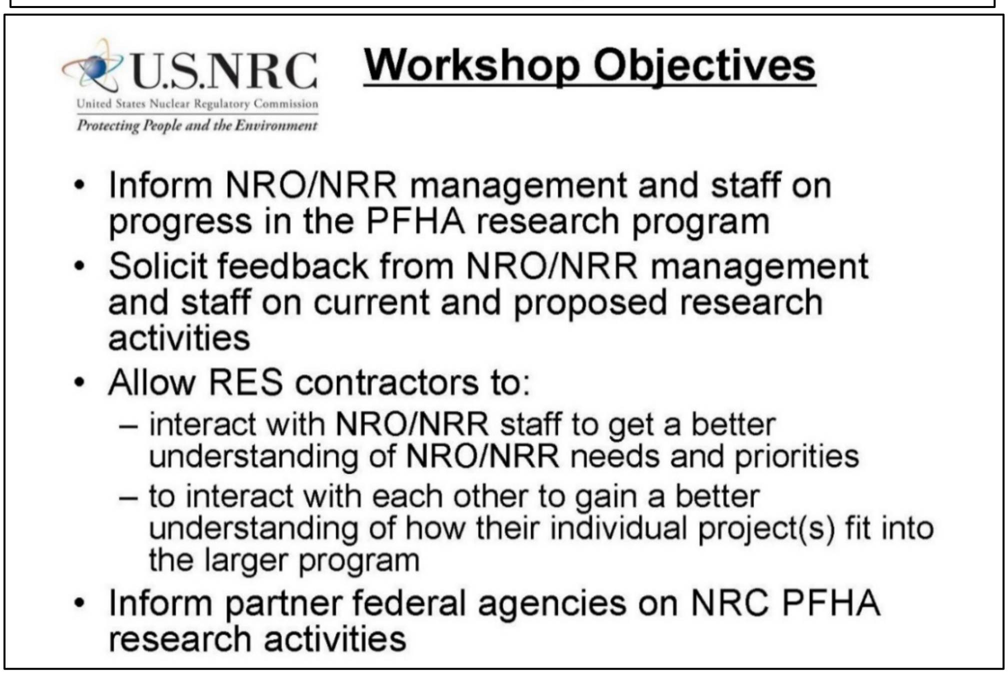
1.3 Proceedings

1.3.1 Day 1: Session I: Program Overview

The workshop commenced with opening remarks from RES Division of Risk Analysis (DRA) management. The opening remarks covered workshop objectives and described how the PFHA research relates to the NRC's broad interests in external hazards assessment and the NRC's risk-informed regulatory framework.

1.3.1.1 Opening Remarks. Richard Correia, Director, Division of Risk Analysis, Office of Nuclear Regulatory Research; William Ott, Chief, Environmental Transport Branch, Division of Risk Analysis





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NRC's Risk-Informed Regulatory Framework

Traditional "Deterministic" Approach

- **Unquantified probabilities**
- **Design-basis accidents**
- **Defense in depth and safety margins**
- **Can impose unnecessary regulatory burden**
- **Incomplete**

Risk-Informed Approach

- **Combination of traditional and risk-based approaches through a deliberative process**

Risk-Based Approach

- **Quantified probabilities**
- **Thousands of accident sequences**
- **Realistic**
- **Incomplete**

Source: Commissioner Apostolakis, PFHA Workshop, ML13057A719

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NRC Interest in Natural External Hazards

- Earthquakes
  - Ground motion
  - Liquefaction
- Flooding
  - Local Intense Precipitation
  - River Flooding
  - Storm Surge (including wind wave and tidal effects)
  - Seiche
  - Tsunami
  - Dam Failure
  - Channel Diversion
  - Ice Effects
- Meteorological
  - High Wind (Tornado, Hurricane, Cyclone) and wind blown debris
  - Extreme Drought
  - Extremes of Air Temperature
  - Extremes of Sea (or river) Temperature
  - Lightning
  - Hail, Sleet or Snow and Icing
  - Humidity

Outside of seismic, NRC approach to external hazards needs updating to conform to the risk-informed approach

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1.3.1.2 NRC PFHA Research Program Overview. Joseph Kanney, NRC

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NRC PFHA Research Program: Overview and Update

Joseph Kanney, Ph.D.
Elena Yegorova, Ph.D.
Jake Philip, PE
Environmental Transport Branch,
Division of Risk Analysis
Office of Nuclear Regulatory Research

First Annual PFHA Research Program Workshop
Rockville, MD
October 14-15, 2015

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Outline

- Overview of PFHA Research Program
  - Research Objectives
  - Main Themes
  - Implementation
- Overview and Status of Current Projects
- Support for NTTF/JLD activities
- Plans for New Work

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PFHA Research Program Overview

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PFHA Research Objectives

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

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Research Plan and User Need Request

- User Need Request (UNR) NRO-2015-002
  - Joint UNR (NRO and NRR)
  - Available internally in ADAMS (*ML14274A661*)
- Research Plan
  - Jointly developed by RES/NRO/NRR staff
  - Detailed version attached to UNR
    - Available internally in ADAMS (*ML14274A664*)
  - Condensed version provided to Commission
    - CTA Note (*ML14318A070*)
    - Publicly Available in ADAMS (*ML14296A442*)

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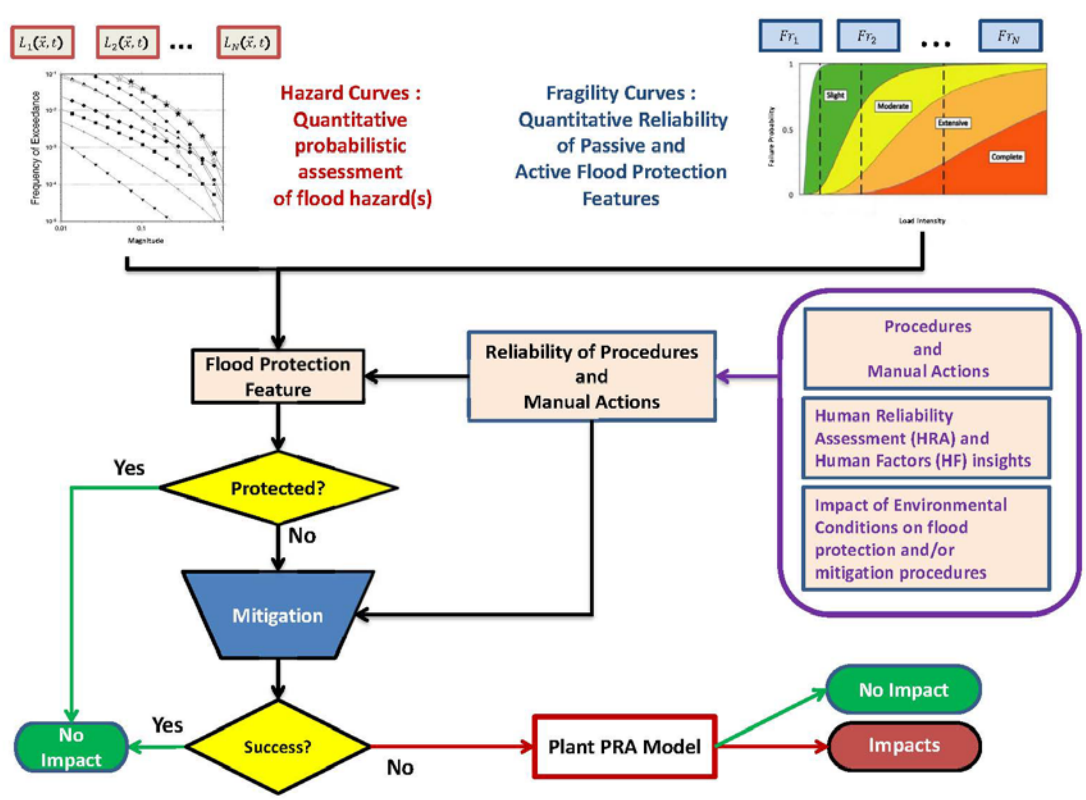

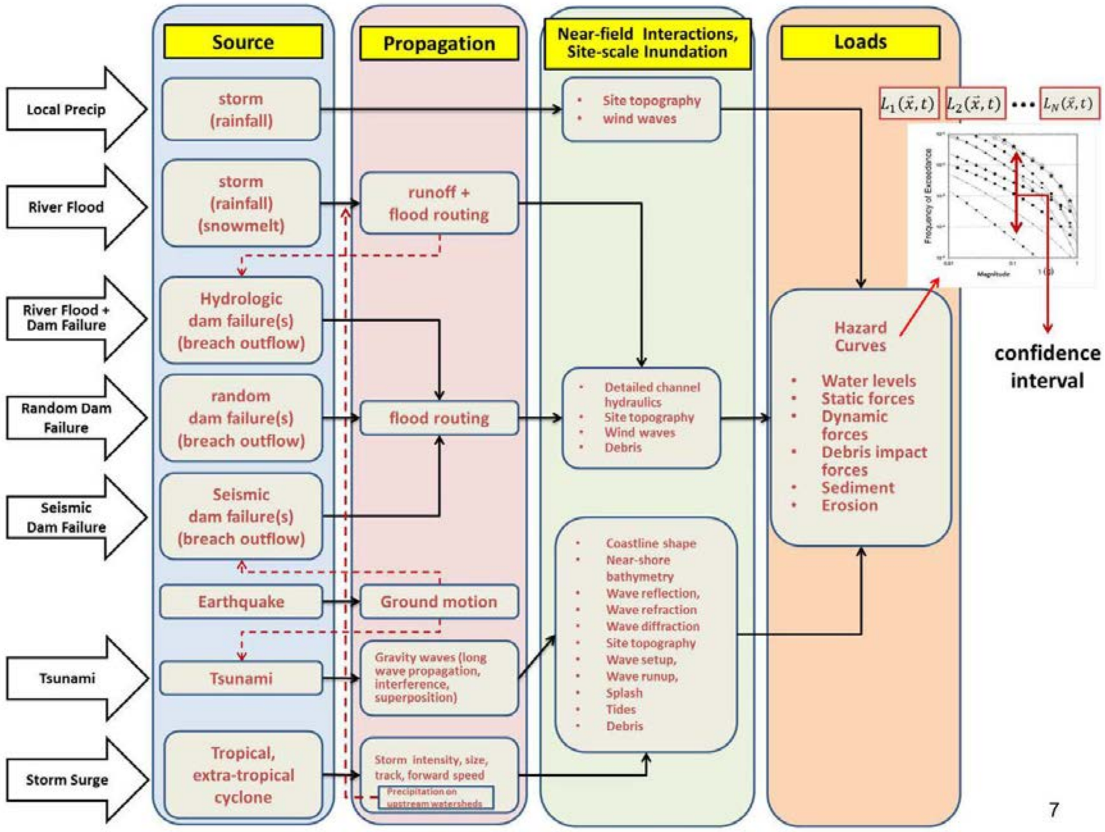

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Key Challenges

- Full hazard curves needed
  - Interested in range of annual exceedance probabilities (AEPs) from moderately rare to extreme floods
    - Right hand tails, AEPs in the range 10^{-4} to 10^{-6} desired
  - Aleatory and epistemic uncertainties need to be characterized and propagated
- Complexity
  - Multiple flood causing mechanisms
  - Mechanisms can combine/co-occur
  - Associated effects
- Component fragility and human reliability information is sparse
- Flooding impacts are nonlinear
  - Cliff-edge effects
  - Rates and duration may be important
- Large uncertainties
  - Sensitivity analysis
  - Which uncertainties can be reduced? How?

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Research Plan Main Themes

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

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Implementation

- Phased Approach
  - Phase 1 (Technical basis, draft guidance)
  - Phase 2 (Pilot studies)
  - Phase 3 (Finalize guidance)
- Implementation time-frame:
  - ~5 years for Phase 1, ~2 years for Phases 2+3
- Contract technical support
  - DOE Laboratory Contracts (PNNL, INL)
  - Interagency Agreements (USACE, USGS, USBR)
- Communication
  - Internal
    - Flooding Issues Technical Advisory Group (FITAG)
    - Research seminars
  - Internal/External
    - Annual PFHA Workshop (NRC staff, contractors, selected external invitees)
  - External
    - NRC Regulatory Information Conference (RIC)
    - Professional meetings & conferences
    - Interagency working groups

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Overview and Brief Status of Current Projects

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Current Projects

- **Leveraging Available Flooding Information**
  - Development of Flood Hazard Information Digests (INL)
  - Guidance on Application of Frequency Analysis Methods
    - Guidance on Application of State-of-Practice Flood Frequency Analysis Methods and Tools (USGS)
    - Technical Basis for Extending Frequency Analysis Beyond Current Consensus Limits (USBR)

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Leverage Available Flooding Information

- **Development of Flood Hazard Information Digests for Operating NPP sites**
  - INL (Kellie Kvarfordt, Curtis Smith)
  - Organize flooding information and build database of currently available site-specific flood hazard information
  - ***Flooding Hazard Information Needs Workshop and Workshop Summary Completed***
  - ***Review of existing NRC databases completed***
  - ***Work plan for designing, implementing and demonstrating flood hazard information database completed***

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Leverage Available Flooding Information (Cont.)

- **Guidance on Application of State-of-Practice Flood Frequency Analysis Methods and Tools**
  - USGS (Tim Cohn, William Asquith, Julie Kiang)
  - Focus on best practices for characterizing the full uncertainty in flood frequency estimation using current consensus methods
  - Provide guidance on judging the validity of extrapolating hydrologic hazard curves to the ranges of interest for nuclear power plant applications.
  - ***Contract awarded in mid-September***

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Leverage Available Frequency Information (Cont.)

- **Technical Basis for Extending Frequency Analysis Beyond Current Consensus Limits**
  - USBR (Joseph Knight)
  - Develop guidance for extending frequency analysis methods beyond current consensus limits for riverine flooding applications
  - Focus on describing alternative methods for integration of the characterizations from multiple approaches to estimate rainfall and floods with AEPs $1x10^{-5}$ to $1x10^{-6}$.
  - Expand on the streamflow-based statistics methods and rainfall-runoff methods used at USBR
  - Uncertainty characterization and hydrologic risk concepts developed at USBR
  - ***Literature review in progress***

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Current Projects (Cont.)

- **PFHA Framework Development**
  - Technical Basis for Probabilistic Flood Hazard Assessment – Riverine Flooding
  - Probabilistic Flood Hazard Assessment Framework Development
  - Structured Hazard Assessment Committee Process for Flooding (SHAC-F)

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PFHA Framework

- **Technical Basis for Probabilistic Flood Hazard Assessment – Riverine Flooding**
  - PNNL (Rajiv Prasad, Philip Meyer)
  - Critical review of the state of practice in PFHA modeling for riverine flooding (absent dam failure)
    - Data-driven and simulation approaches
  - ***Draft NUREG report currently under review***
  - ***Final report should be completed by end of October***

17

PFHA Framework (Cont.)

- **Probabilistic Flood Hazard Assessment Framework Development – LIP, Riverine**
  - USACE (Aaron Byrd, Brian Skahill)
  - Develop PFHA Framework for range of flooding scenarios and annual exceedance probabilities (AEPs)
  - Focus on local intense precipitation (LIP) and riverine flooding
  - ***Literature review completed***
  - ***Framework elements currently being investigated comprise:***
    - ***Markov Chain Monte Carlo (MCMC) simulation***
    - ***Bayesian Hierarchical Modeling for both precipitation and stream flows (spatial and temporal correlations)***
    - ***Bayesian Model Averaging (epistemic uncertainty)***

18

PFHA Framework (Cont.)

- **Structured Hazard Assessment Committee Process for Flooding (SHAC-F)**
  - PNNL (Rajiv Prasad, Philip Meyer) and Coppersmith Consulting (Kevin Coppersmith)
  - Develop a Structured Hazard Assessment Committee process for Flooding (SHAC-F)
  - Assess need for a hierarchy of study complexity to address range of flooding issues
  - Develop example applications of framework
    - Local intense precipitation (LIP), riverine flooding
    - Virtual workshops
  - ***Literature review of SSHAC projects completed***
  - ***Work Plan for LIP Virtual Workshops completed***
  - ***1st LIP virtual workshop (data) completed***
  - ***2nd LIP virtual workshop (models) completed***

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Current Projects (Cont.)

- **Application of Improved Modeling Techniques for Processes and Mechanisms Associated with Flooding**
  - Numerical Modeling of Local Intense Precipitation Processes (UC Davis)
  - Estimating Precipitation-Frequency Relationships in Orographic Regions (USBR)
  - Quantifying Uncertainties in Probabilistic Storm Surge Models (USACE)

20

Improved Modeling Techniques

- **Numerical Modeling of Local Intense Precipitation Processes**
  - UC Davis (Levent Kavvas, Kei Ishida, Mathieu Mure-Ravaud)
  - Assess capability of regional numerical weather simulation models to accurately simulate extreme precipitation events
    - Mesoscale convective systems
    - Tropical cyclones and/or remnants
    - Extratropical cylcones
  - Use models to investigate impact of climate change on extreme precipitation events
  - ***Critical review existing literature completed***
  - ***Initial review of extreme rainfall events completed***
  - ***Draft work plan for simulation of select storm events submitted in early September, currently being finalized***

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Improved Modeling Techniques (Cont.)

- **Estimating Precipitation-Frequency Relationships in Orographic Regions**
  - USBR (David Keeney, Kathleen Holman)
  - Critical review of historical precipitation analysis with focus on applicability to orographic regions
    - Orographic storm analysis methods
    - Regional precipitation-frequency analysis
  - Recent applications of methods in USBR dam risk studies
  - Extension of USBR methods
  - ***Critical review in progress***
  - ***Compilation of USBR applications in progress***

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Improved Modeling Techniques (Cont.)

- **Quantifying Uncertainties in Probabilistic Storm Surge Models**
  - USACE (Norberto Nadal-Caraballo, Jeff Melby, Mary Cialone, Victor Gonzalez, Chris Massy)
  - Fully quantify epistemic and aleatory uncertainties inherent in probabilistic storm surge modeling.
  - Assess propagation of uncertainties in joint probability analyses of storm surge hazard
  - ***Literature review on previous storm surge modeling studies has been completed***
  - ***Draft Report on Epistemic Uncertainties in Storm Recurrence Rate Models is under review***
  - ***Work plan for Exploring Technically Defensible Data, Models, and Methods for Defining Joint Probability of Storm Parameters completed***

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Current Projects (Cont.)

- **Reliability of Flood Protection and Mitigation**
  - Performance of Penetration Seals (FRM)
  - Erosion Processes in Embankment Dams (USBR)
  - Effects of Environmental Factors on Manual Actions for Flood Protection and Mitigation at Nuclear Power Plants (PNNL)

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Reliability of Flood Protection and Plant Response to Flooding Events (Cont.)

- **Performance of Penetration Seals**
  - Fire Risk Management Inc. (Mark Cummings)
    - Subcontractors: Alion, Nuvia
  - Develop standard testing procedures, acceptance criteria, and protocols to assess effectiveness and performance
  - Testing of selected penetration seal designs
  - ***Contract recently awarded***

25

Reliability of Flood Protection and Mitigation

- **Erosion Processes in Embankment Dams**
  - USBR (Tony Wahl)
  - Study dam breach processes through physical hydraulic model tests
    - Construct 2 zoned physical models of rockfill dams with clay cores and filter zones.
    - One model to be tested with overtopping flow, and the second to be tested with internal erosion through a designed embankment defect (piping)
    - Post-test data analysis will include the development of correlations between measured variables, comparison to established relationships from previous research on this topic, and comparison of test results to predictions made with breach erosion computer models.
  - ***Shakedown test of new test facility completed***
    - ***Homogeneous cohesive embankment, with internal erosion through a pre-formed flaw***
  - ***First rockfill dam model under construction***

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Reliability of Flood Protection and Mitigation

- **Effects of Environmental Factors on Manual Actions for Flood Protection and Mitigation at Nuclear Power Plants**
  - PNNL (Rajiv Prasad, Kristi Branch, Garill Coles, Angela Dalton, Nancy Kohn)
    - Consider environmental factors (EFs) and environmental conditions (ECs) that can occur during flooding events and the manual actions taken to prepare/respond
    - Develop a framework for assessing impact of ECs on manual actions
    - Review and apply current literature to assess impacts to performance
  - ***Draft report describing flood causing mechanisms and associated environmental conditions, framework, and methods for site-specific application currently under review***

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Plant Response to Flooding Events

- **Modeling Total Plant Response to Flooding Events**
  - INL (Curtis Smith, Zhegang Ma)
  - Dynamic analysis approach that depict scenarios through simulation methods
  - Combination of margins analysis, mechanistic physics-based modeling, and probabilistic risk assessment approaches
  - Use LIP as example application
  - ***Work plan has been completed***
  - ***Letter report on Margins Assessment Approaches completed, currently being reviewed***
  - ***Currently working on dynamic simulation components:***
    - ***Flooding event trees***
    - ***Plant system and 3-D physical layout models***
    - ***Validation of smooth particle hydrodynamics (SPH) model***

28

Dynamic and Nonstationary Processes

- **Regional Climate Change Projections: Potential Impacts to Nuclear Facilities**
  - PNNL (Ruby Leung, Rajiv Prasad)
  - Annual review of climate science and modeling research and assessments of potential impacts to NPPs
  - Hydrological and non-hydrological impacts
  - ***Project Update webinar held June 15th***
    - ***Reviewed scope of reports, information sources to be used, initial observations***
  - ***First annual report to be submitted October 30th***

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Support for NTTF Phase 2 Decisions

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NTTF/JLD Support

- **Fukushima Near-Term Task Force (NTTF) Recommendations**
  - Flooding Walkdowns
    - **Flood protection features and procedures in current licensing basis**
  - Flooding Hazard Re-Evaluations
    - **Compare to current design basis**
  - Assess need for further regulatory actions (Phase 2 Decision-making)
- **Phase 2 Decision-making needs to be formulated soon (4-6 months)**
- **Phase 2 Decision-making needs to be based on currently available approaches**
  - Assess and communicate what methods are currently available to estimate flooding hazards and inform risk estimates
  - What is technically defensible today?
    - Annual exceedance probability
    - Uncertainties
- **PFHA Research Program support for NTTF Phase 2 Decision-making**
  - Make available RES staff expertise
  - Selected intermediate work products (e.g. letter reports)
  - Facilitate focused discussions with contractors

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Plans for New Project Starts

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Projected FY16 New Starts*

- Critical review of State of Practice in Probabilistic Risk Assessment for Dams
  - Failure mode identification and fragility characterization
  - System modeling approaches
  - Operational and HRA/HF issues
  - Regulatory confidence as a function of available information
  - Planned start Q1 FY16
- Application of Land Use/Land Cover Change Models for Assessing Potential Changes in Watershed Flooding Risks
  - State of practice in modeling biophysical landscape change and human activity
  - Assess capability to model changes in hydrological processes and flood risks
- Eastern U.S. Paleoflood Hydrology Study
  - Candidate reach: Tennessee River Gorge below Chattanooga
  - Planned NRC/EPRI/TVA collaboration, (potential USACE and USBR)
  - Feasibility study first
    - short timeline
    - modest cost
  - Detailed study if feasibility study is successful

*** Subject to availability of funding**

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Projected FY17-19 Work*

- Further Development of SHAC-F
  - Coastal flooding mechanisms
- Probabilistic treatment of combined processes/events
- Assess Probabilistic Tsunami Modeling Methods
- Work with Industry, other Agencies to Develop Pilot Tests
  - Inland location, coastal location

*** Subject to availability of funding**

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Questions?

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1.3.1.3 NRO Perspectives on Flooding Research Needs. Michelle Bensi and Christopher Cook, NRC

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NRO Perspectives on Flooding Research Needs

First Annual NRC PFHA
Research Program Workshop
October 14-15, 2015

Regulatory Applications Related to Research User Need

Support of…

- New reactor licensing
  - Licensing and oversight mission of NRO
  - Review of new reactor applications
    - Siting
    - Design of structures for flood hazards
    - Probabilistic risk analysis

Activities related to NRO mission

- Reactor oversight process
- Risk-informed licensing actions

To be covered as part of NRR presentation on flooding research needs

- Future regulatory actions related to flooding
  - Implementation of NTTF Recommendation 2.1
  - Flood hazard assessments
  - Plant response assessments

Activities for which NRO provides technical support

2

NRO Perspectives on Flooding Research Needs

SUPPORT FOR NEW REACTOR LICENSING

3

Motivation

- NRC utilizes a risk-informed regulatory framework
- PRA Policy Statement
  - Formalized the Commission's commitment to risk-informed regulation through expanded use of PRA
  - NRC will increase the use of PRA methods in regulatory matters to the extent supported by the state-of-the-art in PRA methods/data and in a manner that complements the NRC's deterministic approaches

4

Motivation (con'd)

- As the NRC has become increasingly risk-informed, the assessment of flood hazards has lagged behind other natural hazards
- Need for probabilistic approaches for hazard assessment and PRAs
  - New reactors
  - Operating reactors (discussed later)
- Build on and adapt existing approaches to advance state of practice efficiently

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Background: Existing NRC guidance

- Flood hazard evaluation
  - NUREG-0800 (Standard Review Plan), Section 2.4, Hydrology
  - Regulatory Guide (RG) 1.59, Design Basis Floods for Nuclear Power Plants (Rev. 1977)
  - ANSI/ANS 2.8-1992, Determining Design Basis Flooding at Power Reactor Sites (withdrawn 2002)
  - Note: One early site permit applicant submitted probabilistic storm surge assessment, but later opted to use deterministic methods
- Flood Protection
  - RG 1.102, Flood Protection for Nuclear Power Plants (Rev. 1976)

Existing flood hazard regulatory guidance is deterministic and does not provide a framework or method for use of probabilistic approaches

- RG 1.59 and RG 1.102 currently under revision
  - Deterministic framework maintained

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Background: Existing NRC guidance

- Probabilistic risk analysis (PRA)
  - All new reactors are required to perform a PRA
    - NUREG-0800 (Standard Review Plan), Chapter 19, Probabilistic Risk Assessment and Severe Accident Evaluation for New Reactors
    - RG 1.200, "An Approach for Determining the Technical Adequacy of Probabilistic Risk Assessment Results for Risk-Informed Activities"
    - ASME-ANS RA-Sa-2009 (PRA Standard)
  - As part of PRAs for new reactor applications to date, flooding has been screened or treated in limited manner
    - Flooding continues to be treated deterministically as part of Chapter 2.4, Hydrology

7

Existing Approaches

- Probabilistic methods for assessment of flood hazards have been used in the U.S. outside of commercial nuclear power plant siting
  - Applications do not typically include detailed assessment or propagation of uncertainty

However…

- Return periods of relevance for nuclear power plant sites are significantly longer than for other applications
- Modifications to existing approaches will (generally) be necessary to cover full range of relevant return periods

8

Existing Approaches: NRC PSHA Experience

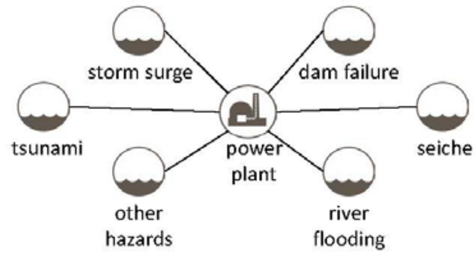
- NRC guidance related to probabilistic seismic hazard analysis (PSHA) provides a robust framework for:
  - Identification and quantification of aleatory variability and epistemic uncertainties
  - Propagating uncertainties through an analysis
- Tools include:
  - Use of logic trees
  - SSHAC Process
- Understand whether NRC's existing guidance and experience can or should be applied to assessment of flood hazards
  - Efficiency in development
  - Appropriate rigor and consistency across hazards

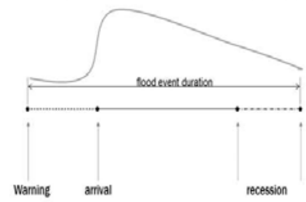
9

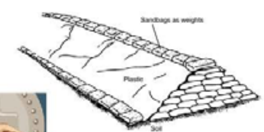
Existing Approaches: Challenges to Adaptation

Unique challenges for flooding:

- Complexity and number of flood mechanisms
  - Associated effects
  - Longer time frames
  - Combined effects
- Complex and diverse protective and mitigation measures
  - Manual actions
- Cliff-edge effects
- Incorporating operating experience
  - Latent deficiencies (e.g., missing seals)







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NRO Perspectives on Flooding Research Needs

TECHNICAL SUPPORT OF REGULATORY DECISION- MAKING FOR OPERATING REACTORS

11

Background: Post-Fukushima Activities Related to Flooding

NTTF 2.3 – Walkdowns

Licensees identify and address degraded, nonconforming, or unanalyzed conditions relative to a plant's current licensing and design bases.

NTTF 2.1 – Hazard Reevaluations

Licensees reevaluate flooding hazard based on present day guidance/methods used to define the design basis for new reactors.

NTTF 2.1 – Interim Actions

If the design basis does not bound reevaluated hazard: Licensees evaluate the need for interim actions while the longer-term integrated assessment is performed

NTTF 2.1 – Integrated Assessment & Focused Evaluations

If the design basis does not bound reevaluated hazard: Licensees assess plant response

Regulatory Actions

NRC staff determines whether additional regulatory actions are necessary to provide additional protection against the updated flooding hazards

12

Background: Post-Fukushima Activities Related to Flooding

- March 12, 2012 50.54(f) letter
  - Gather sufficient information to determine whether licenses should be modified, suspended, or revoked
  - Walkdowns, hazard reevaluations, integrated assessments
- SRM to COMSECY-14-0037
  - Include graded approach regarding integrated assessments
  - Be risk-informed and performance-based
  - Reduce unnecessary conservatisms; identify areas with insufficient conservatisms
  - Evaluate changes to guidance to introduce more realism
  - Focus on scenarios with cliff-edges and potential for substantial safety benefit
  - Consider available physical margin data
  - Develop regulatory decision criteria and guidance

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Background: Post-Fukushima Activities Related to Flooding

- COMSECY-15-0019 provides R2.1 closure plan
  - Revised plant response assessment approach
    - Focused evaluations
      - LIP
      - Flood protection and available physical margin)
    - (Revised) integrated assessments (IAs)
  - Framework for regulatory decision-marking
    - Utilize existing regulatory processes
    - Use quantitative and qualitative risk-insights from the IAs
      - Maintenance of defense in depth
      - Balance between protection and mitigation
      - Degree of reliance on procedures and temporary measures
      - Degree of reliance on non-safety related features
      - Identification of vulnerabilities and actions to address them
      - Change in hazard and risk (absolute versus relative), as available

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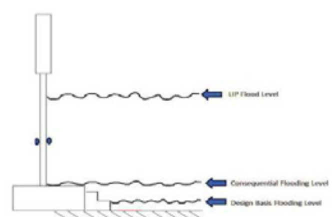
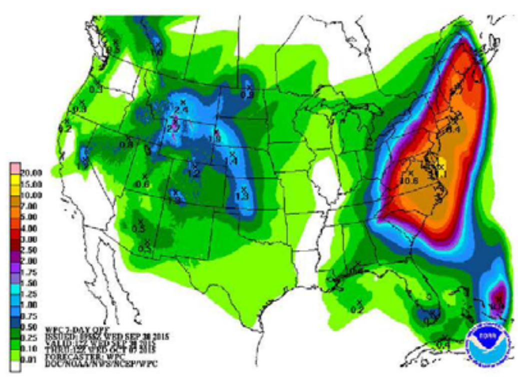
R2.1 Hazard Reviews LIP Warning Time and QPFs

- LIP warning time white paper
  - Industry developed; NRC endorsed (with NWS support)
  - Focuses on warning time and action triggers associated with consequential rainfall events
  - Conservative bias
  - Utilizes forecasting tools
    - Monitoring threshold: NWS quantitative precipitation forecasts (QPF) for medium range forecast
    - Action trigger: Probabilistic QPF for short range forecast





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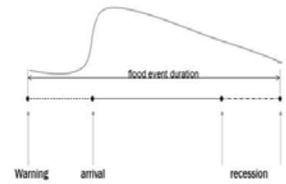
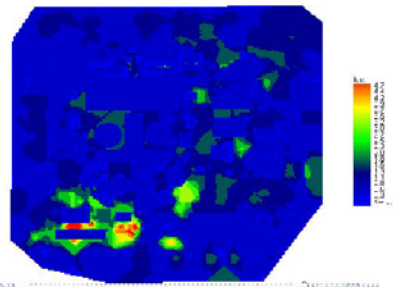
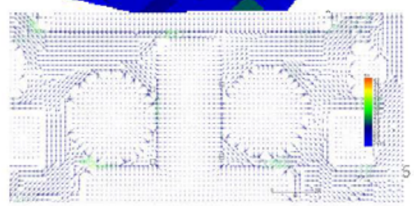
R2.1 Hazard Reviews: Lessons-learned

Importance of understanding…

- Flood event duration
  - Warning time
  - Period of inundation
  - Duration of exceedance
- Emphasis on depths over elevation
- 2-D representations
  - Tabulation of point values provides incomplete characterization
- Associated effects







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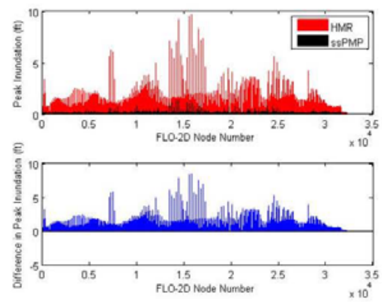
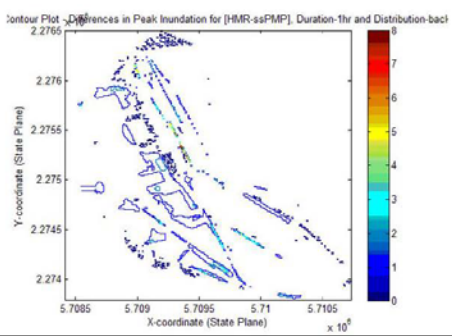
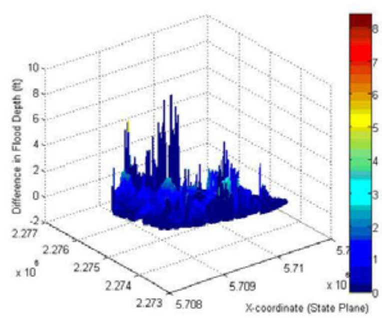
R2.1 Hazard Reviews: Site-Specific PMP

- Deterministic
- Deviates from existing guidance (in most cases)
- Performed by a single contractor for a number of sites
- Analysis relies upon extensive use of professional judgement







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R2.1 Hazard Reviews: Probabilistic Hazard Assessment

- Storm surge evaluations using probabilistic methods (JPM)
  - Differences in approaches between licensees
  - Sources of judgement
  - Errors identified
- Surge evaluation on one of the Great Lakes using probabilistic methods (EST)
- Challenges due to lack of guidance and diversity in approaches used by licensees

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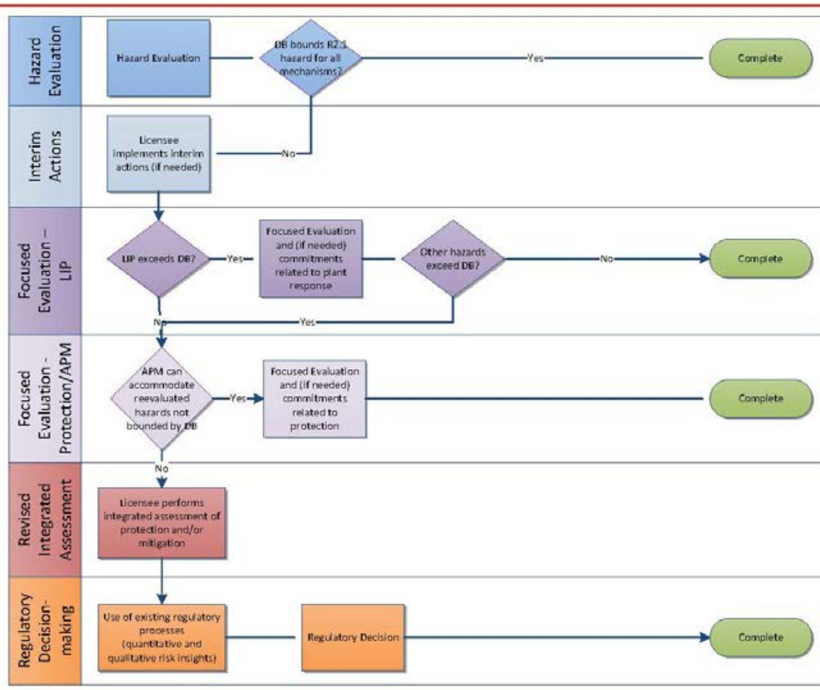
Revised R2.1 Process



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Summary: Short Term Research Needs

To support R2.1 regulatory decision-making…

- Identify, to the extent possible, technically-supported approaches and currently available approaches
- Focus on developing estimates of hazards with a frequency of 10^{-3} to 10^{-4} per year (*or proxy*) for certain mechanisms that exceed plant design bases
- Immediate need (~next 4-6months)
- Assess and communicate what is available *now*
- Understand associated uncertainties

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Summary: Longer Term Research Needs

- Development and demonstration of a technically-defensible, comprehensive PFHA framework for flood hazard curve estimation for diversity of flood mechanisms
  - Extreme precipitation
  - Rainfall-runoff
  - Dam failure
  - Storm surge
  - Tsunami
  - Combined events
- Guidance for assessing the reliability of flood protection and plant response to flooding events
  - Support for external flooding PRAs
- Assessment of the potential impacts of dynamic and nonstationary processes

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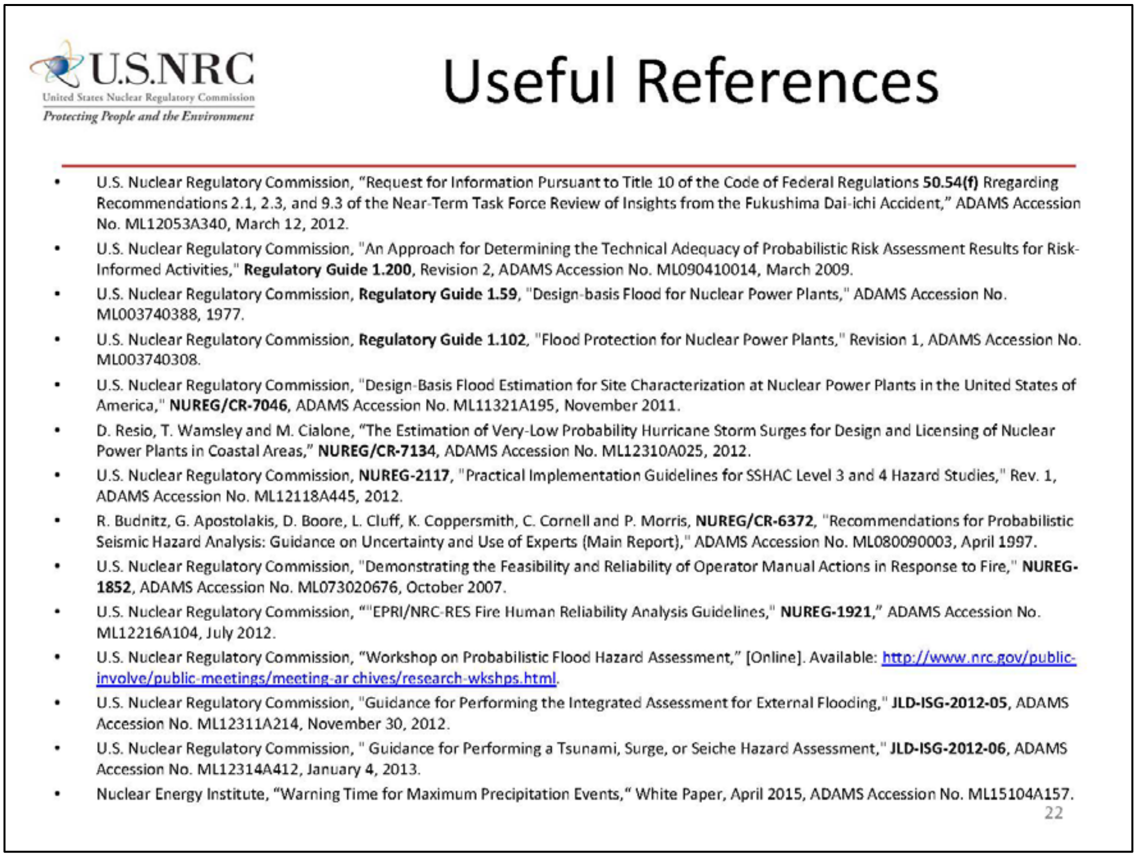

Useful References

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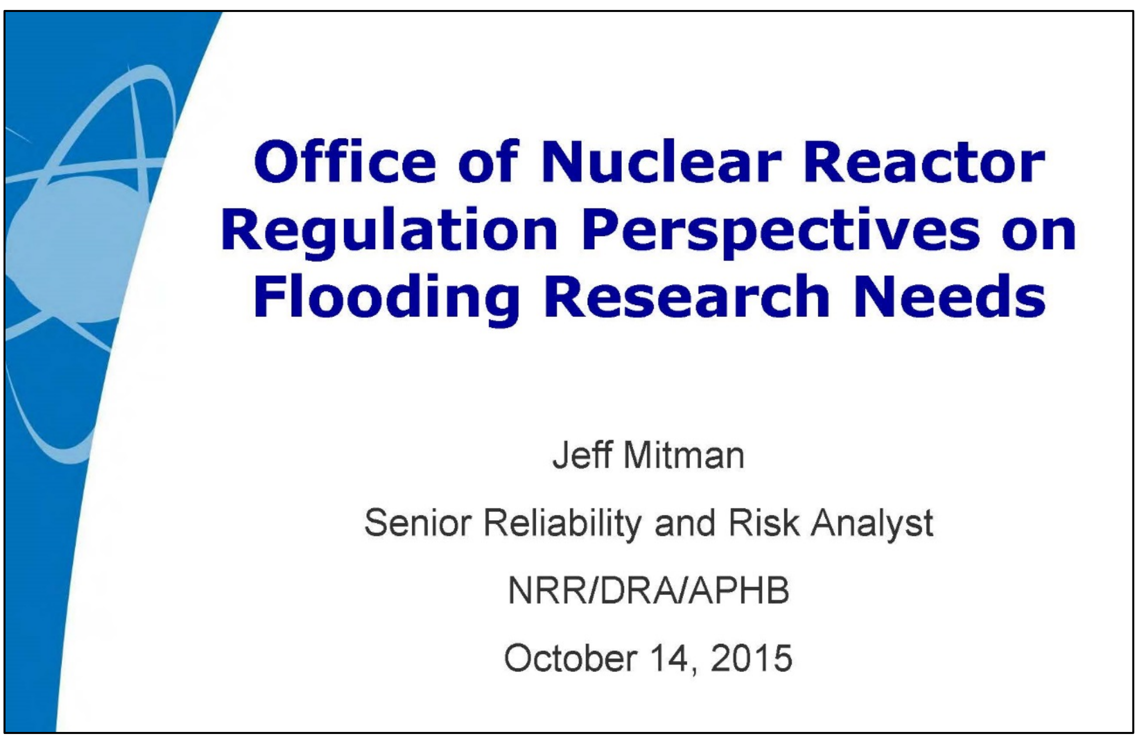
22

1.3.1.4 Office of Nuclear Reactor Regulation Perspectives on Flooding Research Needs.
Jeffrey Mitman, NRC

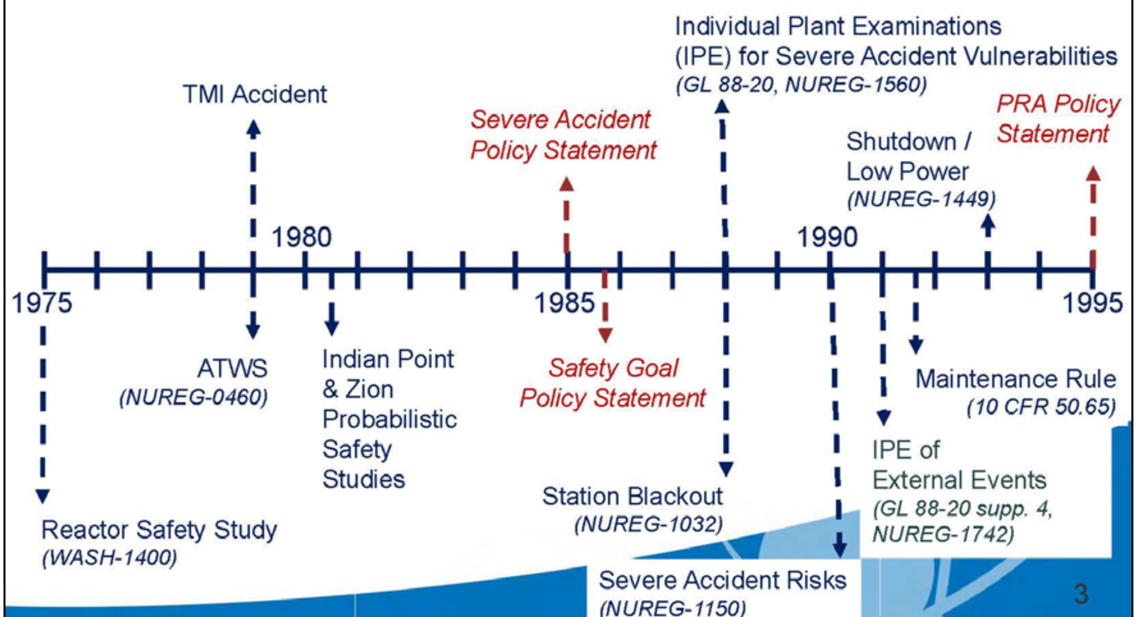


Risk Measures and Policy

- Risk Characterization: Effect on people
  - Likelihood of prompt fatalities - corresponds to large early release frequency (LERF) of 1E-5 per reactor per year
  - Likelihood of latent cancer fatalities - corresponds to a core damage frequency (CDF) of 1E-4 per reactor per year
- Commission policy statement: Safety goals for operations of nuclear power plants (1986)
- Commission policy statement: Use of PRA methods in nuclear regulatory activities (1995)

2

Early History – Risk Studies



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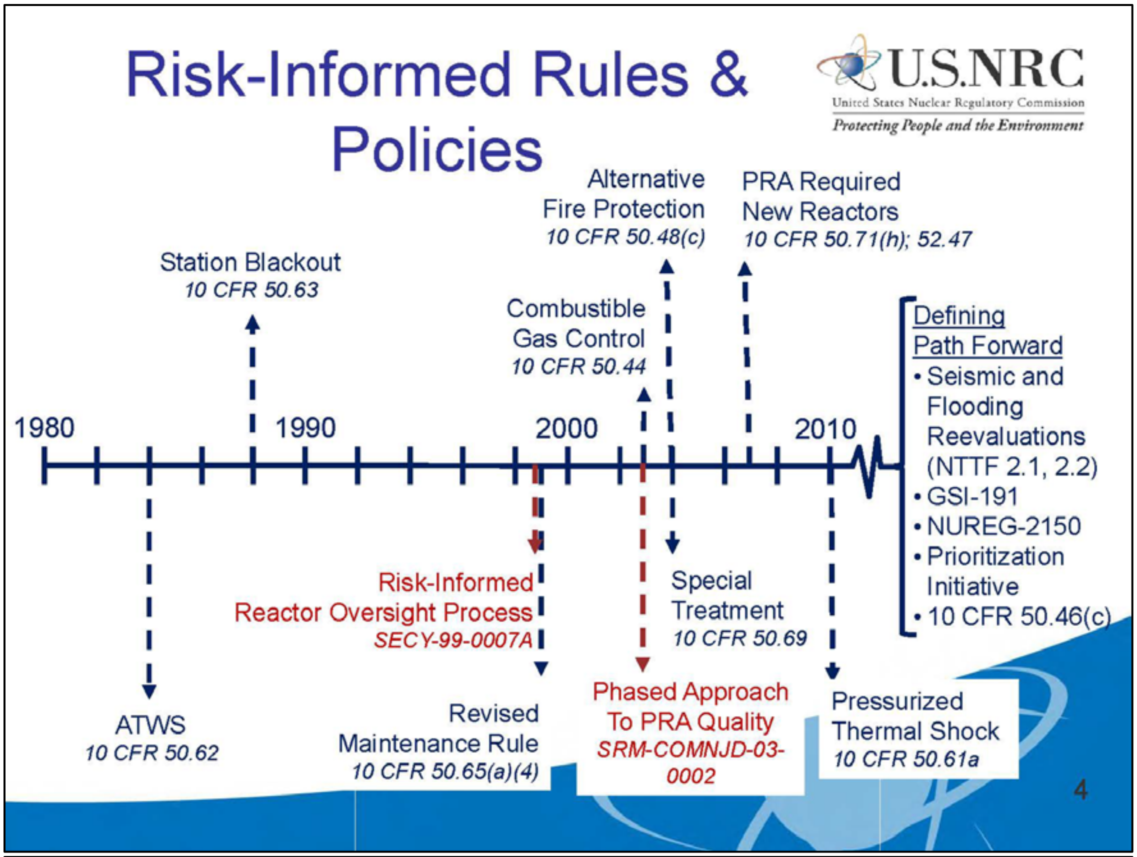
Risk-Informed Rules & Policies
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Station Blackout
10 CFR 50.63
Alternative Fire Protection
10 CFR 50.48(c)
PRA Required New Reactors
10 CFR 50.71(h); 52.47
Combustible Gas Control
10 CFR 50.44
1980
1990
2000
2010
Defining Path Forward
• Seismic and Flooding Reevaluations (NTTF 2.1, 2.2)
• GSI-191
• NUREG-2150
• Prioritization Initiative
• 10 CFR 50.46(c)
Risk-Informed Reactor Oversight Process
SECY-99-0007A
Special Treatment
10 CFR 50.69
ATWS
10 CFR 50.62
Revised Maintenance Rule
10 CFR 50.65(a)(4)
Phased Approach To PRA Quality
SRM-COMNJD-03-0002
Pressurized Thermal Shock
10 CFR 50.61a
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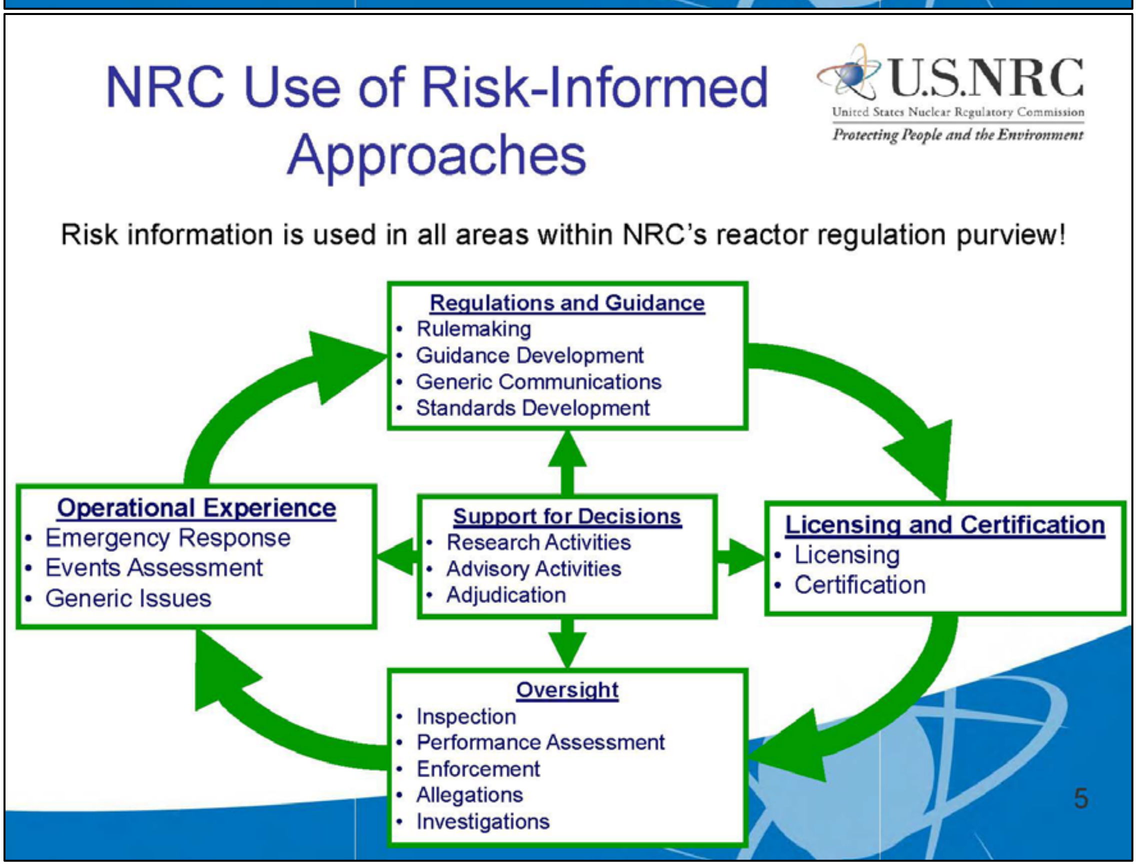
NRC Use of Risk-Informed Approaches
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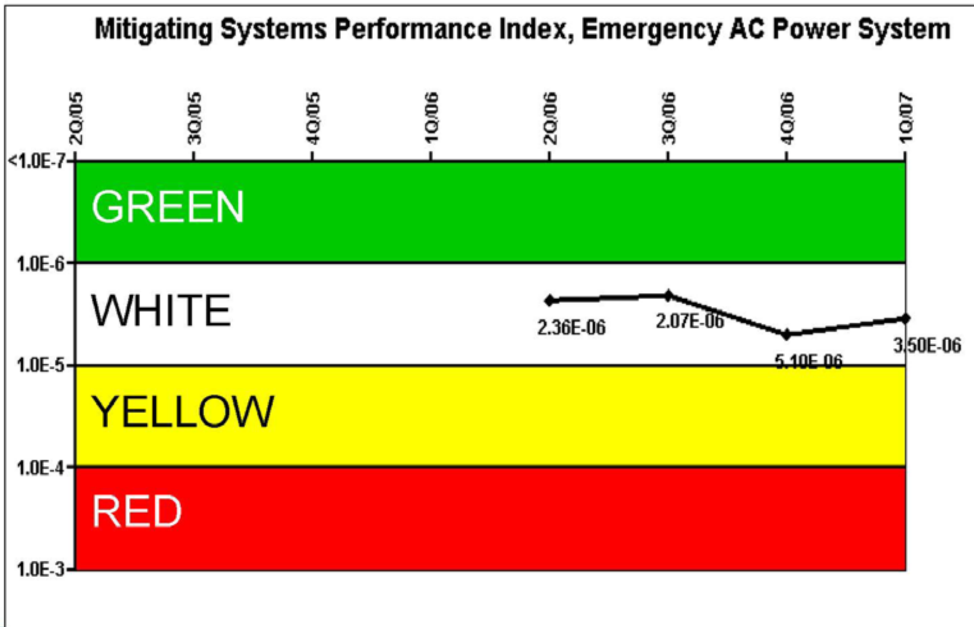
Risk information is used in all areas within NRC's reactor regulation purview!
Regulations and Guidance
• Rulemaking
• Guidance Development
• Generic Communications
• Standards Development
Operational Experience
• Emergency Response
• Events Assessment
• Generic Issues
Support for Decisions
• Research Activities
• Advisory Activities
• Adjudication
Licensing and Certification
• Licensing
• Certification
Oversight
• Inspection
• Performance Assessment
• Enforcement
• Allegations
• Investigations
5

Significance Determination Process (SDP)



Thresholds: White > 1.00E-6 Yellow > 1.00E-5 Red > 1.00E-4

6

PRA Assumptions/Limitations

- Models are abstraction of reality and are generally based on number of assumptions
- PRA model assumptions are decisions or judgments made in PRA model development related to either:
  - Source of model uncertainty
  - Scope or level of detail
- When using PRA, decision makers should understand:
  - Sources of uncertainty and assumptions
  - Impact of these assumptions
- All models have uncertainties; PRA analysts strive to identify and understand them
- "All models are wrong, but some are useful" George Box

7

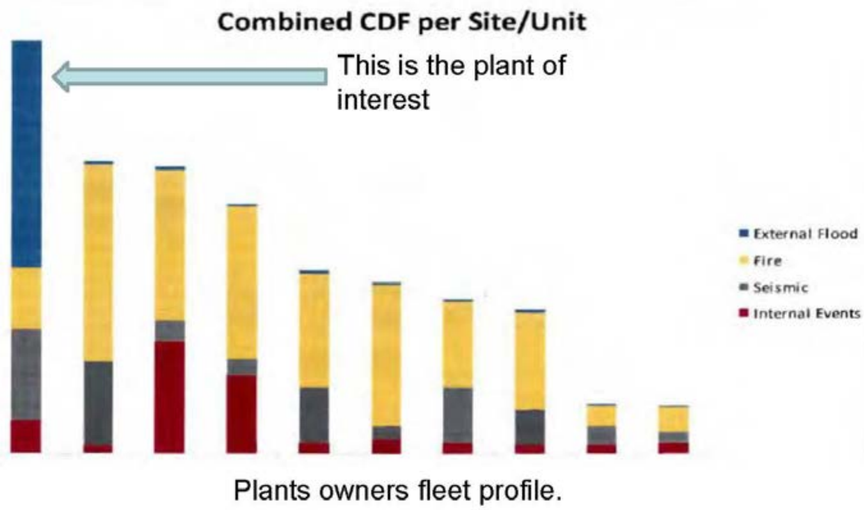
Challenges - Healthy Skepticism of PRA

- Modeling assumptions
  - Mathematical approximations (e.g. linear failure rate, λT)
  - Ability to identify all relevant failure modes and to think in "failure space"
  - Ability to model human cognitive process
- Availability of data
- Reliance on expert estimation
- Vulnerable to bias
- Presumption of binary states – Boolean, not fuzzy logic
- Uncertainties and their propagation
  - Epistemic
  - Aleatory (stochastic)
- Especially for SDP precision is not goal but accuracy is important
- We know there will be significant uncertainty and process is setup to deal with it
- Timeliness is critical

Significance Determination Process (SDP)

Flooding Example

Combined CDF Per Site/Unit



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Finding Background

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- In August 2012 NRC conducted post Fukushima flooding walkdown
- NRC found multiple deficient electrical penetrations (Crouse-Hinds conduit couplings) that also perform as flood seals at Air Intake Tunnel (AIT)
- Licensee's follow-on inspection identified 43 coupling which lacked required internal flood sealant material

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AIT Crouse-Hinds Conduit Couplings

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AIT Crouse-Hinds Conduit Couplings

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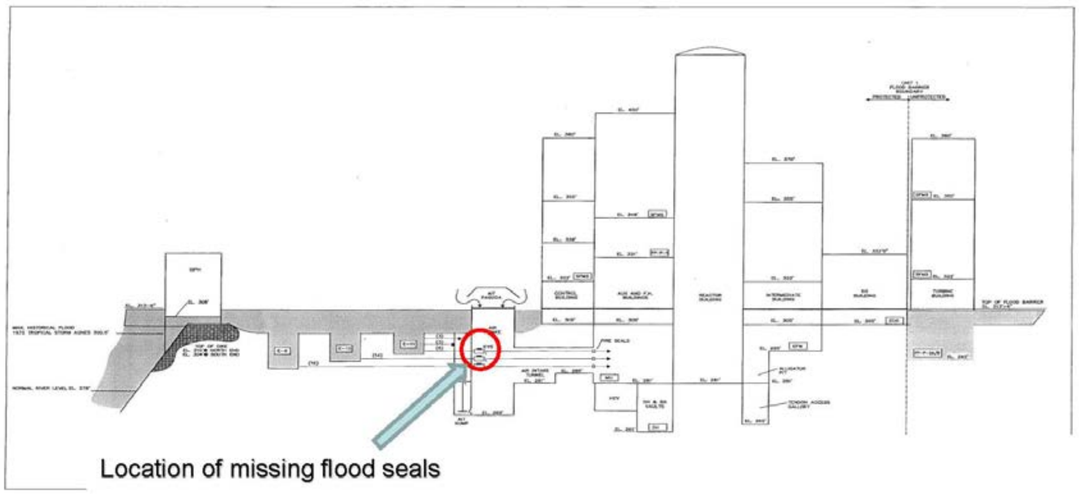
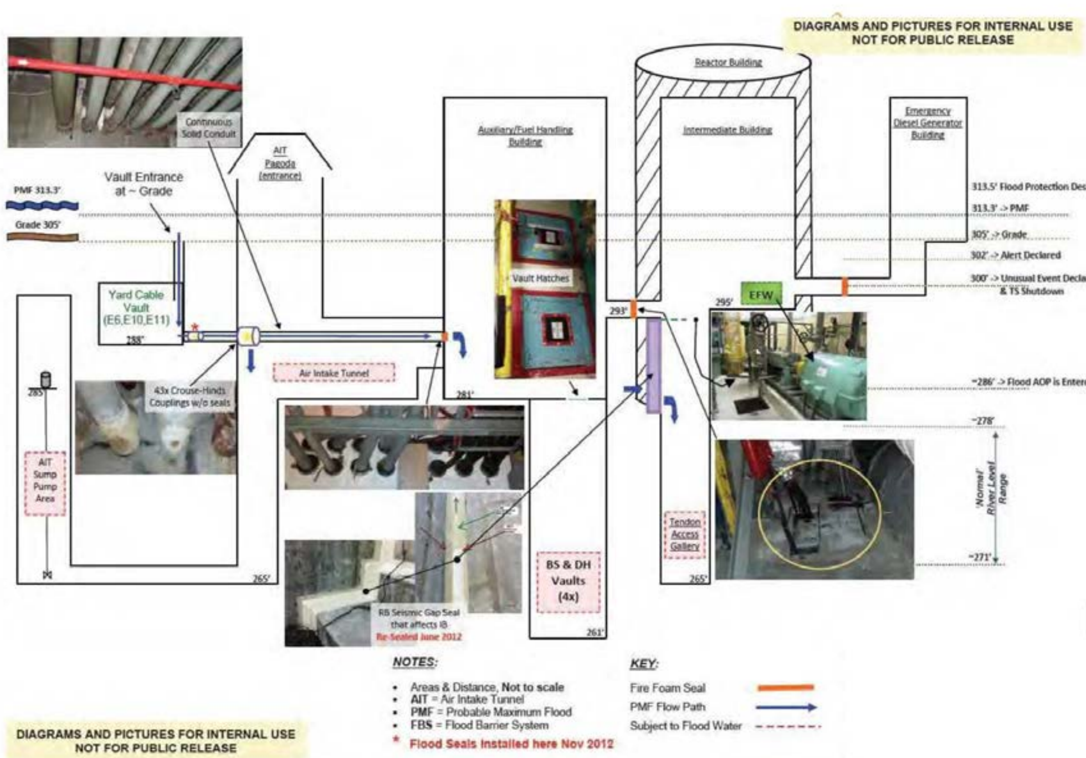
Simplified Plant Cross-Section





Risk Evaluation

- Developed event tree (ET) and fault tree (FT) from individual plant examination for external events (IPEEE)
  - Modified as needed
- Checked licensee initiating event frequency (IEF) against available data
- Calculated delta core damage frequency (CDF) for one year exposure time using NRC's SPAR model and Saphire code
- Conducted sensitivity cases

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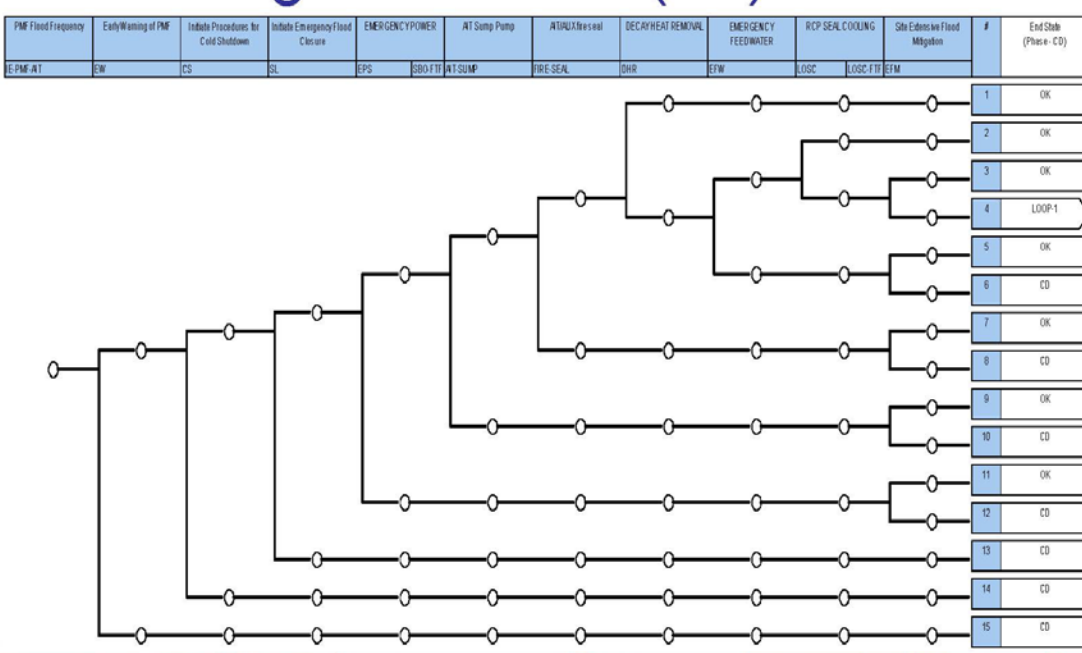
Flooding Event Tree (ET)



Initiating Event Frequency (IEF)

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- Licensee has extensive analysis on watershed
- Builds on Army Corp of Engineers PMP analysis
- Licensee started to update in 2010 and continued post Fukushima 50.54 (f) letters
- NRC reviewed licensee work and took no exceptions to it
- NRC derived flood bin frequencies from licensee work

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NRC's Analysis using USGS Bulletin 17b

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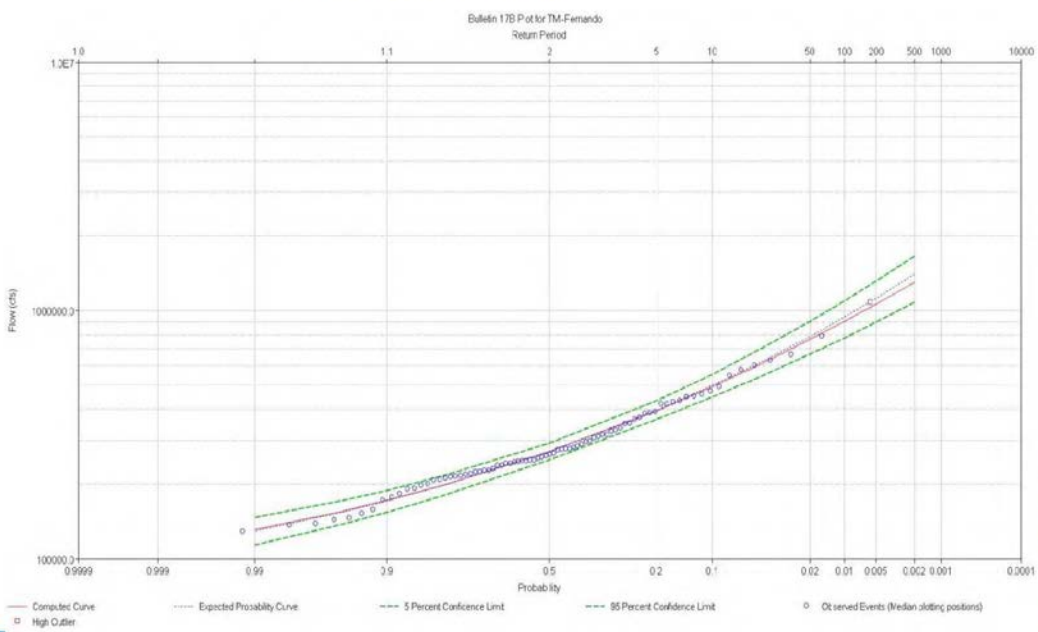

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Licensee's Discharge vs. Return Period

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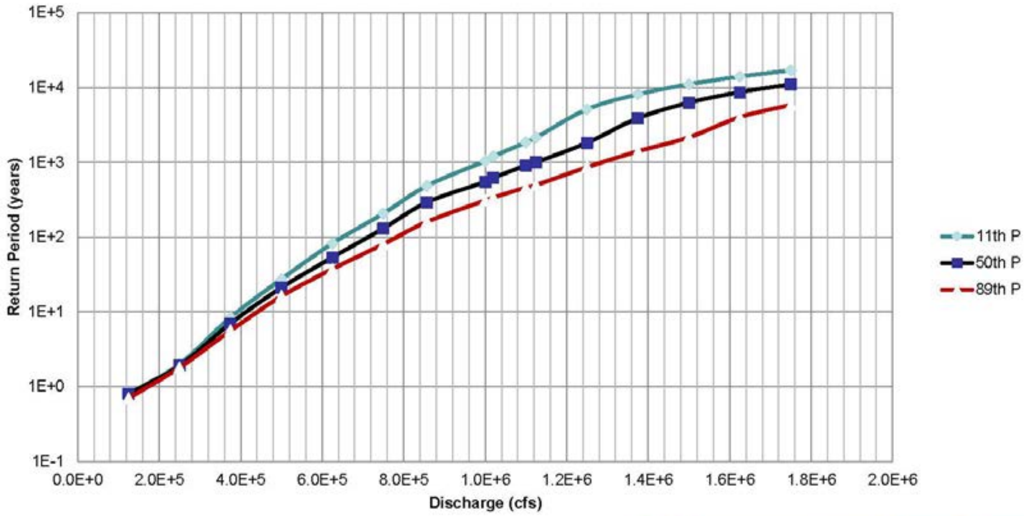

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Licensee's Elevation vs. Return Period (log)

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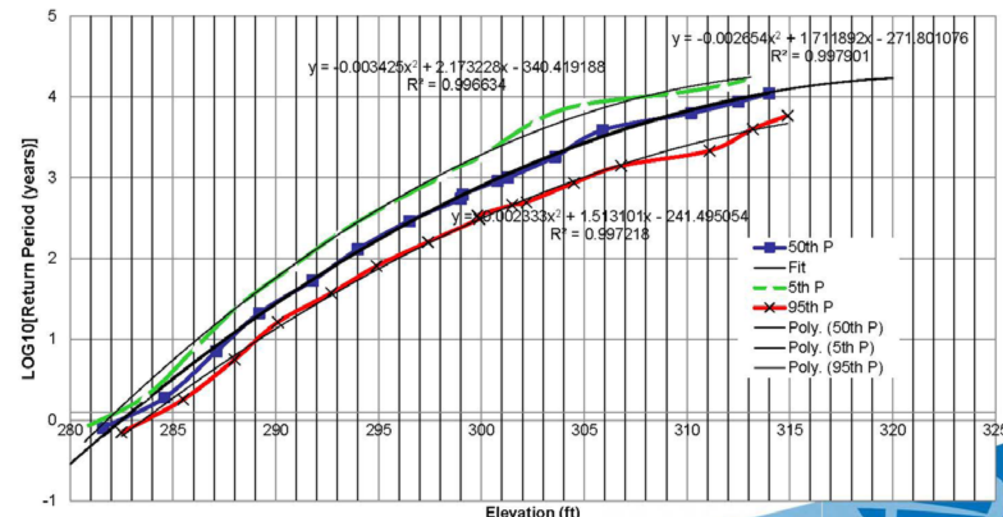

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NRC Derived Flood Bin Frequencies

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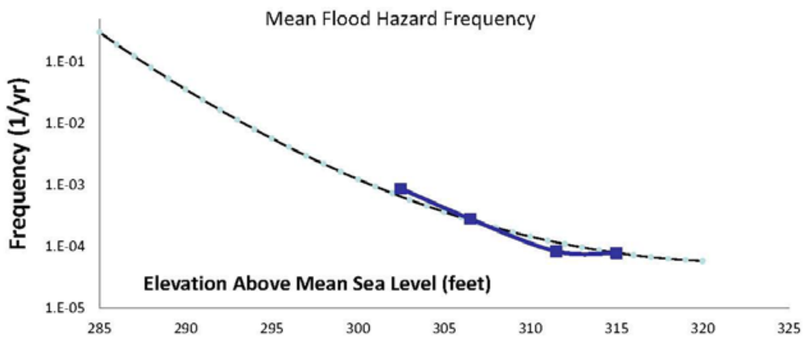

Flood Bin Number	Flood Bin Lower Bound (feet)	Flood Bin Upper Bound (feet)	Bin Elevation (feet)	Bin Frequency 5th (per year)	Bin Frequency Expected Value (per year)	Bin Frequency 95th (per year)	Bin Return Period Expected Value (years)
1	300	304	302.5	3.45E-04	8.75E-04	2.36E-03	1,142.7
2	304	309	306.5	1.10E-04	2.84E-04	8.09E-04	3,521.8
3	309	314	311.5	3.00E-05	8.38E-05	2.51E-04	11,939.0
4	315	315	315.0	4.99E-05	7.91E-05	2.29E-04	12,640.2

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Comparison of Pressurized Water Reactor IEF with Flood Frequencies

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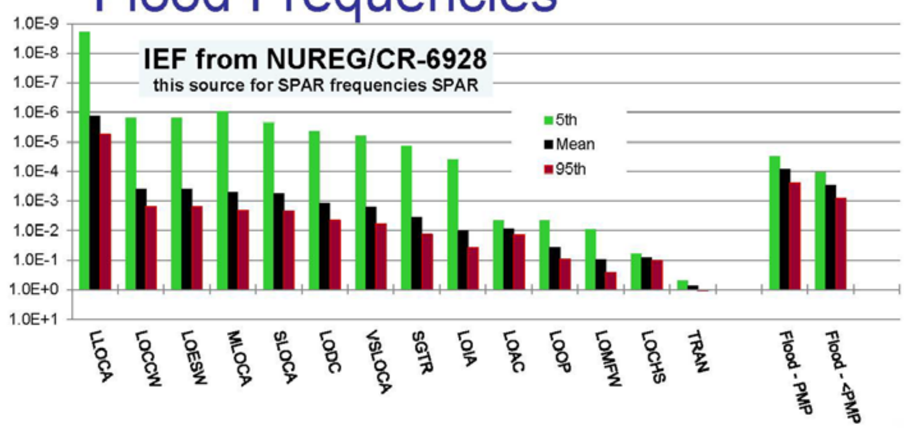

- NUREG/CR-6928 not latest source for IEF but IEF do not change substantially
- In this case: Flood frequencies are small but so are uncertainties

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Risk Results

- Delta CDF (PMP) = 4.5E-6
- Delta CDF (<PMP) = 7E-8
- Sensitivity cases
  - Using 95th of IEF Delta CDF = 1.2E-5
  - Floods that last longer than PMP would threaten emergency feedwater (EFW) which would substantially increase risk
  - Debris was not considered
  - Failure probability of non-safety AIT sump pump significant contributor
  - Failure probability of fire seals to act as flood seal also significant contributor. If assumed to fail, delta CDF = 3E-5
  - Reactor coolant pump seal failure not significant contributor – this is substantially different from other PWR flooding analysis

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Needs Summary

- Hazard curve with flood elevations vs return period or frequency
- SDP process is intended to be 90 day process from start to finish
  - Risk analysis needs to take less than 45 days

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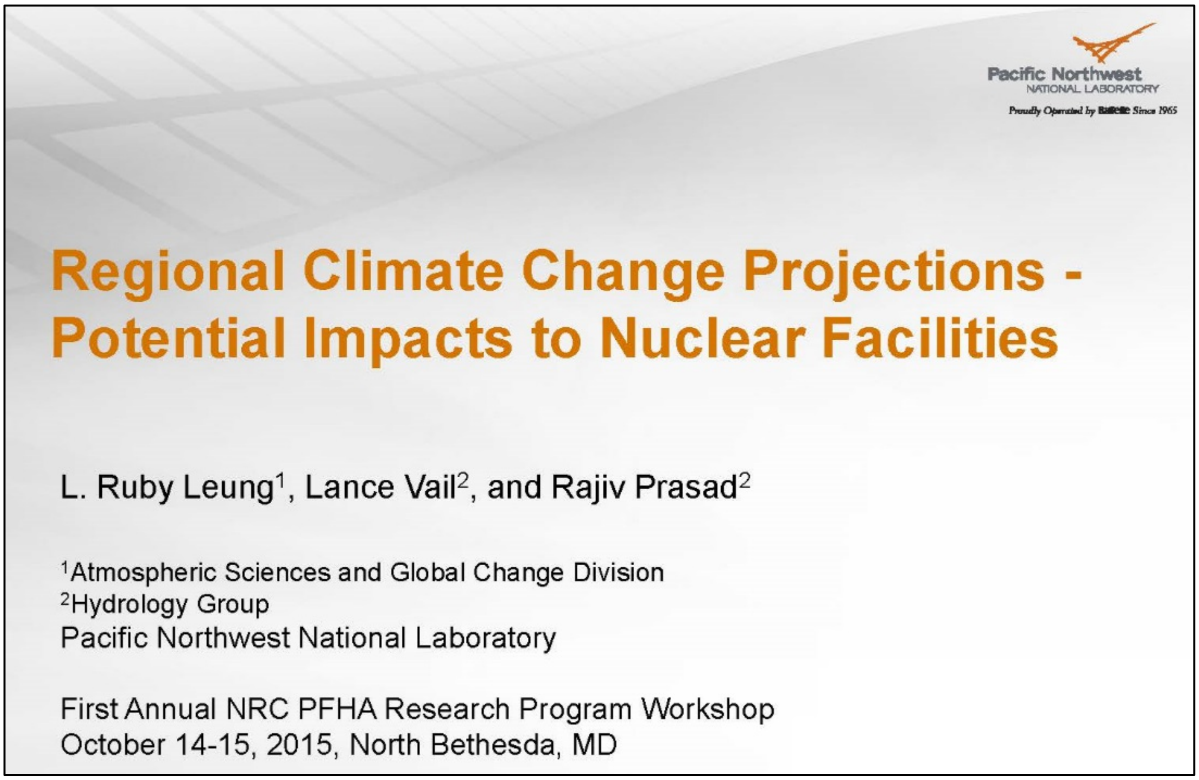
1.3.2 Day 1: Session II: Climate

Session II of the workshop focused on NRC-funded climate change research devoted to understanding the scope and scale of potential impacts to nuclear facilities. The NRC PFHA Research Program has one funded project in this area with Pacific Northwest National Laboratory (PNNL). Thus, PNNL researchers gave the only presentation for this session, listed below and followed by a copy of the slides.

1.3.2.1 Regional Climate Change Projections—Potential Impacts to Nuclear Facilities.
Ruby Leung, Rajiv Prasad, and Lance Vail, PNNL



Tasks and Deliverables

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- Prepare documents to summarize:
  - Recent scientific findings
  - Activities of federal agencies with direct responsibility on climate change science
  - Quality assessment of the above relevant to NRC concerns on regional level
- Deliverables:
  - Annual letter report (12, 24, 36 months)
  - Final annual letter report
  - Two annual webinars (12, 24 months)
  - One research seminar on main points of third annual letter report (36 months)
  - Participate in three annual workshops with NRC staff (12, 24, 36 months)

NRC Climate Change Information Needs

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	NRC Need		Climate Change Information Needs					
Topic	Safety (1)	Environmental (2)	Sea Level Rise	Precipitation	Temperature	Wind	Hurricane	Humidity
Local Intense Precipitation	1	3	3	1	2	3		
River Flooding	1	2	3	1	2	3		3
Drought	3	1		1	2	3		3
Tsunami	1		1					
Storm Surge	1	2	1				1	
Alternative Cooling Systems		2			1			2
Cooling System Performance	2	2			1			2
Stream Temperature		2			1	2		3
Alternative Energy		3			1	1		
Energy Demand		3	2	2	1			3
Forecasting	2	3	2	1	1	2	2	3
Water Quality		1	1	1	1			
Wind Load	1					1		

1 Primary
2 Secondary
3 Tertiary

3

Safety Need versus Environmental Need

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- What is extreme?
  - Annual Exceedance Probability (AEP)
    - Safety < 0.001
    - Environmental > 0.01
  - Standard Deviations
    - Safety >+3σ
    - Environmental <+2σ
- Analysis Horizon
  - Safety – License duration (40 years for new reactors) with annual updates
  - Environmental – License duration without updates

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Climate Change in NRO EISs

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- Reference: Appendix I Turkey Point Units 6 and 7 COLA EIS
- Crosswalk NRC Need (defined by RG 4.2) with most recent USGCRP Assessment
- Considers climate change as a change in environmental baseline and not as an impact
- Final determination "Based on the reasonably foreseeable changes in the affected environment as a result of climate change, as defined in the USGCRP Assessment, the NRC staff determines that the operational impact to {resource area} is likely to {increase/decrease/not change} relative to the operational impacts to the current baseline environment"
- No SMALL, MODERATE, or LARGE is directly associated with climate change in environmental review

5

Overview of Climate Information Needs on Local Intense Precipitation

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Local Intense Precipitation		
NRC Need	Definition	
		nterest.

6

Stationarity is Dead – So What?

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- Stationarity was never a belief in the hydrologic community, it was just an assumption to simplify some probabilistic analysis methods.
- Stationarity/nonstationary must consider time scale of change:
  - Nonstationarity in climate was consider for Yucca Mountain since its initial consideration as a waste repository over 30 year ago.
  - NRC has a limited regulatory horizon on NPPs.
- We will not toss out historical observations but will augment ongoing observations with climate projections.
- Nonstationarity was common in streamflow because of changes in upstream diversion and regulation.
- Climate change likely will shift AEPs differently for shorter and longer return periods.

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IDF – Intensity Duration Frequency

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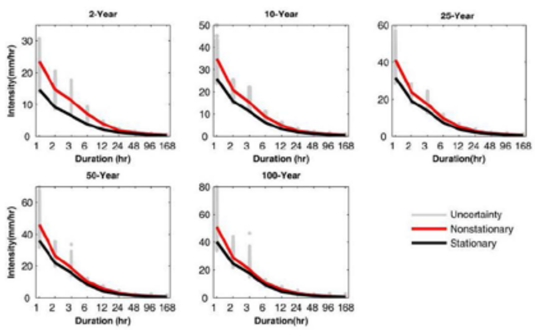
- Updating of NOAA Atlas 14
  - Only goes out to 1000 yr return period
  - Provides a narrow error bound that is not representative of total uncertainty
- Significant research in Nonstationary IDFs is ongoing
  - Cheng, L. & AghaKouchak, A. Nonstationary Precipitation Intensity-Duration-Frequency Curves for Infrastructure Design in a Changing Climate. *Sci. Rep.* 4, 7093: DOI:10.1038/srep07093 (2014)
  - Limited to <1000 yr



A stationary climate assumption in IDF design may lead to underestimation of extreme precipitation by as much as 60% at locations that currently exhibit increasing trends in precipitation (Cheng and AghaKouchak, 2014).

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PMP – Probable Maximum Precipitation

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- Concept diverges from probabilistic approach but remains the basis of most hydrology safety analyses
- Recent research has considered methods to update PMP based on climate
  - Kunkel, Kenneth E., et al. Probable maximum precipitation and climate change. *Geophys. Res. Lett.* 40.1402-1408 (2013)
- But generally there is little interest in PMP in climate research community, although there has been increasing attention to PMP in the engineering community

9

Patterns in Climate and Extreme Hydrologic Events

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- Significant climate research is considering changes in climate patterns or features that may represent key extreme events
  - Atmospheric rivers
  - Hurricane frequency and patterns
- The concept of utilizing such climate pattern information for extreme hydrologic events is not new, but the skill of climate models has advanced to the point where the concept can be realized
  - Foufoula-Georgiou, E. A Probabilistic Storm Transposition Approach for Estimating Exceedance Probabilities of Extreme Precipitation Depths. *Water Res. Res.* 25:5, 799-815, 1989

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Region-Specific Climatic Extremes

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Increase in Extreme High Temperatures

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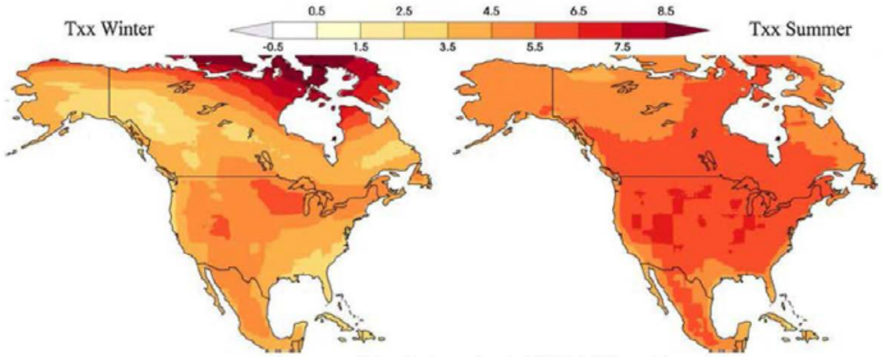
- Increase in extreme high temperatures is mainly due to a shift of the PDF by the mean warming
- Changes in large-scale circulation such as blocking may be a factor, but model projections are uncertain (consistent with uncertain change in skewness)
- Reduced soil moisture due to increasing temperature can further increase extreme high temperature through land-atmosphere interactions

Changes in temperature of extreme hot days in K
(2080-2100 minus 1985-2005) in RCP8.5



(Grotjahn et al. 2015 Clim. Dyn.)

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Extreme Precipitation Changes

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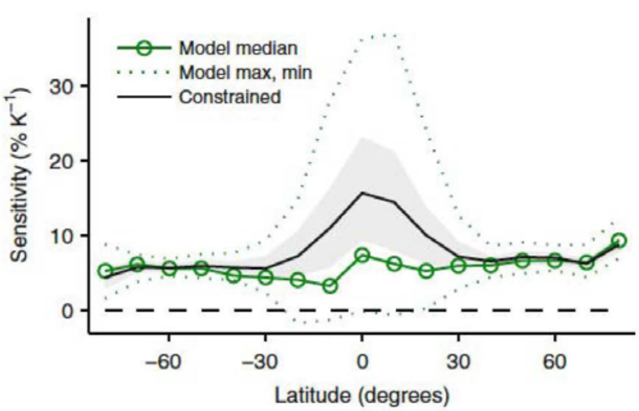
- Extreme precipitation depends on three factors: precipitation efficiency, vertical motion, and saturation specific humidity profile
- As the atmosphere holds more moisture in a warmer climate (Clausius-Clapeyron or CC ~ 7% K^{-1}), the last factor plays an important role

Change in 99.9th percentile daily extreme precipitation



(O'Gorman 2015 CCCR)

- Extreme precipitation changes are often expressed as percentage change per K warming
- Much larger uncertainty in the tropics than extratropics
- In the extratropics, changes ~ 6% K^{-1}

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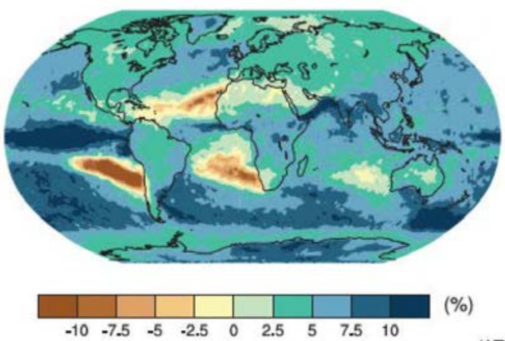
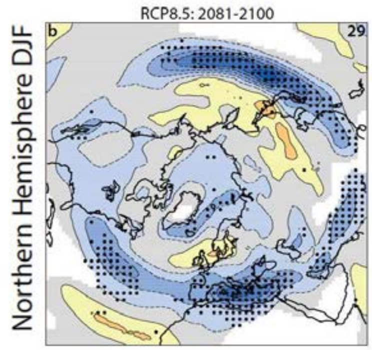
Extratropical Extreme Precipitation

- Why the changes are close to the CC rate?
  - In a non-convective environment, changes in large-scale vertical motion are weak – constrained by planetary rotation
  - Uncertainty in regional changes due to uncertainty in projecting poleward shift of storm tracks
  - In a convective environment - no theory, and convection is poorly parameterized in climate models





(IPCC AR5 WGI report)

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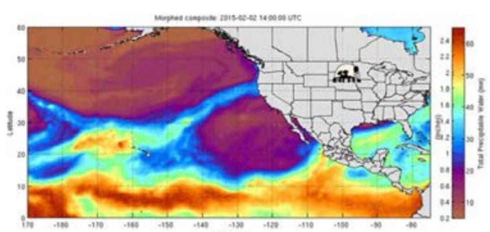
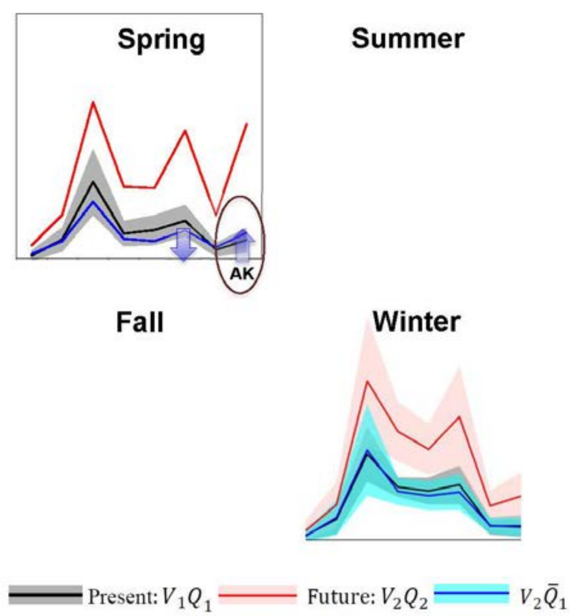
Increase in Atmospheric River Frequency



- Moisture increase dominates the AR change with overall negative effect from wind changes
- AR frequency increases manyfold (e.g., Alaska coast)
- Significant dynamical contribution to the increase of AR near Alaska due to poleward jet shift



(Gao et al. 2015 GRL)

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Extreme Convective Precipitation

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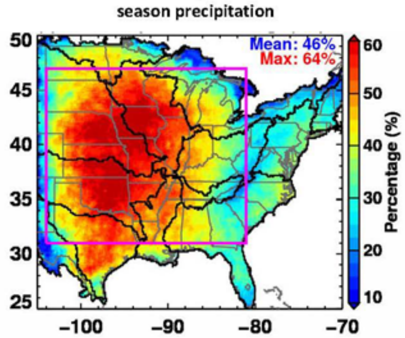
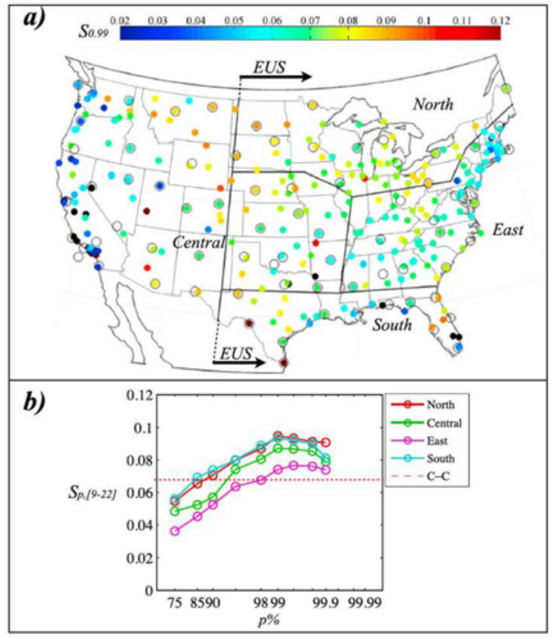
- Analysis of observations suggests that convective extreme precipitation may increase at a super CC rate (> 7% K^{-1})
- Climate models cannot simulate mesoscale convective systems (MCSs), so there is large uncertainty in their projections of extreme convective precipitation

MCS accounts for up to 64% of warm-season precipitation





(Lepore et al. 2014 GRL)

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Hazardous Convective Weather

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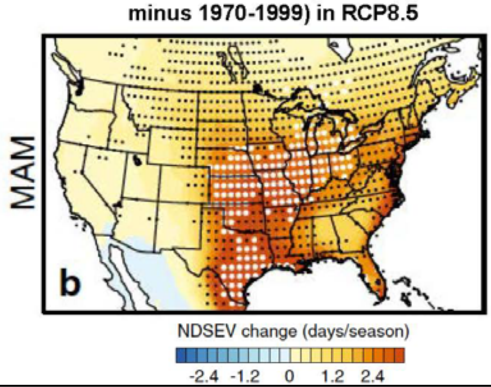
- Hazardous convective weather (HCW) includes tornadoes, hail, and damaging winds
- Ingredients of HCW:
  - Vertical wind shear (S06) – organization and longevity of severe convective
  - Thermodynamics (CAPE) – propensity of updraft development
  - Convective initiation

Change in number of days with severe thunderstorm environment (NDSEV) (2070-2099 minus 1970-1999) in RCP8.5



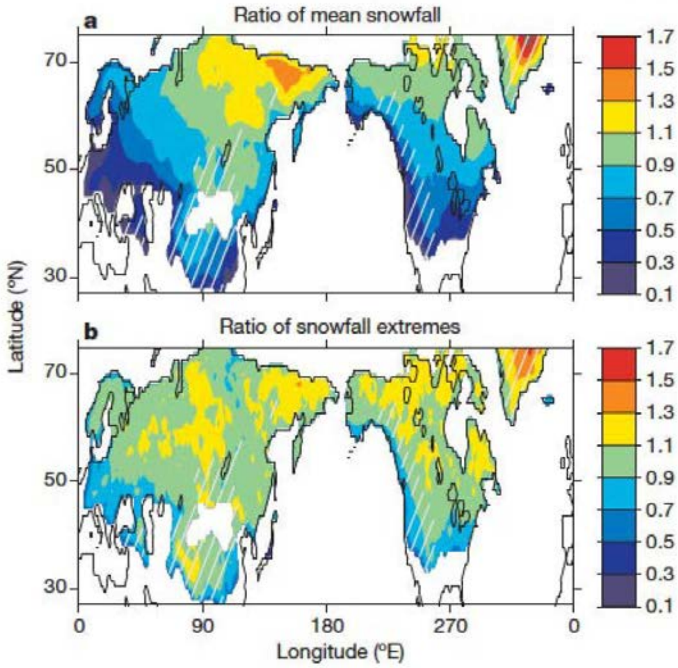
Projecting future changes:
- Increase in low level moisture increases CAPE
- Decrease in wind shear except in MAM
- Overall increase in NDSEV in all seasons, particularly MAM
- But large-scale environment does not fully constrain HCW

(Diffenbaugh et al. 2013 PNAS)

17

A Muted Response in Extreme Snowfall to Warming

- Competition between increasing saturation specific humidity and and decreasing snowfall fraction with increasing temperature gives rise to an optimal temperature for snowfall extreme
- Extreme precipitation increases with temperature
- Temperature change is small near the optimal temperature for extreme snowfall



(O'Gorman 2014 Nature)

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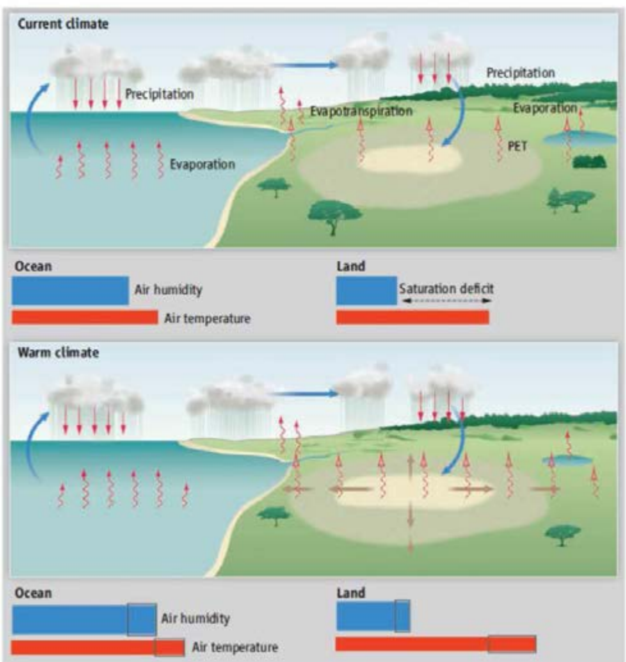
Increasing Aridity in a Warmer World



- Land warms about 50% more than the ocean because of limited availability of surface water
- Water vapor over land does not increase fast enough relative to the warming
- Larger saturation deficit increases PET and enhances aridity (P/PET)
- Regional changes are more complicated

(Sherwood and Fu 2014 Science)

Multidecadal Drought Risk

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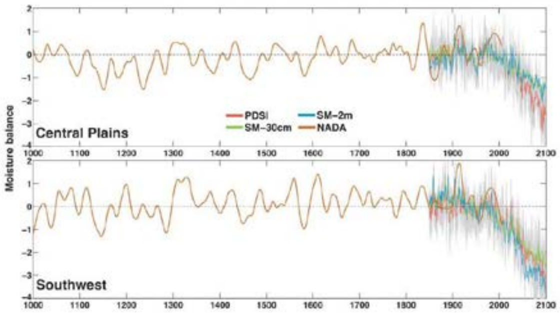
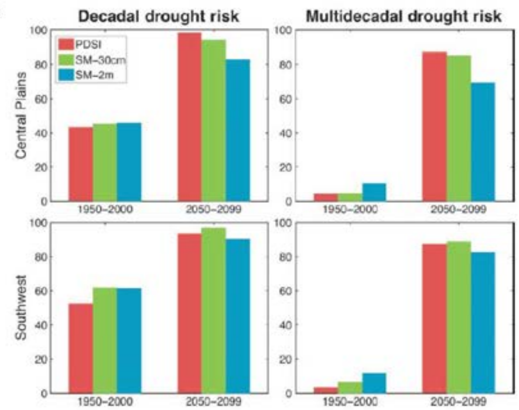


- Future drought severity in Central Plains and Southwest is beyond the driest Medieval climate anomaly of 1100 – 1300

- The risk of decadal (11 years) and multidecadal (35 years) drought risk is significantly higher in the future

(Cook et al. 2015 Sci. Adv.)



Poleward Shift of Locations of Cyclone Maximum Intensity

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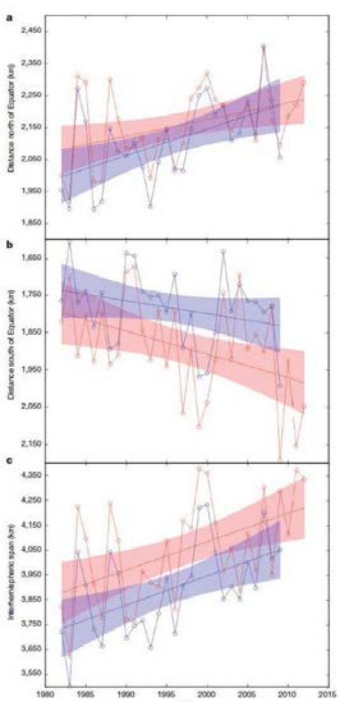
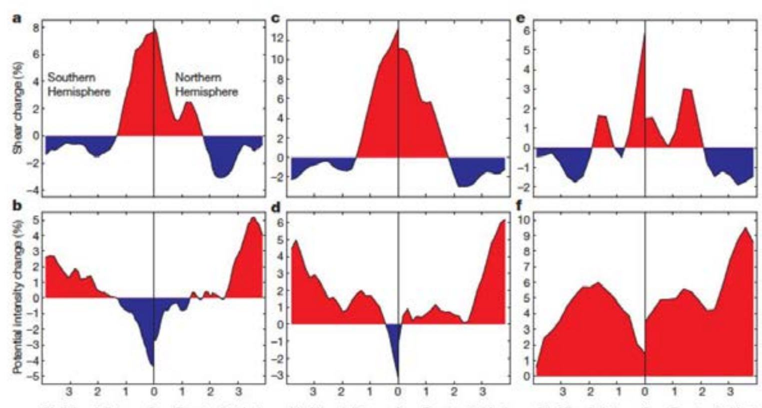


- The latitudes of lifetime-maximum intensity (LMI) have shifted poleward in both hemispheres in the last 30 years
- Linked to changes in environmental conditions consistent with expansion of Hadley circulation



(Kossin et al. 2014 Nature)

21

Atmospheric Patterns that Steered Sandy onto the US Coast

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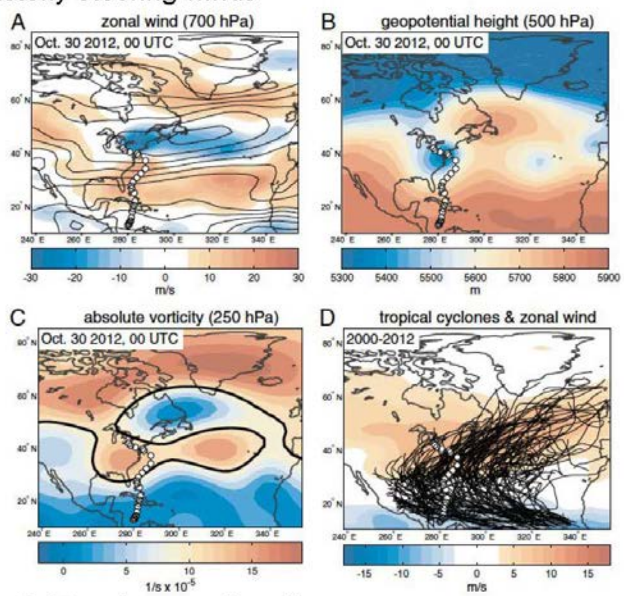
Equatorward shift of jet stream: easterly steering winds

Blocking anticyclone in Atlantic



Cyclonic Rossby wave breaking

(Barnes et al. 2015 PNAS)

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Sea Level Rise

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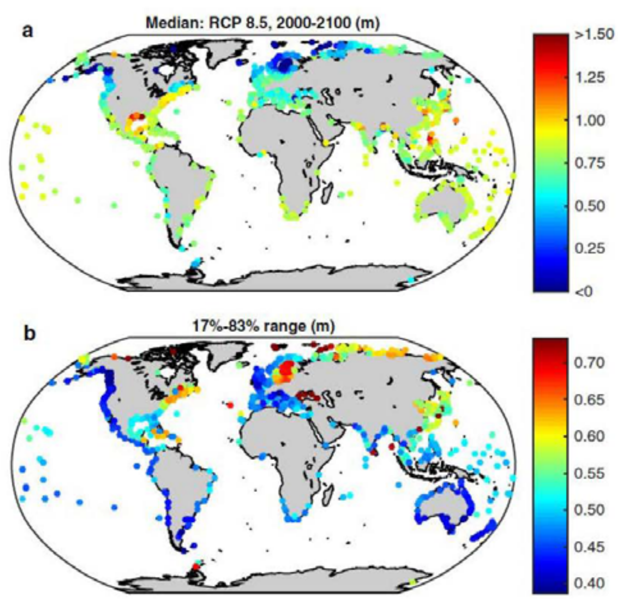
- Global coupled climate models are used to project dynamical sea level changes due to climate
- Large biases remained in equatorial and southern oceans, and continental ice sheet is missing in some coupled models
- By the end of the century, uncertainty related to Antarctic ice sheet dominates uncertainty in projecting regional SLR, but uncertainty in projecting dynamic sea level in North Atlantic dominates uncertainty in projecting SLR in Northeast US



(Kopp et al. 2014 Earth Future)

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Climate Modeling

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- The skill of climate models has increased due to increasing model resolution, improved physics parameterizations, and representing processes missing from previous models
- A hierarchy of models and simulations are increasingly used in the last decade to advance theories and understanding of model biases and uncertainty
- There are multiple evidences that simulations of important climatic features such as jet stream and storm tracks converge at ~ 50km resolution, suggesting future generations of climate models applied at such resolution may provide more robust simulations and projections of large-scale circulation
- Future directions in climate modeling include adoption of seamless prediction (unified modeling) approach, interoperable modeling framework, disruptive computing technology, more attention to uncertainty quantification
- The first US Climate Modeling Summit was held in February 2015: brought together six premier US climate modeling centers (NOAA GFDL, NOAA NCEP, NASA GISS, NASA GMAO, CESM, DOE ACME) to strategize priorities of national interest
- CMIP6 – final endorsement of MIPs in April 2015; GMD special issue on final CMIP6 experimental design and forcing by December 2015

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Hydrologic Modeling

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- Recent advances in hydrologic modeling have been predominately driven by advances in IT resources and the need to support assessments of impacts of climate change on water resources
- Enhanced data management infrastructure and new spatial data products (including remotely sensed information) have allowed more rapid and automated data assimilation into hydrologic models
- In order to assimilate products provided by the climatological community as inputs to their analyses, the hydrologic community has recently developed capabilities to provide meteorological records with multivariate coherence in space and time that allows generation of meaningful streamflow records based on the climate results
- The hydrological process models have not been noticeably altered over the past decades - while programming has improved and the spatial resolution has improved, the fundamental process representations remain rather simple expressions of conservation of mass (hydrology), conservation of energy (water temperature) and conservation of momentum (hydraulics)
- Improvement in spatial resolution and data assimilation of spatial data make it easier to use models but, unfortunately, no less likely to misuse models by not adequately confirming the model configuration and parameterization

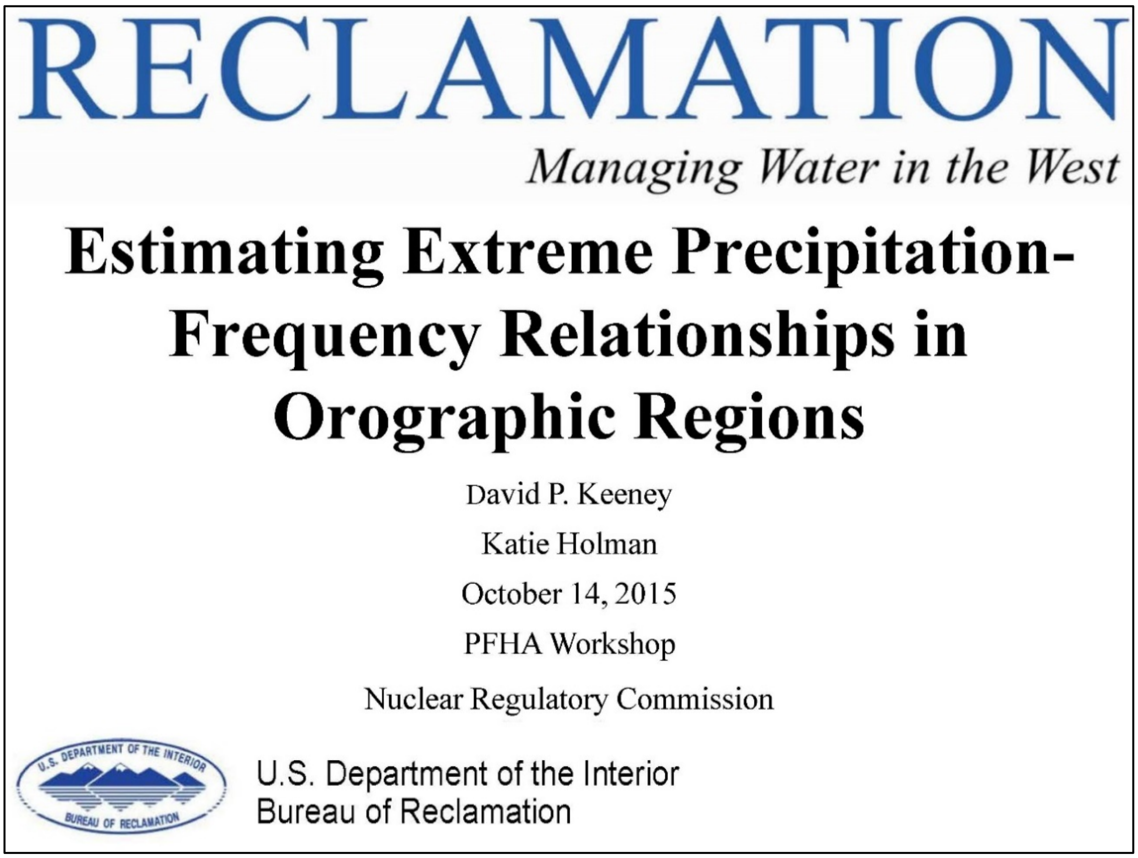
25

1.3.3 Day 1: Session III: Precipitation

Session III of the workshop focused on NRC-funded precipitation-related research. Researchers from the U.S. Bureau of Reclamation (USBR) discussed statistical modeling approaches for estimating extreme precipitation in orographic regions (i.e., regions where complex terrain influences precipitation processes). Researchers from the University of California at Davis presented work exploring the feasibility of direct numerical simulation of intense precipitation processes associated with mesoscale convective systems and tropical cyclones. A joint presentation by staff from PNNL and Coppersmith Consulting, Inc. (CCI), discussed research conducted to extend and adapt the Senior Seismic Hazard Assessment Committee (SSHAC) process used in probabilistic seismic hazard assessments (PSHAs) to develop a structured hazard assessment committee for flooding (SHAC-F) and specifically to apply the process to local intense precipitation flooding.

1.3.3.1 Estimating Precipitation—Frequency Relationships in Orographic Regions.

David Keeney and Katie Holman, USBR



Outline

- Background
- Objectives of project
- Precipitation-frequency relationships
- Common practice at Reclamation
- Taylor Park Dam study
- Moving forward

RECLAMATION

Background

- NRC requested research to improve PMP estimates in Eastern US
- Reclamation completed a pilot study for the Carolinas in 2011
- Phase II focuses on regional precipitation-frequency analyses in orographic regions

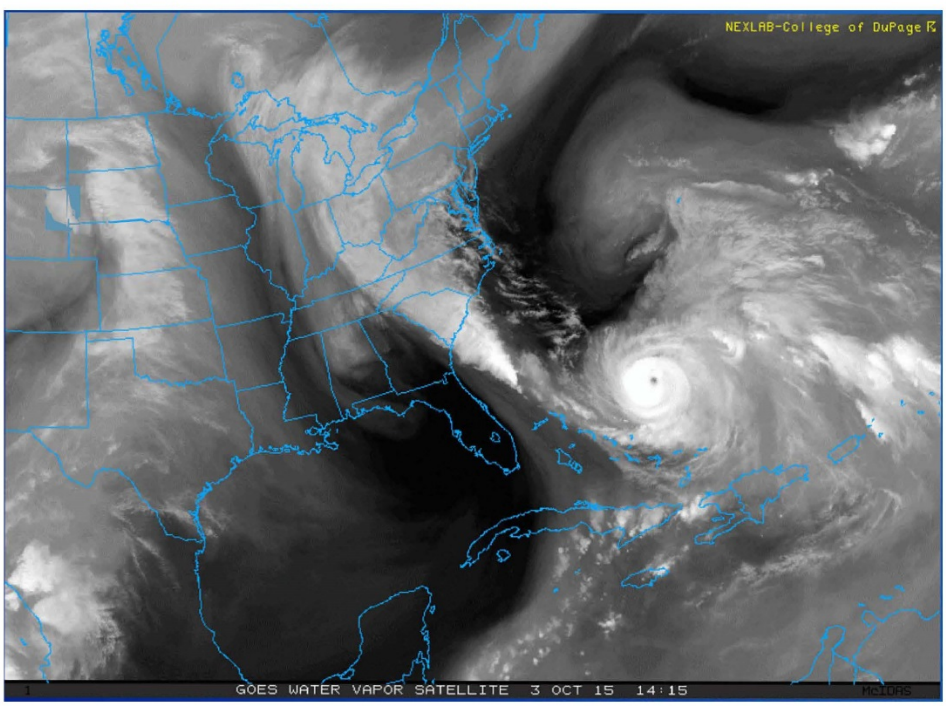
RECLAMATION

Objectives of the Phase II Project

- Literature review of historical precipitation analysis including recent advances
- Orographic storm methodology

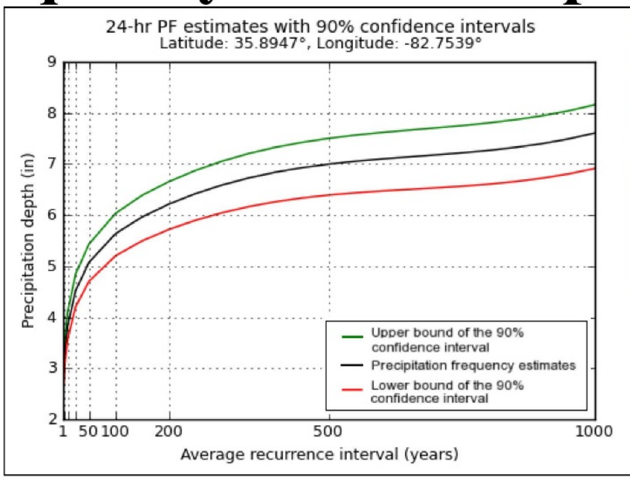
- Precipitation-frequency analysis

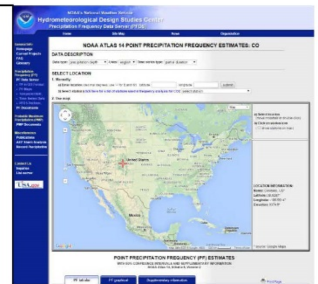
RECLAMATION



RECLAMATION

What is a precipitation-frequency relationship?





A statistical relationship that characterizes the amount of precipitation expected in a certain amount of time for a given return period

RECLAMATION

Data Sources

HYDROMETEOROLOGICAL REPORT NO. 41

Probable Maximum and TVA Precipitation over the Tennessee River Basin above Chattanooga

- PMP (HMRs)
- Point observations
  - GHCN
  - SNOTEL
  - COOP sites (e.g. CoCoRaHS)
- Gridded observations
  - Livneh et al. (2013) dataset
- Simulated data
  - Reanalysis data (e.g. NARR)
  - Climate model output

RECLAMATION

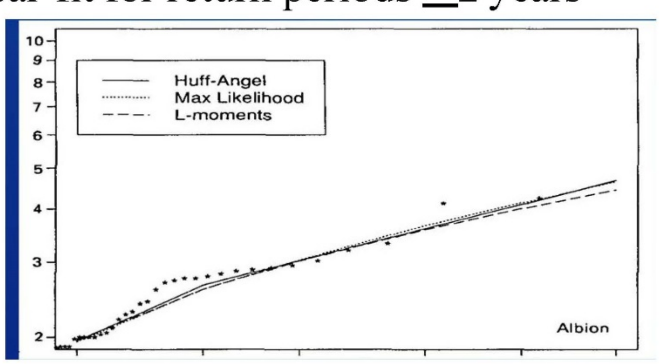
Methods of Estimation

- Huff-Angel
- Australian Rainfall and Runoff
- Maximum Likelihood Estimation
- Regional L-moments

RECLAMATION

Huff-Angel

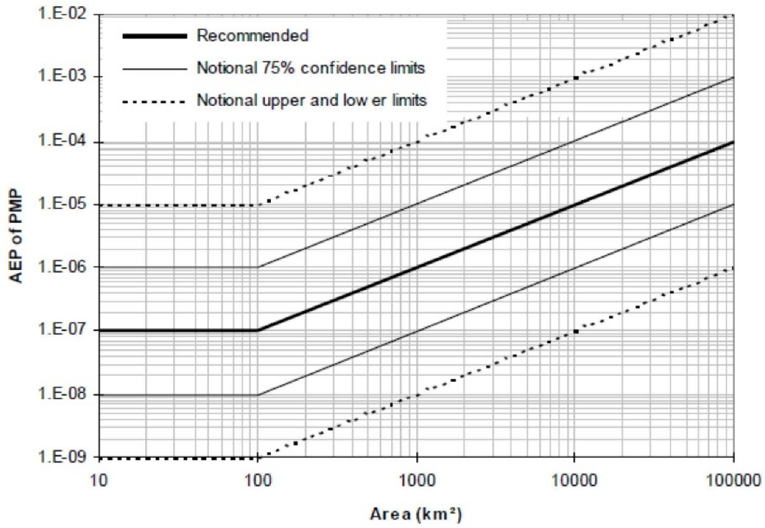
- From Bulletin 71 in 1992
- Update to TP40, focus on Midwest
- Log-log graphical analysis
- Return periods from 2 months to 100 years
- Linear-fit for return periods $\geq$ 2 years



RECLAMATION

Australian Rainfall and Runoff

- Use watershed drainage area to estimate AEP of Probable Maximum Precipitation (PMP)

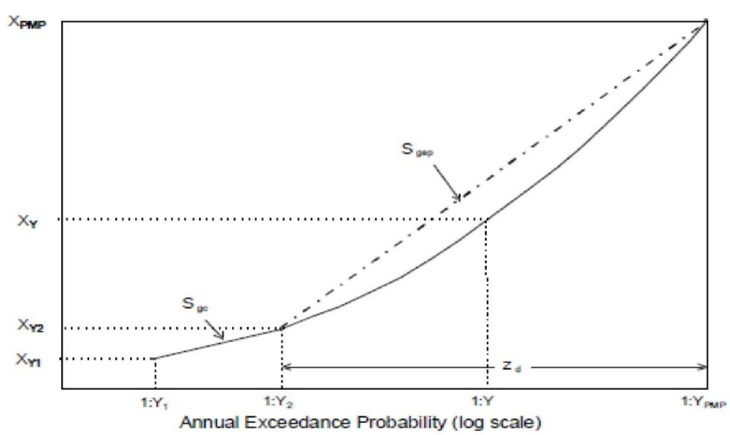


Figures 6 from Nathan and Weinmann (1998)

RECLAMATION

Australian Rainfall and Runoff

- Requires values for 1-in-50 and 1-in-100 year events (NOAA Atlas 2 and 14)
- Extrapolate out to AEP of PMP



Figures 7 from Nathan and Weinmann (1998)

RECLAMATION

Maximum Likelihood Estimation

- Assume a distribution
- Estimate parameters based on set of observations
- Sensitive to short records (poor estimation)

RECLAMATION

Maximum Likelihood Estimation

- Assume a distribution
- Estimate parameters based on set of observations
- Sensitive to short records (poor estimation)

RECLAMATION

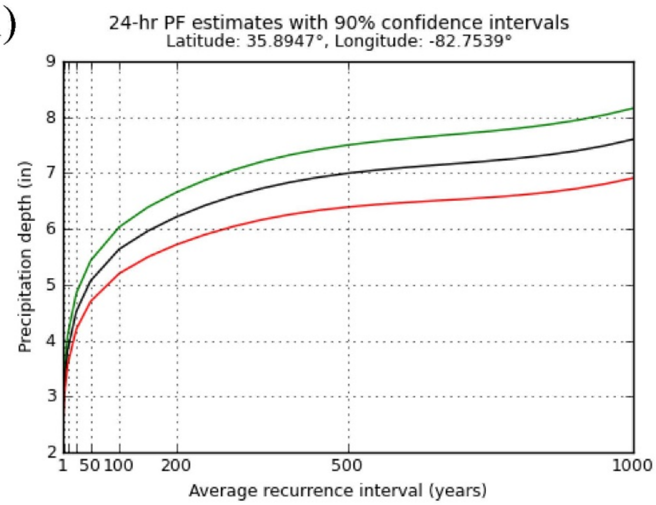
Regional L-moments

- From Hosking and Wallis in 1991
- Requires homogenous region (subjective)
- Utilizes data from many sites (minimize sampling errors)
- Goodness-of-fit test to obtain probability distribution

RECLAMATION

NOAA Atlas 14 - Point

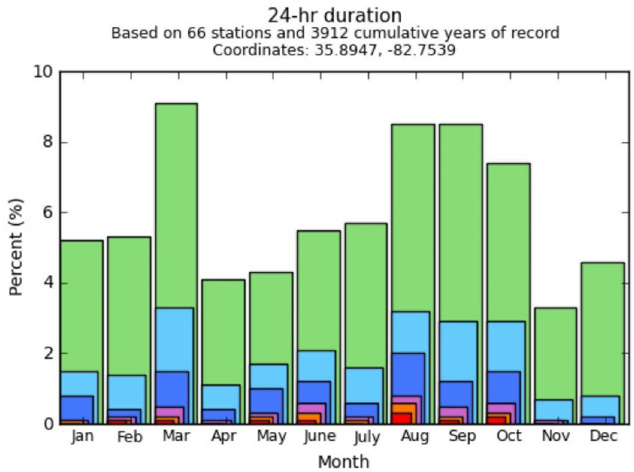
- Based on annual max
- Includes uncertainty (90% confidence interval)



RECLAMATION

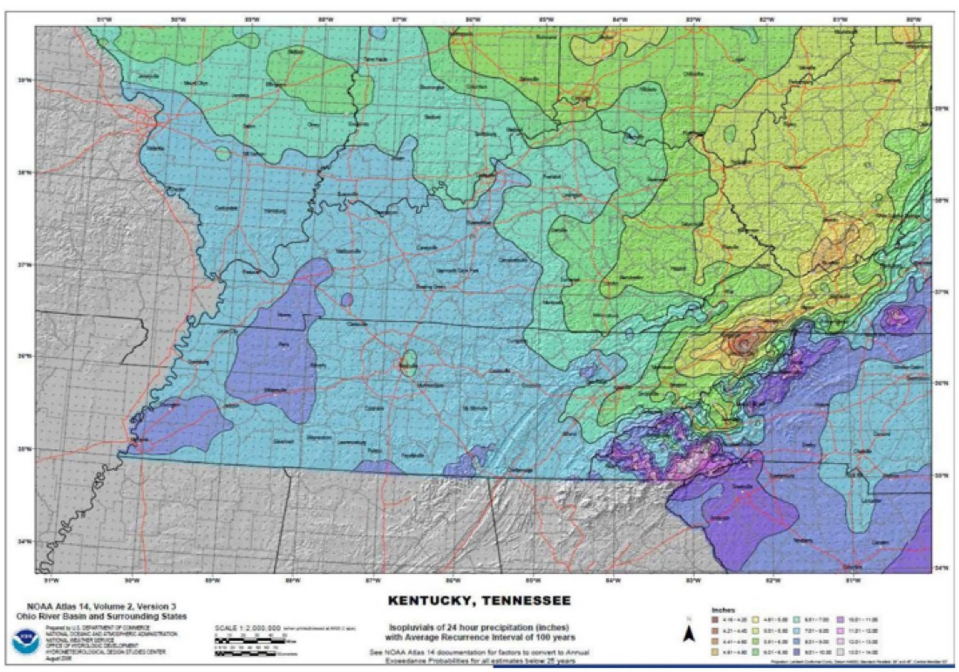
NOAA Atlas 14 - Point

- Can estimate seasonality by using monthly plots



RECLAMATION

NOAA Atlas 14 - Gridded



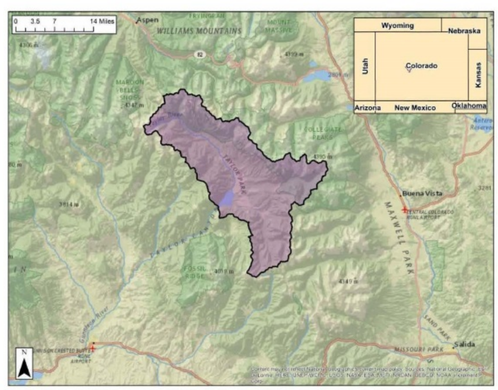
RECLAMATION

Reclamation methods

- Moving away from deterministic studies
  - Calculate PMP for historical purposes
  - Less interest in Inflow Design Floods or Probable Maximum Floods
- Precipitation-frequency analyses
  - ARR Method
  - Regional L-moments
- Incorporate uncertainty
  - Precipitation-frequency analysis
  - Hydrometeorological parameters (e.g. soil moisture, SWE, etc.)

RECLAMATION

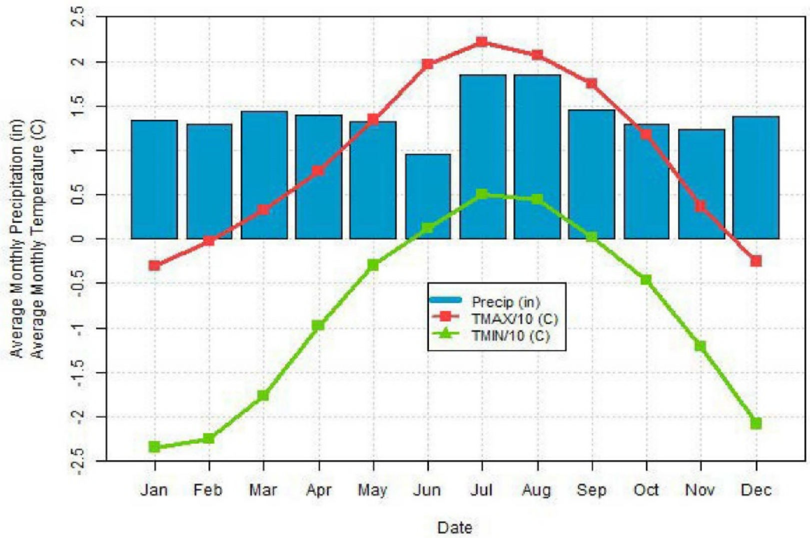
Taylor Park Dam



- Location:
  - On the Taylor River, 32 miles west of Buena Vista, CO
- Dam:
  - Constructed between 1935-1937
  - 206’ high earthfill structure
  - Elevation near 9,200’
  - Controls runoff from 255 mi^2
- Purpose:
  - Irrigation

RECLAMATION

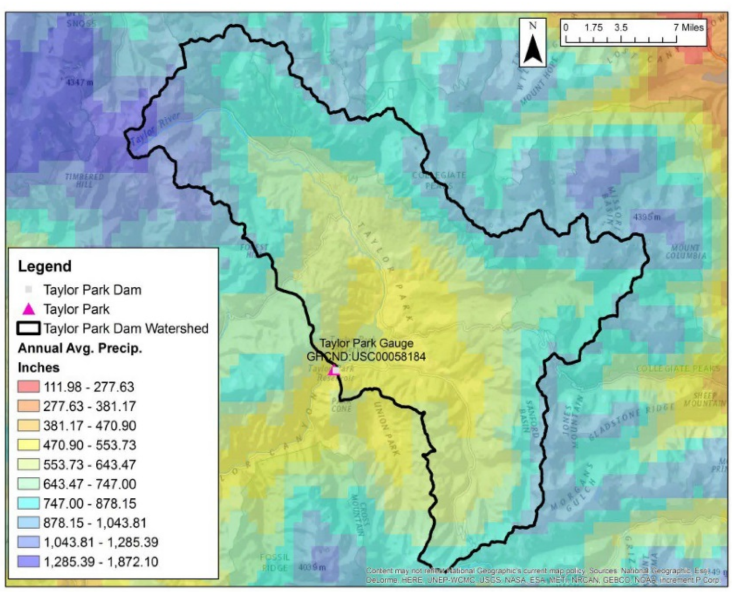
Regional climate - Point



Taylor Park Gauge 1963-2014

RECLAMATION

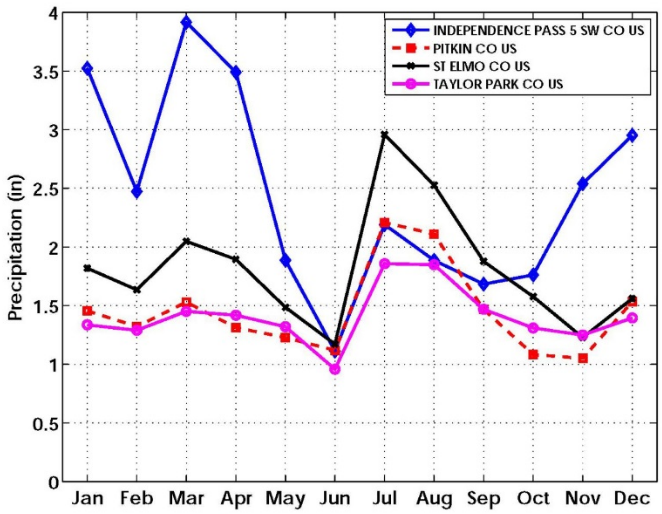
Regional climate - Gridded

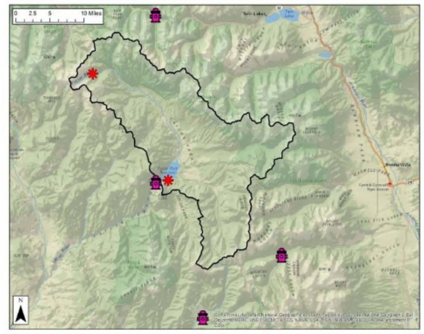


Average Annual Precipitation between 1981-2010 (PRISM)

RECLAMATION

Regional climate

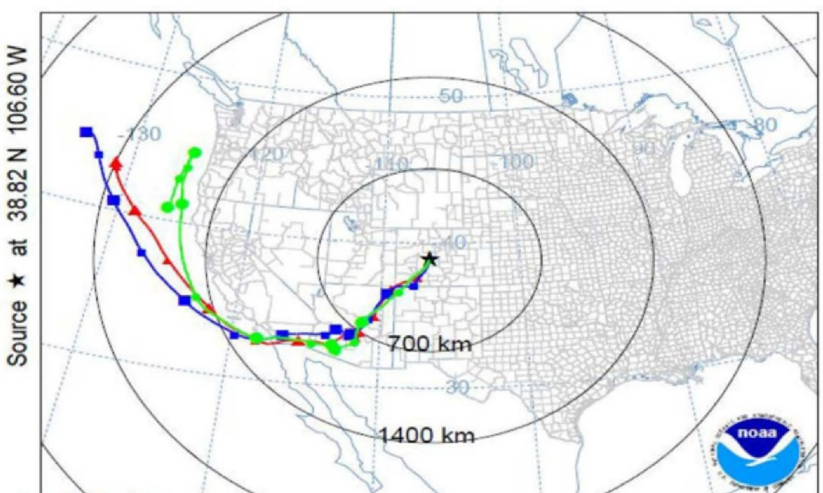


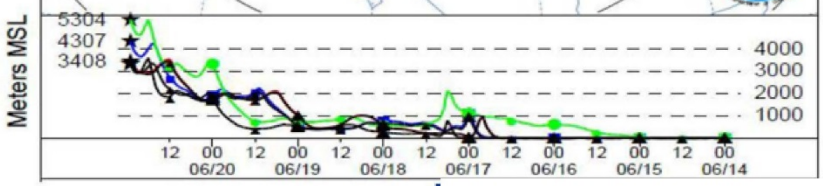


STATION NAME	START YEAR	END YEAR	% AVAIL.	ELEVATION (FT)
TAYLOR PARK CO US	1940	2014	99.46	9214
PITKIN CO US	1909	1986	97.06	9240
ST ELMO CO US	1909	1953	94.18	9498
INDEPENDENCE PASS 5 SW CO US	1947	1980	98.60	10555

RECLAMATION

Moisture sources

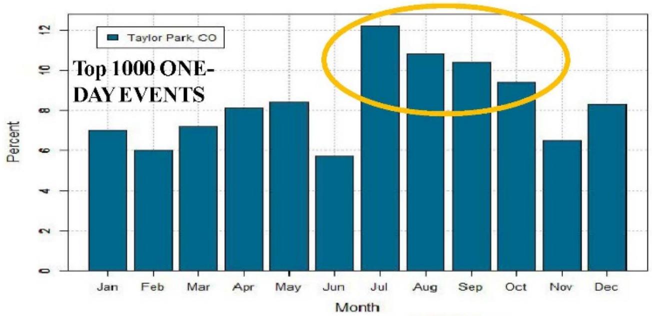


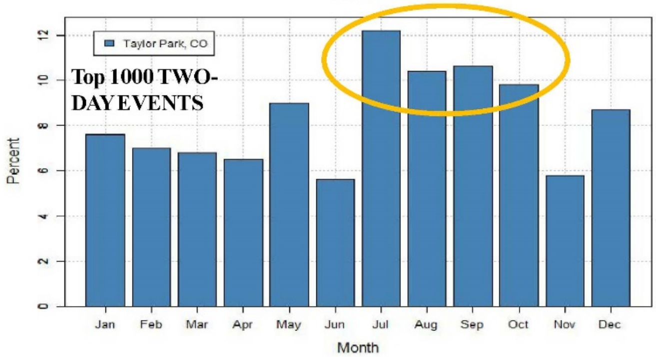


Ending 2300 UTC 20 June 1995

RECLAMATION

Heavy precipitation events





While late-summer/early-fall has the largest 1-day and 2-day totals, we focus on spring (April, May, June) due to concerns with rain-on-snow events

RECLAMATION

L-moments analysis

- Regional statistical method
- “Space for time” – multiple gauges within homogeneous region
- Compute L-moment statistics for each gauge in homogeneous region
- Remove discordant gauges
- Compute regional growth curve based upon selected distribution
- Scale growth curve (point, basin, region)

RECLAMATION

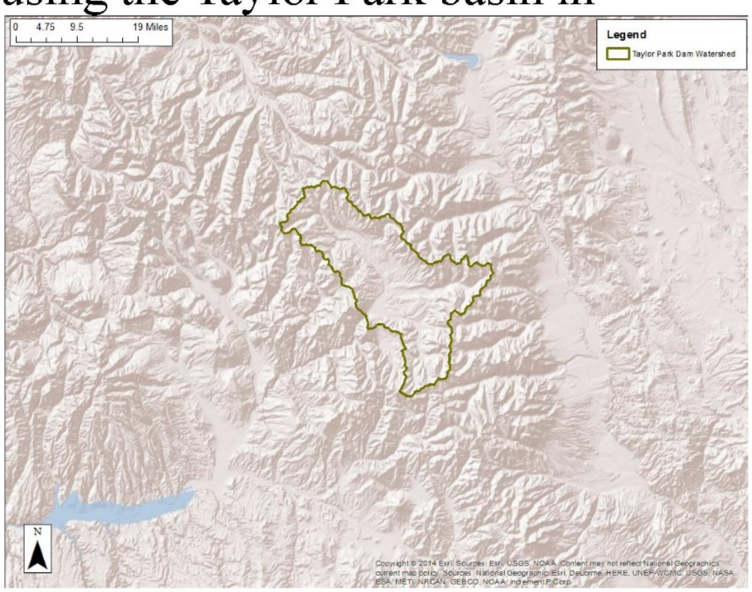
Homogeneous Region (HR)

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

RECLAMATION

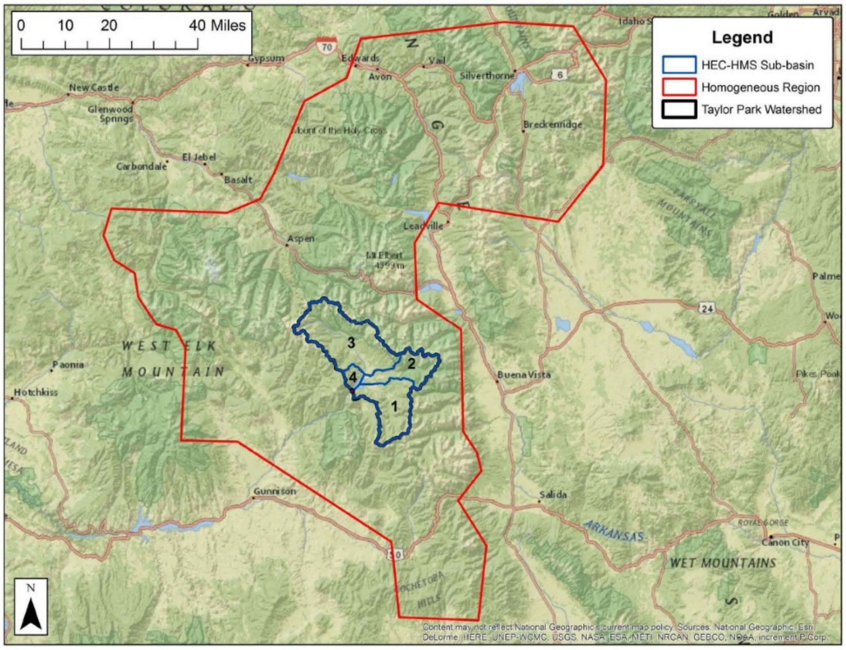
Delineating the HR

Example using the Taylor Park basin in central C



RECLAMATION

Taylor Park HR



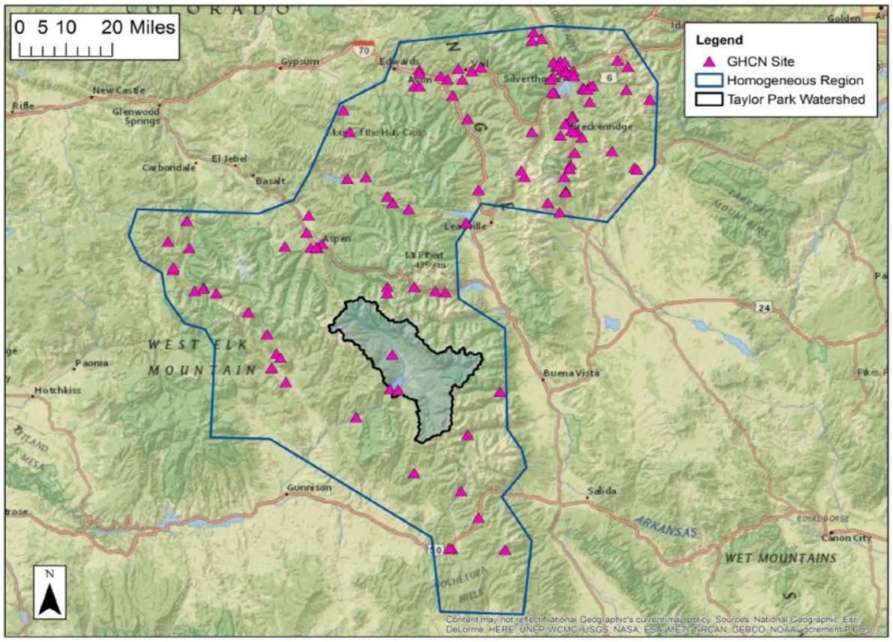
RECLAMATION

Precipitation observations

- GHCN-Daily dataset
  - Downloaded data in HR using Python
  - Identified two-day max totals in April, May, and June for each year and site
    - Converted two-day totals to 48-hour values using scale factor (1.04) from HMR 49
  - Sites must have 87% availability for at least 10 years
  - Remove sites with discordancy value > 3

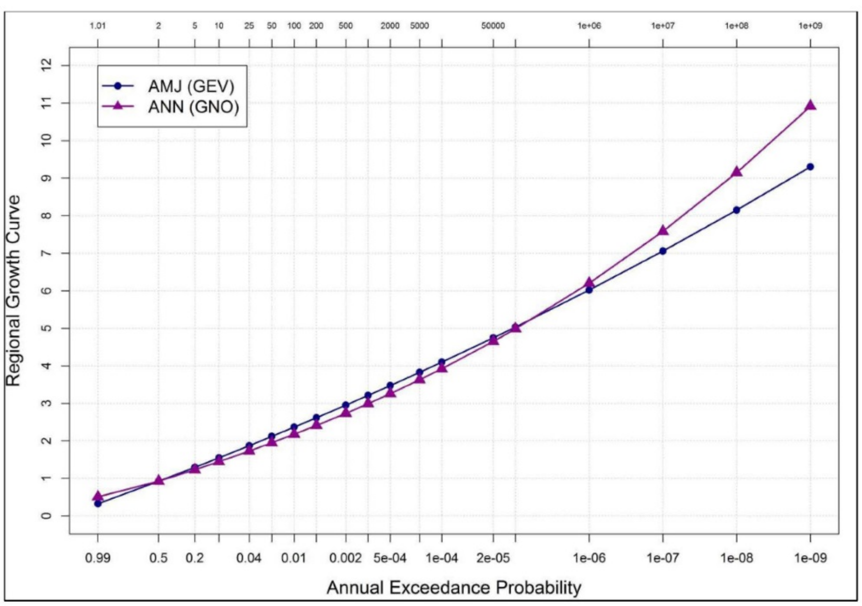
RECLAMATION

GHCN sites in the HR



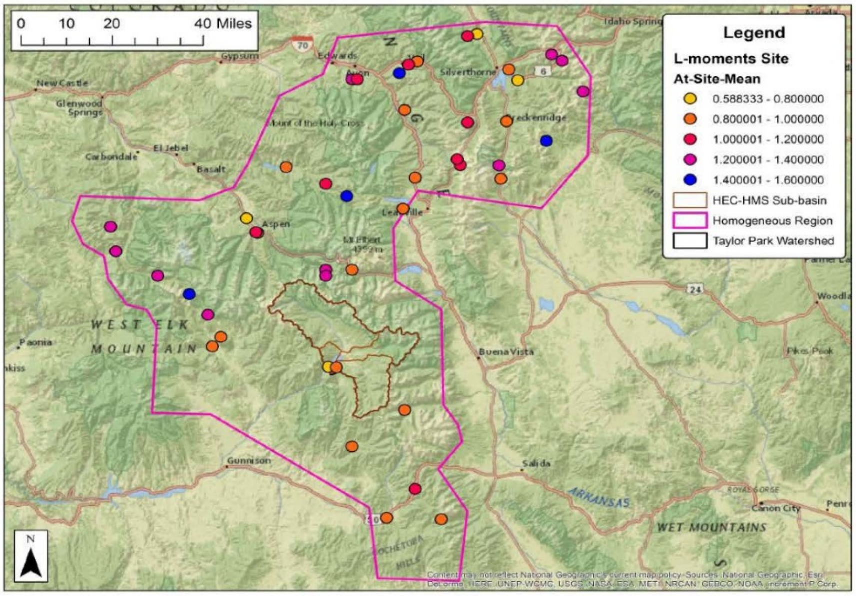
RECLAMATION

Regional growth curve



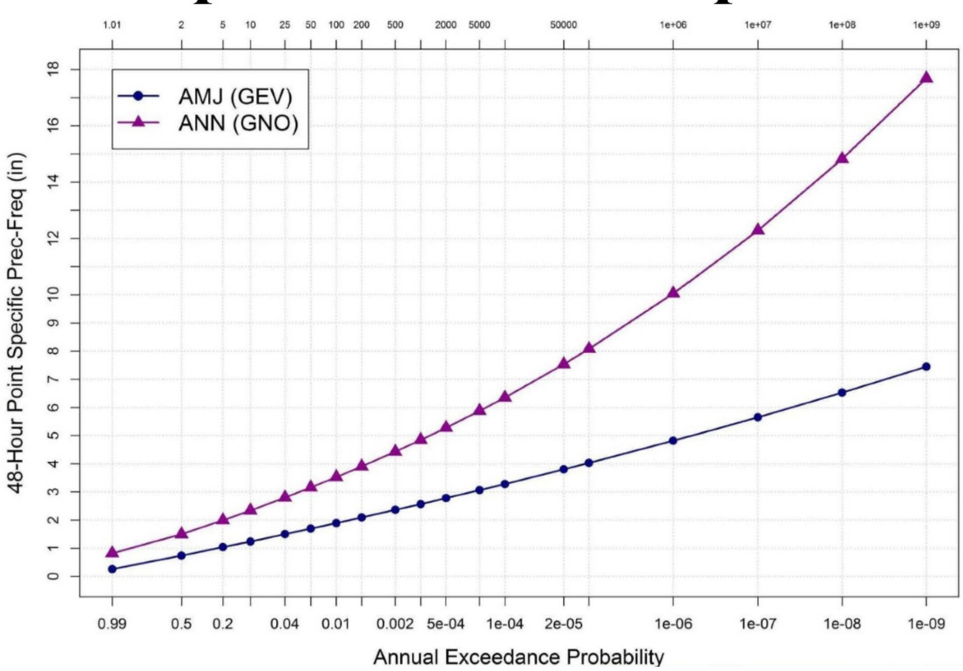
RECLAMATION

Location, location, location



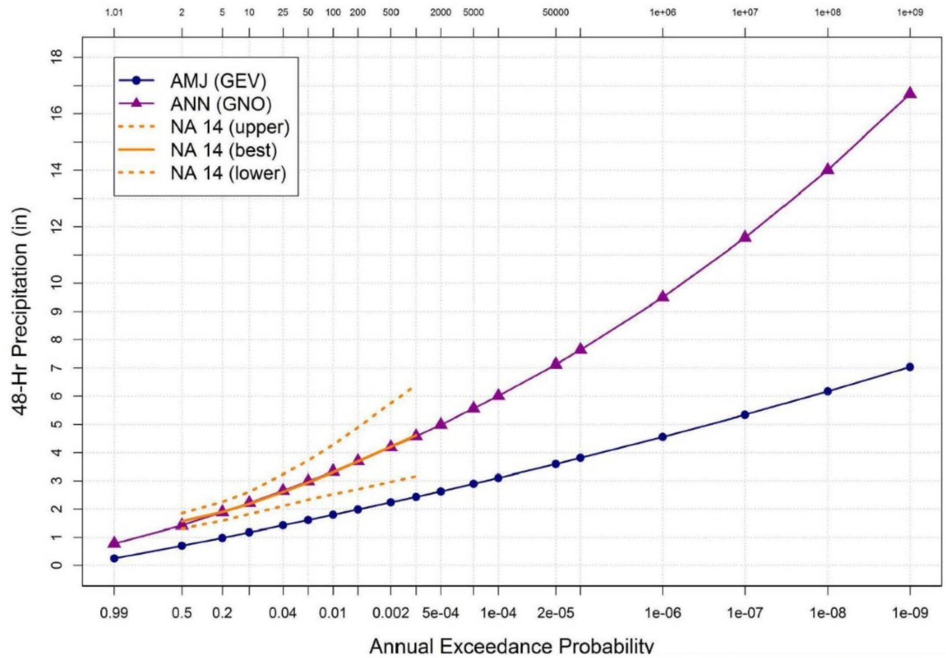
RECLAMATION

Point-specific relationship



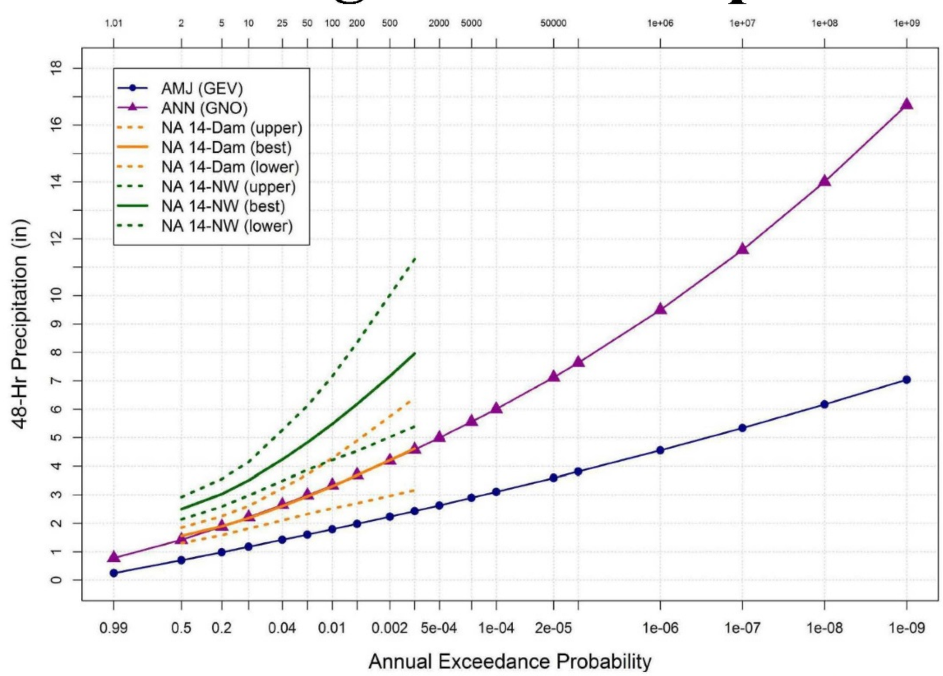
RECLAMATION

Basin-average relationship



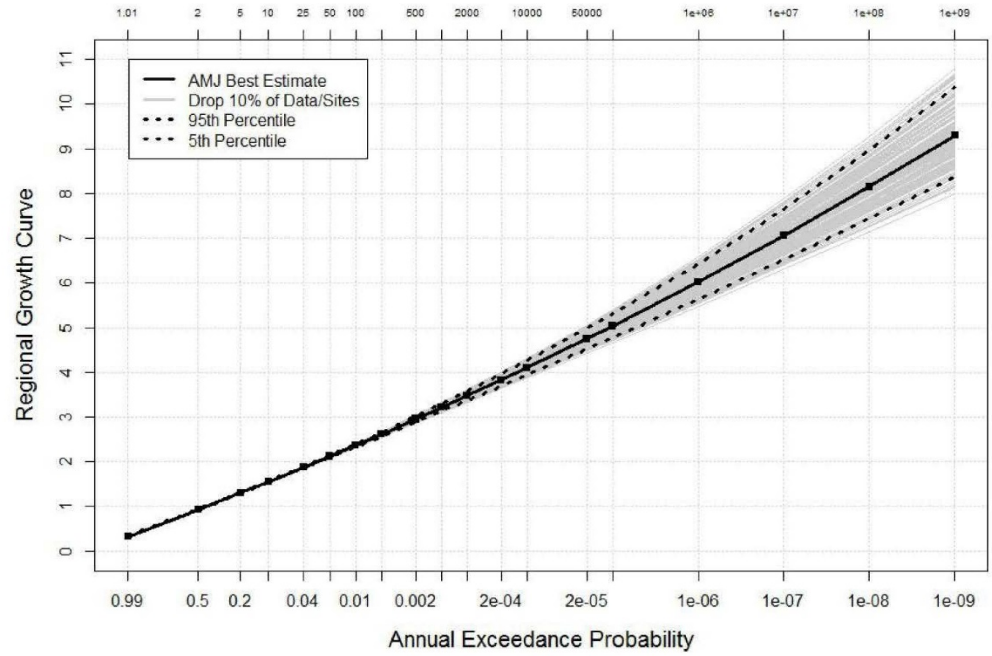
RECLAMATION

Basin-average relationship



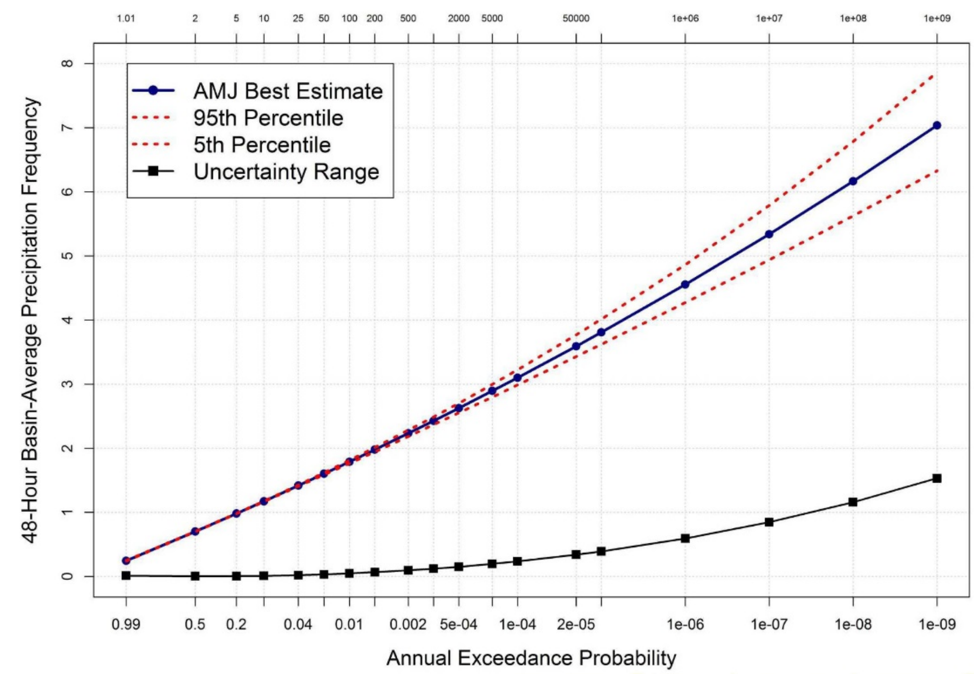
RECLAMATION

Uncertainty in RGC



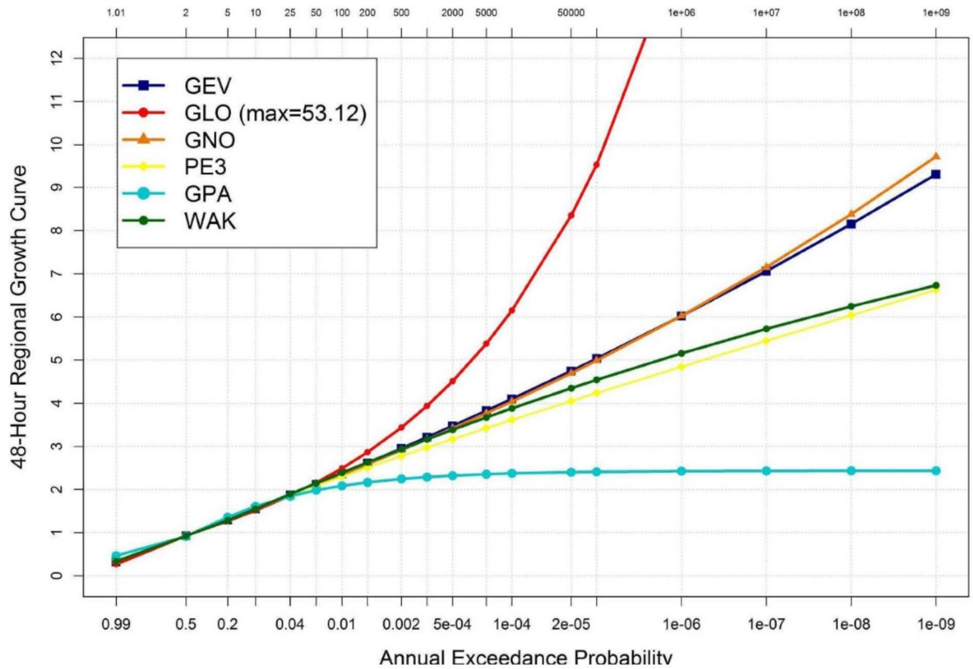
RECLAMATION

Propagating RGC uncertainty



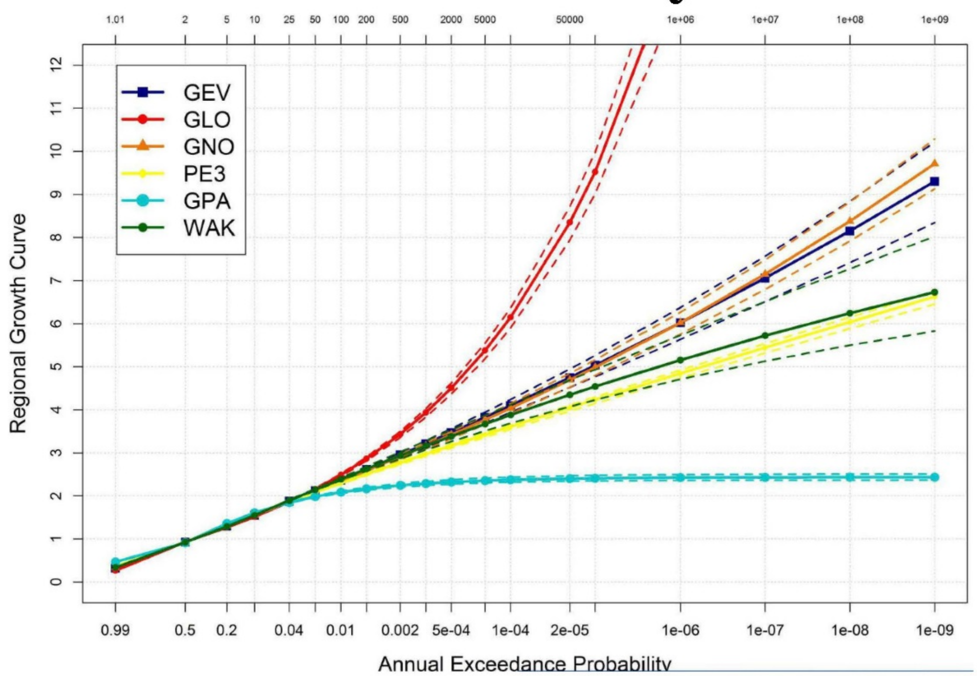
RECLAMATION

RGC distributions



RECLAMATION

Distribution uncertainty



RECLAMATION

Uncertainty

Regional Growth Curve

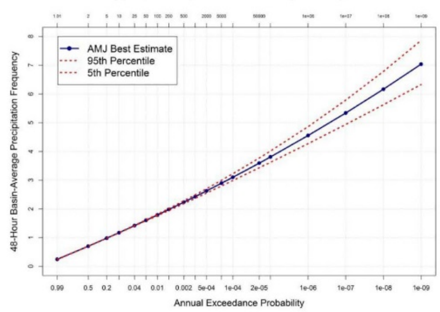
At-Site Mean

Areal-Reduction Factor

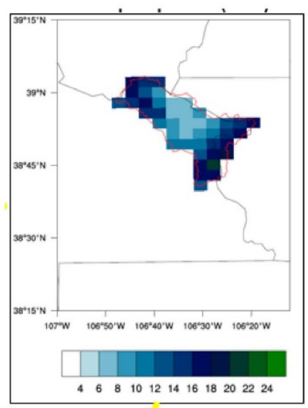
RECLAMATION

Hydrologic hazard analysis

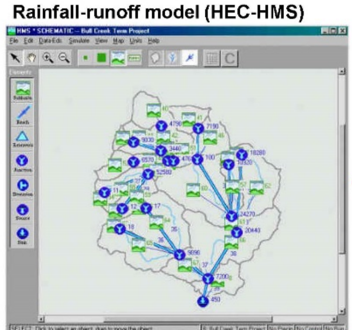
Basin-average precipitation-frequency relationship



Accumulated precipitation (96 hr)



Rainfall-runoff model (HEC-HMS)



HEC-HMS figure from www.ce.utexas.edu
Precip data from NOAA/CIRES

RECLAMATION

Additional Tools

- Weather Research and Forecasting (WRF) model
  - Ensembles to estimate uncertainty in events
  - Modify terrain (and gradients in terrain)

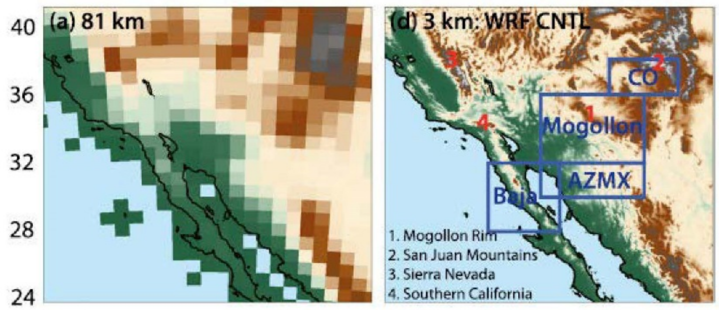
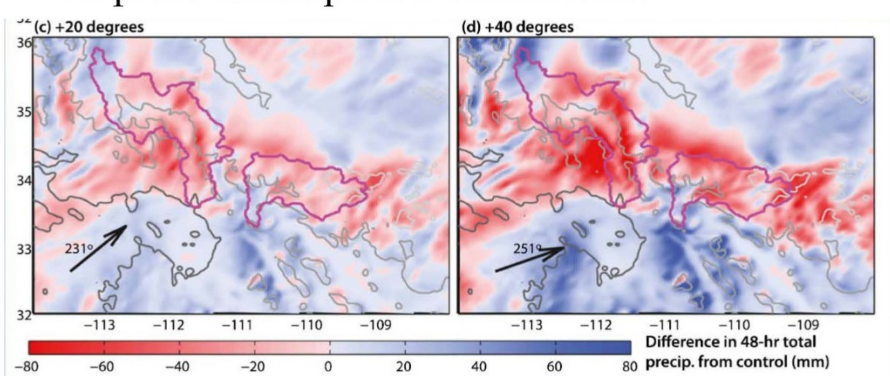


Figure 1 from Hughes et al. (2014)

RECLAMATION

Additional Tools

- Linear model of orographic precipitation
  - Describes the pattern of precipitation arising from forced ascent of saturated air over topography
  - Explore assumptions behind PMP



RECLAMATION

Additional Tools

- Bayesian Hierarchical Model
  - Composed of multiple levels that represent model formulation
  - Represents uncertainty in a system
  - Requires no homogenous region
  - Includes probability distribution for each model parameter

RECLAMATION

Conclusions

- Many methods for estimating precipitation-frequency relationships
  - Reclamation focuses on two methods
- Regional L-moments statistics to compute precipitation-frequency relationships
- Good for use in orographic regions
  - Topography plays a major role
- Uncertainty
  - Trying to improve estimation methods while propagating through hydrologic hazard analyses

RECLAMATION

Questions/Comments

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David P. Keeney
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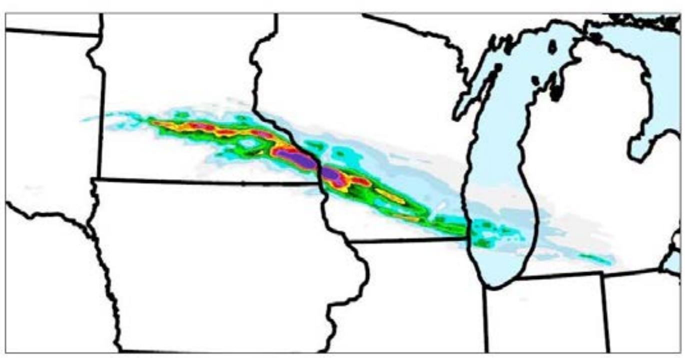
RECLAMATION

1.3.3.2 Numerical Simulation of Local Intense Precipitation. M. Levent Kavvas, Kei Ishida, Mathieu Mure-Ravaud, University of California at Davis

Numerical Simulation of Local Intense Precipitation



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UNIVERSITY OF CALIFORNIA
HYDROLOGIC RESEARCH LABORATORY

M. Levent Kavvas
Kei Ishida
Mathieu Mure-Ravaud

UCD HRL | First Annual NRC PFHA Research Program Workshop | 1 /75

Objective of the 3-yr project (according to the statement of work):

"The objective of this work is to assess the suitability of a regional numerical weather model to simulate local intense precipitation processes and serve as a test bed for moisture maximization and storm transposition techniques, ultimately updating extreme precipitation estimates and quantifying uncertainty bounds."

This project started on May 12, 2015 (the receipt of the final modified contract from USGS). Hence, 5 months have passed since the start of this project.

SCOPE OF WORK OF THIS PROJECT:

Task 1: Literature review of previous studies related to local intense precipitation in the conterminous United States (Project Year 1).

Task 2: Work Plan Development (Project Year 1)
a) to select two representative case studies of severe storms over Conterminous United States;
b) to select the datasets to be used for initial and boundary conditions for numerical model runs;
c) select multi-sensor data for the analysis of precipitation processes, the calibration and validation of numerical model simulations and for uncertainty analysis;
d) lay out the methodology for the calibration and validation of the numerical atmospheric model with respect to the two selected severe storm events;
e) lay out the uncertainty analysis methodology for the computation of uncertainties associated with various model configurations.

3

Task 3: Numerical model simulations for the two selected severe storm events (Project Year 1).

Task 4: Numerical experiments on the investigation of the atmospheric conditions that result in extreme precipitation (Project Years 2 and 3).

Task 5: Transfer of knowledge, gained in the project, to the NRC staff (Project Year 3)

Task 6: Preparation of an NRC contractor report (NUREG/CR) (Project Year 3).

Outline of the Accomplished Work

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

2. **Preparation for the numerical simulations for two storm events**
   - Initial and boundary conditions
   - Observation data for model configuration and validation
   - Choosing candidates
   - Choosing the nested-domains

Classifications of extreme precipitation events

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

Classifications of extreme precipitation events

- Schumacher and Johnson (2005) performed a radar-based analysis of a large sample of extreme rain events during 1999-2001 over the eastern 2/3 of the US (excluding Florida).
- Precipitation events were selected using rain gauge data.
- An event was considered as "extreme" if one or more gauges reported a 24-h rainfall total greater than the 50-yr recurrence interval amount for that location determined by Hershfield (1961).
- Classification and the number and the percentage of all extreme precipitation events associated with that storm type.

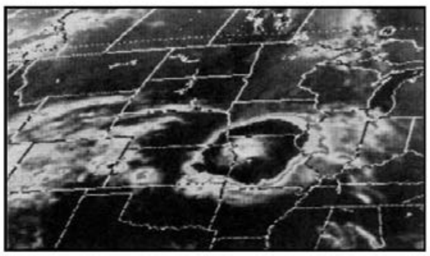
System	Number Events	Total
MCS	76	65.5%
Synoptic	31	26.7%
Tropical	9	7.8%

Classifications of Mesoscale Convective Systems (MCS)

1. Satellite-based classifications: once satellite imagery became available in the 1970s, studies of large-scale MCSs became a popular topic.

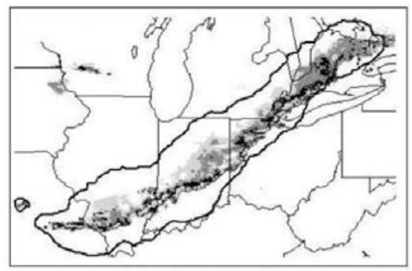
Examples:

Mesoscale Convective Complexes



Maddox (1983)

Persistent Elongated Convective Systems

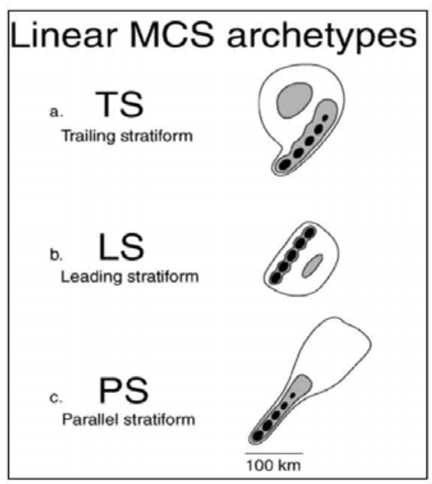


Jirak et al. (2003)

Classifications of Mesoscale Convective Systems (MCS)

2. Radar-based classifications:

Two regions of precipitation are usually observed in a MCS: **heavy convective showers** in the region of convective updrafts, and **stratiform rain** whose location relative to the convective region depends on the storm-relative winds.



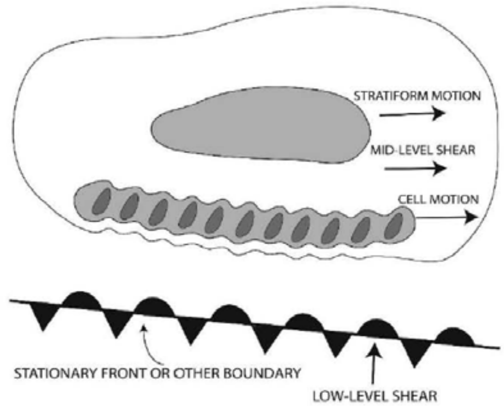
Schematic reflectivity drawing of three idealized linear MCS archetypes. Levels of shading (lighter to darker) roughly correspond to 20, 40 and 50 dBZ. From ***Parker and Johnson (2000)****.*

Classifications of Mesoscale Convective Systems (MCS)

Schumacher and Johnson (2005) proposed **2 other categories of MCS** corresponding to specific configurations of the system propagation relative to individual cell movement **suitable for tremendous precipitation** over a given location.

➢ Training Line/Adjoining Stratiform (TL/AS):

"Linear MCS with **cell motion approximately parallel to the convective line** ... as the cells move in a line parallel direction, there is very little motion in the line perpendicular direction, which distinguishes them from the TS and LS archetypes."

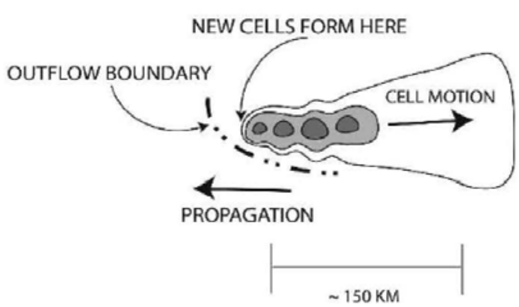


Schematic diagram of the radar-observed features of the TL/AS pattern of extreme-rain-producing MCSs. From Schumacher and Johnson (2005)

Classifications of Mesoscale Convective Systems (MCS)

➢ Backbuilding/Quasi-stationary (BB):

" Convective cells repeatedly form upstream of their predecessors and pass over a particular area, leading to large local rainfall totals. Decaying cells move downstream and are replaced by cells reaching their mature stage".



Schematic diagram of the radar-observed features of the BB pattern of extreme-rain-producing MCSs. From Schumacher and Johnson (2005)

Classifications of Mesoscale Convective Systems (MCS)

Schumacher and Johnson (2005) obtained the following distribution for extreme rain events in the MCS category during 1999-2001 over the eastern 2/3 of the US (excluding Florida):

MCSs	Number Events	% of MCSs	% of all events
Training Line/Adjoining Stratiform (TL/AS)	24	31.6%	20.7%
Backbuilding/Quasi-stationary (BB)	15	19.7%	12.9%
Trailing Stratiform (TS)	13	17.1%	11.2%
Other MCS	12	15.8%	10.3%
Parallel Stratiform (PS)	7	9.2%	6.0%
Multiple MCSs	3	3.9%	2.6%
Leading Stratiform (LS)	2	2.6%	1.7%
Total	76	100%	65.5%

Numerical simulation of MCSs and tropical cyclones

❑ Numerical weather models mainly used in the literature to simulate **MCSs**:

- MM5: Pennsylvania state University/National Center for Atmospheric Research (PSU/NCAR) Mesoscale Model (Dudhia et al., 1999)
- RAMS: Regional Atmospheric Modeling System (Pielke et al., 1992)
- ARPS: Advanced Regional Prediction System (Xue et al., 1995)
- MC2: Mesoscale Community model (Benoit et al., 1997)
- NCOMMAS: National Severe Storms Laboratory (NSSL) Collaborative Model for Mesoscale Atmospheric Simulation (Wicker and Wilhelmson, 1995)
- BRAMS: Brazilian Regional Atmospheric Modeling System (http://brams.cptec.inpe.br/)
- WRF: Weather Research and Forecasting Model (Skamarock et al., 2008)

❑ Numerical weather models mainly used in the literature to simulate **tropical cyclones**:

- GFDL: Geophysical Fluid Dynamics Laboratory Hurricane Prediction System (Kurihara et al., 1995; Kurihara et al., 1998; Bender et al., 2007).
- MM5: Pennsylvania state University/National Center for Atmospheric Research (PSU/NCAR) Mesoscale Model (Dudhia et al., 1999)
- WRF: Weather Research and Forecasting Model (Skamarock et al., 2008)

Outline

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

2. Preparation for the numerical simulations of two storm events
    - Initial and boundary conditions
    - Observation data for model validation
    - Choosing candidates
    - Choosing the nested-domains

Initial and boundary conditions for numerical model runs

❑ **Historical period:**

• Climate Forecast System Reanalysis (**CFSR**; Saha et al., 2010) will be used for initial and boundary conditions.
• CFSR is produced by National Centers for Environmental Prediction (**NCEP**) in the United States.
• CFSR is a so-called second generation reanalysis. It utilizes a newer data assimilation system than those in the first generation reanalysis.
• The provided spatial and temporal resolutions of CFSR are **0.5 x 0.5 degree and 6-hourly**.

❑ **Future conditions:**

• Future climate change projection data simulated by the Community Climate System Model version 4 (**CCSM4**) based on Representative Concentration Pathway (**RCP**; Moss et al., 2010) **4.5** will be used for a climate change experiment in Task 4.
• CCSM4 is a coupled climate model developed by National Center for Atmospheric Research (NOAA) to simulate the global climate system (Bitz et al., 2012)
• RCP 4.5 is a future climate change scenario of an intermediate stabilization pathway in which radiative forcing reaches approximately 4.5 W/m2 by 2100 and is stabilized after 2100 (Clarke et al., 2007).

Observation data for model configuration and validation

•The **NCEP Stage-IV** precipitation analyses will be used for the validation of numerical model runs and analysis of precipitation processes.

• Stage-IV is a mosaic of regional multi-sensor analysis generated by National Weather Service River Forecast Centers (RFCs)

• **It combines rain gauge data and radar-estimated rainfall.**

• Available from 01/01/2002 to 08/31/2015

• ~ 4 km resolution

• **Three time resolutions** are available: **1-h, 6-h, and 24-h** time intervals. The 6- and 24-hourly analyses are constantly quality controlled manually by the 12 RFCs. 1-h analyses undergo less consistent quality control.

• Several recent studies used Stage-IV precipitation analyses to investigate extreme precipitation events in the United States (e.g. Davis et al., 2006 Moore et al., 2014)

Numerical simulation of one MCS and one tropical cyclone (TC)

• Next step : Assessment of the capability of the WRF model to simulate local intense precipitation caused by one MCS and one TC.

• We need to find a candidate for each case (one MCS and one TC) which has not already been subject to extensive numerical modelling.

• Numerous MCSs and TCs have been reported in the literature.

Examples of MCSs reported in the literature

Type	Date	Location	Reference
TL/AS	19-20 Jul 1999	NE	Schumacher and Johnson (2005) Schumacher and Johnson (2008)
	31 May-1 Jun 2000	MN, WI, IA	
	15 May 2001	MN, WI	
BB	6 -7 May 2000	MO	
	19-20 Jun 2001	KS	
	25-26 Jul 1999	KS	
BB/quasi-stationary	27-28 May 1998	AR	Schumacher and Johnson (2009)
	5-6 May 2000	OK	
	3-4 Jun 2000	TX	
	18 Jun 2007	TX	
	20 Aug 2007	MO	
Quasi-stationary	28 Jul 1997	CO	Petersen et al. (1999)
Quasi-stationary	27 Jun 1995	VA	Pontrelli et al. (1999)
BB	27-28 Jul 2011	IA, IL	http://www.weather.gov/dvn/072711_dubuqueflashflood

TL/AS: Training Line/Adjoining Stratiform BB: Backbuilding

Tropical cyclones for 2002-12 according to the "State of climate" from 2002 to 2012

Year	Name	Date	Cat.	Remarks
2002	Bertha	08/04 -> 08/09	TS	*Local precipitation amounts of 25-50 mm in southern Mississippi and Alabama*
	Edouard	09/01 -> 09/06	TS	
	Fay	09/05 -> 09/08	TS	*Produced on average more than 175 mm of rain over southeastern Texas*
	Gustav	09/08 -> 09/15	2	
	Hanna	09/12 -> 09/15	TS	*Brought 75-125 mm of precipitation to the Florida panhandle*
	Isodore	09/14 -> 09/27	3	*Brought extremely heavy rains (200-300 mm) to the Yucatan Peninsula. Rainfall exceeded 200 mm from eastern Louisiana to the western Florida panhandle, and also extended northward across Mississippi and Alabama. 300 mm at New Orleans*
	Kyle	09/20 -> 10/14	1	
	Lili	09/21 -> 10/04	4	*100-150 mm of precipitation between 2 and 5 October across central and eastern Louisiana. 80 mm at New Orleans*

- TS: tropical storm (stage before Hurricane, that is to say: 18m/s < surface wind < 32m/s)
- [1,2,3,4,5]: Hurricane intensities according to the Saffir-Simpson scale

2003	Bill	06/28 -> 07/02	TS	*Produced more than 150 mm of rain across eastern Louisiana, Mississippi, and western Alabama during 30 June - 1 July*
	Claudette	07/08 -> 07/17	1	*Crossed eastern Texas on 15-16 July, generally producing totals of 75-100 mm*
	Erika	08/14 -> 08/17	1	*Produced 75-100 mm of rain in northeastern Mexico and a range of 25-75 mm of rain in southern Texas*
	Grace	08/30 -> 09/02	TS	*Brought 75-100 mm of rain to southeastern Texas on 31 August*
	Henri	09/03 -> 09/08	TS	*Brought 100-125 mm of rain to west-central Florida on 6 September*
	Isabel	09/06 -> 09/20	5	*Rainfall totals averaged 100-200 mm across eastern North Carolina and Virginia, and 50-100 mm across West Virginia and eastern Ohio.*
2004	Alex	07/31 -> 08/06	3	
	Bonnie	08/03 -> 08/14	TS	
	Charley	08/09 -> 08/14	4	
	Frances	08/24 -> 09/10	4	*Brought more than 175 mm of rain to Florida, Georgia, and the western Carolinas*
	Gaston	08/27 -> 09/01	1	*Produced extreme precipitation in the eastern part of South Carolina*
	Ivan	09/02 -> 09/24	5	*Produced more than 150 mm of rain from Alabama to Pennsylvania*
	Jeanne	09/13 -> 10/28	3	*Produced more than 100 mm rainfall totals from Florida to the western Carolinas*
	Matthew	10/08 -> 10/10	TS	

2005	Dennis	07/04 -> 07/10	4	
	Emily	07/11 -> 07/21	5	
	Katrina	08/23 -> 08/31	5	
	Ophelia	09/06 -> 09/23	1	
	Rita	09/18 -> 09/26	5	
	Wilma	10/16 -> 10/30	5	
2006	Alberto	06/10 -> 06/14	TS	
	Ernesto	08/24 -> 09/01	1	
2007	Erin	08/15 -> 08/17	TS	*Remnants of Tropical Storm Erin produced heavy rainfall from Texas to Kansas and Missouri*
	Olga	12/11 -> 12/13	TS	
2008	Fay	08/15 -> 08/27	TS	
	Gustav	08/25 -> 09/04	4	
	Hanna	08/28 -> 09/07	1	
	Ike	09/01 -> 09/14	4	

2009	Claudette	08/16 -> 08/18	TS	
	Ida	11/04 -> 11/10	2	
2010	Bonnie	07/22 -> 07/24	TS	
2011	Irene	08/21 -> 08/28	3	*Caused major flooding in the Northeast. Participated to above-average precipitation in the Northeast and Ohio Valley*
	Lee	09/01 -> 09/06	TS	*Participated to above-average precipitation in the Northeast and Ohio Valley*
2012	Debby	06/23 -> 06/27	TS	*Florida had its wettest summer on record, partially attributable to TS Debby*
	Isaac	08/21 -> 09/01	1	*Florida had its wettest summer on record, partially attributable to Hurricane Isaac. Produced heavy rainfall across Puerto Rico and the Dominican Republic.*
	Sandy	10/21 -> 10/29	3	*The most well-publicized and destructive storm of the year. Brought record early-season snowfall to the Appalachians.*
2013	The "State of climate 2013" does not mention any specific tropical cyclone affecting the USA this year. According to the report, the 2013 season ties 1982 for the fewest hurricanes in the recent historical record from 1950 to present.			

Choosing candidates for simulations

- Candidates must be **in the time range of the NCEP Stage-IV** product (i.e., 2002-2015)
- Candidates must have produced **local intense precipitation.**
- Detailed information about precipitation ranges for intense precipitation events is generally difficult to find.
- Yet, such ranges have been documented in Stevenson and Schumacher (2014) for extreme precipitation events in the Central and Eastern United states during 2002-11.
- Stevenson and Schumacher (2014) identified extreme precipitation events using the NCEP stage-IV precipitation analyses and the 50- and 100-yr recurrence interval thresholds constructed by Hershfield (1961) for three durations: 1, 6, and 24 hours.
- Events were classified as either synoptic systems, tropical systems, or MCSs.

Choosing candidates for simulations

Stevenson and Schumacher (2014) identified the top 10 events in terms of the largest extent of the extreme precipitation field, corresponding to points where the 100-yr return period, 24-hr Hershfield (1961)'s threshold was exceeded:

Rank	Points	Date	Location	Type of system	Extreme precipitation range (mm)
1	295	28–29 Aug 2011	Northeast	Tropical (Irene)	128.9–345.3
2	256	1–3 May 2010	OH–MS Valley	Synoptic	127.9–295.8
3	167	8 Sep 2011	Northeast	Synoptic	142.6–277.2
4	151	7–9 Sep 2004	Southeast	→ Tropical (Frances)	127.3–452.9
5	140	16–18 Sep 2004	Southeast	Tropical (Ivan)	127.4–364.4
6	136	5–6 Sep 2011	Southeast	Tropical (Lee)	181.2–289.4
7	135	19 Aug 2007	North	→ MCS–TL/AS	152.4–351.3
8	115	15 Sep 2004	North	MCS–TL/AS	152.8–344.9
9	89	6 May 2007	Plains	Synoptic	127.1–180.0
10	84	1–2 Sep 2006	Southeast	Tropical (Ernesto)	207.8–438.9

Candidates:
- MCS: TL/AS on 08/19/2007
- TC: Hurricane Frances (2004)

Choosing nested-domains for simulations

• The resolution in the inner domain should be fine enough to adequately simulate local intense precipitation (e.g. convective cells).

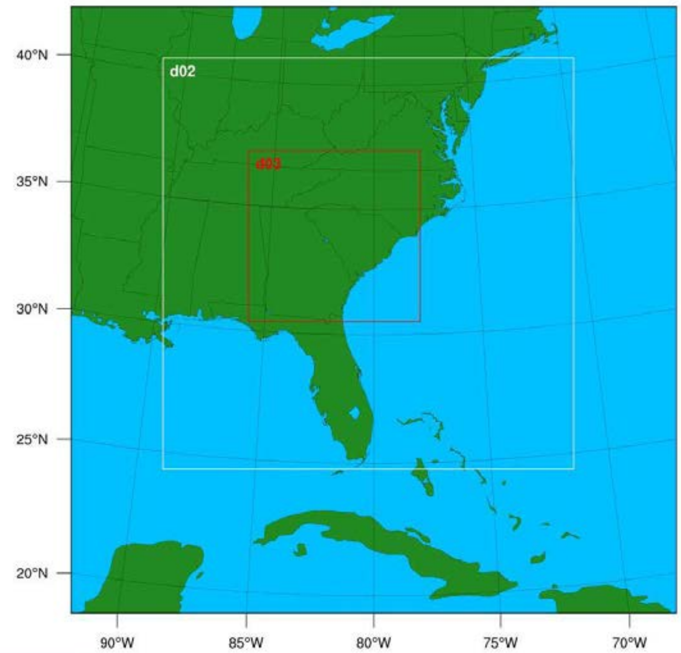
• The resolution should be large enough and the sizes of the domains small enough so that the exercise is computationally feasible.

• The inner domain should be large enough to catch as much land precipitation as possible as the storm is evolving

• Stage-IV precipitation data should be available for all time steps in the inner domain

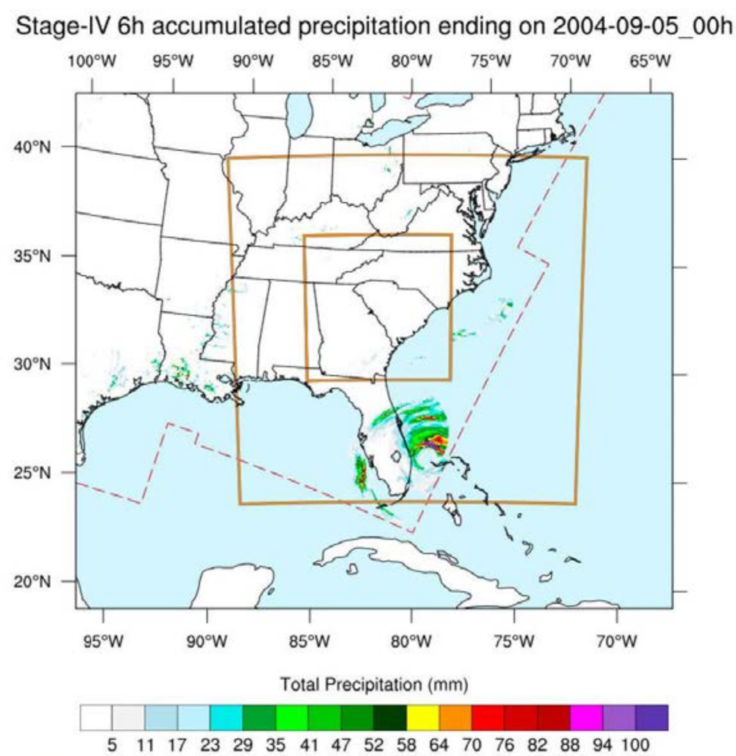
• Nested-domains presented thereafter are preliminary domains: the choice of nested-domains affects the simulation results => the locations and sizes of the domains are to some extent "calibration parameters"

Choice of preliminary nested-domains for the simulation of Hurricane Frances (2004)

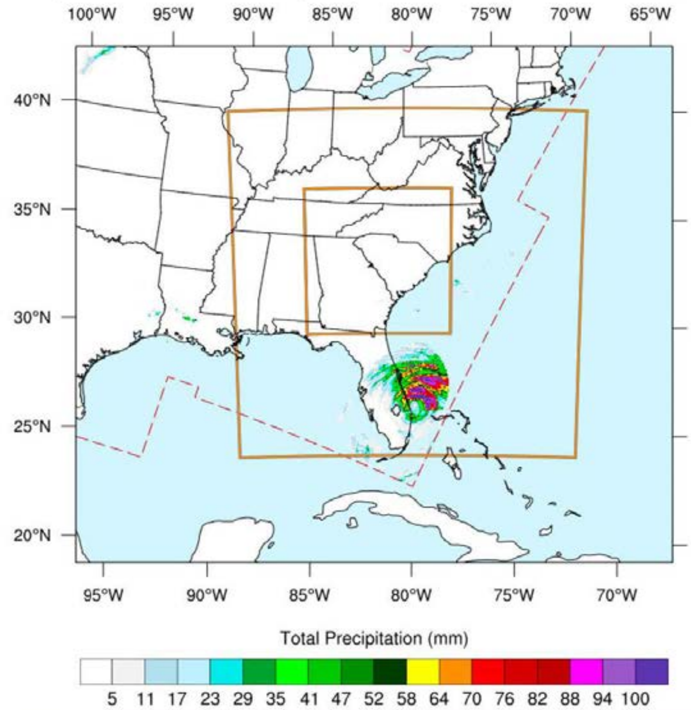


Resolution:
45km – 15 km – 5km

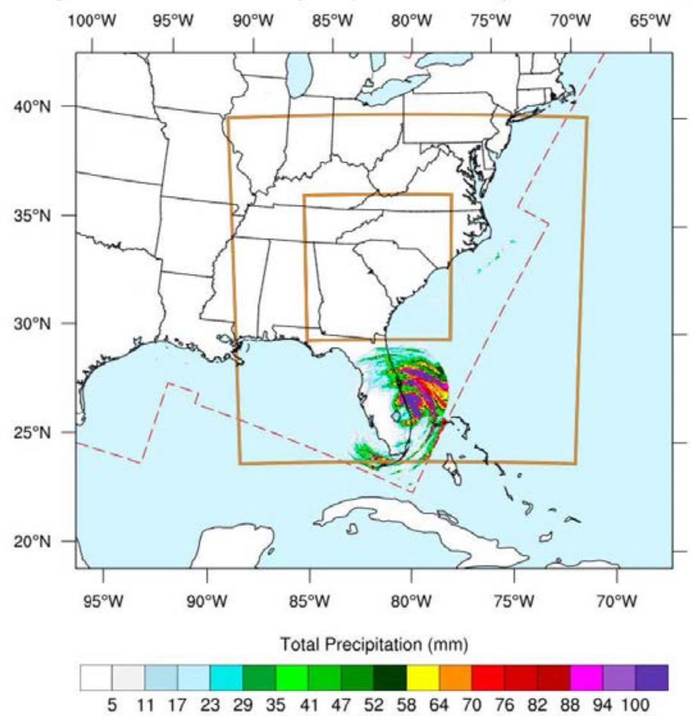
Domain Sizes:
d01: 60x60
d02: 121x121
d03: 151x151



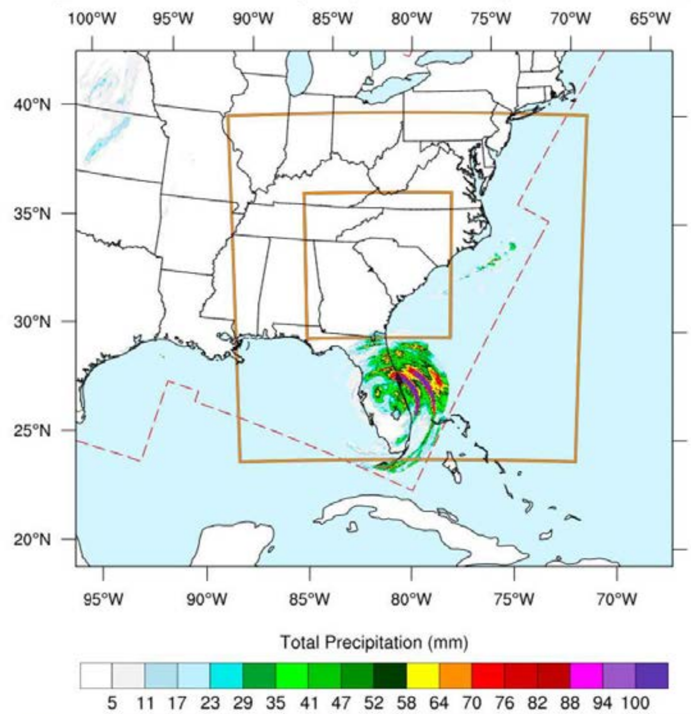
Stage-IV 6h accumulated precipitation ending on 2004-09-05_06h



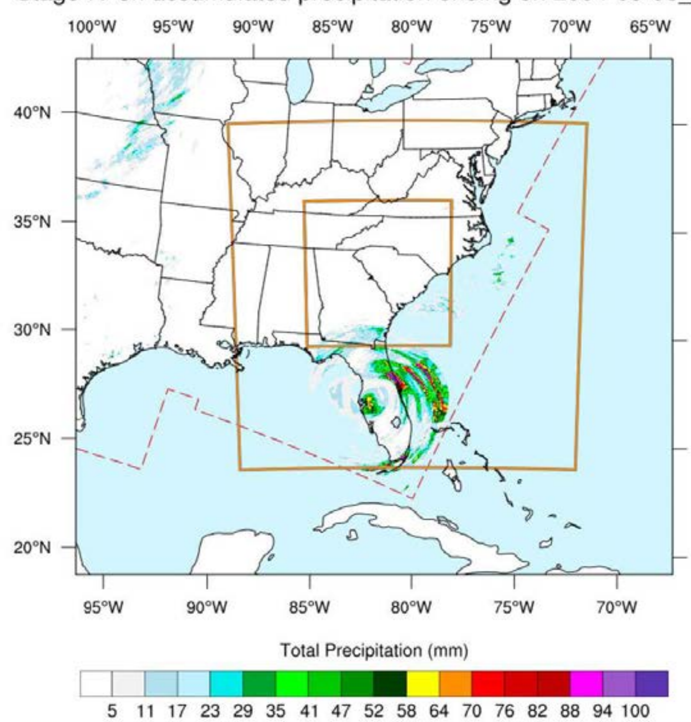
Stage-IV 6h accumulated precipitation ending on 2004-09-05_12h



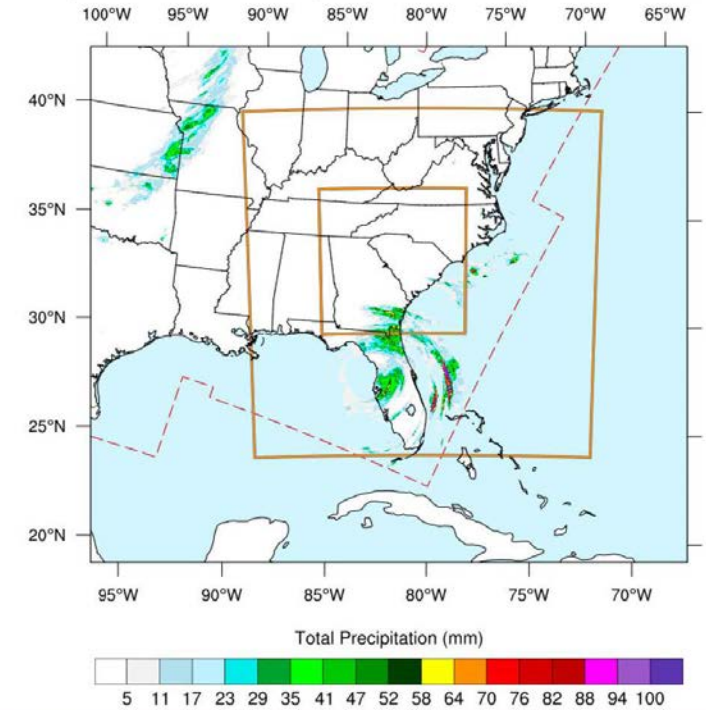
Stage-IV 6h accumulated precipitation ending on 2004-09-05_18h



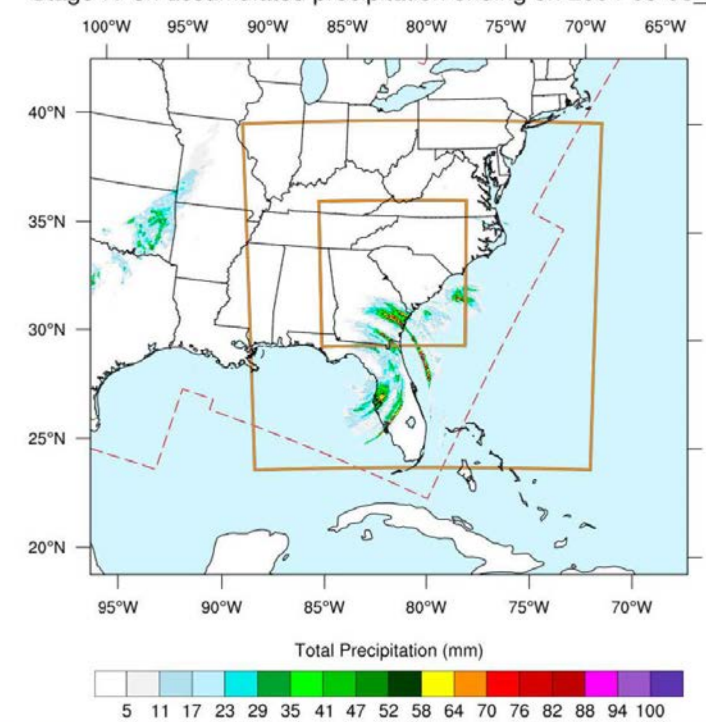
Stage-IV 6h accumulated precipitation ending on 2004-09-06_00h

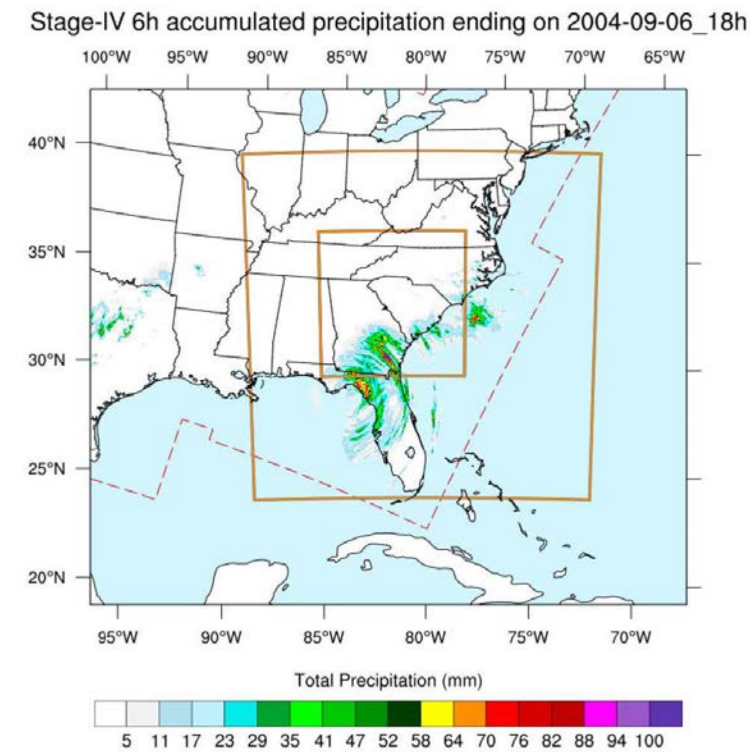


Stage-IV 6h accumulated precipitation ending on 2004-09-06_06h



Stage-IV 6h accumulated precipitation ending on 2004-09-06_12h





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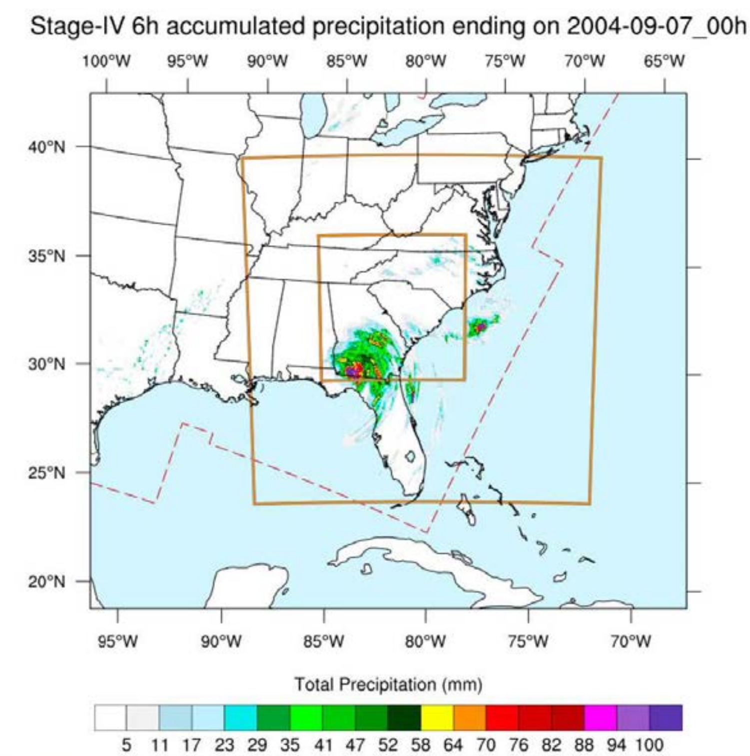

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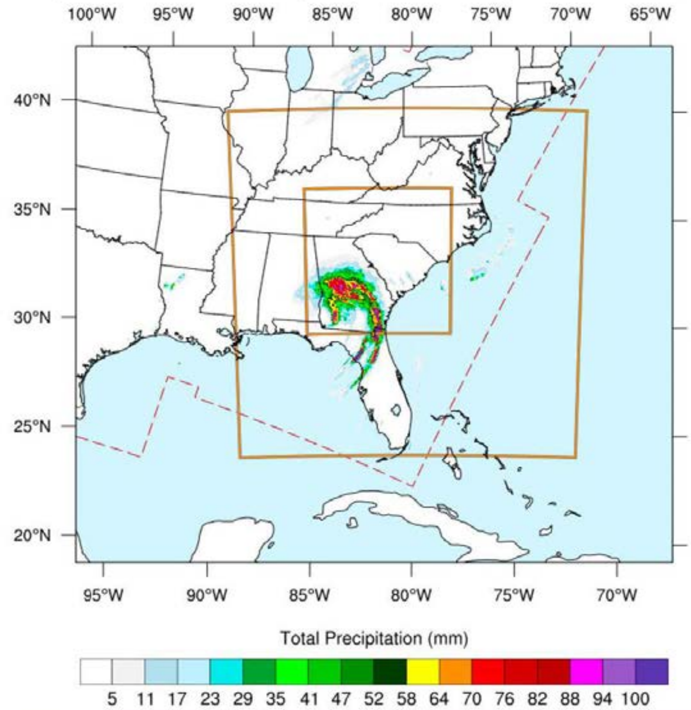
Stage-IV 6h accumulated precipitation ending on 2004-09-07_06h



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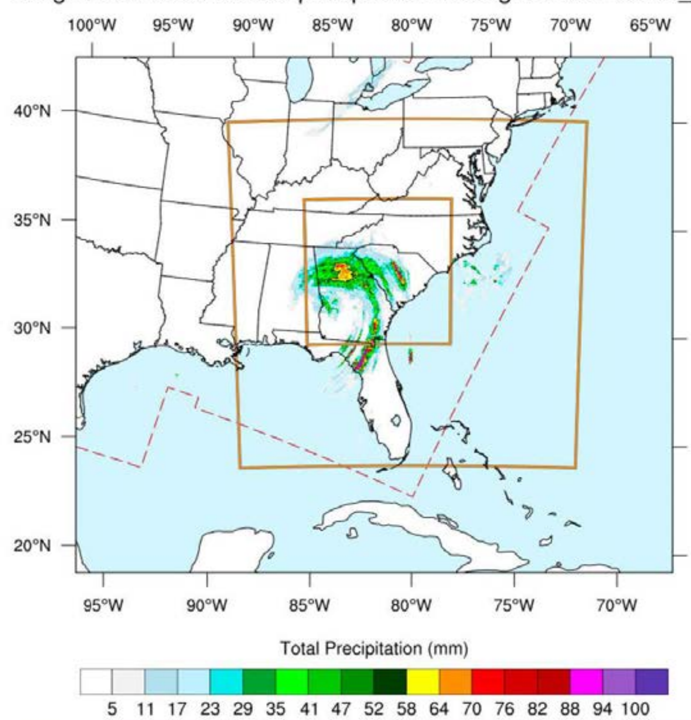
Stage-IV 6h accumulated precipitation ending on 2004-09-07_12h



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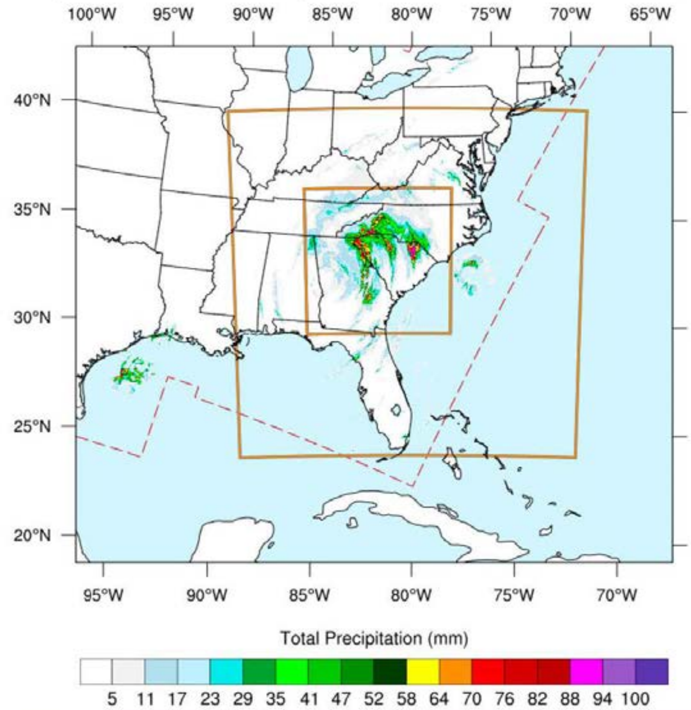
Stage-IV 6h accumulated precipitation ending on 2004-09-08_00h



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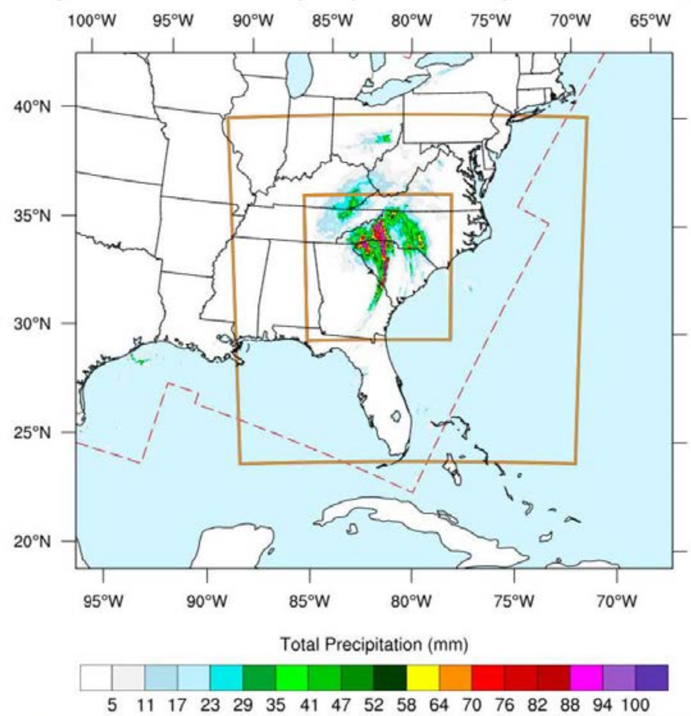
Stage-IV 6h accumulated precipitation ending on 2004-09-08_06h



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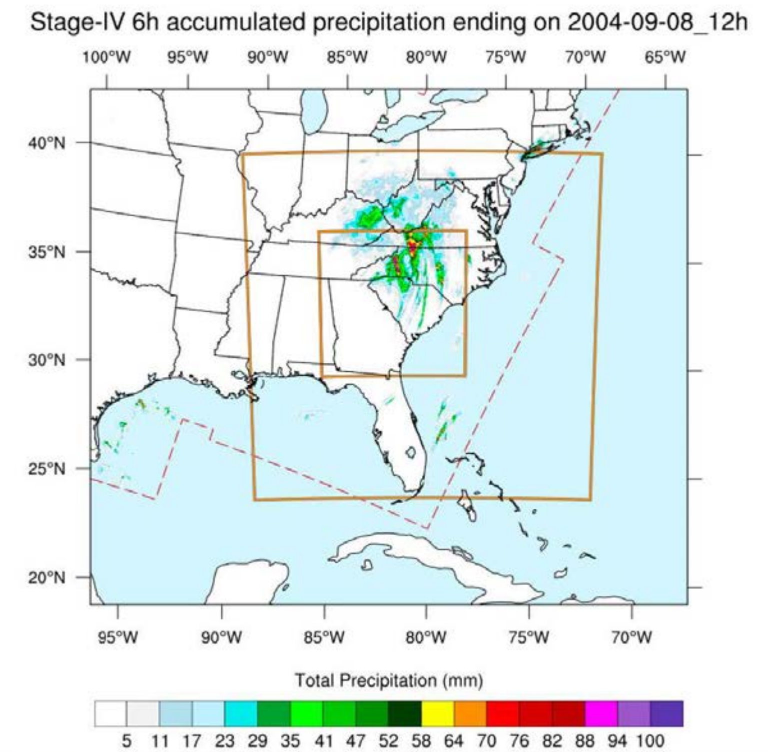

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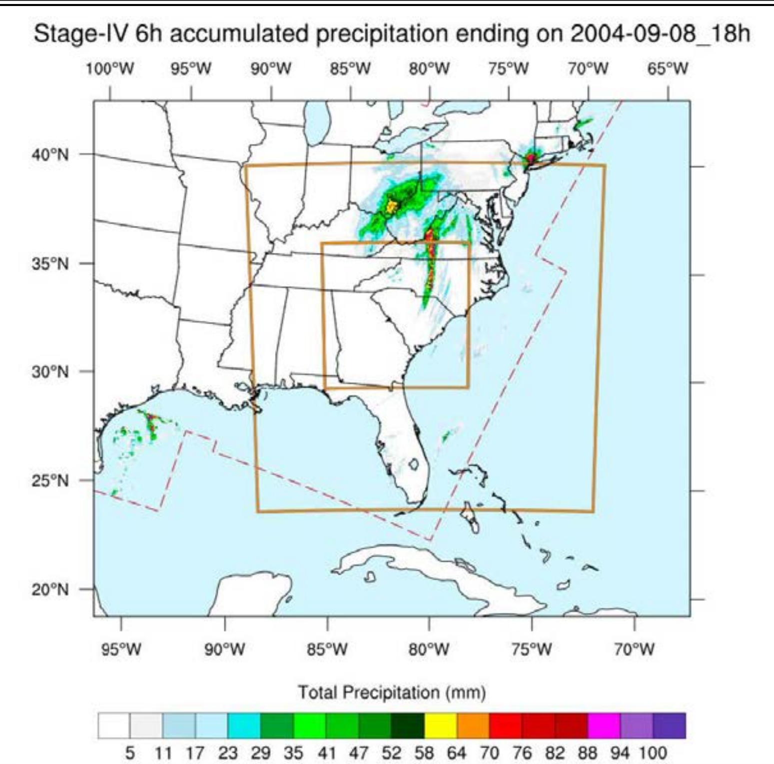

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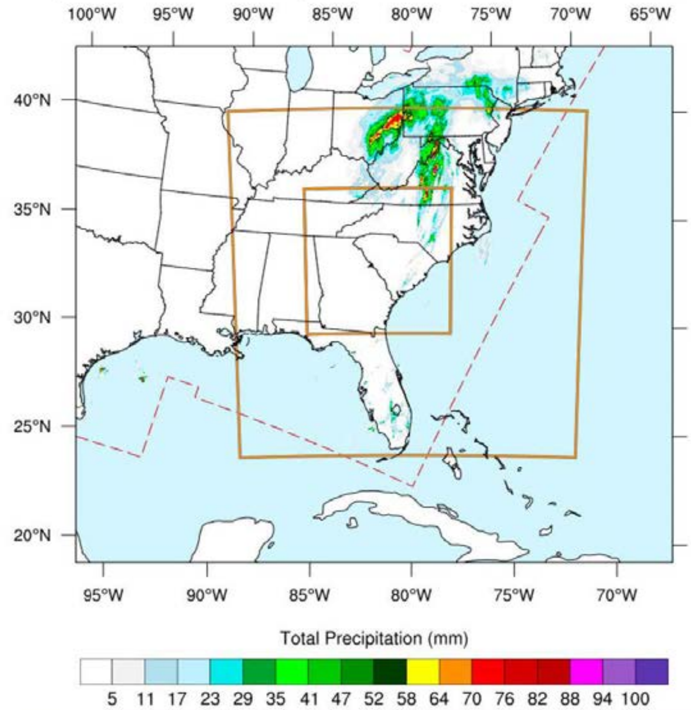
Stage-IV 6h accumulated precipitation ending on 2004-09-09_00h



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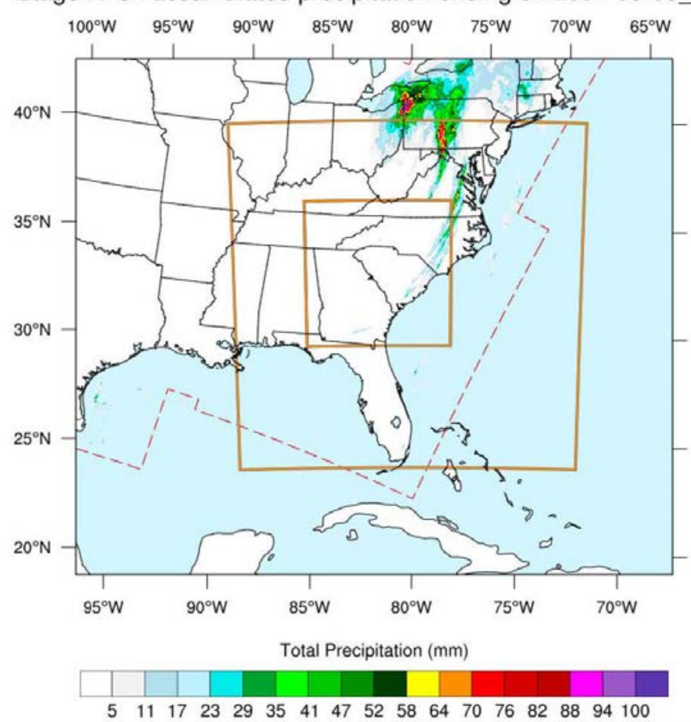
Stage-IV 6h accumulated precipitation ending on 2004-09-09_06h



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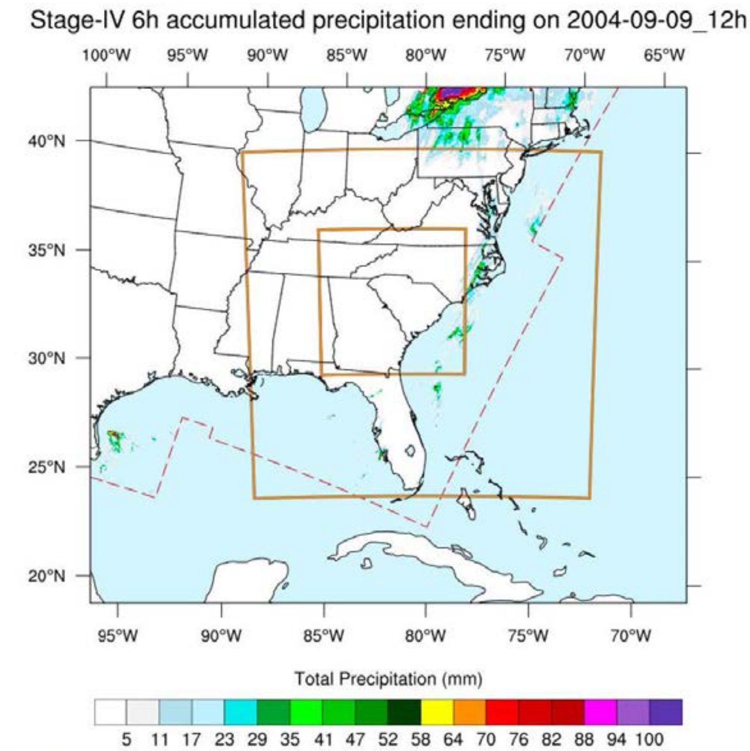
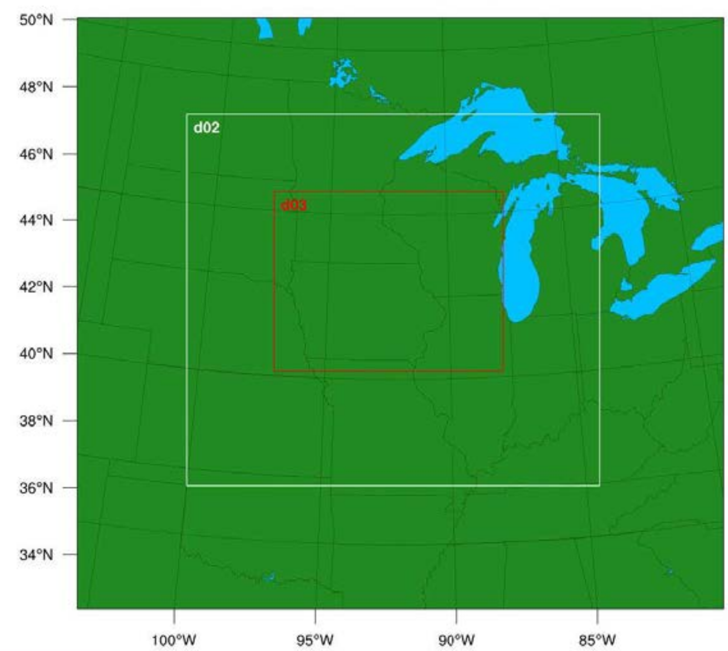


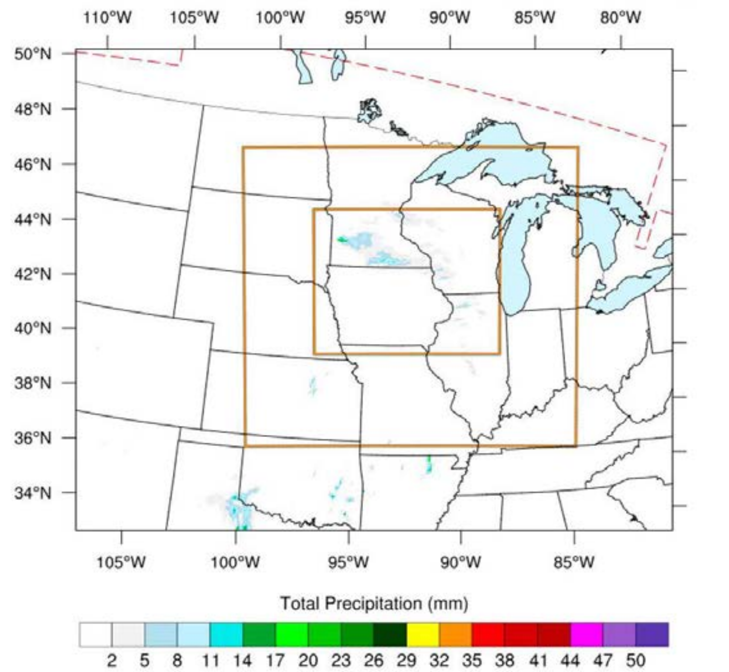
Choice of preliminary nested-domains for the simulation of the TL/AS MCS on 08/19/2007



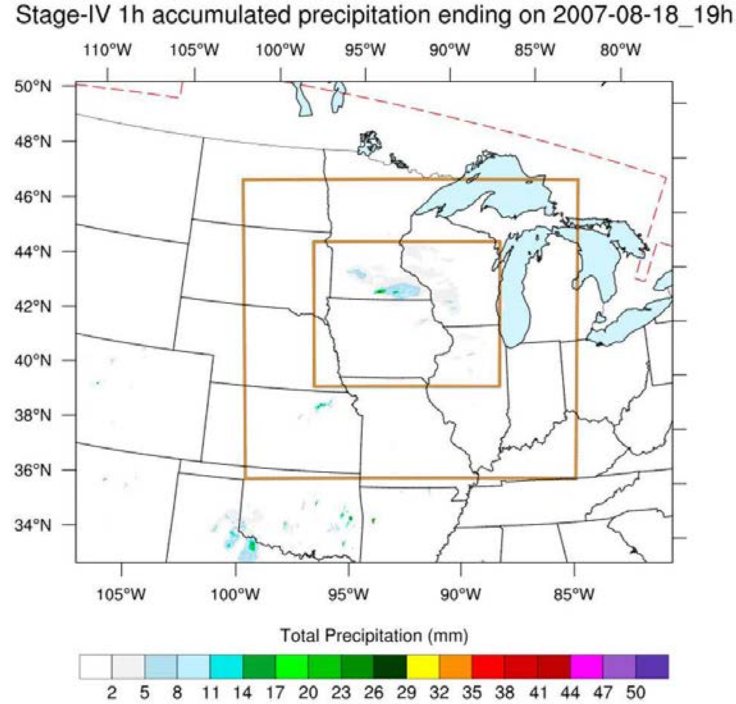
Resolution:
45km – 15 km – 5km

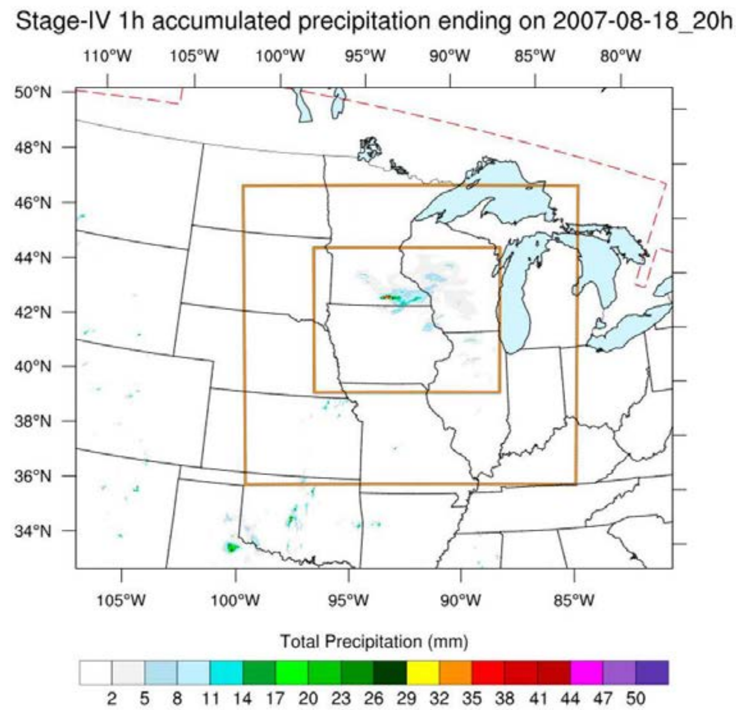
Domain Sizes:
d01: 48x44
d02: 91x82
d03: 151x118

Stage-IV 1h accumulated precipitation ending on 2007-08-18_18h



Stage-IV 1h accumulated precipitation ending on 2007-08-18_19h





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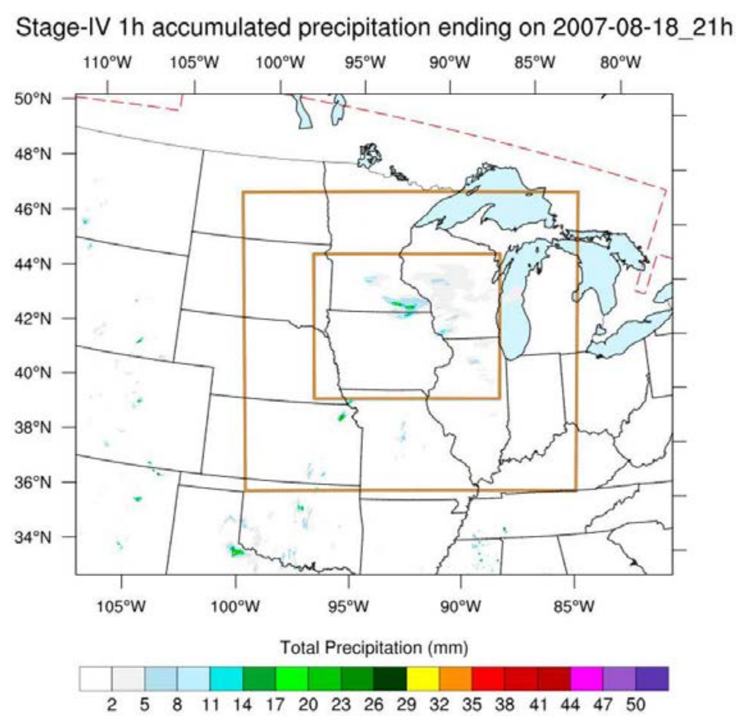

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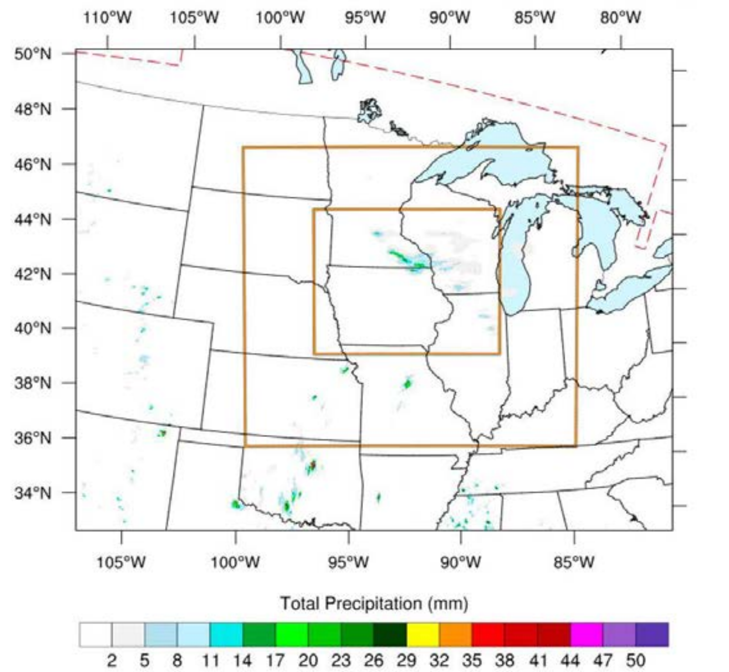
Stage-IV 1h accumulated precipitation ending on 2007-08-18_22h



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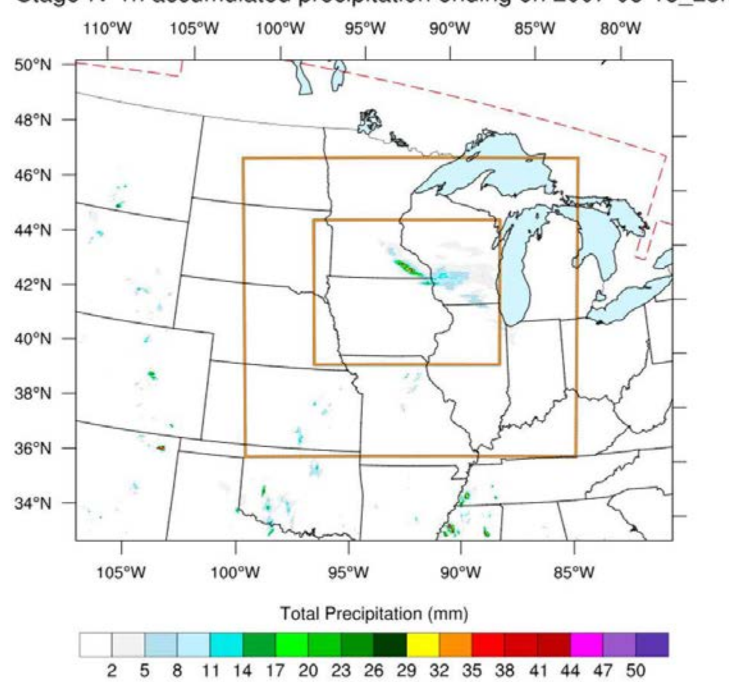
Stage-IV 1h accumulated precipitation ending on 2007-08-18_23h



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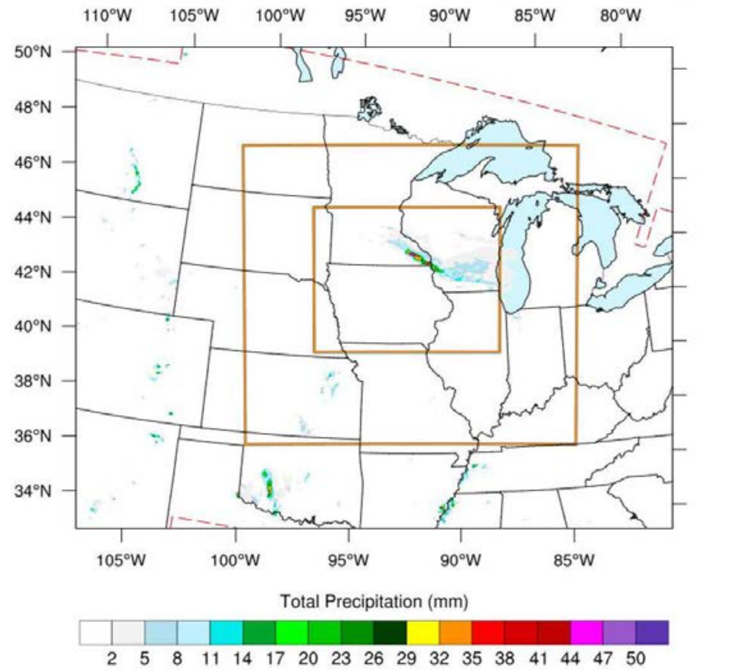
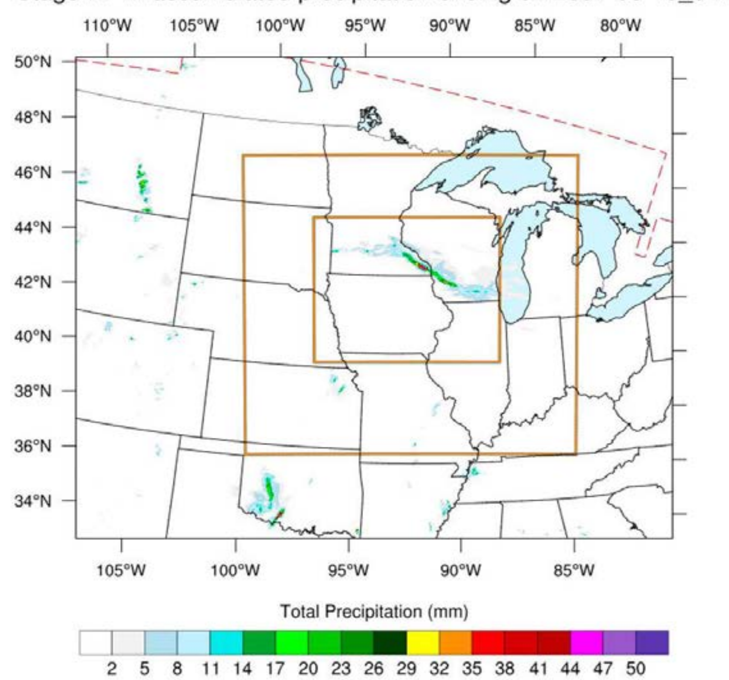
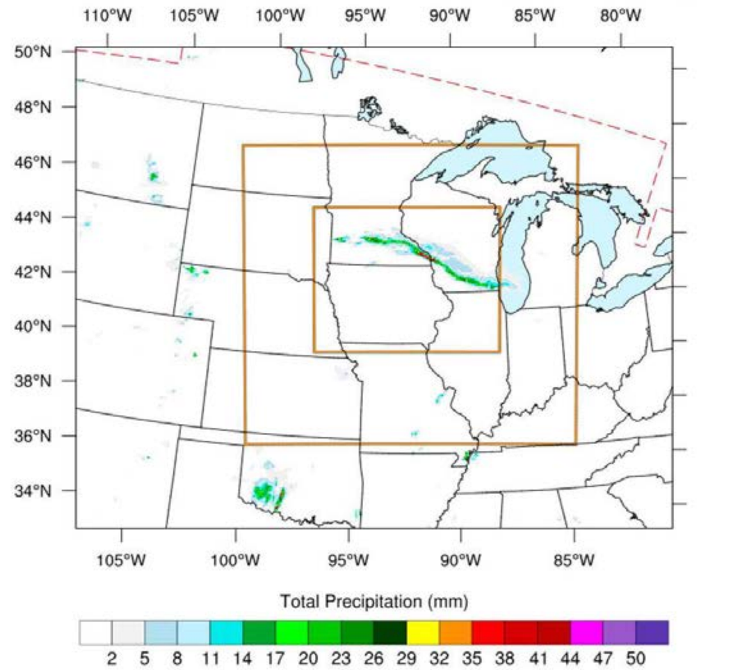
Stage-IV 1h accumulated precipitation ending on 2007-08-19_00h



Stage-IV 1h accumulated precipitation ending on 2007-08-19_01h



Stage-IV 1h accumulated precipitation ending on 2007-08-19_02h



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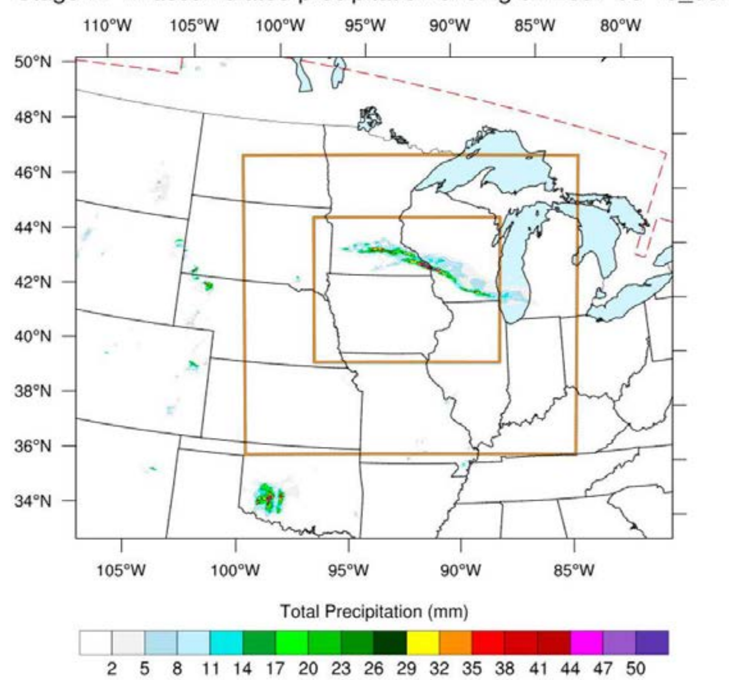
Stage-IV 1h accumulated precipitation ending on 2007-08-19_03h



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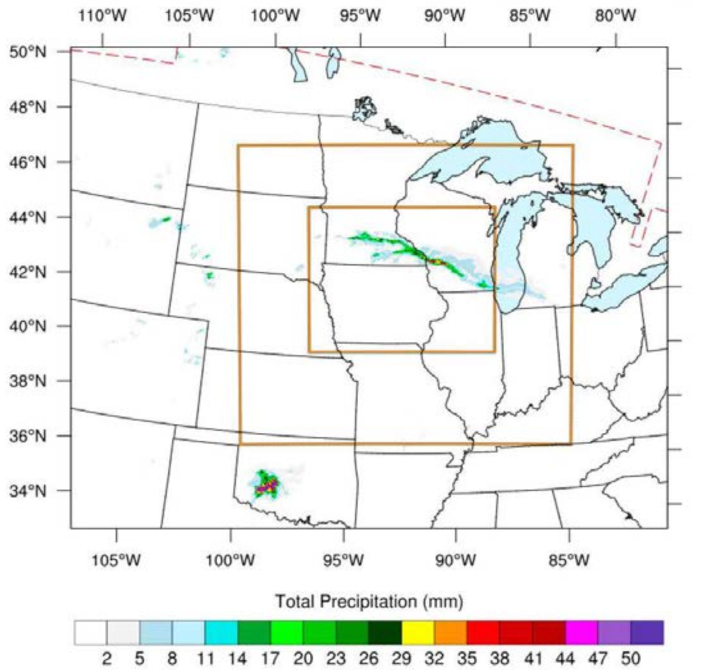
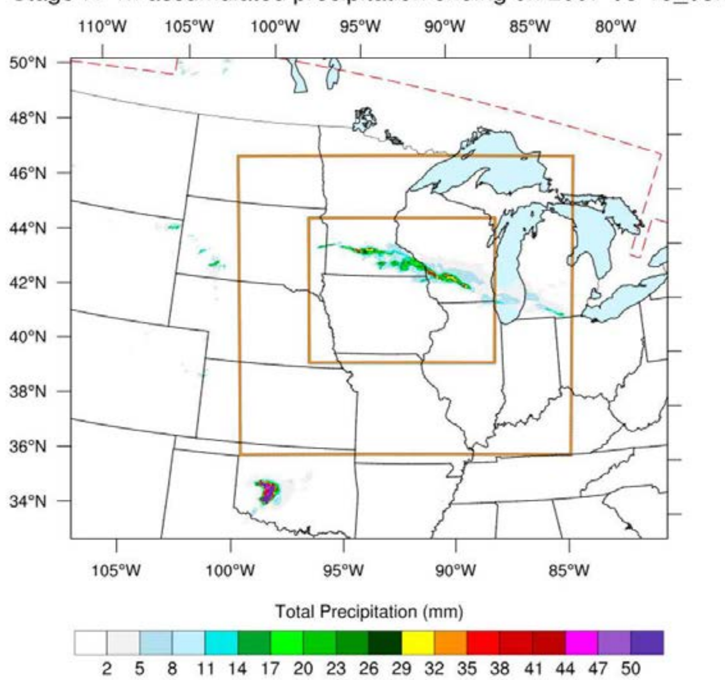
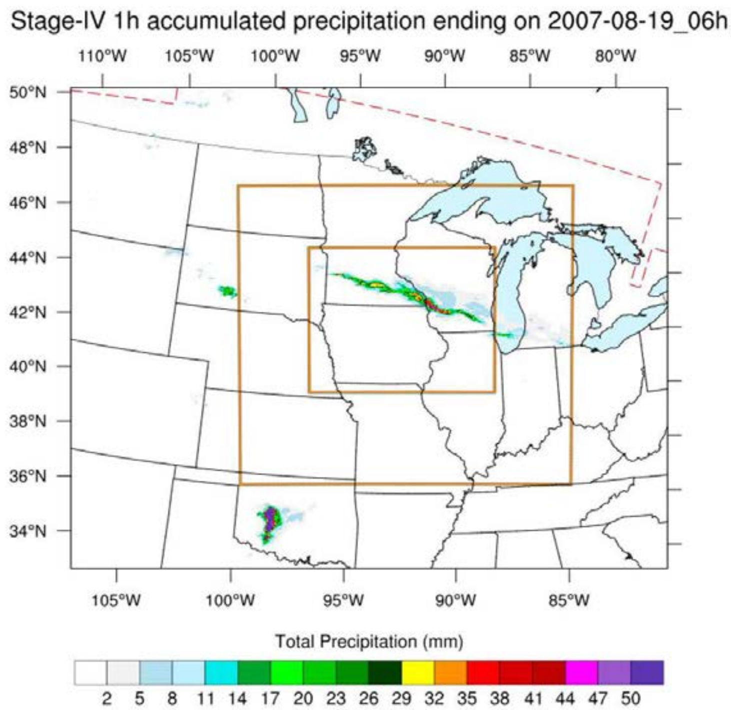
Stage-IV 1h accumulated precipitation ending on 2007-08-19_04h



Stage-IV 1h accumulated precipitation ending on 2007-08-19_05h





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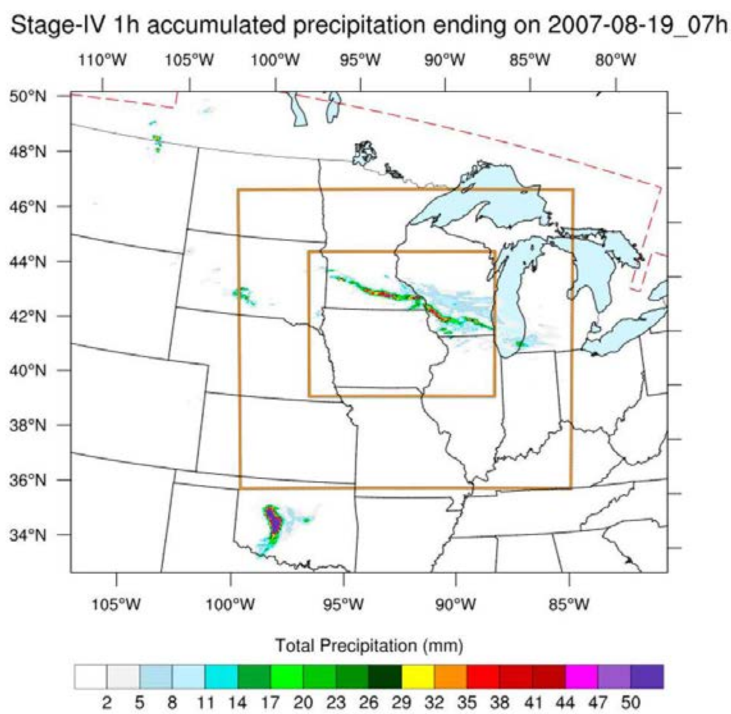
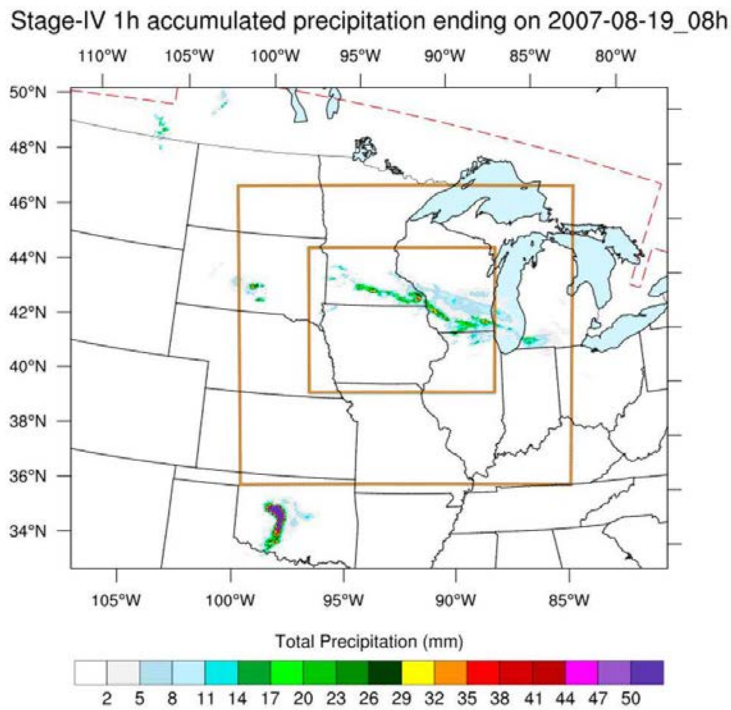
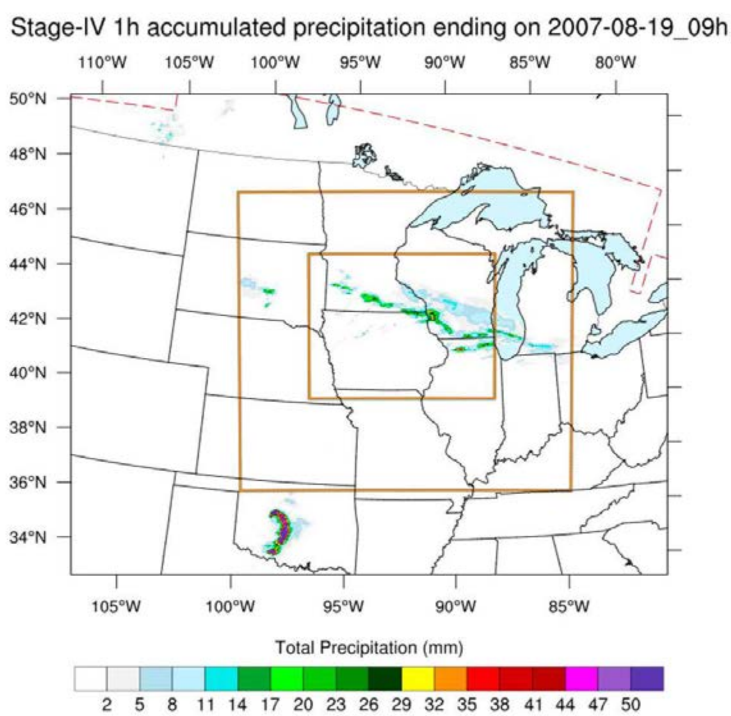
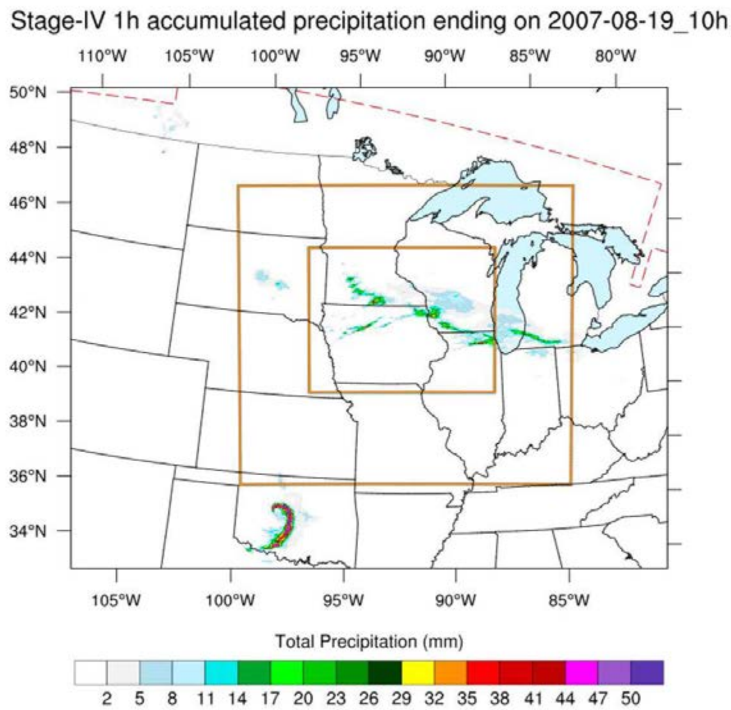


UCD HRL | First Annual NRC PFHA Research Program Workshop | 60/75


Stage-IV 1h accumulated precipitation ending on 2007-08-19_08h
110°W 105°W 100°W 95°W 90°W 85°W 80°W
50°N 48°N 46°N 44°N 42°N 40°N 38°N 36°N 34°N
105°W 100°W 95°W 90°W 85°W
Total Precipitation (mm)
2 5 8 11 14 17 20 23 26 29 32 35 38 41 44 47 50


Stage-IV 1h accumulated precipitation ending on 2007-08-19_09h
110°W 105°W 100°W 95°W 90°W 85°W 80°W
50°N 48°N 46°N 44°N 42°N 40°N 38°N 36°N 34°N
105°W 100°W 95°W 90°W 85°W
Total Precipitation (mm)
2 5 8 11 14 17 20 23 26 29 32 35 38 41 44 47 50



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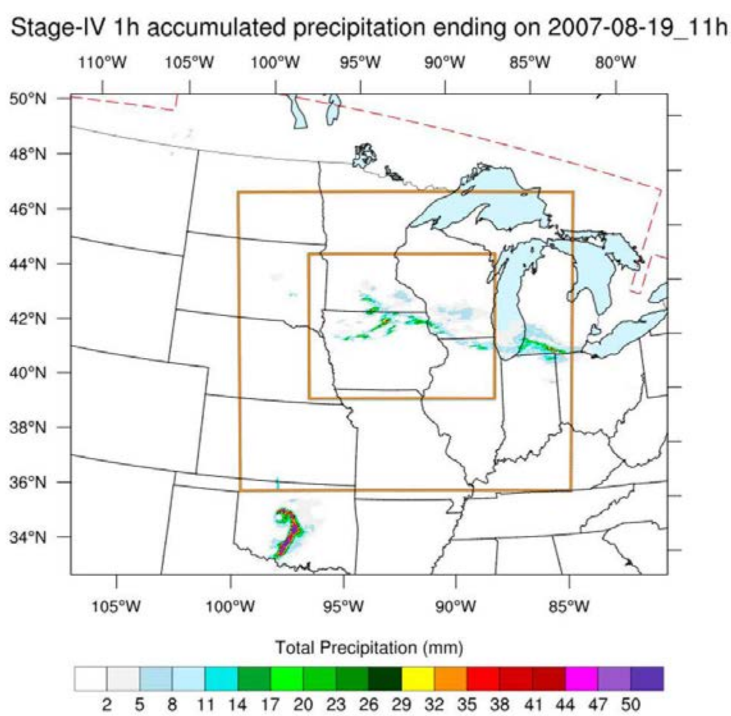

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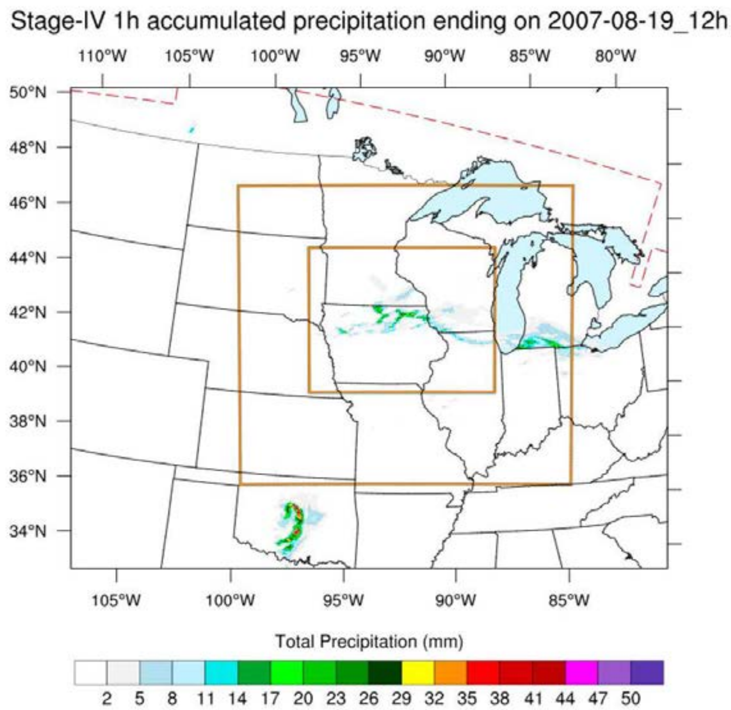

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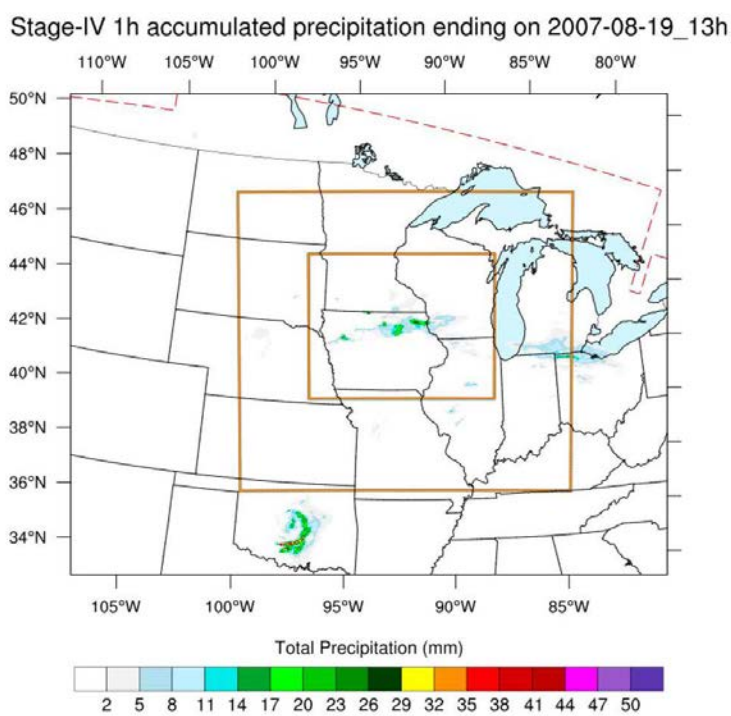

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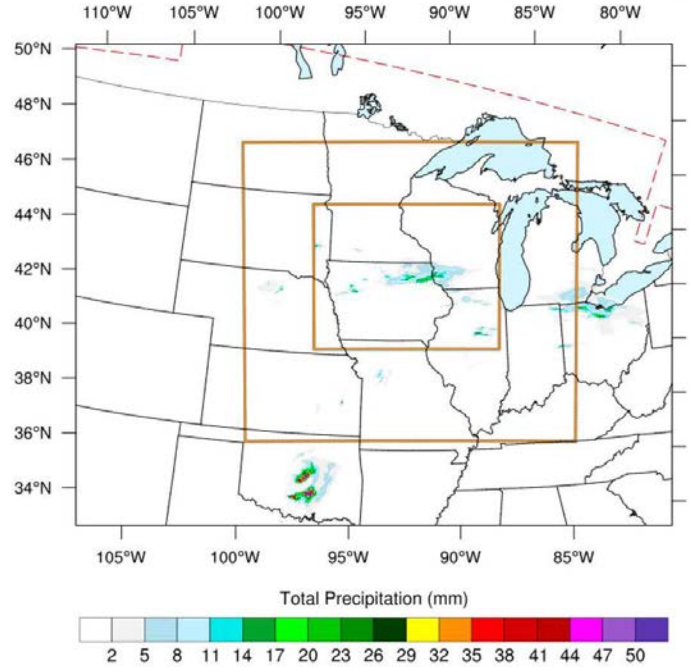
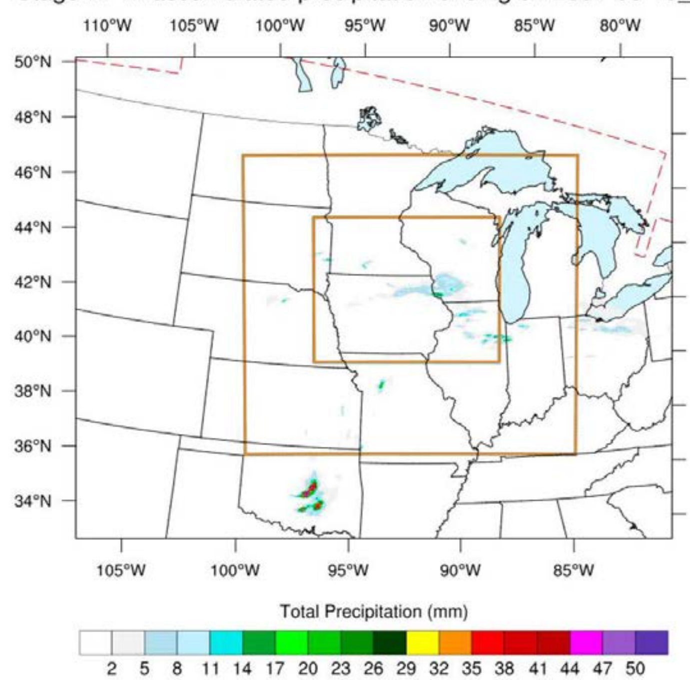
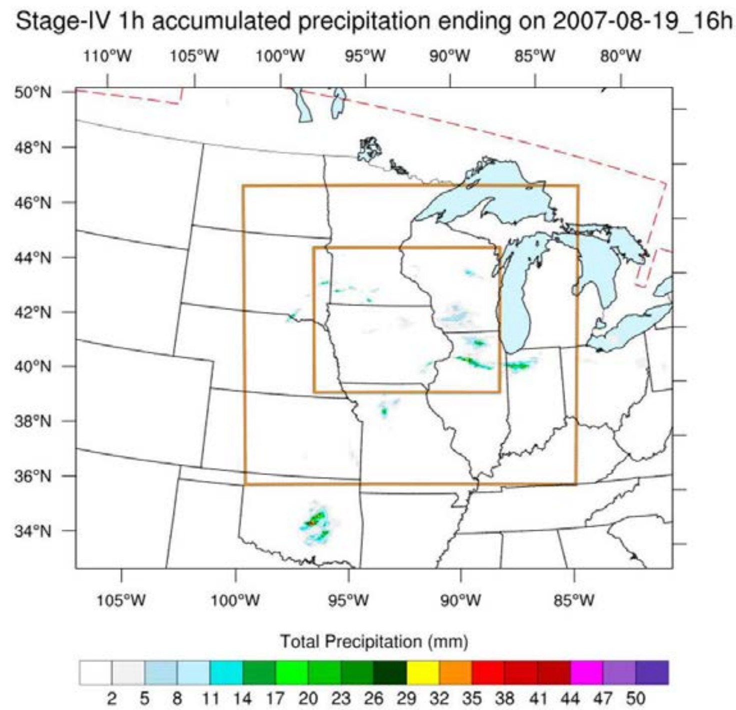
Stage-IV 1h accumulated precipitation ending on 2007-08-19_14h



Stage-IV 1h accumulated precipitation ending on 2007-08-19_15h





What comes next

Performing the simulations of Hurricane Frances (2004) and the TL/AS MCS on 08/19/2007.

Performing a sensitivity study of the results to the "calibration parameters":

- Parameterization schemes (Microphysics, Long/Shortwave radiation, Cumulus param ...)
- Starting date
- Time step
- Vertical resolution
- Horizontal resolution (if necessary)
- Locations and sizes of the domains (if necesssary)
- Reanalysis data used for initial and boundary conditions (if necessary)
- Other WRF options (if necessary)

Parameterization schemes suggested in WRF user's guide for different applications

Application	1-4 km grid distances, convection-permitting runs for 1-3 days run (as for the NCAR spring real-time convection forecast over the US in 2013)	10-20 km grid distances, 1-30 day runs (eg. NCAR daily real-time runs over the US)	Regional climate case at 10-30 km grid size (eg. Used in NCAR 's regional climate runs)	Hurricane application - 36,12, and 4 km nesting used by NCAR's real-time hurricane runs in 2012
Microphysics	New Thompson et al.	New Thompson et al.	WSM6	WSM6
Longwave radiation	RRTMG	RRTMG	RRTMG	RRTMG
Shortwave radiation	RRTMG	RRTMG	RRTMG	RRTMG
Radiation time step	10	15	10	10
Surface layer	Eta similarity: based on Monin-Obukhov	Monin-Obukhov	Monin-Obukhov	Monin-Obukhov
Land surface	Noah Land Surface Model	Noah Land Surface Model	Noah Land Surface Model	Noah Land Surface Model
Planetary boundary layer	Mellor-Yamada-Janjic	Yonsei University	Yonsei University	Yonsei University
Cumulus param.	No parameterization	Grel-Freitas	Tiedtke scheme (only on 36 and 12 km grid)	Tiedtke scheme (only on 36 and 12 km grid)

Parameterizations for numerical simulation of TCs from the literature review

	Trenberth et al. (2007)	Davis et al. (2008)	Fierro et al. (2009)	Xiao et al. (2009)	Khain et al. (2010)	Sippel et al. (2011)
TC date and name	Ivan (2004) and Katrina (2005)	5 landfalling atlantic hurricanes	Hurricane Rita (2005)	Jeanne (2004), Katrina (2005) and Rita (2005)	Katrina (2005)	TC Debby (2006)
Grid resolution	4 km	12 - 4 - 1.33 km	inner from 1 to 5 km (sensitivity study)	12 - 4 -1.33 km	9 - 3 km	27 - 9 - 3 km
Number levels	34	X	43	X	31	27
microphysics	X	WSM3	New Thompson et al.	WSM3	New Thompson et al.	WSM6
PBL	Yonsei University scheme	Yonsei University scheme	Mellor-Yamada-Janjic scheme	Yonsei University scheme	X	Yonsei University scheme
cumulus param.	No parameterization	Kain-Fritsch (only on 12 km)	Kain-Fritsch (outer domain only)	Kain-Fritsch (outer domain only)	X	Kain-Fritsch (on 27 and 9 km)

Parameterizations for numerical simulation of MCSs from the literature review

	Correia Jr et al. (2008)	Schumacher et al. (2008)	Anabor et al. (2009)	Zhang and Pu (2011)	Trier et al. (2011)	Zhao (2012)	Cai and Yu (2012)	Wheatley et al. (2014)
MCS date	X	6-7 May 2000	X	12-13 June 2002	13 June 2002	3 July 2008	17 April 2011	4-5 July 2003
MCS location	X	Missouri	South America	Kansas, Oklahoma, Texas	Oklahoma	China	China	Indiana and Ohio
MCS type	idealized 2D MCS	Quasi stationary BB	Composite 10 serial MCSs	X	TL in the morning	Quasi stationary BB	X	X
Size grid	10 km	9-3-1.33 km	10 km	9-3 km	3 km	15-5 km	13.5-4.5 km	15-3 km
Nb levels	51	48	32	38	42	41	X	51
Microphysics	WSM6	Lin (Purdue)	Lin (Purdue)	Lin (Purdue)	Thompson et al.	Eta (15 km), Lin (5 km)	6 WSM6	Ensemble
Longwave radiation	X	RRTM	RRTM	RRTM	RRTM	RRTMG	sensitivity study	Ensemble
Shortwave radiation	X	Dudhia	Dudhia	Dudhia	Dudhia	RRTMG	sensitivity study	Ensemble
Land surface	X	Noah	5-layer from MM5	Noah	Noah	5-layer from MM5	X	Noah
PBL	Yonsei University	Yonsei University	Yonsei University	Yonsei University	Mellor-Yamada-Janjic	Yonsei University	X	Ensemble
cumulus param.	Kain-Fritsch	Kain-Fritsch (9 km)	Kain-Fritsch	Kain-Fritsch (9 km)	No param.	Grell-Devenyi (15 km)	Grell-Devenyi (13.5 km)	Ensemble

Validation of model results

Model results will be validated in two ways:

- ❑ Simulated and observed precipitation fields will be plotted and the plots will be compared to each other.

In particular, Stage-IV precipitation analyses will be interpolated to the WRF grid in order to plot and calculate the error.

- ❑ Simulated and observed precipitation fields will be compared by means of goodness-of-fit statistics.

Analysis of the uncertainties associated with the model configurations (i.e. uncertainties due to model parameter selection, initial and boundary conditions, etc):

- Tabulate the sum of squared errors between the model simulation and the corresponding observation corresponding to each model configuration (the particular combination of parameterization options) separately for the selected MCS event and the selected TC event;

- Compute the signal strength corresponding to each of the model configurations separately for the selected MCS event and the selected TC event, and present them in tabular form;

- Compute the hit-and-miss statistics for each of the model configurations for the selected MCS and TC events, and present them in tabular form.

Acknowledgement

U.S.NRC
Protecting People and the Environment

Dr. Joseph Kanney

Dr. Elena Yegorova

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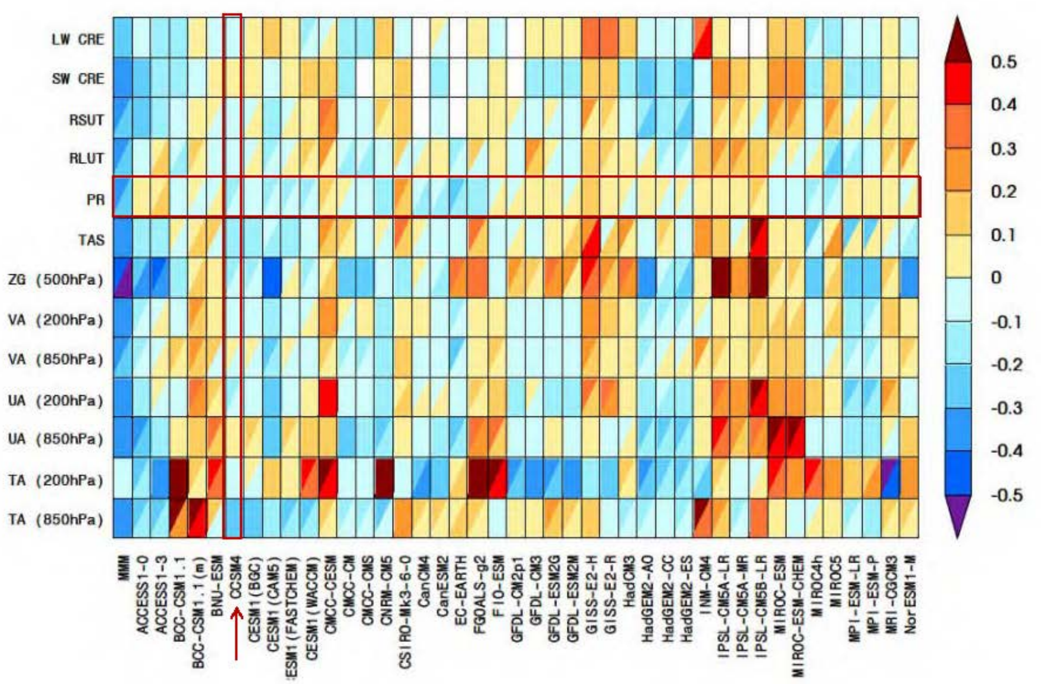
Appendix

Analysis of GCM Representation of Historical Climate Using Global Scale Metrics



Maddox's definition of a MCC

• Size:

A – Cloud shield with continuously low IR temperature ≤ -32°C must have an area ≥ 100,000 km^2

B – Interior cold cloud region with temperature ≤ -52°C must have an area ≥ 50,000 km^2

• Initiation condition: Size definitions A and B are first satisfied

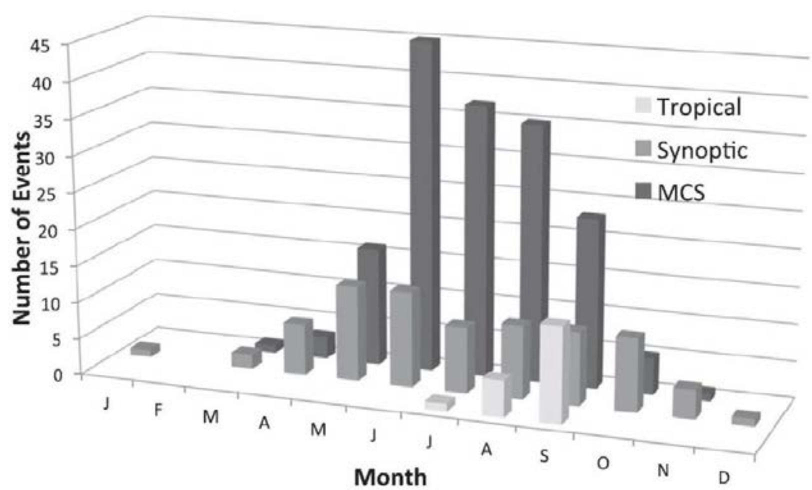
• Duration: Size definitions A and B must be met for a period ≥ 6h

• Maximum extent: Continuous cold cloud shield (IR temperature ≤ -32°C) reaches maximum size

• Shape: Eccentricity (minor axis/major axis) ≥ 0.7 at time of maximum extent

• Termination condition: Size definitions A and B are no longer satisfied

The 100-yr, 24-h monthly distribution of system type for 2002-11 events in Stevenson and Schumacher (2014)



Regional divisions considered in Stevenson and Schumacher (2014)

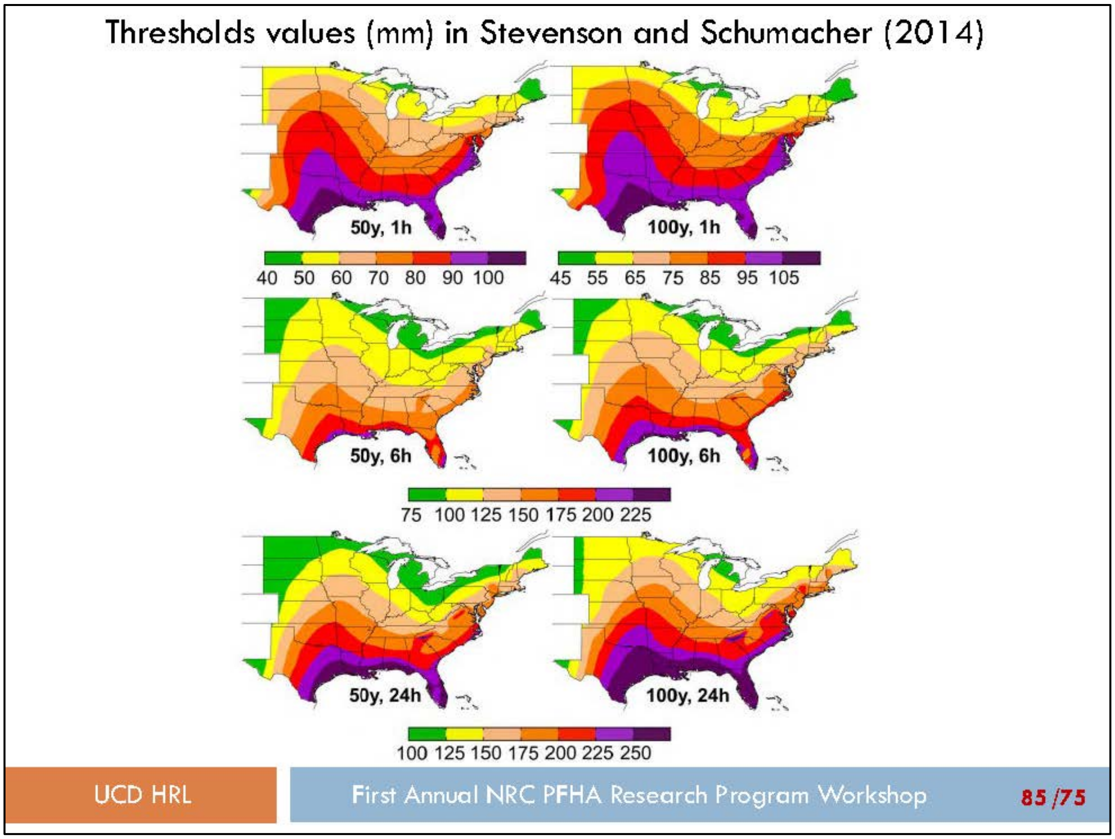
The regions are as follows:

1) Plains 2) North
3) Northeast 4) Ohio-Mississippi Valley
5) South 6) Southeast

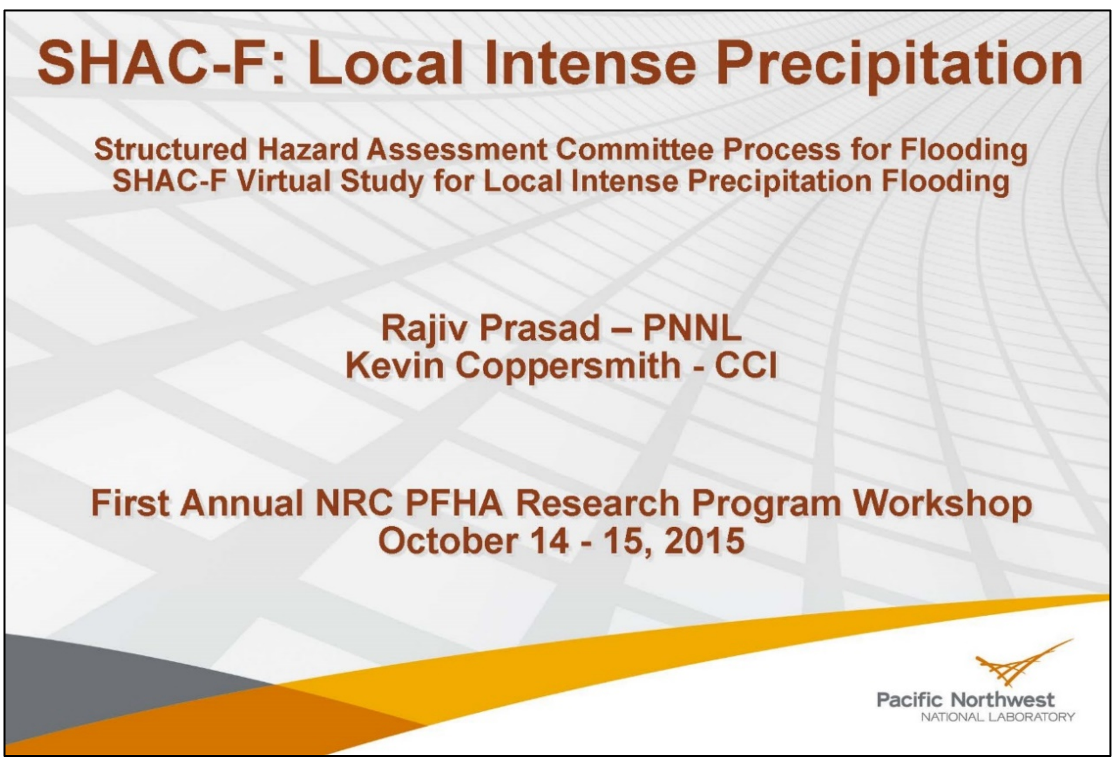
Quality control on Stage-IV in Stevenson and Schumacher (2014)

TABLE 1. The percentage of points discarded for this study for the two different recurrence intervals (50 and 100 yr) and three different time intervals (1, 6, and 24 h).

	1 h	6 h	24 h
50 yr	84.0%	11.3%	6.0%
100 yr	89.0%	17.5%	9.5%



1.3.3.3 SHAC-F (Local Intense precipitation). Rajiv Prasad, Robert Bryce, Philip Meyer and Lance Vail, PNNL; and Kevin Coppersmith, CCI



SHAC-F Project: Purpose and Approach

- Purpose
  - Adapt the well-established Senior Seismic Hazard Assessment Committee (SSHAC) approach to Probabilistic Flood Hazard Assessment (PFHA)
  - Termed the "Structured Hazard Assessment Committee Process for Flooding" (SHAC-F)
  - Develop SHAC-F framework and guidance
- SSHAC process
  - Provides assurance that all data, models, and methods have been evaluated and that full range of knowledge and uncertainties is captured in the hazard analysis: provides needed inputs for PRA
- Approach for development of the SHAC-F framework
  - Based on virtual implementation of the SSHAC process to PFHA for selected flood mechanisms
  - Development of a Template Project Plan for selected flood mechanisms

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SHAC-F Project: Purpose and Approach

- Selected flood mechanisms
  - Local intense precipitation (LIP) flooding
  - Riverine flooding without snowmelt
  - Riverine flooding from combined rainfall and snowmelt
- Project adapts and tailors elements of SSHAC process
  - Implementing typical steps of SSHAC to PFHA in virtual studies
  - Documenting lessons learned
  - Refining Template Project Plan
- Activities and Products
  - SHAC-F Work Plan: defines the activities associated with the virtual studies for the SHAC-F project
  - PFHA Template Project Plan: defines all elements of an actual SHAC-F study for a selected flood mechanism
    - Goal is to produce PFHA Template Project Plans
    - Guidance for SHAC-F PFHA studies

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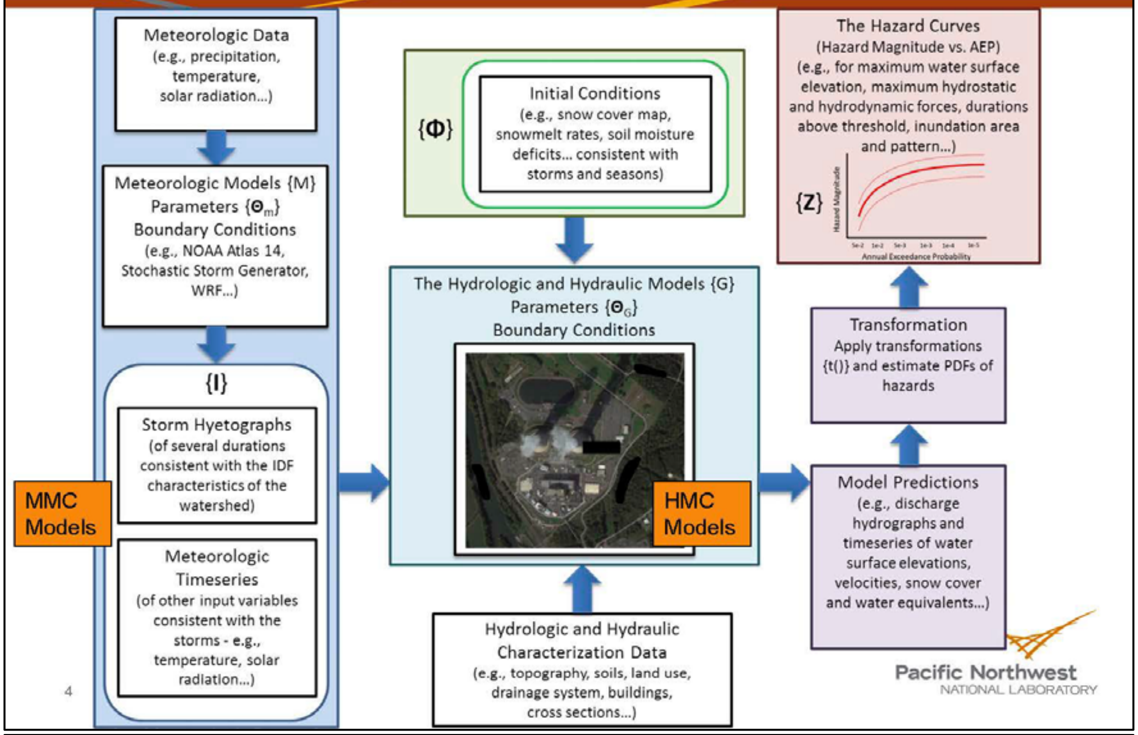
PFHA Framework – LIP PFHA



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SHAC-F Project Structure

- Task 1 - Review of SSHAC Literature and Develop SHAC-F Work Plan
  - Drafts completed June 2015
- Task 2 - SHAC-F virtual study for LIP PFHA
  - Virtual study ongoing
  - Two workshops conducted
  - Compilation of lessons learned completed
  - LIP PFHA Template Project Plan is being developed
- Task 3 -SHAC-F virtual study for Riverine Flooding without and with Snowmelt
  - In 2016

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Task 1a - Review of SSHAC Literature and Develop Work Plan

- Compilation and review of literature
  - SSHAC guidance documents
  - Project reports, mainly Probabilistic Seismic Hazard Assessments for nuclear facilities
  - Professional literature on case histories and lessons learned
- Summary table
  - Literature citations
  - Summary and lessons learned
  - Implications to SHAC-F
- Used as a tool during the development of SHAC-F Work Plan and LIP PFHA Template Project Plan

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Literature review structure and example

Study/Year	Citation	Summary and Lessons Learned	Implications to SHAC-F Study
Lessons Learned from SSHAC Projects [2010 – 2014]	Coppersmith, K.J., J.J. Bommer, A.M. Kammerer, and J. Ake, 2010. Implementation Guidance for SSHAC Level 3 and 4 Processes, Proceedings, *10th International Probabilistic Safety Assessment & Management Conference*, Seattle, WA, June 7-11, 2010. Bommer, J.J., Coppersmith, K.J., Kammerer, A., Ake, J., 2010. The Value of SSHAC Level 3 and 4 Processes for Community-Based Seismic Hazard Assessments, Proceedings, SH3: Global, regional and local initiatives on seismic hazard assessment: Toward Setting New Standards, *European Seismological Commission, 32nd General Assembly*, Montpellier, France, September 6-10, 2010 Coppersmith, K.J., and Bommer, J.J., 2012. Use of the SSHAC Methodology within Regulated Environments: Cost-Effective Application for Seismic Characterization at Multiple Sites, *Nuclear Engineering and Design*, v. 245, p. 233– 240. Bommer, J.J., and Coppersmith, K.J., 2013. Lessons Learned from Application of the NUREG-2117 Guidelines for SSHAC Level 3 Probabilistic Seismic Hazard Studies for Nuclear Sites, *Structural Mechanics in Reactor Technology* (SMiRT-22) Conference Proceedings, San Francisco, CA, August 18-23, 2013	A number of papers and presentations have been given related to the lessons learned from actual application of the SSHAC process in projects. Most of the conclusions are procedural in nature, rather than related specifically to seismic issues, and are intended to assist those who are planning, conducting, or reviewing comparable studies. For example, the pros and cons of SSHAC Level 3 and 4 studies have been identified; the cost-effectiveness of conducting a regional SSHAC Level 3 study followed by site-specific studies conducted at a Level 2 is discussed; the advantages of promoting expert interactions within a SSHAC process is discussed relative to other expert elicitation procedures that frown on interaction; the need for clear roles and responsibilities of project participants to ensure proper team dynamics is discussed in the context of real experience, and the manner in which SSHAC studies can be tailored for the specific technical issue being addressed is also considered.	A careful consideration of the identified SSHAC processes that work and those that don't can lead to efficiencies in any studies going forward. Further, the adaptation and tailoring of the SSHAC process to deal with PFHA issues can be done in light of similar attempts to do so for other technical issues and actual projects. It is anticipated that the SHAC-F project will lead to those additional insights that allow the SSHAC process to be tailored to LIP and riverine PFHA.

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Task 1b - Develop SHAC-F Work Plan

- Methodology Development Team (MDT)
  - Rajiv Prasad (with expertise in flooding analysis)
  - Kevin Coppersmith (with expertise in probabilistic analysis of natural hazards using SSHAC processes)
  - Robert Bryce (with experience managing a recent large scale SSHAC analysis for a nuclear facility)
- SHAC-F Work plan
  - Steps based largely on required steps for SSHAC process, guidance, and experience
  - Roles, responsibilities, project structure, workshops
  - Virtual studies designed to arrive at procedural guidance, not hazard results
- Articulate project goals
  - Documentation of the SHAC-F project process and results
  - Lessons learned from virtual studies
  - Develop PFHA Template Project Plans

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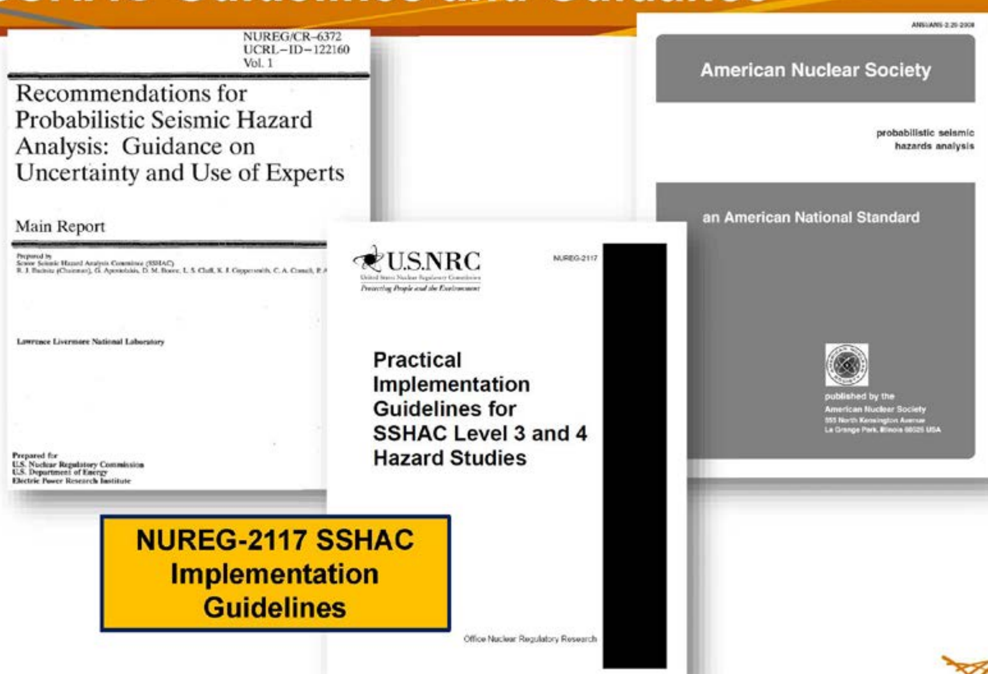
SSHAC Guidelines and Guidance



NUREG-2117 SSHAC Implementation Guidelines

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Goal of a SSHAC Process

- The fundamental goal of a SSHAC process is to properly carry out and completely document the activities of evaluation and integration, defined as:
  - Evaluation: The consideration of the complete set of data, models, and methods proposed by the larger technical community that are relevant to the hazard analysis.
  - Integration: Representing the center, body, and range of technically defensible interpretations in light of the evaluation process (i.e., informed by the assessment of existing data, models, and methods)."

NUREG-2117 and planned updates

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Roles in a SSHAC Level 3 Process

TI Team

EVALUATOR EXPERT	Impartial and objective evaluator of potentially applicable data, models, and methods
INTEGRATOR	Builds models that capture the full range of technically defensible interpretations
RESOURCE EXPERT	Has particular knowledge of a relevant data set, method or models
PROPONENT EXPERT	Advocates a particular hypothesis or technical position; will often promote a model that they have developed
SPECIALTY CONTRACTOR	Retrieves new data or undertakes new analyses to inform evaluators
PARTICIPATORY REVIEWER	Provides procedural and technical review; ensures capture of full range of views and robust technical justifications of integrated models

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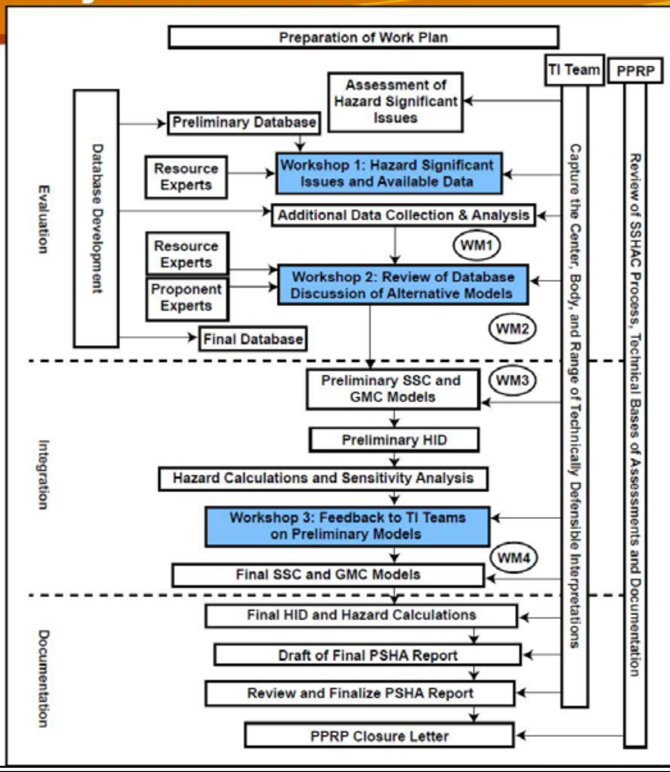
SSHAC Project Structure



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Goals of an Actual SHAC-F PFHA and of the Virtual SHAC-F Project

- Actual SHAC-F PFHA Study
  - Exercise the full SSHAC process,
    - PTI, TI Leads and Teams, PPRP, Proponent and Resource Experts, Observers
    - Three multi-day workshops focused on established themes
    - Compilation and evaluation of actual data, models, and methods
    - Integration (model-building) by TI Teams to capture aleatory and epistemic uncertainties: feedback from PPRP
    - Full quantification and documentation of hazard
- Virtual SHAC-F Project
  - Review the steps in SSHAC project to understand the roles and activities
    - Performed as a Level 3 project
    - Limited number of participants, must assume multiple roles
    - Step through the process with goal of identifying the process that is most suited to PFHA: not building an actual PFHA model
    - Arrive at a Template Project Plan for conducting an actual SHAC-F project
      - Defines roles and responsibilities, activities, schedule, deliverables
      - Project structure appropriate for PFHA for selected mechanisms

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Task 2: SHAC-F for LIP PFHA

- The virtual study was conducted as a Level 3 study: a super set of Levels 1 and 2
- MDT identified a real site to use as the basis for the virtual study
  - Allowed us to:
    - Identify what real data were available
    - Assess applicability of models to real terrain, building configuration
    - Test the process included in the draft Template Project Plan against realities of site and study needs
- Conducted Workshop 1: Significant Issues and Available Data
  - Held as a 1 day workshop with one-half day continuation prior to Workshop 2
  - Developed a workshop report to document the work performed and the lessons learned
  - Revised the draft Template Project Plan to reflect lessons learned

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Workshop Report for LIP PFHA Workshop 1

- Report documents Workshop 1 presentations and outcomes
  - Introduction
    - Goals of the Workshop
    - Approach
  - Workshop Agenda
  - Presentations
    - Introductory Presentations
    - Meteorological Model Characterization (MMC) Significant Issues and Available Data
    - Hydrologic/Hydraulic Model (MMC) Significant Issues and Available Data
  - Technical Integration Team Summaries and Actions
  - Participatory Peer Review Panel Comments
  - Technical Integration Team Leads Responses to PPRP Comments

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Example of Data Identified: Meteorological

- Modeled Distributed Data
  - North American Land Data Assimilation System (NLDAS)
  - Collection period 1979-current, hourly; 1/8th degree
  - Biases – location specific
  - Forcings
    - U wind component (m/s) at 10 meters above the surface
    - V wind component (m/s) at 10 meters above the surface
    - Air temperature (K) at 2 meters above the surface
    - Specific humidity (kg/kg) at 2 meters above the surface
    - Surface pressure (Pa)
    - Surface downward longwave radiation (W/m^2)
    - Surface downward shortwave radiation (W/m^2)
    - Precipitation hourly total (kg/m^2)
    - Fraction of total precipitation that is convective (no units)
    - CAPE: Convective Available Potential Energy (J/kg)
    - Potential evaporation (kg/m^2)

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Example of Data Identified: Imagery

- National Agricultural Imagery Program (NAIP)
  - Collected during leaf-on periods
  - Generally collecting True Color (RGB); some counties also collecting a near-infrared band
  - Horizontal accuracy is within 6-m of photo-identifiable ground control points
  - Current imagery for site flown on June 21, 2013
    - Currently at 30 cm pixel resolution
  - Historic NAIP imagery (typically at 1m resolution)
    - 2003 – 5 year cycle; 2009 – 3 year cycle
  - Satellite Remote Sensing Sources
  - Worldview-3 (0.31m panchromatic; 1.24m 8-band multi-spectral; tasked)
  - Radarsat-2 (synthetic aperture radar - excellent at picking up on flood extents; up to ~1-m; tasked)
  - Many more…

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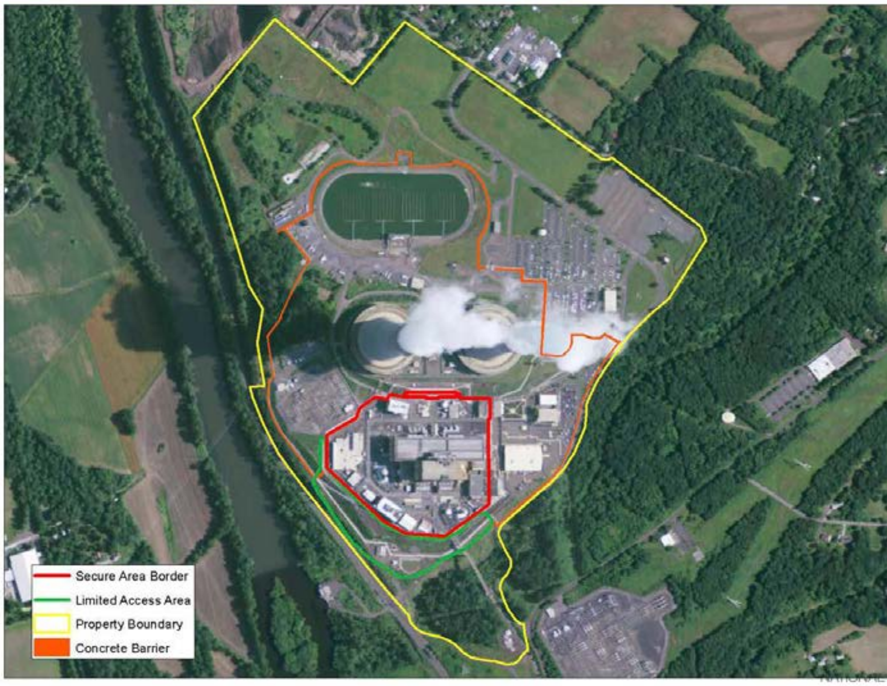
Example of Data Identified: Site Scale Imagery



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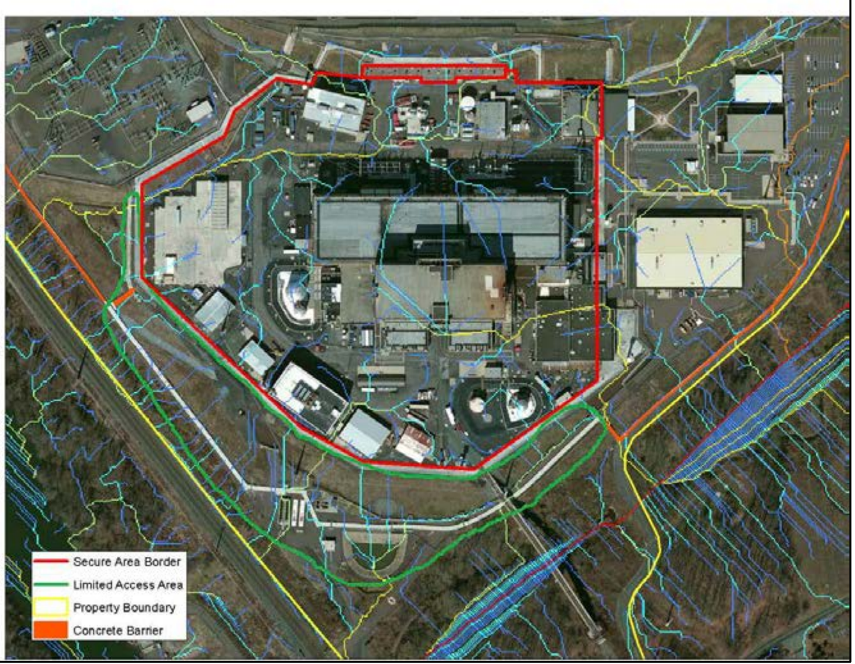
Example of Data Identified: Hydrology

- Derived Channels
- Does not include effect of buildings on surface flow



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Workshop 1 Lessons Learned (examples)

- A project kickoff meeting and site tour is necessary
  - A project kickoff meeting is held to
    - Provide an overview of the project purpose, schedule, and milestones
    - Discuss the LIP analysis framework with the project team
    - Review the SHAC-F Level 3 process that will be used to conduct the study, including the roles and responsibilities of all participants
    - Promote communication amongst members of the MMC and HMC Technical Integration Teams
    - Provide an opportunity for project teams to meet to solidify plans for future workshops and working meetings
    - Provide an overview of the project Quality Assurance program
    - Present the elements of the project communication tools
    - Discuss the path forward to Workshop 1
  - A site tour should be held to:
    - Familiarize the project team with site layout and hazards important to LIP
    - Site staff prepared and engaged to describe topography, facility entry points of interest, features relevant to LIP analysis
    - Review experience of site staff in past storm events

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Workshop 1 Lessons Learned (examples)

- Identification of available data applicable for LIP PFHA is facilitated by first considering various MMC and HMC models that might be exercised and the data required to drive the models
  - For seismic hazard, significant issues are first identified because the basic SSC and GMC models are relatively well-defined
  - Resource experts can then provide specific attributes of various data to meet the input requirements for various models
  - For LIP PFHA, subdivision of data between MMC and HMC (primarily hydraulic model) makes sense

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SHAC-F for LIP PFHA – Workshop 2

- Conducted Workshop 2: Alternative Models
  - Purpose: Proponent experts present, discuss, and debate alternative MMC and HMC models and methods
  - TI Team identifies and discusses the technical bases for the alternatives, the associated uncertainties, and the pros and cons of their implementation in LIP PFHA
  - Identify interface issues between the MMC and HMC models
  - To document the attributes of the models and methods for subsequent consideration in an actual SHAC-F study
  - Discuss the path forward for the SHAC-F project.

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SHAC-F for LIP process – Workshop 2

- Held as a 1.5-day workshop
- Meteorological models were presented by proponent experts, reviewed and discussed by TI Team on day 1
- Hydrologic/hydraulic models were presented by proponent experts, reviewed and discussed by TI Team during day 2
- Developed a workshop report to document the work performed and the lessons learned (in progress)
- Revised the LIP PFHA Template Project Plan to reflect lessons learned (in progress)

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MMC Model Evaluation Questions

- Will your model or method
  - Develop an ensemble of local-scale precipitation hyetographs?
  - Provide defensible estimates beyond 10,000 year recurrence ($1x10^{-4}$ AEP)?
  - Provide the probability for each hyetograph?
  - Minimize the number of ensemble members required to provide a defensible basis for NRC flood hazard analysis?
  - Reflect current research on non-stationarity?

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HMC Model Evaluation Questions

- Will your model or method
  - Estimate water elevation at a specific location as a function of time
  - Estimate hydrodynamic loads on walls
  - Estimate debris impacts
  - Estimate wind waves and wave runup
  - Represent roofs and roof drainage (flow under eves)
  - Represent very shallow flow
  - Represent culverts
  - Represent Vehicle Barrier Systems
  - Represent upwelling through storm drains
  - Represent uncertainty in site conceptual model
  - Represent uncertainty in flow parameters (roughness, infiltration)
  - Maximize the number of ensemble members analyzed (limit simulation domain, sensitivity analysis to limit parameter space)

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LIP PFHA: MMC Model Evaluation

	Will this approach develop an ensemble of local-scale precipitation hyetographs	Will this approach provide defensible estimates beyond 10,000 year recurrence	Will this approach provide p() for each hyetograph	Will this approach minimize the number of ensemble members required to provide a defensible basis for NRC flood hazard analysis	Will this approach reflect current research on non-stationarity
Atlas 14	Yes, representing an annual maximum series, or a set of samples for a given quantile value.	Values can be extrapolated, but existing uncertainty estimates are unlikely to be defensible. Uncertainty estimates could be improved by considering unmodeled sources of uncertainty (e.g., alternative probability models, station correlation, etc.)	Yes, the annual maximum series by definition defines the annual exceedance probability. Simulation of values at a given quantile by definition have an exceedance probability defined by the quantile.	Latin hypercube sampling or importance sampling could be used to reduce the number of samples. Sampling a given quantile value requires AEP neutrality in which the AEP of the hazard is assumed to be identical to that of the precipitation event.	No. NOAA Atlas 14 is based on past events with limited information about how changes over time have occurred in the observations.
Atlas 14 extension	Yes, representing an annual maximum series, or a set of samples for a given quantile value.	Use of the PMP value will result in more conservative estimates of low probability event magnitudes, but may not improve the accuracy of these estimates. Use of extreme rainfall events used to estimate the PMP will improve the defensibility of low probability events and the estimates of uncertainty. Uncertainty estimates could be improved by considering unmodeled sources of uncertainty (e.g., alternative probability models, station correlation, etc.)	Yes, the annual maximum series by definition defines the annual exceedance probability. Simulation of values at a given quantile by definition have an exceedance probability defined by the quantile.	Latin hypercube sampling or importance sampling could be used to reduce the number of samples. Sampling a given quantile value requires AEP neutrality in which the AEP of the hazard is assumed to be identical to that of the precipitation event.	No. NOAA Atlas 14 is based on past events with limited information about how changes over time have occurred in the observations.

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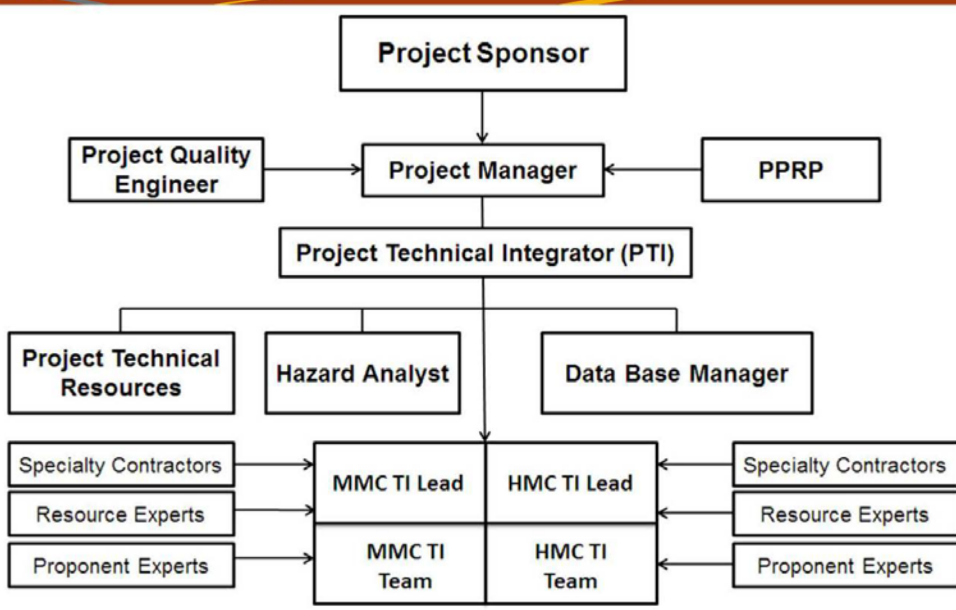
LIP PFHA Project Structure



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LIP PFHA Template Project Plan

- Topics addressed in the Template Project Plan
  - Selection of SHAC-F Level(s)
  - Development of Project Plan
  - Selection of Project Participants
  - Development of Project Databases
  - Compilation of Available Data
  - Collection of New Data
  - Data Dissemination
  - Workshops
  - Development of Models and Hazard Input Documents
  - Hazard Input Documents
  - Preliminary Hazard Calculations and Sensitivity Analyses
  - Final Hazard Calculations
  - Documentation and Peer Review

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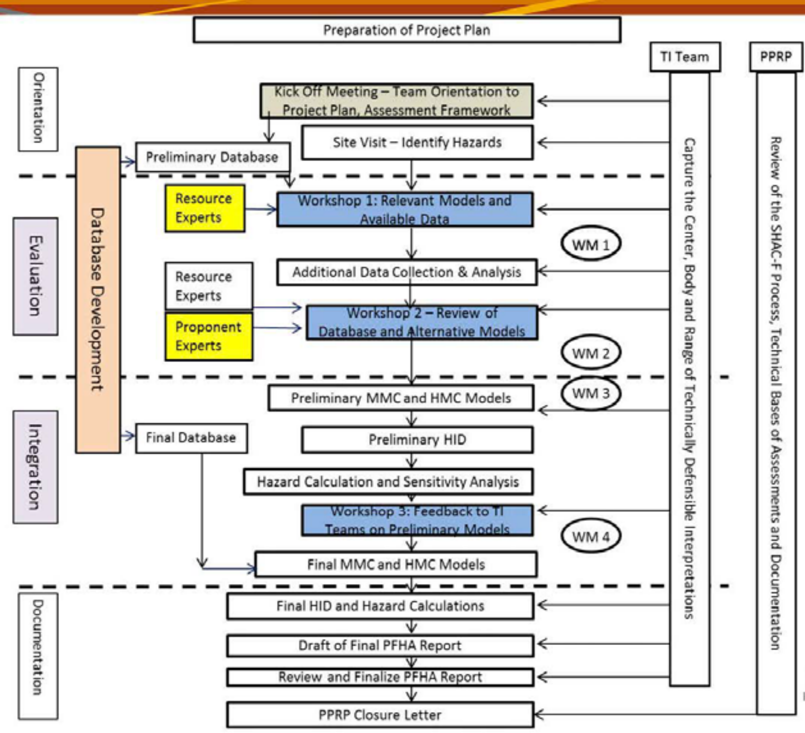
SHAC-F LIP PFHA Project Structure



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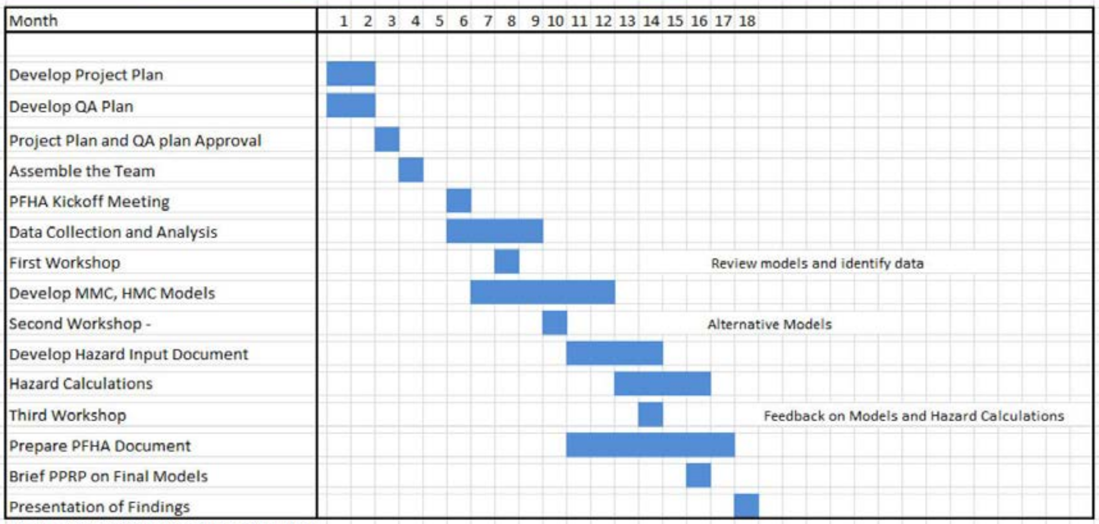
Idealized SHAC-F LIP PFHA Schedule of Activities



PFHA = Probabilistic Flood Hazard Analysis
MMC = meteorological model characterization
HMC = hydraulic/hydrologic model characterization

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SHAC-F Project Next Steps

- Complete the Workshop 2 report
  - Compile a list of example data sources for LIP analyses
  - Compile a list of models that may be appropriate for LIP analyses
  - Identify a list of resource and proponent experts that could be called on to work on an LIP study
  - Identify key points of contention and uncertainties
- Update the Template Project Plan for LIP with our lessons learned
- Finalize the Template Project Plan for LIP PFHA
- Finalize Guidance for LIP PFHA

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SHAC-F Project Status and Conclusions

- Use of virtual approach to step through typical SSHAC steps is effective and insightful
- Presence and common understanding of PFHA framework is essential
- Certain elements of SSHAC process should be customized for LIP PFHA
- Template Project Plan for actual SHAC-F LIP PFHA is being developed and updated as project proceeds
  - A key deliverable
- Insights developed from LIP PFHA virtual study will benefit planning and implementation of SHAC-F Riverine PFHA virtual study
  - There is an opportunity to combine Riverine PFHA virtual study to address both floods without and with snowmelt

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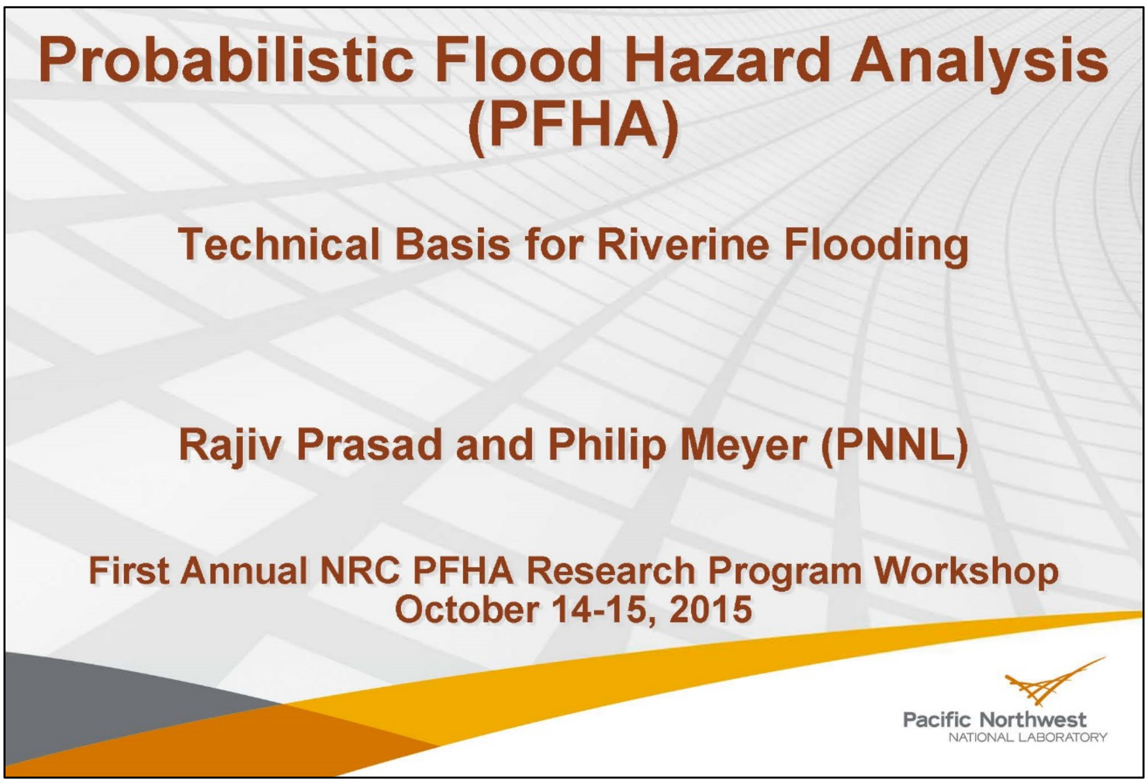
1.3.4 Day 2: Session IV: Riverine and Coastal Flooding Processes

Session IV of the workshop included presentations on NRC-funded research related to riverine and coastal flooding processes. Researchers from PNNL began the session by discussing work that compared statistical and simulation-based approaches for probabilistic assessment of riverine flooding hazards. Representatives from the U.S. Army Corps of Engineers (USACE) followed with a presentation on research to develop a PFHA framework for riverine flooding. The U.S. Geological Survey (USGS) and USBR presented a joint discussion on the current state of practice in riverine flood frequency analysis. A second research team from USACE followed with a discussion on its work to investigate uncertainty quantification in current probabilistic storm-surge modeling frameworks. A USBR researcher gave the final presentation, which described physical modeling to investigate erosion processes in earthen embankment dam breach .

1.3.4.1 PFHA Technical Basis for Riverine Flooding. Rajiv Prasad and Philip Meyer, PNNL

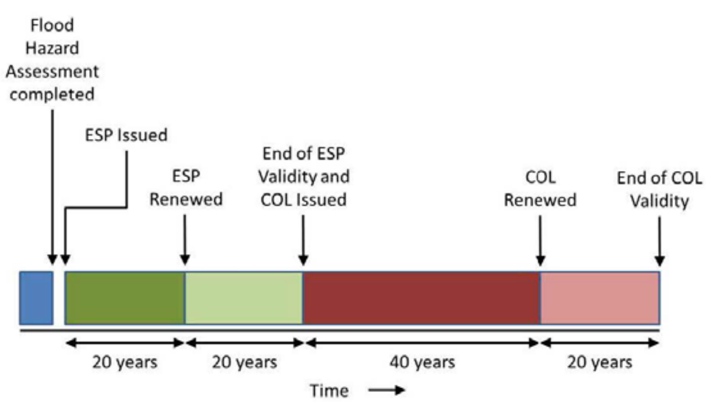


PFHA – the Need

- Long-stated NRC policy for implementing risk-informed approaches for external hazards including floods
  - in this report riverine floods are the topic
- Current practice for external flood hazard assessment
  - is based on deterministic, "probable maximum" events
  - does not allow for determination of exceedance probabilities
  - NRC guidance suggests that average annual exceedance probability (AEP) of about 1×10^{-6} is acceptable for flood design bases
- Risk-informed approaches need AEPs
- Probabilistic Risk Assessments
  - need the complete probability distribution of flood hazards

PFHA – the Scope

- Scope of PFHA
  - Riverine floods
  - Estimate flood hazards of AEPs 1×10^{-3} to 1×10^{-4}
- Temporal Scope
  - ~100 – 120 years based on approximate NPP permitting and licensing timeline
- Spatial Scope
  - From watershed scale to site scale



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PFHA at other Federal Agencies

- The Bureau of Reclamation
  - Seven general methods, PMF is considered the upper bound
  - Flood frequency analysis
    - Uses historical and paleoflood data
  - Hydrograph scaling and volumes
    - Assumes the probability of peak discharge is same as that of the discharge hydrograph
    - Unit hydrographs
  - GRADEX
    - Distribution of direct runoff is same as that of extreme annual precipitation
  - Australian rainfall-runoff method
    - Flood frequency analysis and rainfall-runoff modeling
    - Select rainfall-runoff model parameters such that rainfall of a certain AEP produces a flood of the same AEP

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PFHA at other Federal Agencies

- The Bureau of Reclamation (contd.)
  - Stochastic Event Flood Model (SEFM)
    - Drive a deterministic flood simulation model input by inputs derived from sampling of from their distributions
    - Preserves dependencies between climate and hydrologic parameters
    - Precipitation inputs from a regional precipitation frequency analysis
    - Estimate distributions of model outputs by nonparametric plotting position formula
  - Stochastic rainfall-runoff modeling with CASC2D
    - Similar to SEFM but uses a 2-D, distributed-parameter, physically-based hydrologic model
- Best Practices Manual (Reclamation and USACE)
  - Best Practices in Dam And Levee Safety Risk Analysis (http://www.usbr.gov/ssle/damsafety/Risk/methodology.html)

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PFHA at other Federal Agencies

- U.S. Army Corps of Engineers
  - Best Practices Manual (Reclamation and USACE)
    - Best Practices in Dam And Levee Safety Risk Analysis (http://www.usbr.gov/ssle/damsafety/Risk/methodology.html)
- Federal Energy Regulatory Commission
  - Currently uses deterministic approaches (PMF)
  - Guidelines for Risk-Informed Decision-Making are in development
    - Essentially adopts the Best Practices Manual
    - PMF is compared to probabilistic analyses; not used as upper bound
- Federal Emergency Management Agency
  - Guidelines for selecting inflow design floods
    - Historically deterministic (PMF)
    - Updated guidelines recommend risk-informed hydrologic hazard analysis using the Best Practices Manual

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PFHA at other Federal Agencies

- U.S. Department of Energy
  - SSCs categorized based on consequences of failure
    - Flood design categories (FDCs) 1–5 based on ANSI/ANS-2.26-2004
    - If SSC fails unconditionally, FDC 1–5 designed for 500, 2,000, 10,000, 25,000, and 100,000-year water surface elevations
    - If SSC design is credited, FDC 1–5 designed for 100, 200, 2,500, 6,250, and 10,000-year
    - For FDC 3 and higher, site-specific PFHA is required
  - Site-specific PFHA
    - Step 1: if a flood screening analysis shows SSCs are potentially affected, perform a preliminary PFHA using frequency analysis
    - Step 2: based on results of screening and preliminary PFHA, perform a comprehensive flood hazard assessment (CFHA)
    - CFHA is performed using modeling of precipitation/snowmelt-runoff using hydrologic modeling and characterization of uncertainty

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PFHA – the Definition and Methods

- PFHA is defined as the estimation of the probability density functions (PDF) or the cumulative distribution functions (CDF) of all relevant flood hazards that SSCs could be exposed to at an NPP site
  - Multiple hazards from riverine floods
    - Flood hazards are functions of the characteristics of the flow field
  - Multiple, differently located SSCs should be considered
    - At the site scale, flow field is significantly affected by buildings and obstructions
  - PFHA is site-specific
    - Each site is different–from meteorologic to watershed and riverine characteristics to site layout
- PFHA Methods
  - Data-driven approach (flood frequency analysis)
  - Runoff simulation approach

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Flood Hazards

Flood Hazard	Flood Characteristic	Effects on SSCs	Relevant Scale
Hydrostatic load	Water-surface elevation	Loss of functionality from exceedance of the design basis	Site scale
Hydrodynamic load	Water-surface elevation, flow velocity, flow density	Loss of functionality from exceedance of the design basis	Site scale
Inundation pattern	Water-surface elevation	Accessibility leading to loss of functionality	Site scale
Accumulation of water in SSCs	Water-surface elevation, time of inundation of openings	Loss of functionality	Site scale
Erosion	Flow velocity, discharge, turbulence, and duration	Loss of functionality	Site scale
Deposition	Flow velocity, discharge, turbulence, and duration	Accessibility leading to loss of functionality	Site scale
Impact load	Water-surface elevation, flow velocity, duration	Loss of functionality from exceedance of the design basis	Site scale
Warning and lead times	Discharge hydrograph	Accessibility leading to loss of functionality	Drainage area to site scale
Inundation duration	Discharge hydrograph, water-surface elevation	Accessibility leading to loss of functionality, loss of functionality from exceedance of the design basis	Drainage area to site scale

Data-driven Approach (Flood Frequency Analysis)

- Uses a non-mechanistic model to represent the frequency of occurrence of peak flows
- Model is a parametric probability distribution with the values of the distribution parameters selected to best match observed data
- Data are the record of observed peak flows, most commonly, the annual peak flows

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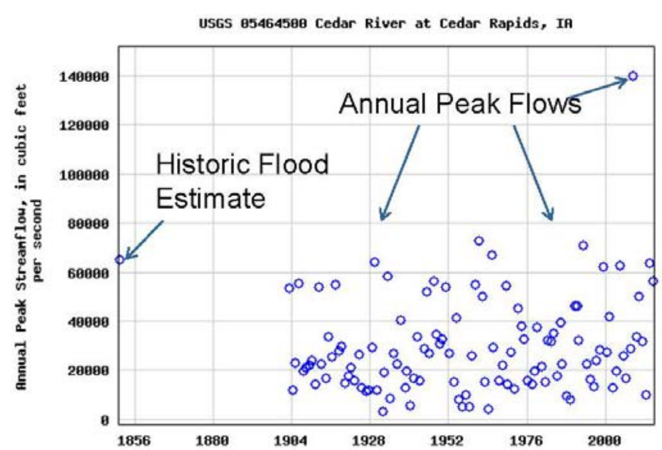
Data – Annual Peak Streamflow



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Extend the Data Record with Other Data Types

- Historical flood information – archived documents or physical evidence (flood marks)
- Paleoflood information – number of occurrences of flood above a certain magnitude, from botanical or sediment study
- Regional information from nearby sites with similar hydrologic behavior (substitute space for time)

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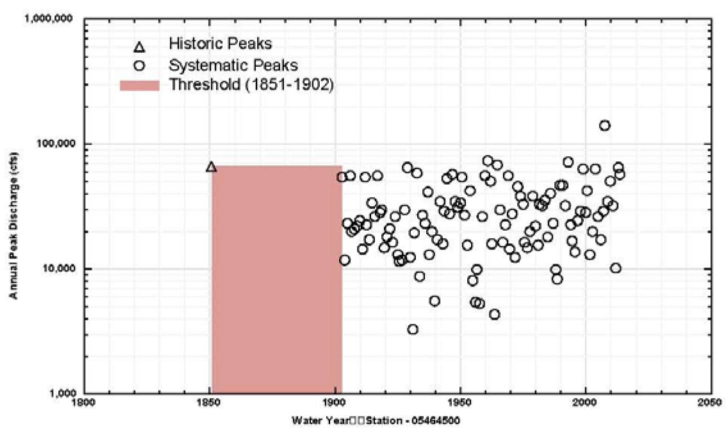
Use of Historical Information

- Knowledge of historic peak + assumption that peak flows in intervening years were below the 1851 peak



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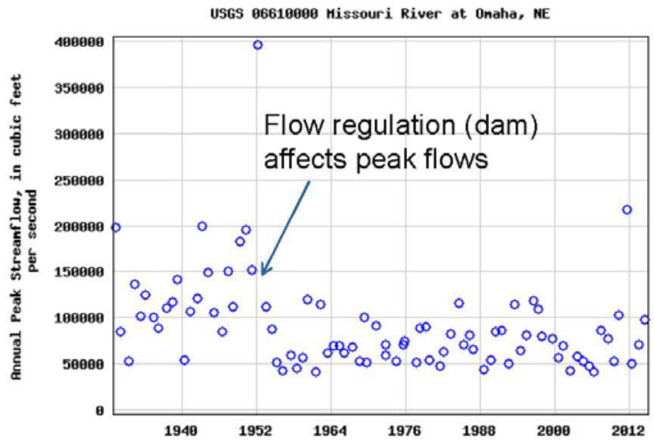
Data Issues

- Data assumed to be independent and drawn from the same distribution – account for nonstationarity



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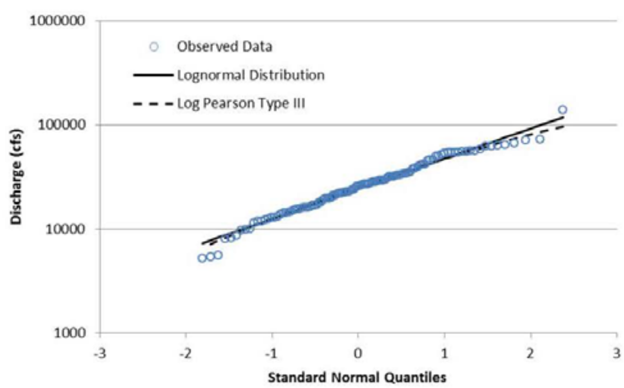
Probability Models

- Many probability distributions have been used
  - Lognormal, generalized extreme value (Weibull, Gumbel), Pareto
  - Log Pearson Type III adopted in U.S. federal guidance



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Parameter Estimation

- A variety of methods have been used
  - Method of moments, L-moments, maximum likelihood, Bayesian estimation
  - U.S. Federal guidelines
    - Use method of moments (Expected Moments Algorithm if incorporating historical/threshold information)
    - Adjust skew with regional information
    - Account for low outliers that can bias estimates

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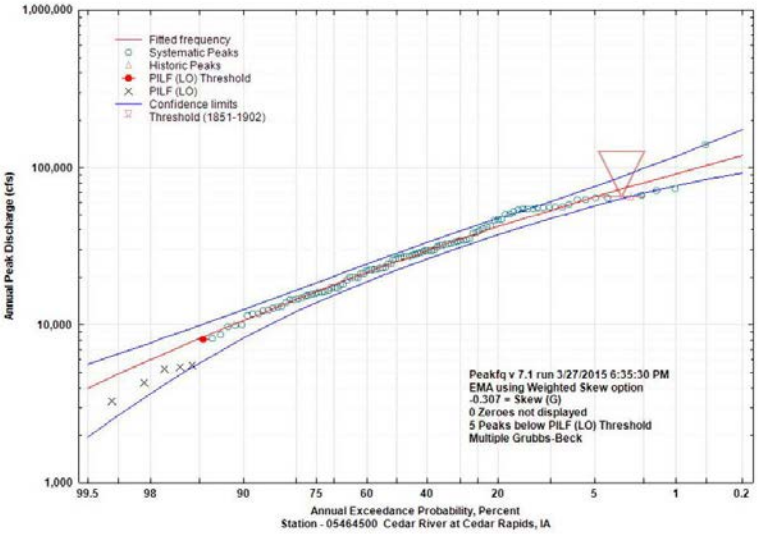
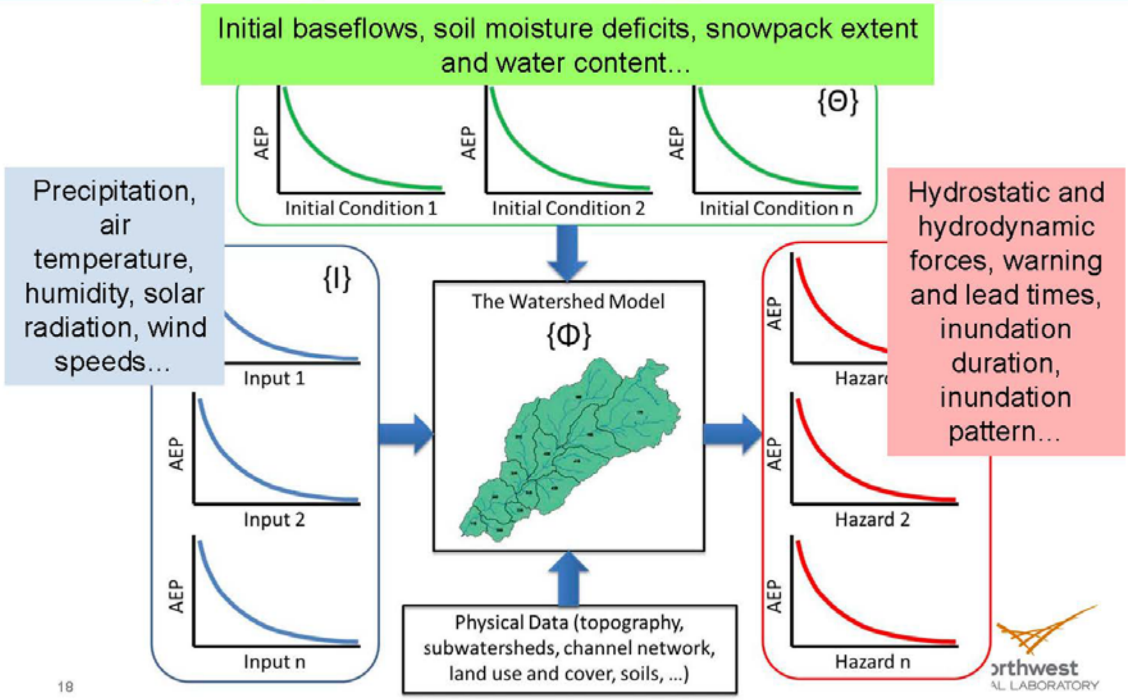
Evaluate Quantiles and Estimate Uncertainty

- Uncertainty – at a minimum, estimate confidence intervals



Runoff Simulation Approach - a Schematic



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Runoff Simulation Approach - components

- The Watershed Model
  - Hydrologic Model
    - Set up using physical watershed data (e.g., topography, subwatersheds, channel network, soils, land use and cover…)
    - Given input meteorologic data and initial conditions, predicts streamflow discharge hydrographs
  - Hydraulic Model
    - Set up using physical watershed data (e.g., topography, channel network, cross sections…)
    - Given initial conditions (baseflow) and streamflow discharge hydrographs, predicts flood characteristics (e.g., water-surface elevations, velocities…)
- The Meteorologic Model
  - Provides meteorologic data sampled from their underlying probability distributions (e.g., a regional precipitation IDF curve)

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Simulation Models

- Hydrologic Models
  - Lumped-parameter conceptual models
    - e.g., unit hydrograph approach
  - Physically-based process models
    - e.g., Stanford Watershed Model, Sacramento Model, HSPF, IHDM, PRMS, HBV, TOPMODEL
  - "Fully-distributed" physically-based models
    - e.g., SHE, DHSVM
  - Semi-distributed, lumped-parameter models
    - e.g., HEC-HMS
- Varying data requirements
- Need calibration and validation
  - Usually against discharge at outlet
  - Few internal state variables used, especially for distributed models

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Simulation Models

- Hydraulic Models
  - Simulate the dynamics of flood flow within the river and stream channels and adjoining floodplain
  - Use mass conservation and momentum equations (e.g., Saint-Venant)
  - One-dimensional forms of the flow equations are typically used
  - Simplifications of momentum equation leads to various approximations
    - Kinematic wave, diffusive wave
  - Full one-dimensional dynamic wave models
    - e.g., NWS DWOPER, NWS DAMBRK, NWS FLDWAV, USACE HEC-RAS
  - Two-dimensional hydraulic models
    - e.g., TUFLOW, Mike 21, TELEMAC

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Required input data

- Physical data
  - Topography
  - Watershed area, subwatersheds, drainage connectivity
  - Land use and cover
  - Soil types
  - Channel lengths, connectivity, cross sections
  - Sources in NUREG/CR-7046
- Hydrometeorologic input data
  - Precipitation
  - Air temperature
  - Solar radiation
  - Wind speeds and direction
  - Temporal resolution and spatial coverage should be adequate

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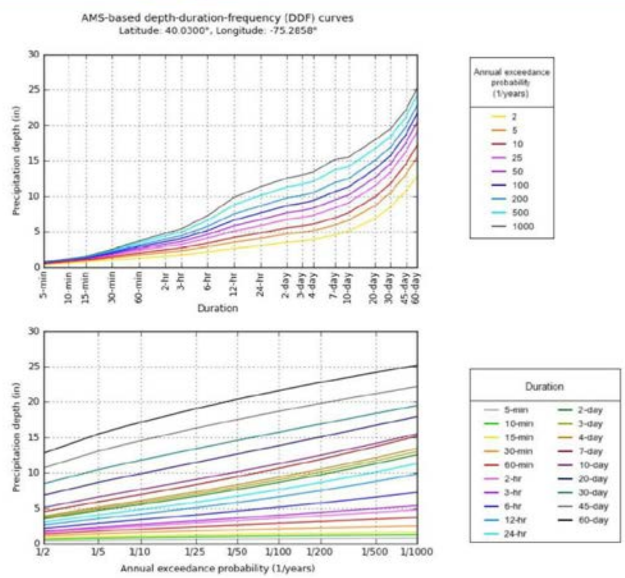
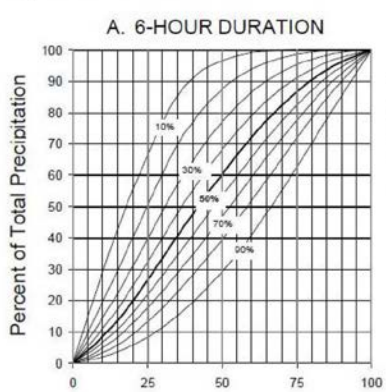
Required input data - precipitation

- Precipitation
  - NOAA Atlas 14
    - IDF and DDF curves
    - Within-storm temporal distributions
  - PRISM, NEXRAD
    - Spatial distribution





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Required input data – initial conditions

- Baseflow
  - Streamflow data (e.g., USGS)
- Snow cover and water content
  - Western U.S. – SNOTEL, Snow Course data (NRCS)
  - Other states – SCAN data (NRCS)
- Soil Moisture
  - Global datasets from European Space Agency, NOAA Climate Prediction Center (surface layer)
  - Point profile measurements from SCAN (NRCS)

Uncertainty

- Uncertainty
  - Aleatory
    - Natural variability, irreducible
  - Epistemic
    - Lack of knowledge, partially reducible
  - Errors
    - Measurement errors
- Quantification of uncertainty
  - Generalized Likelihood Uncertainty Estimation (GLUE)
    - Start with prior distributions of model parameters to generate random sets of parameters
    - Perform simulations using candidate models using input sequences
    - Compare models' predictions to observations using a likelihood measure and discard "nonbehavioral" simulations/models

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Uncertainty

- Quantification of uncertainty
  - Generalized Likelihood Uncertainty Estimation (GLUE)
    - Criticized for “less formal” likelihood measures that lead to wide posterior distributions
    - Can be used with formal likelihood measures
  - Bayesian Total Error Analysis (BATEA)
    - Developed using the Bayesian framework
    - Explicit accounting of input, response, and model errors
      - Many “latent variables” lead to high dimensionality
    - Markov Chain Monte Carlo (MCMC) to explore the parameter hyperspace
    - Applied to assess the performance of VIC model
      - Computational constraints required initial calibration

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Uncertainty

- Quantification of uncertainty
  - Differential Evolution Adaptive Metropolis (DREAM)
    - Similar to BATEA; based on Bayesian framework
    - An MCMC sampler to efficiently explore parameters in complex hyperspace
    - Uses multiple chains for simultaneous search
    - Explicit accounting of input, response, and model errors
    - Starts with uniform priors
    - Final posterior distribution contains all information necessary to characterize input, response, and model uncertainties
    - Able to solve 62 and 64-dimensional problems

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Nonstationarity

- Changes in the behavior of hydrologic systems
  - Changes in river basin
    - e.g., land use and land cover changes
  - Global Climate Change
    - IPCC Fifth Assessment Report
      - Increased temperature and precipitation by mid-century over North America
      - Definition of "extremes" very different from what is needed for very low exceedance probabilities targeted by PFHA
      - Resolution from GCMs not sufficient for watershed-scale modeling
      - GCMs can be downscaled to regions (statistical or dynamic)
      - Bias correction is needed
    - Useful information for riverine PFHA
      - Future changes in overall climate regimes: e.g., watershed of interest can change from a snowmelt-dominated annual floods to rain-on-snow events; over a region, frequency of atmospheric rivers may increase; projected sea-level rise that changes downstream boundary conditions

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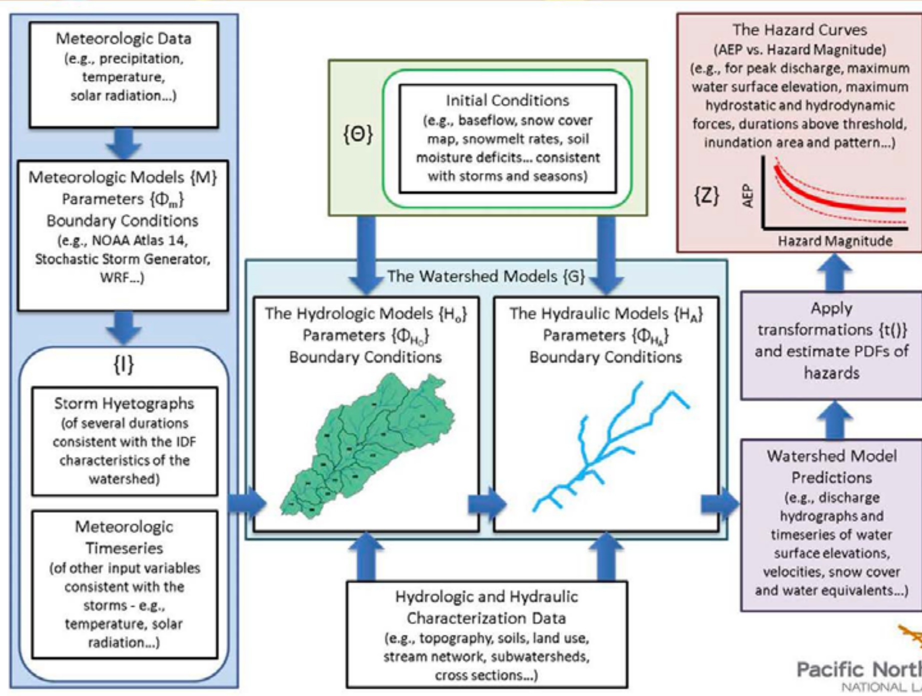
Proposed PFHA Framework



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Proposed PFHA Framework

- Built on the basic aleatory framework
  - Allows for aleatory uncertainties by explicit consideration of variability in meteorologic inputs and initial conditions
- Allows for consideration of epistemic uncertainty
  - Alternative models can be explicitly considered – {M}, $\{H_O\}$, $\{H_A\}$
- Traditional Monte Carlo approach
  - Rapidly growing number of model runs – (n_s x n_m x n_{ic} x n_{p1} x n_{p2})
  - Calibrated model(s)
- Use a Bayesian Framework
  - Allows for combining model parameter identification (calibration) and uncertainty estimation accounting for input, response, and model uncertainties
  - Allows for incremental update given new data – the posterior distribution can be updated by using it as prior

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Proposed PFHA Framework

- The Basic Aleatory Model
  - $\boldsymbol{Z} = g(\boldsymbol{I}, \boldsymbol{\Theta}, \boldsymbol{\Phi})$
    - where
      - $g()$ is a watershed model that simulates flood characteristics,
      - $\boldsymbol{Z}$ is the set of simulated flood hazards,
      - $\boldsymbol{I}$ is the meteorologic sets for annual storms,
      - $\boldsymbol{\Theta}$ is the set of model parameters,
      - $\boldsymbol{\Phi}$ is the set of initial conditions in the watershed
- The Epistemic Component
  - Multiple watershed models are allowed, $\{\boldsymbol{Z}\} = \{g(\dots)\}$
  - Multiple meteorologic models are allowed, $\{\boldsymbol{I}\} = \{m(\dots)\}$
  - Measurement errors are allowed, $\{\boldsymbol{I}\} = \{\boldsymbol{I} + \varepsilon\}$, $\{\boldsymbol{\Phi}\} = \{\boldsymbol{\Phi} + \varepsilon\}$
  - Data errors are allowed, e.g., in topography

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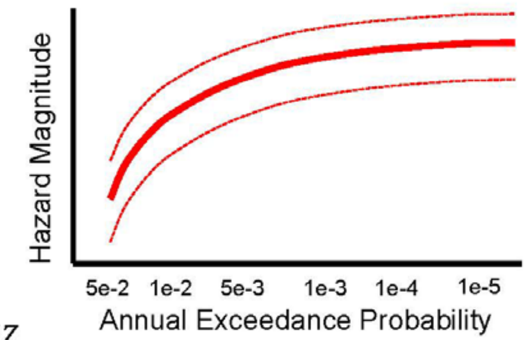
PFHA Framework – the Hazard Curve

- **The Hazard Curve**
  - Plot of hazard magnitude vs. annual exceedance probability



  - For a flood hazard Z,
    - $P(Z > z) = 1 - F(z) = \int_z^{\infty} f(Z)dZ$
      - P is exceedance probability, F is CDF of Z, f is PDF of Z
    - $P(Z > z) = \int \lambda_{I > i} \cdot f(Z > z|_{i, I, \Theta, \Phi})\, dZ\, dI\, d\Theta\, d\Phi$
      - In practice, the integral is evaluated numerically

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PFHA Framework – Annual Maximum and Partial Duration Series

- **Annual Maximum Series (AMS)**
  - One hazard value, the maximum, for a given year
- **Partial-Duration Series (PDS)**
  - All hazard occurrences that exceed a selected threshold value in a given year
    - In a data-driven analysis, need to select independent events
    - In addition to describing the magnitude of events above the threshold, the statistical model must also describe the rate of arrival of events above the threshold
    - The Poisson distribution is often used to describe the rate of arrival
    - The Exponential distribution is used to describe the magnitude
  - The CDF of a PDS and the CDF of the corresponding AMS are related
    - Stedinger et al. (1993)

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PFHA Framework – Annual Maximum and Partial Duration Series

- Relation between AMS and PDS (Stedinger et al. 1993)
  - Let λ be the arrival rate of $z, z > z_0$
  - Let $G(z)$ be the CDF of the PDS; it denotes the probability of events of magnitude between z_0 and z
  - Then, arrival rate of events of magnitude z and greater is
    - $\lambda^* = \lambda[1 - G(z)]$
  - and the CDF of the corresponding AMS is
    - $F(z) = \exp(-\lambda^*) = \exp(-\lambda[1 - G(z)])$
  - The AEP is then
    - $P(Z > z) = 1 - F(z) = 1 - \exp(-\lambda[1 - G(z)])$
  - Therefore, the average return period of event of magnitude z in the AMS
    - $T_a = 1/(P(Z > z) = 1/[1 - F(z)]$
  - and the average return period of event of magnitude z in the PDS
    - $T_p = 1/\lambda^* = 1/(\lambda[1 - G(z)])$
  - are related
    - $T_p = -1/[\ln(1 - 1/T_a)]$

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PFHA Framework – Annual Maximum and Partial Duration Series

- Relation between AMS and PDS (Stedinger et al. 1993)
  - Average return periods of an event of magnitude z in PDS and AMS are related by
    - $T_p = -1/[\ln(1 - 1/T_a)]$

AEP	T_a (years)	T_p (years)	Percent Difference $100 * (T_a - T_p)/T_p$
0.5	2	1.44	39
0.1	10	9.49	5
0.01	100	99.5	0.5
1e-3	1,000	999.5	0.05
1e-4	10,000	9,999.5	5e-3
1e-5	100,000	99,999.5	5e-4
1e-6	1,000,000	999,999.5	5e-5

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Proposed PFHA Framework

- Challenges
  - Selection of likelihood functions
    - Accounting for error structure (nonnormality, heteroscedasticity, and autocorrelation) is necessary
  - Few conditioning data at very low AEPs
    - Paleoflood data can be used
  - Would still require significant computational effort

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Next Steps

- Develop the Framework further
  - Develop detailed flowchart for implementing the Framework using Bayesian approaches, e.g., DREAM
  - Develop methods for consistent treatment of nonstationarity

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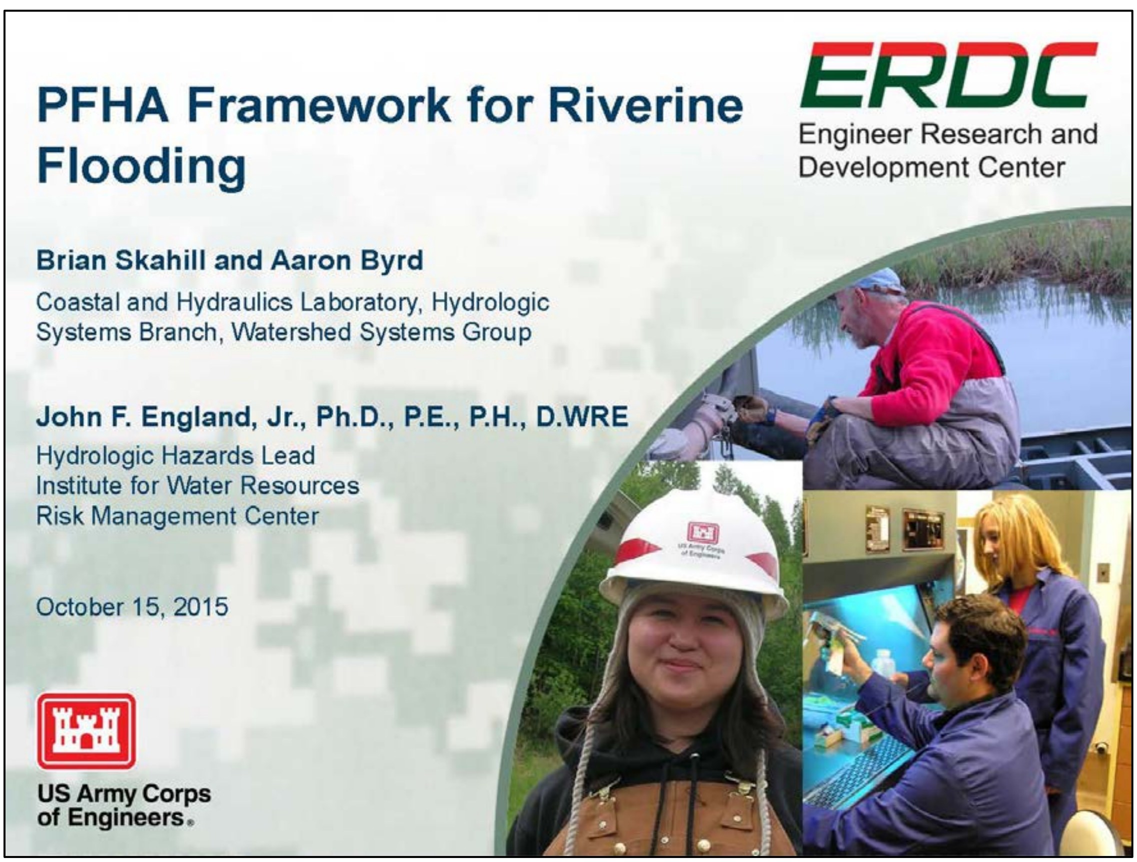
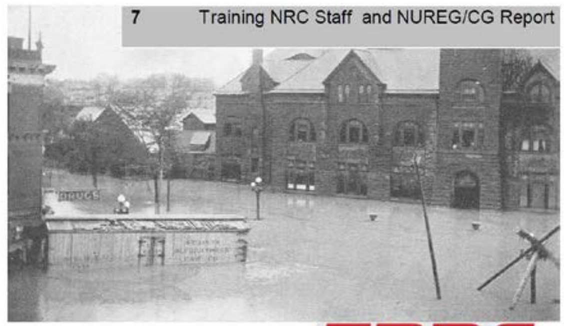
1.3.4.2 PFHA Framework for Riverine Flooding. Brian Skahill and Aaron Byrd, USACE



PFHA Framework Development

Objective. Develop and demonstrate an overall conceptual, mathematical and logical framework for probabilistic flood hazard assessment for inland and riverine sites (e.g. non-coastal sites). The framework will facilitate construction of site-specific flood hazard curves, and support full characterization of uncertainties in site-specific storm flood hazard estimates for the full range of return periods of interest for critical infrastructure facilities such as nuclear power plants.

Task	Component Description
1	Literature review
2	Warm Season and Locally Intense Rainfall
3	Cool Season Rainfall
4	Site-scale Flooding
5	Watershed and Riverine Flooding
6	Dam/Levee Breech Riverine Flooding
7	Training NRC Staff and NUREG/CG Report



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Context

General Requirement. For inland nuclear facility sites a PFHA must be able to incorporate probabilistic models for a variety of processes (e.g., precipitation, runoff, stream flow, operation of water control structures), allow for characterization and quantification of aleatory and epistemic uncertainties, facilitate propagation of uncertainties, and facilitate sensitivity analysis.

DEPARTMENT OF THE ARMY
U.S. Army Corps of Engineers
Washington, D.C. 20314-1000

ER 1105-2-101

CECW-P
CECW-E

Regulation
No. 1105-2-101

3 January 2006

Planning
RISK ANALYSIS FOR FLOOD DAMAGE REDUCTION STUDIES

1. Purpose. This regulation provides guidance on the evaluation framework to be used in Corps of Engineers flood damage reduction studies. It is jointly promulgated by Planning and Engineering.

USACE Engineering Regulation requires the performance of risk and uncertainty analyses in the process of planning, design, and operation of all civil works flood risk management projects.

The ultimate goal of the policy guidance is probabilistic analysis of "all key variables, parameters, and components of flood damage reduction studies."

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Hydrologic Hazard Curve Definition / *Principles*

- A Hydrologic Hazard Curve is a graph of peak flow, volume (for specified duration), or reservoir elevation versus Annual Exceedance Probability (AEP) ***(< 1 in 10,000 for risk assessment)***
- AEP estimates are made for peak flows, runoff volumes and reservoir elevations
- Portray full range of values, with uncertainty, needed for risk-based dam safety decision making for a portfolio or to evaluate a specific facility
- Used to evaluate specific Potential Failure Modes (PFMs)

- *Multiple Methods*
- *Lots of Data*
- *Explicitly Quantify Uncertainty*
- *Research and Development needed- Data/Methods*

- *Temporal Information*
- *Spatial information*
- *Causal information*

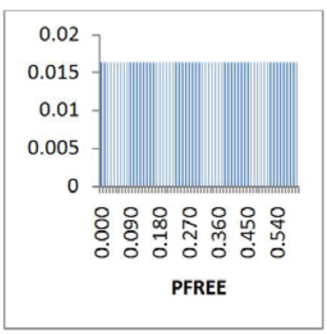
- *We need to be more deliberate to include each concept, and include more information on hydrological processes and hydrological reasoning*
- *Extreme flood and storm data representative of extreme process we're trying to predict?*
- *Combine data evidence from each piece to do this*

From England, John. "Hydrologic Hazard Workshop Lecture 1.2 - Introduction". Hydrologic Hazards for Risk Assessments Training Workshop. August 31 - September 3, 2015. USACE Risk Management Center, Lakewood, CO.

Bayesian Analysis

MCMC

Bayes' Theorem: $p(\mathbf{p}|D) \sim l\,(D|\mathbf{p})\,p(\mathbf{p})$



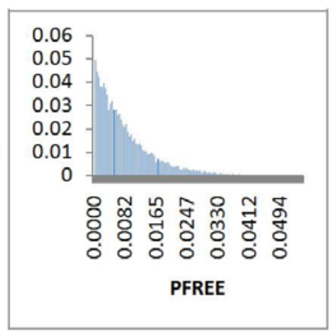
Belief before = p(**p**)
Prior distribution
of **p**

data = *D*

Model $l(D|\mathbf{p})$

Markov Chain (MC) directed random walk of the distribution

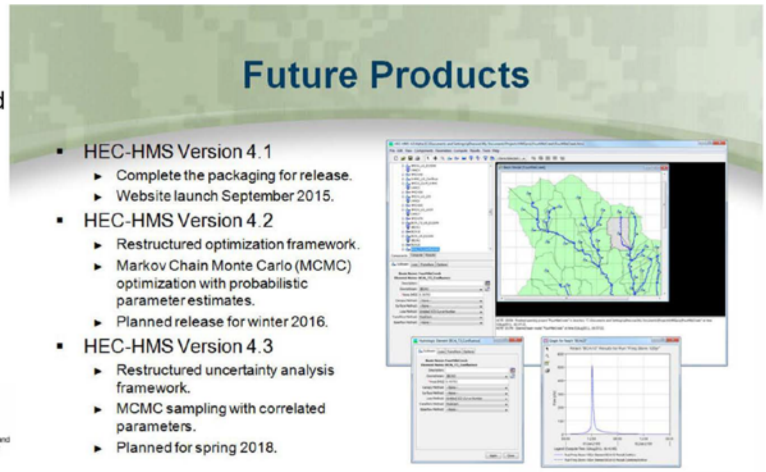
Likelihood
of **p** given *D*

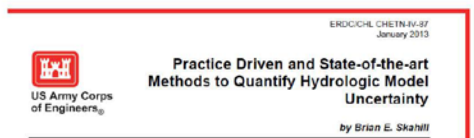


Belief after = $p(\mathbf{p}|D)$
Posterior distribution
of **p** given *D*

Bayesian analysis – hydrologic modeling

USACE has capacity to quantify hydrologic model uncertainty via Bayesian analysis, accounting for input (i.e., aleatory) uncertainty and modeled process (i.e., epistimic) uncertainty. USACE watershed scale precipitation runoff model structures accommodate the modeling of snow accumulation and melt, and stormwater runoff





Hydrologic Engineering Center

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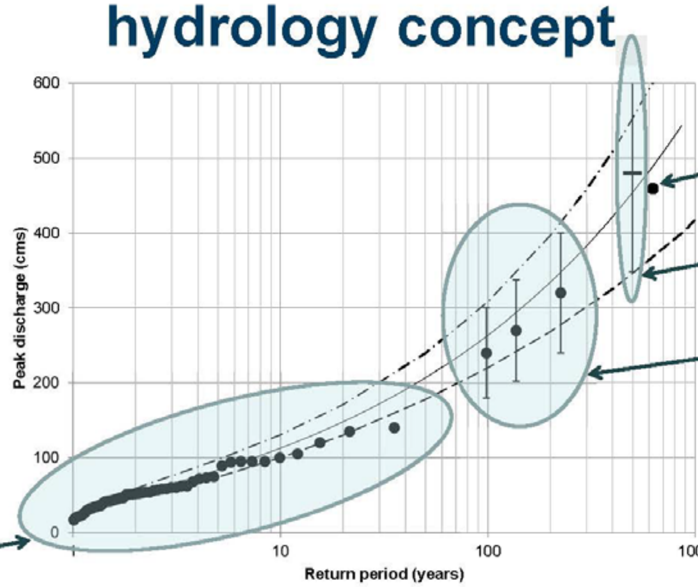
Bayesian analysis – flood frequency hydrology concept

Coherently and flexibly combine different types of data in addition to the systematic record



extreme flood event

expert elicitation via modeling info.

historical floods

data record

Assumptions made explicit; analysis is repeatable and revisable

The intent is to extract the maximum amount of information from all available complementary data sources

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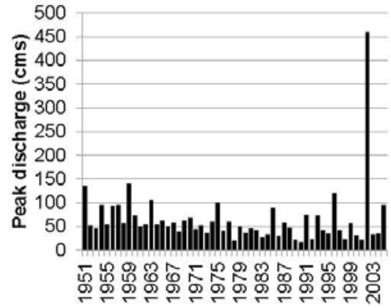
Bayesian analysis – flood frequency hydrology concept

622 km^2 Kamp at Zwettl river basin located in northern Austria

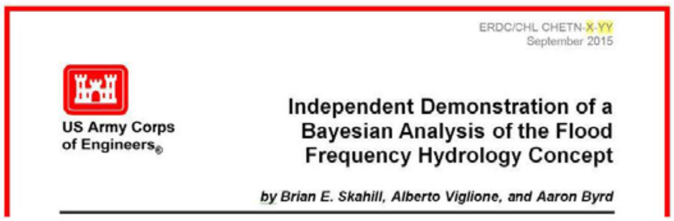
Brief 55 year record (1951-2005) of available annual discharge maxima

“A dam burst Sunday night in the Lower Austria town of Zwettl, where a famed brewery was inundated by flooding earlier in the week, submerging 50 to 60 houses” (http://www.dartmouth.edu/~floods/Archives/2002sum.htm)

The magnitude of the 2002 flood is ~ 3 times that of the second largest flood in the past 100 years, making it difficult to assess the return period of such an extraordinary flood



Statistical tests identify the 2002 flood event as an outlier


ERDC/CHL CHETN-X-YY
September 2015

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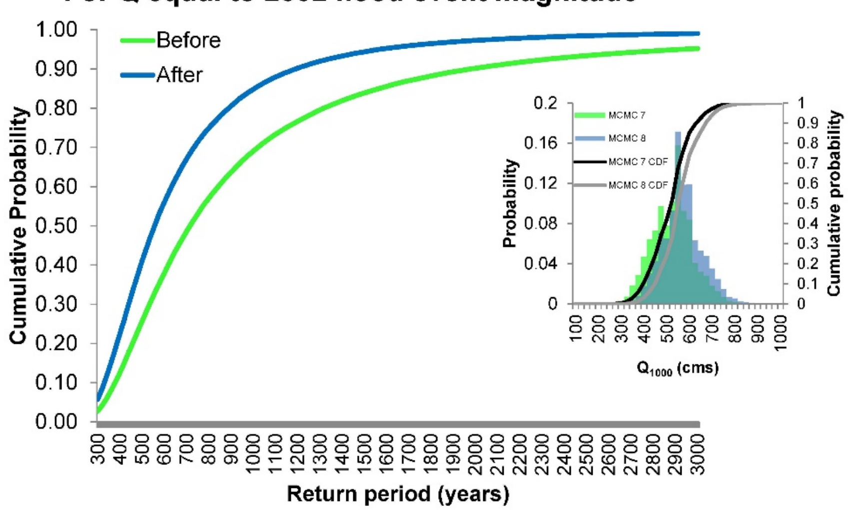
Independent Demonstration of a Bayesian Analysis of the Flood Frequency Hydrology Concept

by Brian E. Skahill, Alberto Viglione, and Aaron Byrd

Bayesian analysis – flood frequency hydrology concept

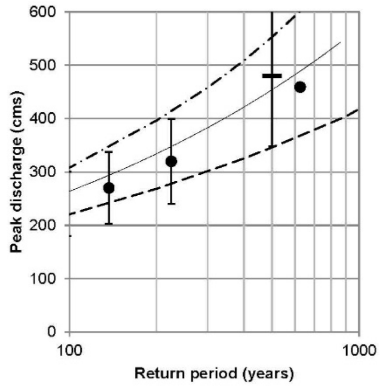
The set of post burn-in random draws from $p(\mathbf{p}|D)$ can be used to make formal probabilistic-based inferences regarding functions of **p**, such as the flood quantiles

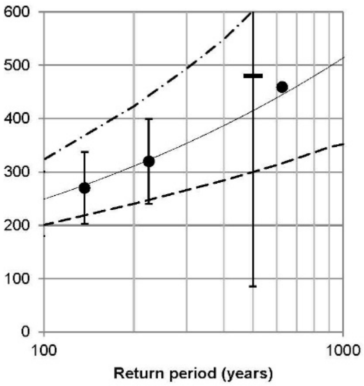
For Q equal to 2002 flood event magnitude



Bayesian analysis – flood frequency hydrology concept

MCMC simulation	Q_{1000} (m³/s)		
	PM	5%	95%
1	241	183	649
2	543	317	1853
3	399	278	647
4	497	347	818
5	557	335	702
6	604	418	747
7	527	369	671
8	571	418	708
9	419	287	653
10	514	352	775
11	598	532	647
12	602	538	653





Evaluate the worth when combining different types of data in addition to the systematic record in flood frequency analysis

MCMC simulation	Data of the Kamp at Zwettl
1	Systematic data (1951-2001)
2	Systematic data (1951-2005)
3	Systematic data (1951-2001) + temporal information expansion
4	Systematic data (1951-2005) + temporal information expansion
5	Systematic data (1951-2001) + causal information expansion
6	Systematic data (1951-2005) + causal information expansion
7	Systematic data (1951-2001) + temporal + causal information expansion
8	Systematic data (1951-2005) + temporal + causal information expansion

Assumptions made explicit; analysis is repeatable and revisable

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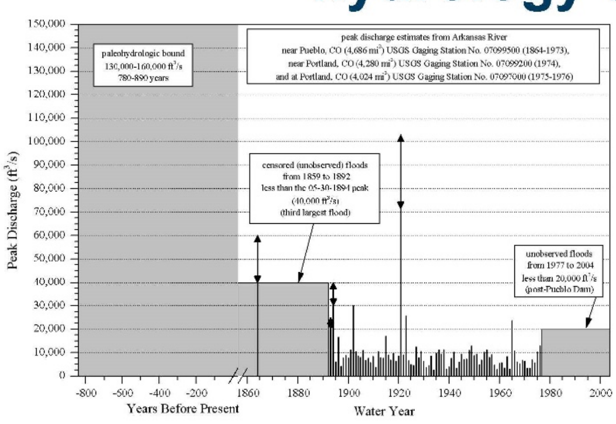
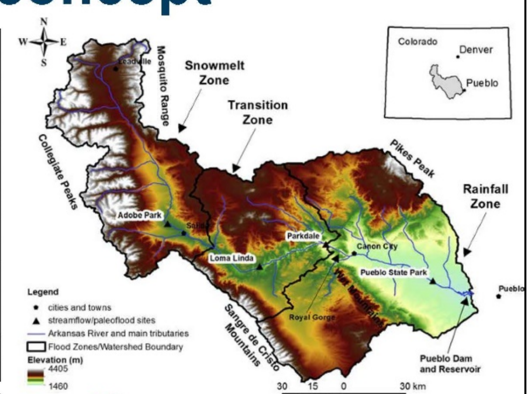
Bayesian analysis – flood frequency hydrology concept





J.F. England Jr. et al. / Journal of Hydrology 510 (2014) 228–245

Physically-based extreme flood frequency with stochastic storm transposition and paleoflood data on large watersheds

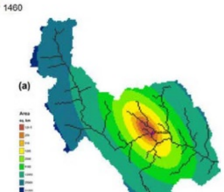


Fig. 6. Storm spatial pattern for TREX model runs and flood frequency: (a) storm rainfall area (31,300 km²) over watershed; (b) restricted storm area (12,950 km²) over watershed based on radar data, storm catalog, and flood runoff mechanisms. River channel network shown as dark lines.

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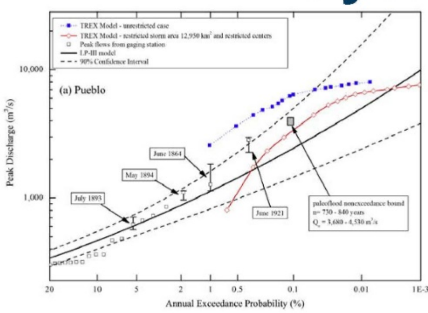
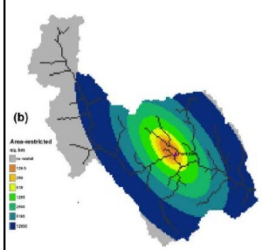
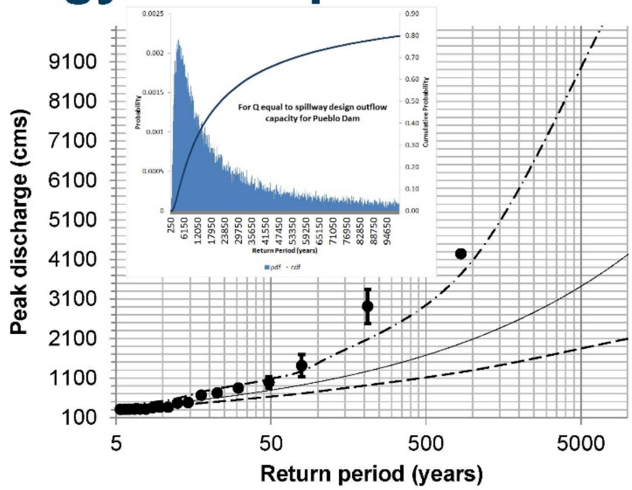
Bayesian analysis – flood frequency hydrology concept







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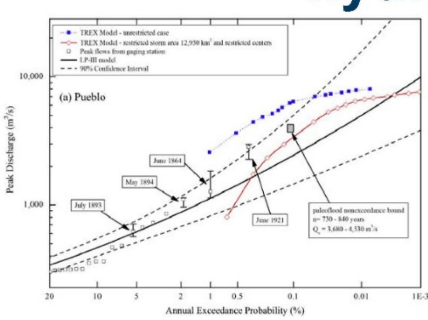
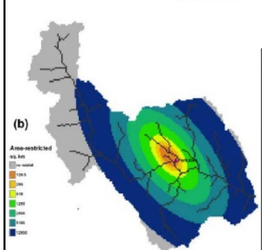
Bayesian analysis – flood frequency hydrology concept

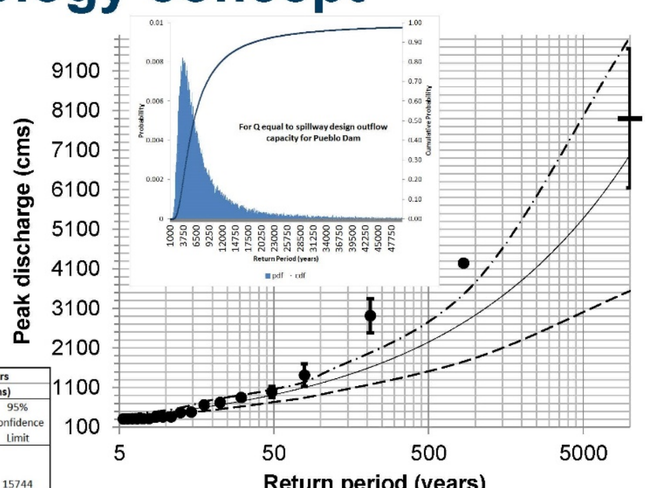




Return Period equals 10,000 years

	Peak Discharge (cms)		
	Model Estimate	5% Confidence Limit	95% Confidence Limit
England et al. (2014) LPIII (EMA)	5012	2407	15744
		Lower 95% Bayesian Credible Bound	Upper 95% Bayesian Credible Bound
GEV (MCMC) s,h,p,d	4217	2092	11243
s,h,p,d,c	6978	3541	9956

s=systematic; h=historical; p=paleoflood; d=dam; c=causal



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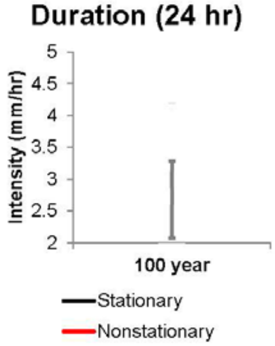
Spatial Bayesian model – rainfall and flood frequency analysis

$p(\theta) \sim f(\theta|\tau,\sigma)$

$\mathcal{L}(x|\theta) = f_x(x|\theta)$

$p(\theta|x) \propto p(\theta)\mathcal{L}(x|\theta)$



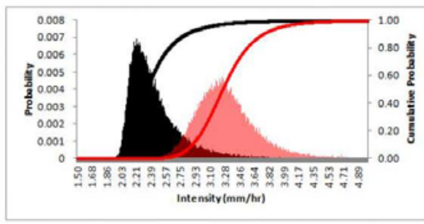
$$y_{ts} \sim \mathrm{GEV}(\mu_s, \kappa_s, \xi_s)$$

$$\mu_s = \boldsymbol{x}_s^\top \boldsymbol{\theta}^\mu + \tau_s^\mu$$

$$\kappa_s = \boldsymbol{x}_s^\top \boldsymbol{\theta}^\kappa + \tau_s^\kappa$$

$$\xi_s = \boldsymbol{x}_s^\top \boldsymbol{\theta}^\xi + \tau_s^\xi$$

$$\tau_s^\nu \sim \mathcal{GP}(\alpha^\nu, \lambda^\nu), \quad \nu \in \{\mu, \kappa, \xi\}.$$



- Blend Bayesian Hierarchical Modeling (BHM) with Bayesian Model Averaging (BMA)
- Combine station data with other data types (e.g., modeled)
- Combine BHM derived spatial information expansion data into Bayesian analysis of the flood frequency hydrology concept

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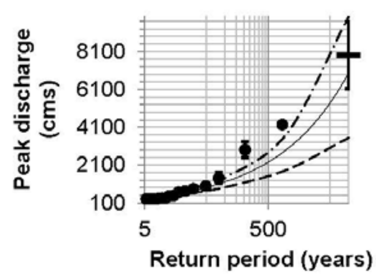
PFHA Framework For Riverine Flooding

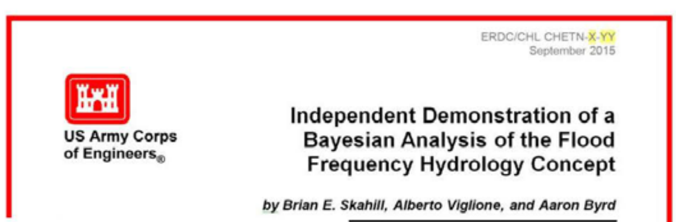
Probabilistic hydrologic hazard curve definition is based on the flood frequency hydrology concept (viz., extract the maximum amount of information from all available data sources – systematic data plus temporal/spatial/causal information expansion data), using formal Bayesian methods to flexibly combine the data.

BHM, BHM with BMA, BHM as spatial information expansion data in application of the flood frequency hydrology concept



How best to include causal information expansion data?

In cooperation with NRC technical staff, develop and demonstrate a set of riverine flooding scenarios that the framework must accommodate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J.F. England Jr. et al. / Journal of Hydrology 510 (2014) 228–245

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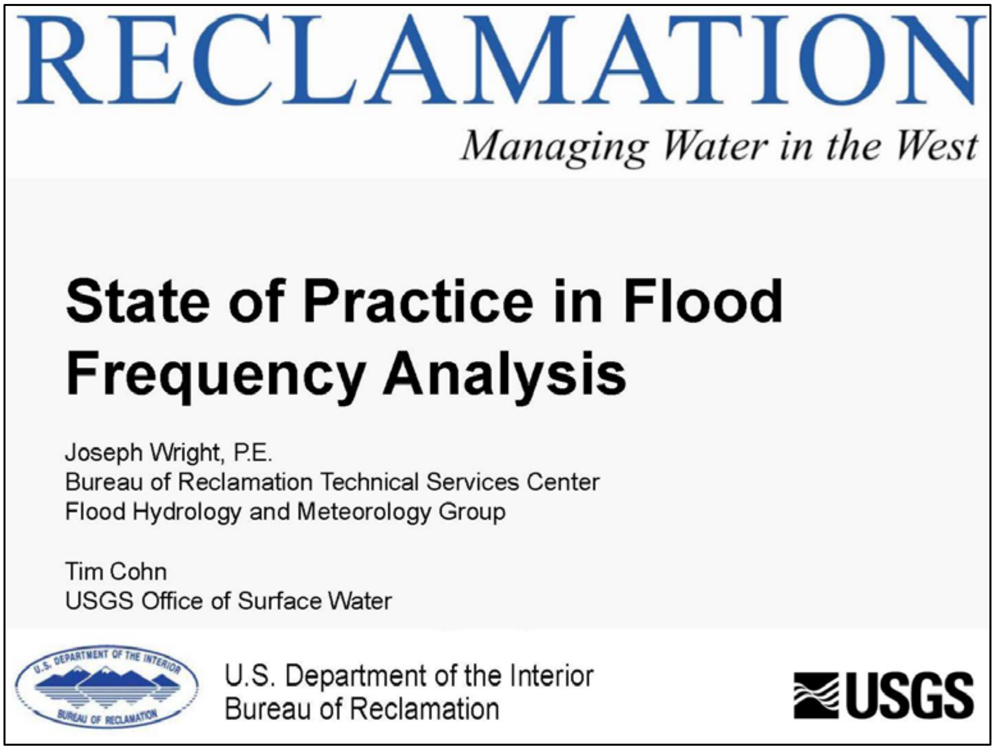
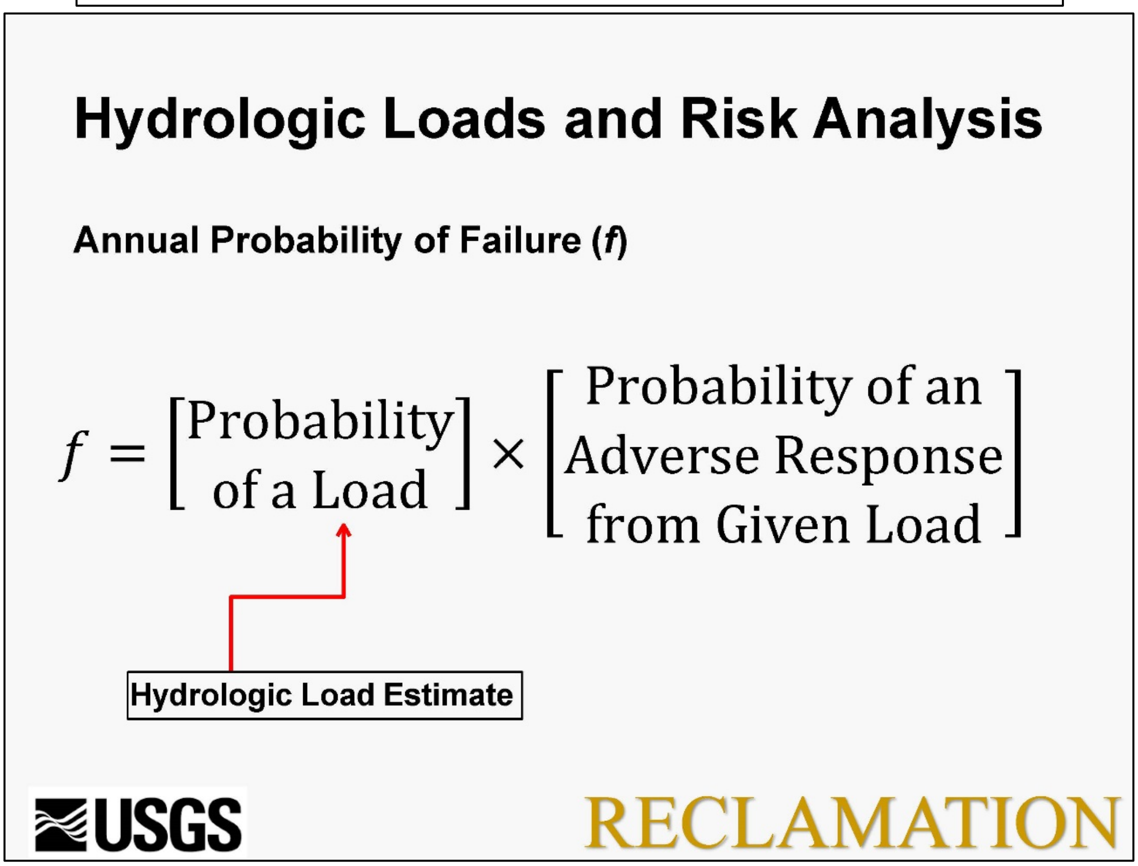
Thank you. Questions? Comments?

1.3.4.3 State of Practice in Flood Frequency Analysis. Timothy Cohn, USGS; and Joseph Wright, USBR





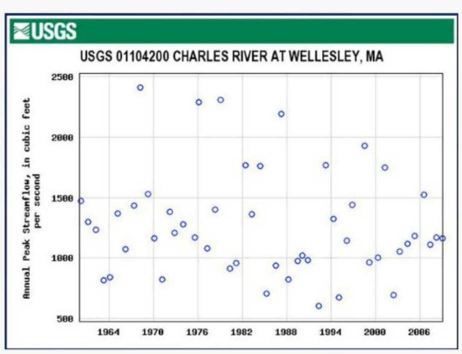
The Problem: Characterizing Flood Risk

- **In practice, flood-risk models, statistical or physical, depend on calibration data**
- **Existing “systematic” streamgage records are short with respect to events we want to describe**
- **Systematic data are expensive and accumulate slowly**
- **“Noah,” “Joseph” and “Nonstationarity” effects complicate problem**

USGS RECLAMATION 3

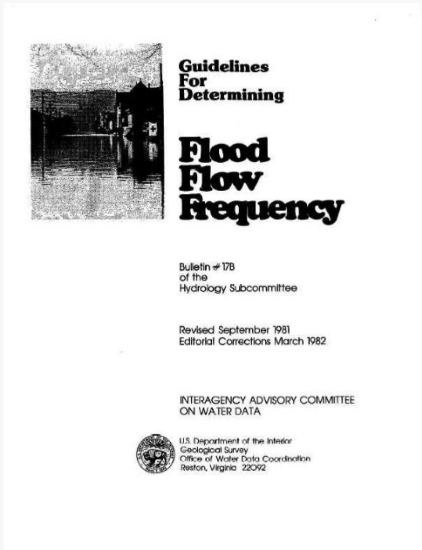
The Fundamental Challenge

- We Have *Short* Records of *Past* Floods
- We Want to Characterize *Future* Floods with *Long* Return Periods



USGS RECLAMATION

Bulletin 17B (1981)

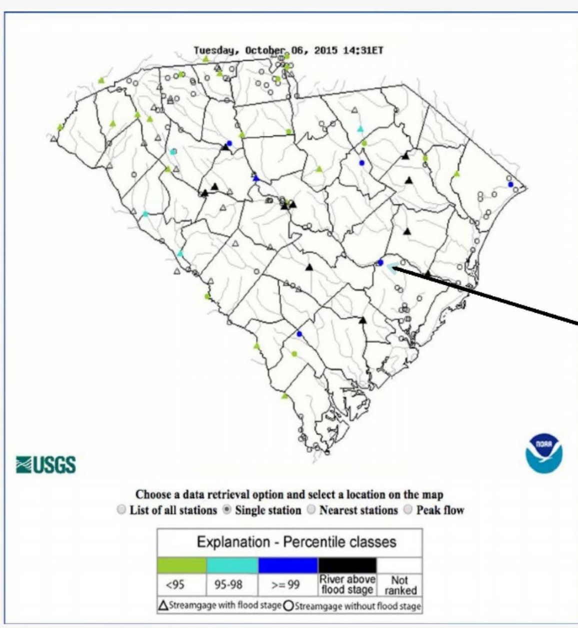

Guidelines For Determining
Flood Flow Frequency
Bulletin # 17B of the Hydrology Subcommittee
Revised September 1981
Editorial Corrections March 1982
INTERAGENCY ADVISORY COMMITTEE ON WATER DATA
U.S. Department of the Interior
Geological Survey
Office of Water Data Coordination
Reston, Virginia 22092

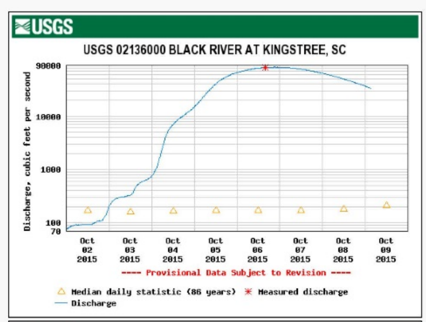
<u>Statistical Approach:</u>

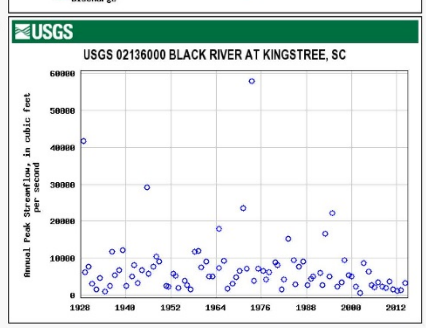
- Log-Pearson Type 3 Dist’n
- Method of Moments
- Regional Skew
- Procedures for Non-Standard Data
  - Weighted moments (Historical information)
  - Conditional Probability Adjustment (Low outliers, zero flows)
- Uncertainty (Confidence Limits)

USGS RECLAMATION

Statistical Approach
Black River at Kingstree (SC)







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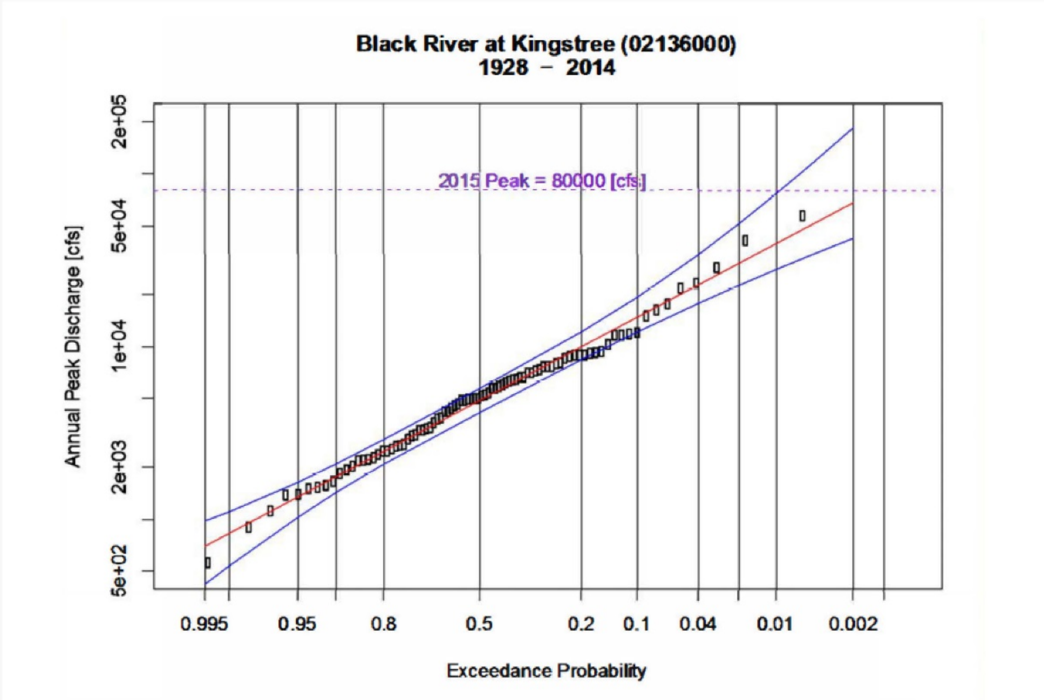

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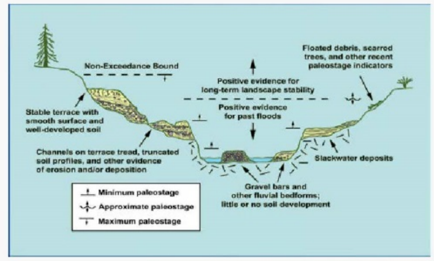
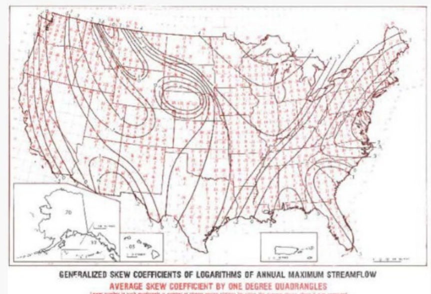
Improving the Precision of Statistical Flood Frequency Estimates

1. **Additional at-site data:**
   - Gage
   - Historical
   - Paleo
2. **Regional Information**
3. **Models**
   - Statistical
   - Process-oriented

USGS 9 RECLAMATION

At-Site and Regional Flood Information





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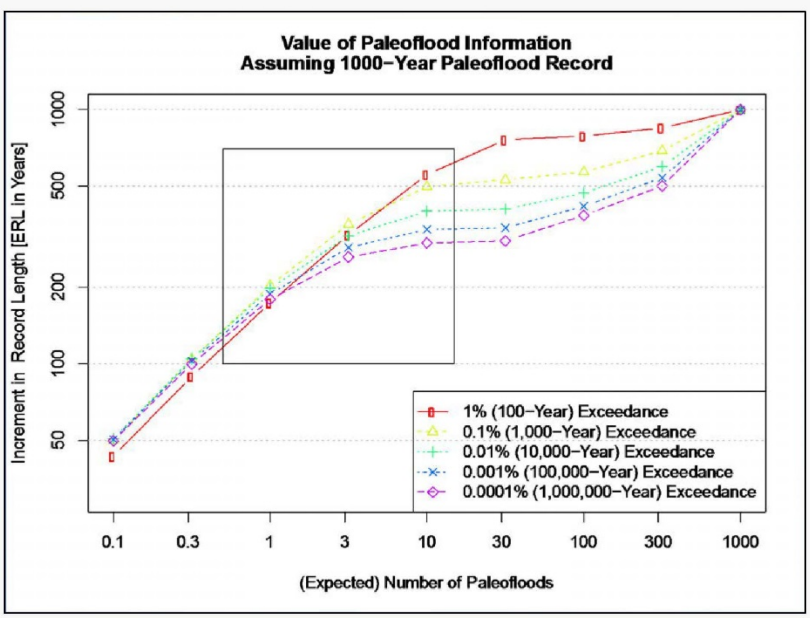
Benefit of Paleoflood Information



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Credible Extrapolation

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

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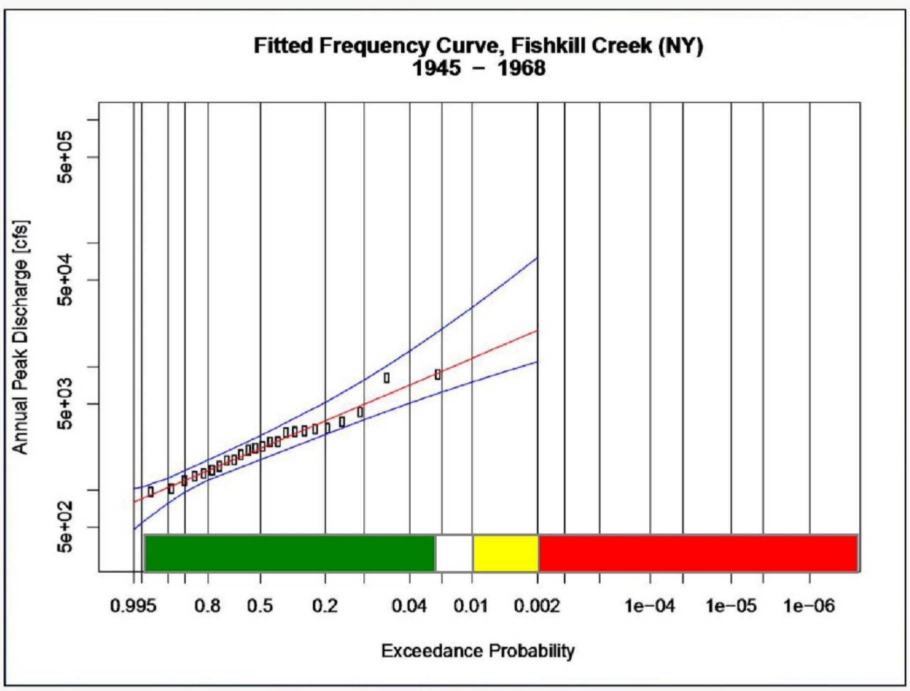

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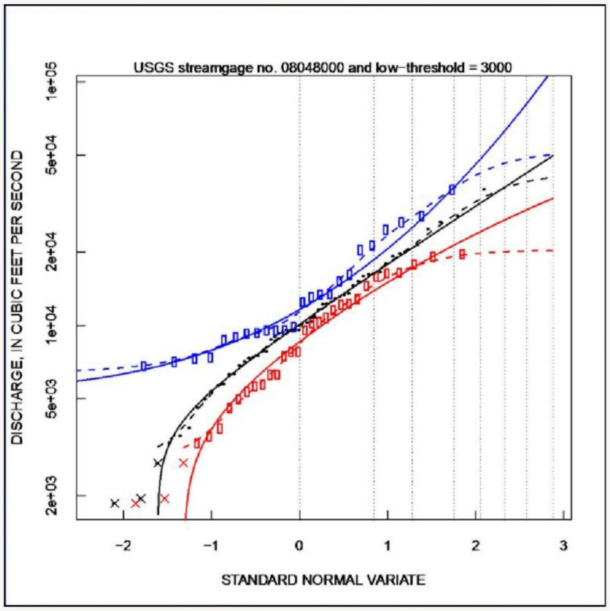
Mixed Populations



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Rainfall-Runoff Modeling

- USBR uses multiple methods. Typically a combination of a physical based model with a statistical component that analyzes historic (and prehistoric) streamflow
- USBR often considers a rainfall-runoff model to represent the extreme flood potential in a watershed that is typically controlled by snowmelt flooding

USGS RECLAMATION

Rainfall-Runoff Models

- Lumped (1-Dimensional)
  - HEC-HMS (HEC-1)
  - SAC-SMA
  - SWMM
- Quasi-Distributed
  - Hydrologic Runoff Unit (HRU) Approach
- Distributed (2-Dimensional)
  - Variable Infiltration Capacity (gridded)
  - WRF-Hydro
  - TREX

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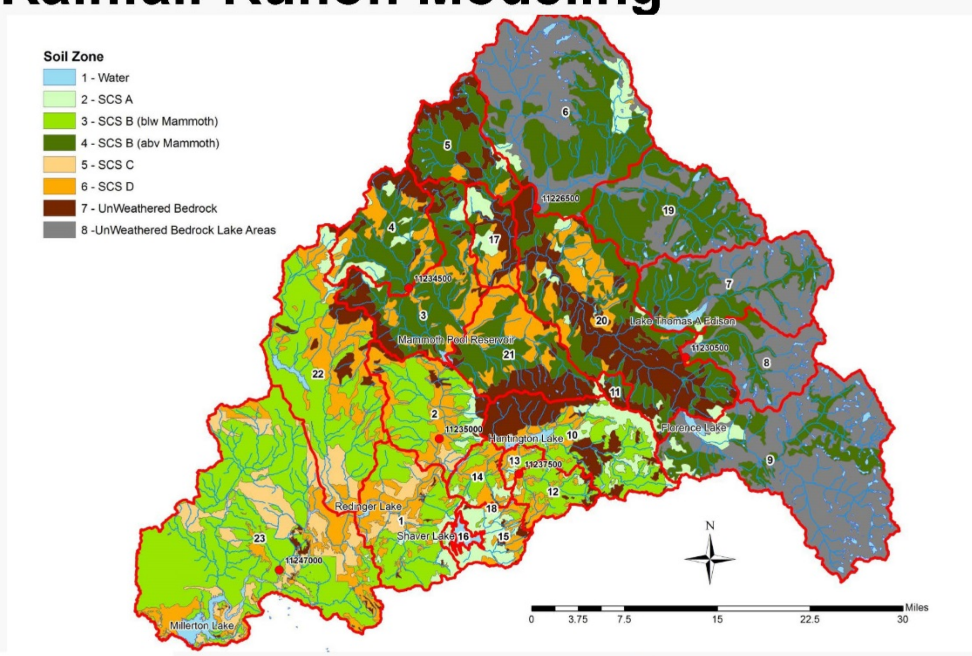
Rainfall-Runoff Modeling



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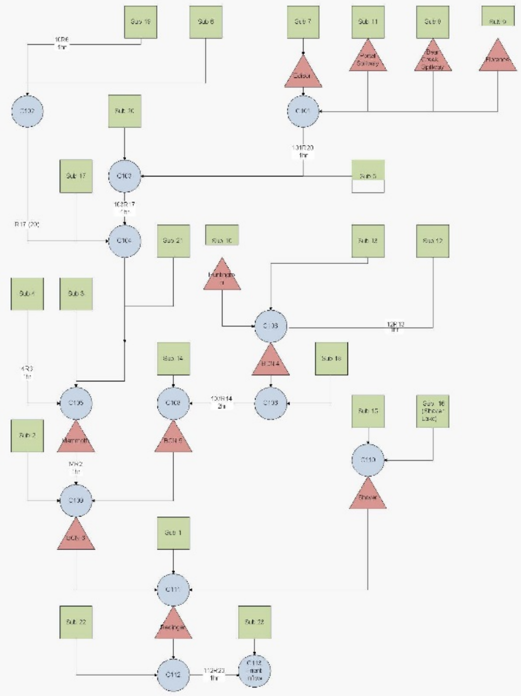
HEC-1

- *23 Sub-basins*
- *11 Routing Structures*
- *8 River Reaches*



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Rainfall-runoff modeling

- "AEP Neutral" – the flood event is equal to the probability of the precipitation event
- Stochastic Event – The probability of the flood event is a function of the combination of multiple conditions – Monte Carlo Simulation
- Combination of "AEP Neutral" and sampling methods. Although not stochastic, this method can be used to better capture the uncertainty

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Rainfall-Runoff Modeling

- Precipitation Frequency
  - Regionalized precipitation (L-moments)
  - Australian Rainfall-Runoff
  - NOAA Atlas 14
- Temporal
  - Derived from observed data
  - Design templates (SCS Type II, USBR 2/3, etc)
- Spatial
  - Derived from observed data (at-site, transposition)
  - Design templates (HMRs)
  - Modeled (WRF)

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How to use Paleoflood Data

- Paleoflood data can be combined with stream gage data to extrapolate peak discharge probabilities beyond the 1 in 100 AEP
- Graphical Approach
- Expected Moment Algorithm (EMA)
- Bayesian Maximum Likelihood (FLDFRQ3)

USGS RECLAMATION

Determining a pre-historic flood

- Flow Computation based on the stage determination from the field data
- Hydraulic modeling method is determined by the scope (and budget) of the study

1. Slope Conveyance using cross-section analysis
2. 1-dimension hydraulic model (HEC-RAS)
3. 2-dimension hydraulic model (HEC-RAS or SRH2D)

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Determining a Pre-historic Flood Age

- Most commonly this is done by radiocarbon analysis
- Archaeological information
- Botanical information
- Historical (outside of the gage record)
- Soil Development
- Other radiometric methods

- We assume the age of the material is equal to the age of the flood
- Uncertainty in analysis of material, and material itself (contamination)

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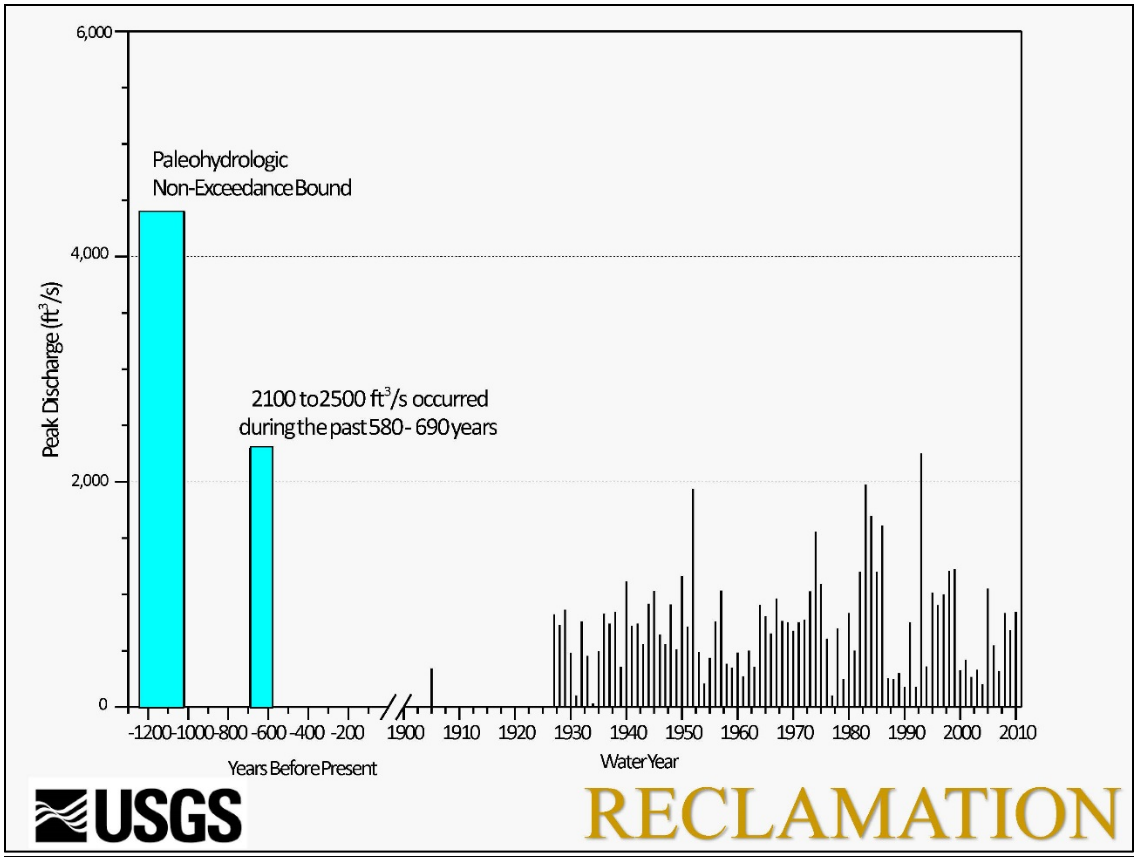
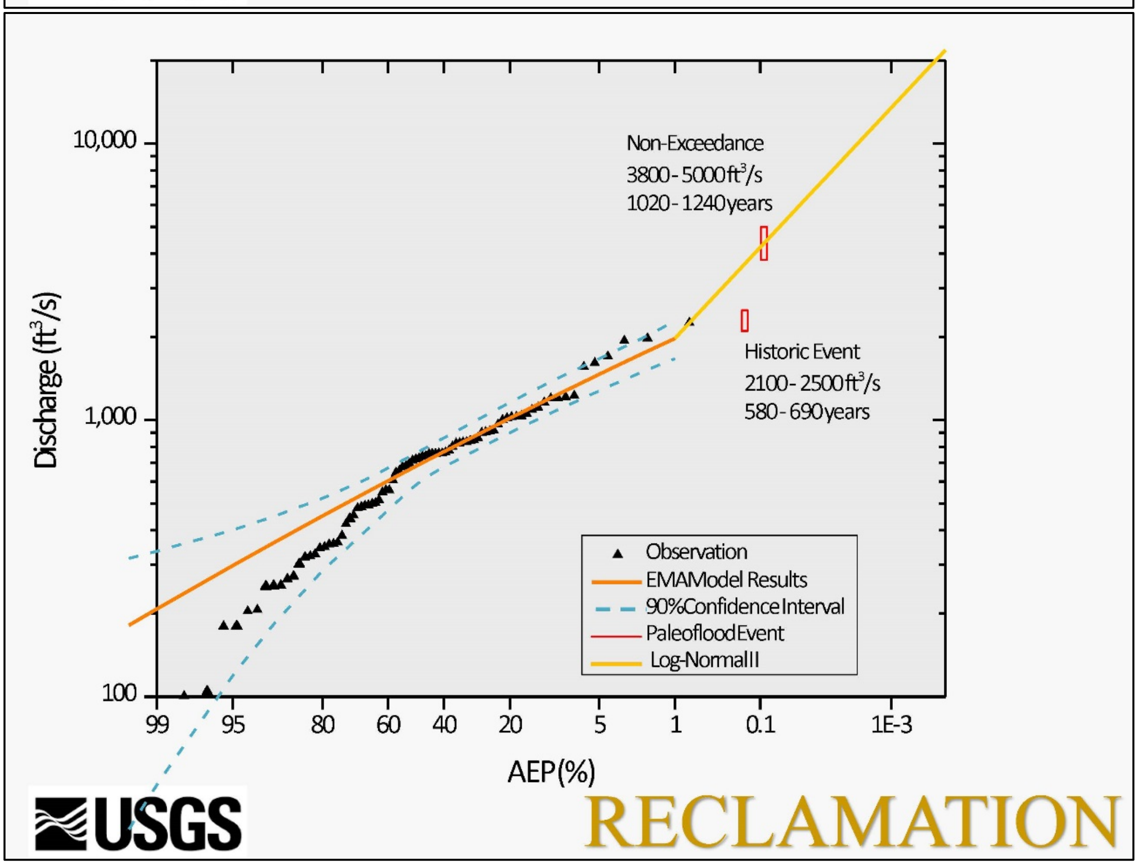

Paleohydrologic
Non-Exceedance Bound
2100 to 2500 ft³/s occurred
during the past 580 - 690 years
Peak Discharge (ft³/s)
6,000
4,000
2,000
0
-1200 -1000 -800 -600 -400 -200
1900 1910 1920 1930 1940 1950 1960 1970 1980 1990 2000 2010
Years Before Present
Water Year
USGS
RECLAMATION


Non-Exceedance
3800 - 5000 ft³/s
1020 - 1240 years
Historic Event
2100 - 2500 ft³/s
580 - 690 years
Discharge (ft³/s)
10,000
1,000
100
99 95 80 60 40 20 5 1 0.1 1E-3
AEP (%)
Observation
EMA Model Results
90% Confidence Interval
Paleoflood Event
Log-Normal II
USGS
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The Challenge of Nonstationarity

- Urbanization
- Landuse changes
- Encroachment on floodway
- Regulation (dams)
- Climate change

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Stationarity c. 1981 (Bulletin 17B)

IV. Data Assumptions

Necessary assumptions for a statistical analysis are that the array of flood information is a reliable and representative time sample of random homogeneous events. Assessment of the adequacy and applicability of flood records is therefore a necessary first step in flood frequency analysis. This section discusses the effect of climatic trends, randomness of events, watershed changes, mixed populations, and reliability of flow estimates on flood frequency analysis.

A. Climatic Trends

There is much speculation about climatic changes. Available evidence indicates that major changes occur in time scales involving thousands of years. In hydrologic analysis it is conventional to assume flood flows are not affected by climatic trends or cycles. Climatic time invariance was assumed when developing this guide.

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Stationarity Today


POLICYFORUM

CLIMATE CHANGE

Stationarity Is Dead: Whither Water Management?

P. C. D. Milly, Julio Betancourt, Malin Falkenmark, Robert M. Hirsch, Zbigniew W. Kundzewicz, Dennis P. Lettenmaier, Ronald J. Stouffer

Climate change undermines a basic assumption that historically has facilitated management of water supplies, demands, and risks.

An uncertain future challenges water planners.


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References and Notes

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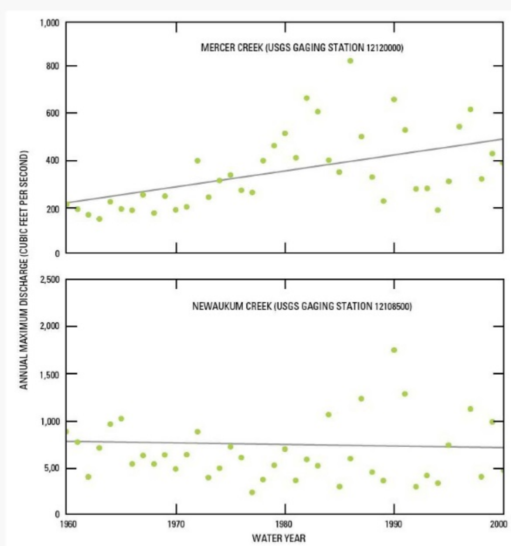
Impact of Development



Annual maximum discharge increased with urban development in Mercer Creek from 1960 to 2000, but remained essentially the same in nearby rural Newaukum Creek during that period.

[Konrad,2003]

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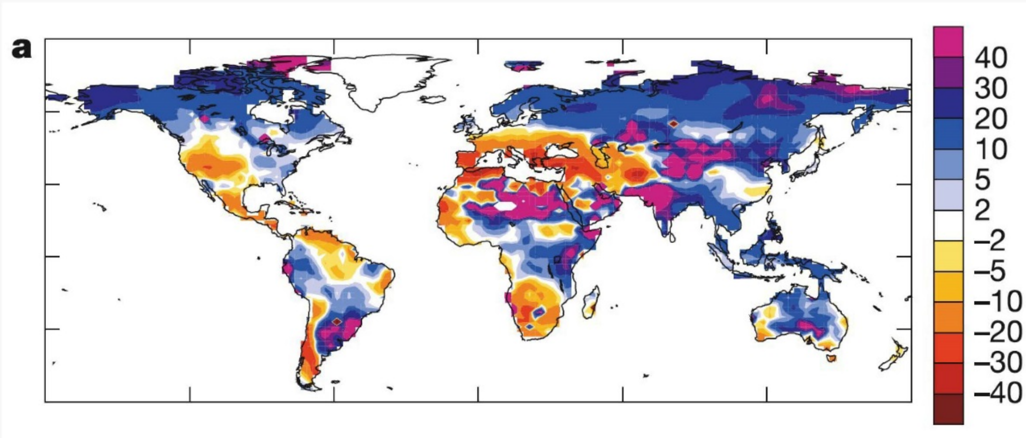
Projected Changes in 21st Century Runoff

100*(projected[2041-2060]-mean[1900-1970])/mean[1900-1970]



[Milly et al., 2005]

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But…
IPCC AR5 (Working Group I):

"While the most evident flood trends appear to be in northern high latitudes, where observed warming trends have been largest, in some regions no evidence of a trend in extreme flooding has been found, e.g., over Russia based on daily river discharge (e.g., Shiklomanov et al., 2007). Other studies for Europe (Hannaford and Marsh, 2008; Petrow and Merz, 2009; Renard et al., 2008) and Asia (e.g., Delgado et al., 2010; Jiang et al., 2008) show evidence for upward, downward or no trend in the magnitude and frequency of floods, so that *there is currently no clear and widespread evidence for observed changes in flooding* (except for the earlier spring flow in snow-dominated regions(Seneviratne et al., 2012a))."

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Conclusions

- Estimating flood risks associated with annual exceedance probabilities less than 10^{-3} is not easy
- Paleoflood information, regional information, and appropriate models greatly improve the precision of flood-frequency estimates
- Nonstationarity challenges all current flood-frequency estimation methods

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Questions?

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1.3.4.4 Quantification and Propagation of Uncertainty in Probabilistic Storm Surge Models

Norberto Nadal-Caraballo, Jeffrey Melby and Victor Gonzalez, USACE

First Annual NRC PFHA Research Program Workshop
North Bethesda, MD – October 14-15, 2015

ERDC
Engineer Research and Development Center

Quantification and Propagation of Uncertainty in Probabilistic Coastal Storm Surge Models

Norberto C. Nadal-Caraballo, PhD

Jeffrey A. Melby, PhD

Victor M. Gonzalez, PE

October 15, 2015

US Army Corps of Engineers

Quantification and Propagation of Uncertainty in Probabilistic Coastal Storm Surge Models

Background

- Part of U.S. NRC's Probabilistic Flood Hazard Assessment (PFHA) research plan.
- Support risk-informed licensing and oversight guidance and tools for assessment of flooding hazards at nuclear facilities.
- Evaluate uncertainty associated with data, models, and methods used in probabilistic **storm surge models** used for **coastal** flood hazard assessment.
- Flooding hazard expressed as hazard curves with confidence limits that represent uncertainty.
- Annual exceedance probabilities (AEPs) of interest for nuclear facilities; including AEPs that go beyond traditional state-of-practice in non-nuclear facilities (e.g., 10^{-4} to 10^{-6}).
- **Critical**: Quantify aleatory variability and epistemic uncertainty and uncertainty propagation.

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Quantification and Propagation of Uncertainty in Probabilistic Coastal Storm Surge Models

Storm surge models

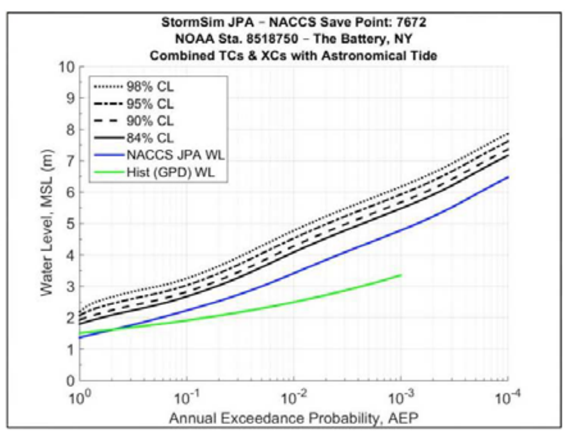
- Joint Probability Method with Optimal Sampling (JPM-OS) is standard-of-practice for quantifying flooding hazards of hurricane-prone coastal sites.
- Overcomes main limitation of measured water level EVA for areas impacted by tropical cyclones: underrepresentation of TCs in historical record.
- Significant JPM studies performed post-Katrina
  - IPET/LACPR (2007/2009)
  - FEMA Mississippi Coastal Analysis Project (2008)
  - North Carolina Coastal Flood Analysis System (2008)
  - USACE/FEMA Texas Coastal Study (2011)
  - USACE/FEMA Region III Storm Surge Study (2013)
  - FEMA Region II JPA (2014)
  - USACE North Atlantic Coast Comprehensive Study (2015)

Comparison of EVA (GPD) results with JPM

NACCS example:

The Battery, NY

- Temporal and spatial data limitations.
- Significantly lower water level for the same AEPs.
- Does not adequately cover entire AEP range of interest for nuclear facilities.

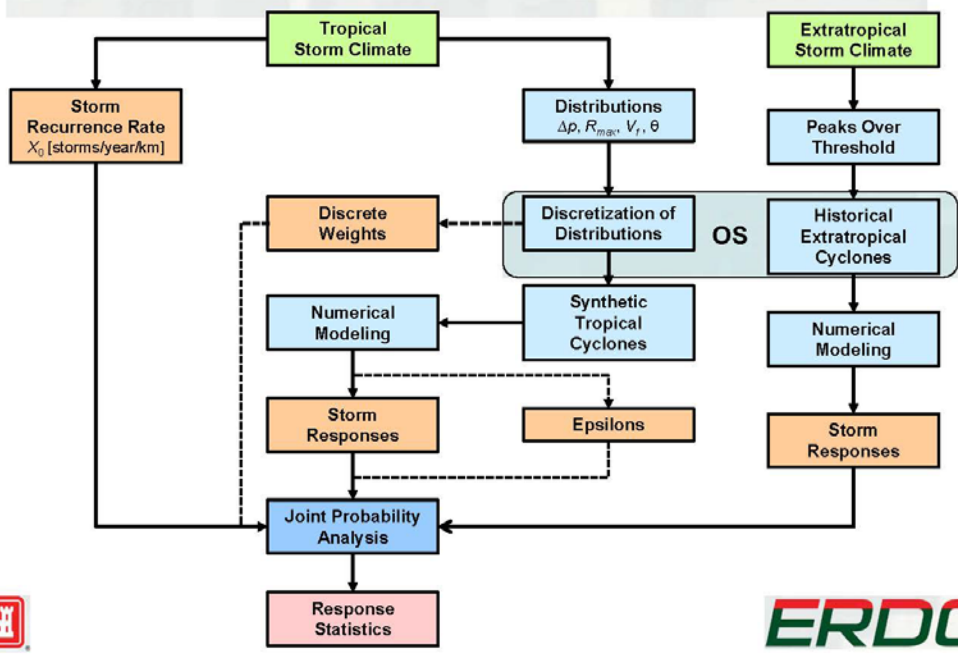


Joint Probability Method for TC

Principal elements of the joint probability method

- Historical storm climatology.
- Historical spatially varying storm recurrence rate (SRR).
- Storm parameterization.
- Storm parameter probability models (e.g., track location, heading direction, central pressure deficit, radius of maximum winds, translational speed, and maximum wind speed).
- Storm parameter distribution discretization.
- Synthetic storm set developed by sampling distributions and computing weights for each parameter combination.
- Synthetic storm meteorological and hydrodynamic simulation.
- Error estimation and other secondary terms.
- Joint probability integration to determine storm responses.

Example of JPM-OS application (NACCS)



Quantification and Propagation of Uncertainty

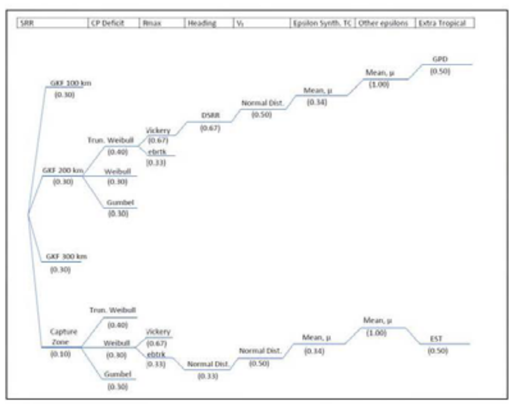
- **Types of uncertainty:**
  - ► Measurement uncertainty
  - ► Sampling uncertainty
  - ► Modeling uncertainty
    - Parametric uncertainty
    - Input uncertainty (boundary conditions)
    - Structural uncertainty (failure of model to represent system)
- **JPM-OS allows for alternate data, models, and methods, each with associated uncertainties:**
  - ► Data sources (e.g., HURDAT, synthetic tracks)
  - ► Meteorological and hydrodynamic models (e.g., PBL Model, ADCIRC)
  - ► Probability distributions (e.g., Weibull, Gumbel, Generalized Pareto)
  - ► Discretization methods (e.g., Bayesian Quadrature, Response Surface)

Quantification and Propagation of Uncertainty

Uncertainty Quantification - analyzed at two levels:

- ► Identification of technically defensible data sources, models, and methods.
- ► Assess whether estimates derived from different data, models, and methods need to be carried forward for evaluation of epistemic uncertainty, discarding those not considered technically defensible.

First level informs the latter.



Example of propagation of uncertainty through logic tree

Project Tasks

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

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Task 2: Epistemic Uncertainty in SRR Models

Task description

- Data sources and methods used for the computation of site-specific storm recurrence rate (SRR) models
  - Annual exceedance probability (AEP) of relevance to the design and operation of NPPs.
- Topics:
  - Technically defensible data sources for use in site specific studies (e.g., NOAA's HURDAT).
  - Appropriate models for estimation of SRRs (e.g., validity of Poisson distribution assumption).
  - Methods for screening historical data and assessing geographic variation in support of site-specific estimation of SRRs (e.g., Gaussian Kernel Function, capture zone).
  - Investigate whether SRR estimates derived from multiple datasets or methods need to be propagated.

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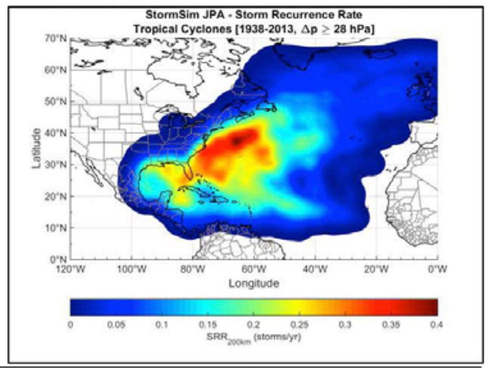
What is an SRR?

- Measure of the frequency with which a particular location is expected to be affected a TC.
- Typical units: storms/yr/km
- Can be stated as number of storms per year passing within a **radius** of ***x*** km, e.g., $SRR_{200\ km}$ (storms/year)



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Task 2: Epistemic Uncertainty in SRR Models

Background: SRR within JPM

- JPM integral:

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

$$\lambda_{r(\hat{x})>r} \approx \sum_{i}^{n} \lambda_i\, P[r(\hat{x}) > r|\hat{x}]$$

where $\hat{x}$ = f(x_o, *θ*, *Δp*, R_{max}, V_t), $\lambda_i = f(SRR)$, *and*
$P[r(\hat{x}) > r|\hat{x}]$ = conditional probability that storm *i* with parameters $\hat{x}_i$ generates a response larger than r

- Forcing vector $(\hat{x})$ typically includes:
  - Track location (x_o)
  - Heading direction (*θ*)
  - Central pressure deficit (*Δp*)
  - Radius of maximum winds (R_{max})
  - Translational speed (V_t)
  - Others: maximum wind speed (W_{max})

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Task 2: Epistemic Uncertainty in SRR Models

- Epistemic uncertainty of response (σ_r)
  - Expressed as confidence limits (e.g., NACCS approach):
    - $CL = \mu_r + z\sigma_r$, where CL = confidence limits, μ_r = mean value of a given TC response, and z = Z-score.
  - Response uncertainty (σ_r) incorporated into JPM integral:

$$\lambda_{r(\hat{x})\pm\sigma_r>r} \approx \sum_{i}^{n} \lambda_i \, P[r(\hat{x})\pm\sigma_r > r|\hat{x}]$$

  - Epistemic uncertainty associated with the implementation of alternate datasets, models, and methods.
    - Methods carried forward and propagation of uncertainty.
    - Family of hazard curves.
    - Mean hazard curve and fractiles.

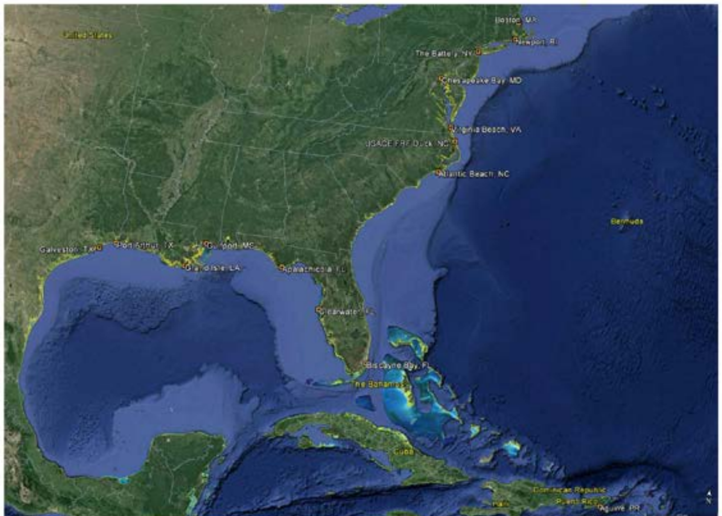
Task 2: Epistemic Uncertainty in SRR Models

Experiments

- Uncertainty comparison and quantification of two methods for the estimation of SRR.
  - Capture zone approach
  - Gaussian Kernel Function (Chouinard and Liu 1997)
- SRR variability related to selection optimal kernel size.
- SRR variability arising from selection of the period of record.
- SRR variability through the analysis of subsets of data through bootstrap resampling.
- Observation or measurement uncertainty in TC data.
- Effect of data partition (by TC intensity) on SRR uncertainty.

Task 2: Uncertainty in SRR Models

Coastal reference locations (CRLs) for uncertainty analysis



Methods for Estimating SRR

Uncertainty related to variation in kernel size

- **Capture Zone (CZ) Approach**
  - ***"Observed"* SRR**

$$SRR_{CZ} = \frac{N_{storms}}{T \times (2 \times R_{CZ})}$$

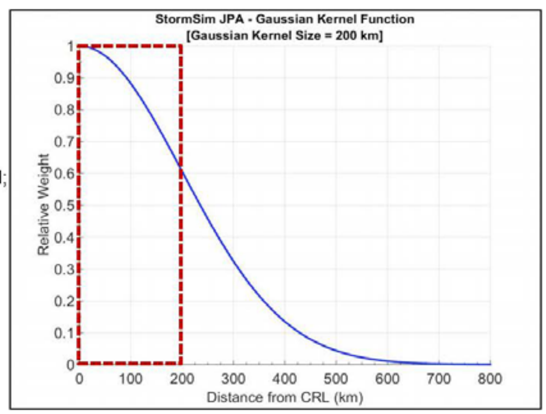
  - N_{storms} = number of storms in area enclosed by a circle capture zone; T = years in record; and R_{cz} = capture zone radius.

- **Gaussian Kernel Function (GKF) (Chouinard and Liu 1997)**
  - **Statistical model of SRR**

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

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

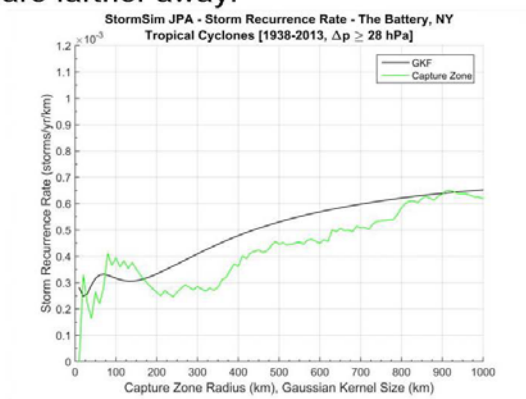
  - λ = SRR in storms/yr/km; T = record length (yr); $w(d_i)$ distance-adjusted weights from Gaussian PDF (storms/km); d_i = distance from location of interest to a storm data point (km); h_d = optimal kernel size (km).



Methods for Estimating SRR

Comparison of CZ approach and GKF

- Example: The Battery, NY
  - Smoothing effect of GKF
  - Higher GKF SRRs due to the consideration of storms which are farther away.



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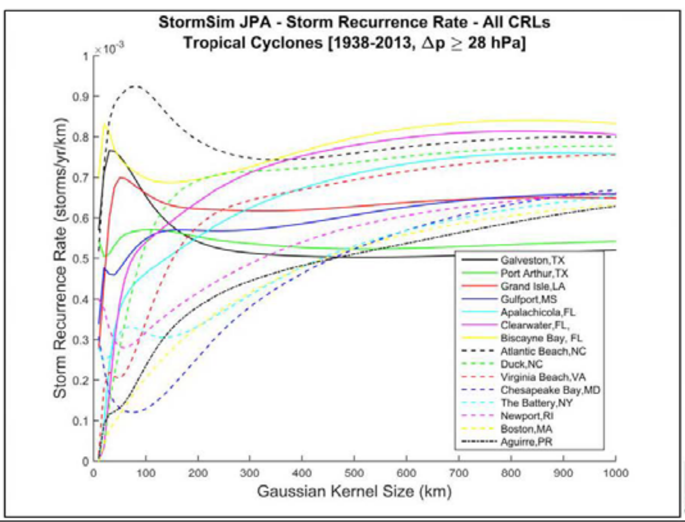
Methods for Estimating SRR

SRR versus GKF at 15 CRLs

- As expected, lower SRR occur at higher latitudes.



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Task 2: Epistemic Uncertainty in SRR Models

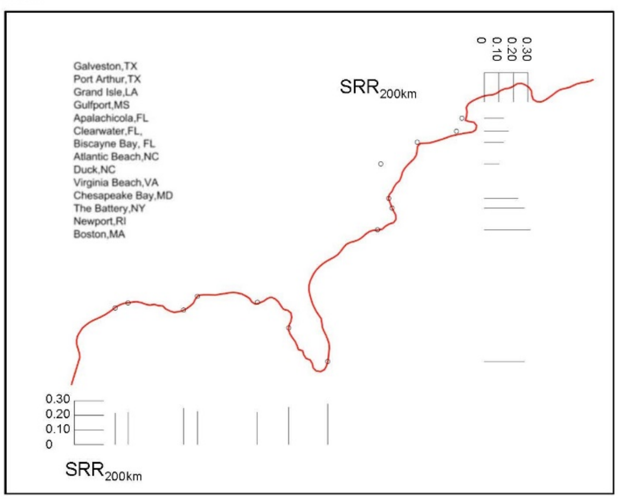
Findings

- The Gaussian Kernel Function was best method for conducting the SRR computational experiments compared to capture zone.
  - GKF can consider larger number of storms than capture zone approach.
  - For same ranges of optimal capture zone radii and Gaussian kernel sizes, GKF SRR estimates exhibited reduced coefficient of variation (CV) when compared to capture zone estimates.
- The lowest SRR uncertainties where observed in CRLs in North Carolina, Florida, Mississippi and Louisiana while the U.S. coast north of Virginia exhibited the largest uncertainties.
- Typically, larger samples result in a reduction of uncertainty and therefore in reduced sensitivity to model decisions.

Task 2: Epistemic Uncertainty in SRR Models

Findings (cont.)

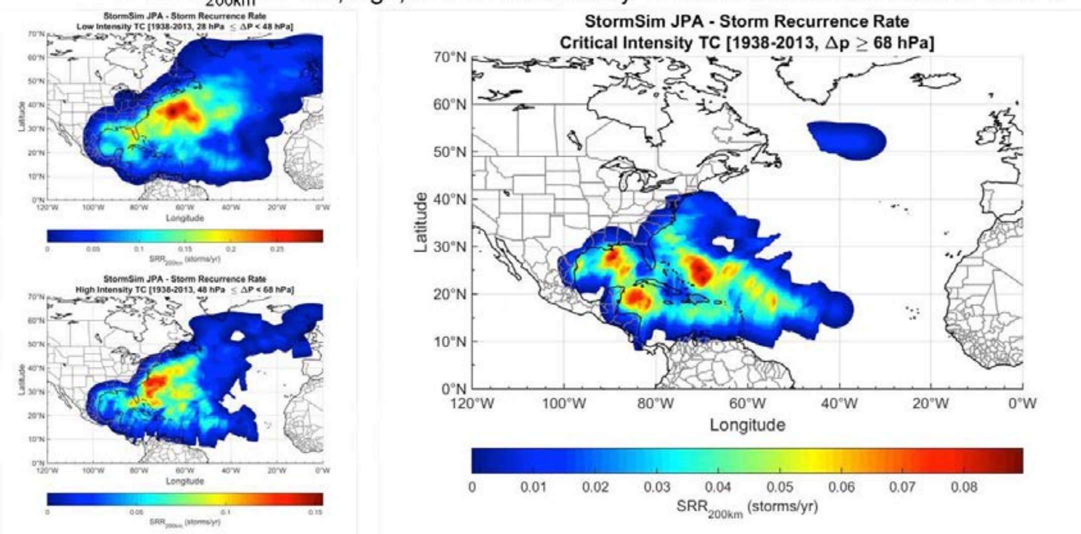
- SRR_{200km} considering all storms with Δp ≥ 28 hPa



Task 2: Epistemic Uncertainty in SRR Models

Findings (cont.)

- SRR_{200km} for low, high, and critical intensity TCs with CI lower threshold of 68 hPa



Task 2: Epistemic Uncertainty in SRR Models

Findings (cont.)

- Total uncertainty was calculated as

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

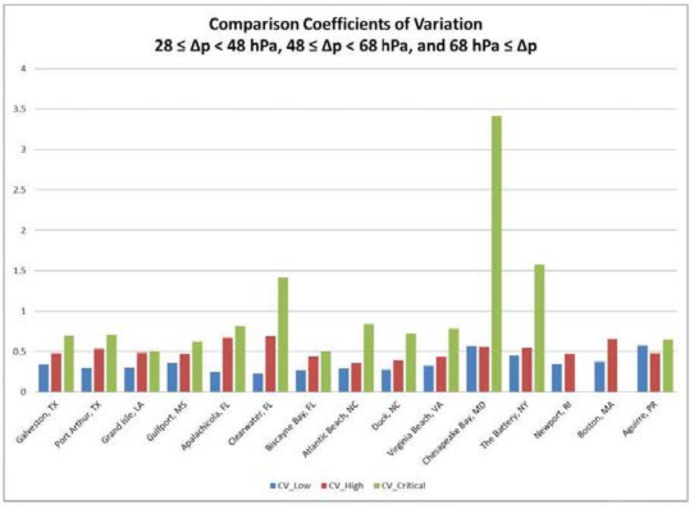
- For TCs with $\Delta p \geq 28$ hPa: Sampling uncertainty was the main contributor to total uncertainty followed by kernel size while observational uncertainty was the lowest contributor.

Type of Uncertainty	Percent of Total Uncertainty $\Delta p \geq 28$ hPa	Percent of Total Uncertainty 28 hPa ≤ Δp < 48 hPa	Percent of Total Uncertainty 48 hPa ≤ Δp < 68 hPa	Percent of Total Uncertainty $\Delta p \geq 68$ hPa
Sampling uncertainty	65	62	71	75
Period of record	19	12	12	7
Gaussian kernel size	15	14	3	4.1
Observational data	1	12	14	14

Task 2: Epistemic Uncertainty in SRR Models

Findings (cont.)

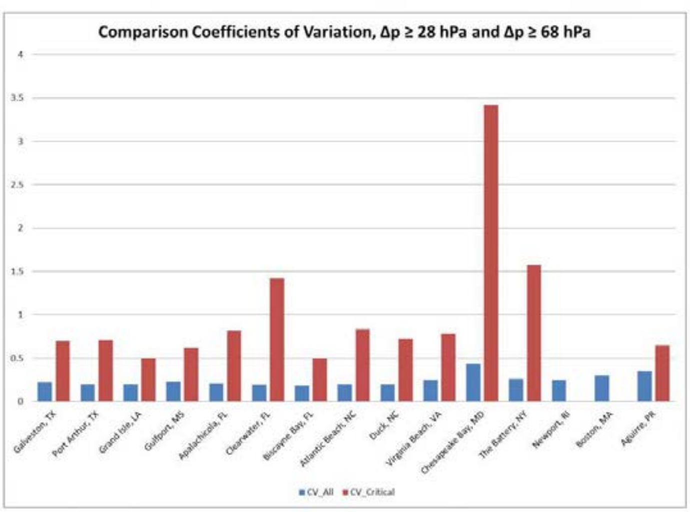
- Comparison of total CV for low, high, and critical intensity storms.



Task 2: Epistemic Uncertainty in SRR Models

Findings (cont.)

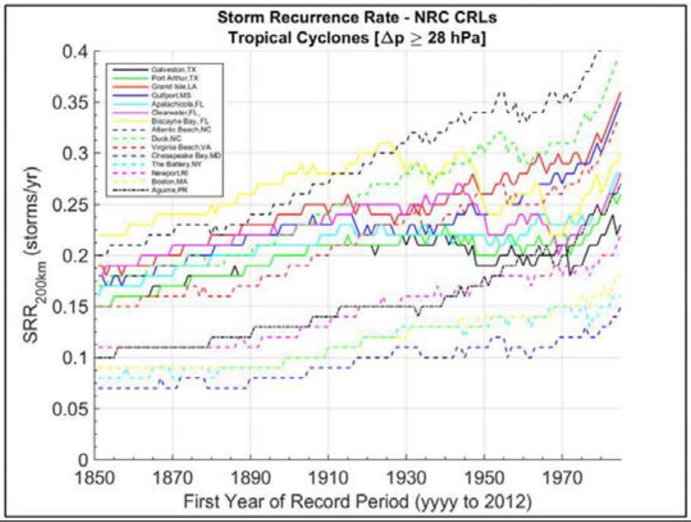
- Comparison of total CV of critical intensity storms and all storms.



Task 2: Epistemic Uncertainty in SRR Models

Findings (cont.)

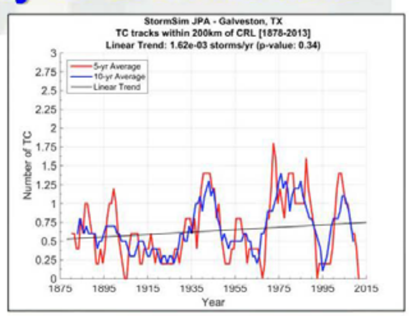
- Variation of $SRR_{200\ km}$ with record length.



Task 2: Epistemic Uncertainty in SRR Models

Findings (cont.)

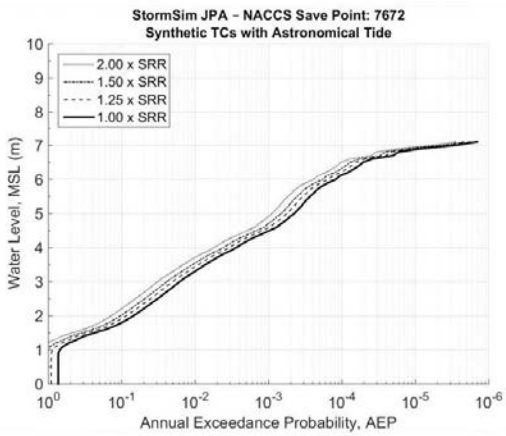
- Trends of TC counts calculated at each CRL using CZ radii of 200 km and 400 km and 5-year and 10-year moving averages were not found to be statistically significant.
- Effect on SRR of El Niño Southern Oscillation (ENSO) and La Niña.
  - Atlantic coast: SRR is noticeably higher in La Niña years.
  - Gulf of Mexico: in general, no significant differences are observed.

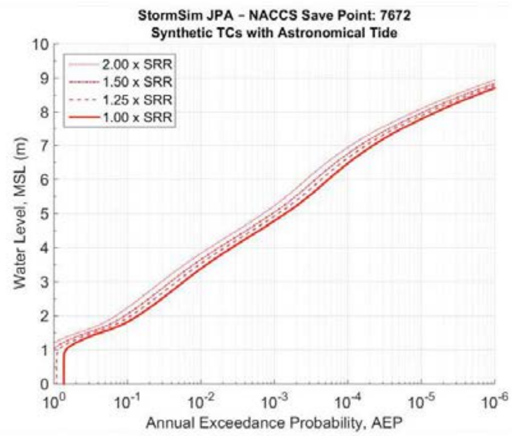


Coastal Reference Location	SRR_{200KM} Normal Year (storms/yr)	SRR_{200KM} Niño Year (storms/yr)	SRR_{200KM} Niña Year (storms/yr)
Galveston, TX	0.24	0.09	0.17
Port Arthur, TX	0.24	0.13	0.16
Grand Isle, LA	0.24	0.29	0.26
Gulfport, MS	0.18	0.31	0.27
Apalachicola, FL	0.19	0.25	0.23
Clearwater, FL	0.22	0.24	0.23
Biscayne Bay, FL	0.27	0.22	0.22
Atlantic Beach, NC	0.28	0.26	0.48
Duck, NC	0.26	0.21	0.45
Virginia Beach, VA	0.23	0.17	0.38
Chesapeake Bay, MD	0.10	0.05	0.19
The Battery, NY	0.10	0.10	0.21
Newport, RI	0.15	0.15	0.23
Boston, MA	0.10	0.11	0.21
Aguirre, PR	0.16	0.07	0.30

Task 2: Epistemic Uncertainty in SRR Models

Propagation of SRR uncertainty at the Battery, NY (SVPT 7672)





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

Task description (IN PROGRESS)

- Identify center, body, and range of technically defensible data and methods to characterize and quantify site-specific storm parameter joint probability.
  - Technically defensible data sources for use in site-specific studies (e.g. HURDAT, synthetic data sets, stochastic models, etc.)
  - Data screening methods for development of probabilistic distribution models and evaluate criteria for selecting storms from the historical record or a synthetic dataset.
  - Distribution models, associated uncertainties, parameter correlations, and adequacy of parameters in the JPM-OS integral.
  - Identify alternate data and methods and evaluate whether the derived estimates need to be considered to account for epistemic uncertainty.

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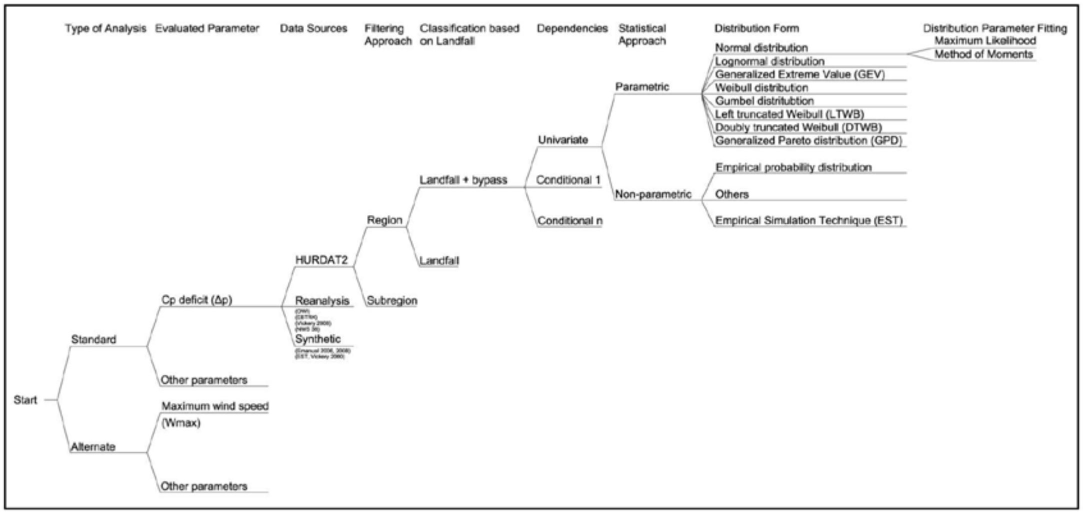
Task 3: Data, Models and Methods for Defining Joint Probability of Storm Parameters

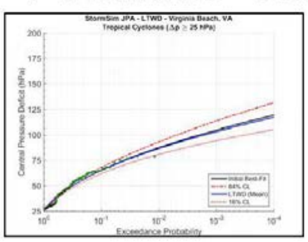
Logic tree approach:

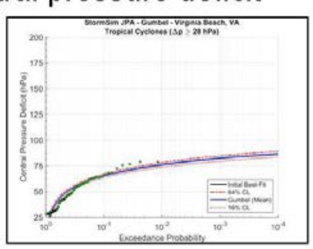


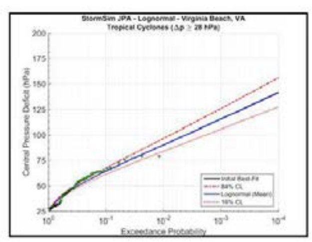
Task 3: Data, Models and Methods for Defining Joint Probability of Storm Parameters

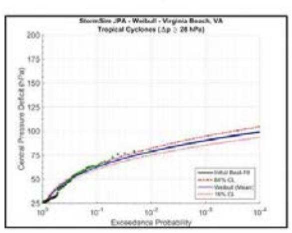
Applicability of statistical distributions

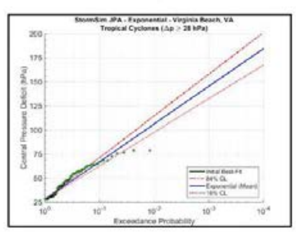
► Parametric – Central pressure deficit











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

RMSD

- ► Parametric distributions and empirical cumulative density function (up to 100 years)

CRL	RMS				
	Lognormal	Gumbel	Exponential	Weibull	LTWD
Galveston, TX	12.52	19.17	5.08	15.29	11.45
Port Arthur, TX	12.12	16.76	6.13	14.38	7.89
Grand Isle, LA	11.62	15.09	8.28	14.33	5.28
Gulfport, MS	14.51	16.63	10.08	16.12	6.95
Apalachicola, FL	6.70	12.29	4.56	10.97	5.78
Clearwater, FL	13.39	13.56	7.31	16.80	9.60
Biscayne Bay, FL	3.99	9.09	13.61	6.47	3.36
Atlantic Beach, NC	2.41	8.68	9.75	6.53	3.30
Duck, NC	6.47	3.56	17.00	3.90	4.04
Virginia Beach, VA	5.58	3.83	14.64	3.32	3.81
Chesapeake Bay, MD	2.68	6.24	13.92	3.56	2.95
The Battery, NY	2.86	6.64	10.27	5.75	2.48
Newport, RI	3.39	5.27	10.96	5.62	2.79
Boston, MA	3.76	6.04	8.98	5.96	3.43
Mean	7.29	10.20	10.04	9.21	5.22

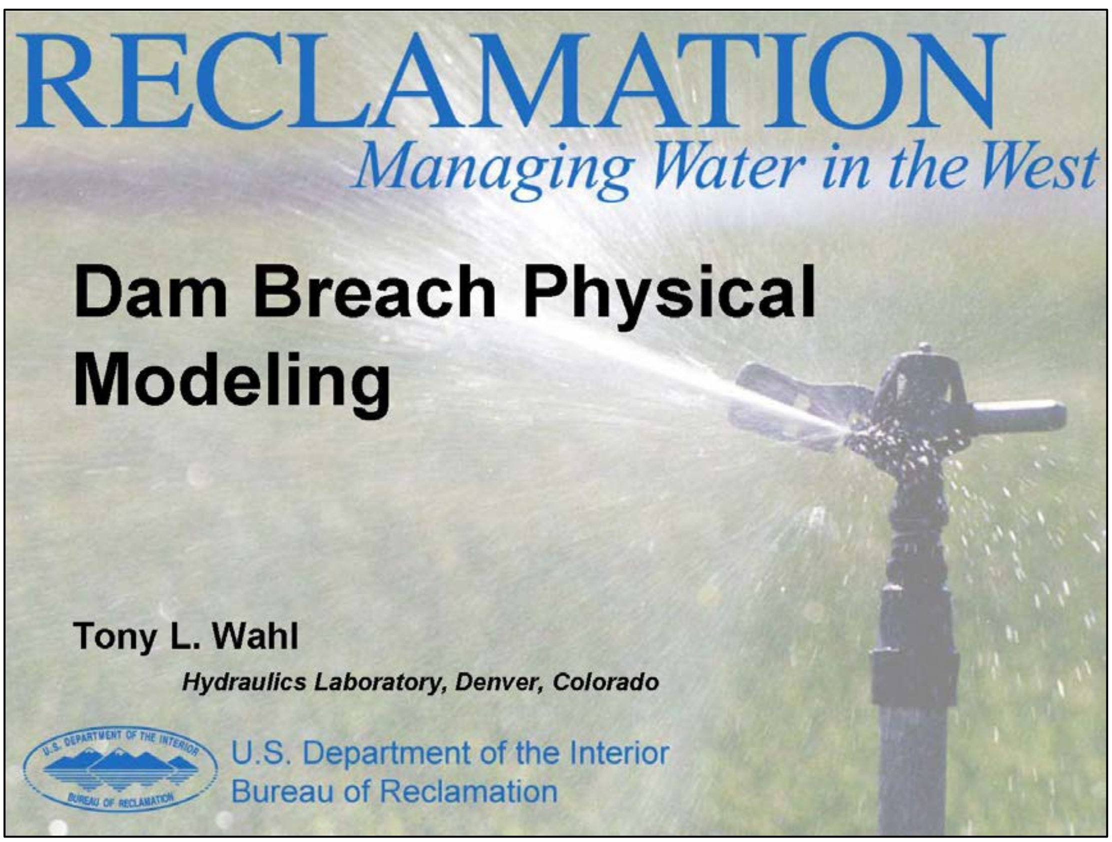
ERDC

Subsequent Task 3 Research

- Historical parameters (e.g., W_{max}, R_{max}, V_f)
- Synthetic data sets
  - ► Have been used in JPM studies as a source of parameter data.
    - Empirical track simulation models
      - ▷ Vickery et al. 2000
      - ▷ Emanuel et al. 2006
    - Downscaling models
      - ▷ GMC-CHIPS (Emanuel et al. 2006, 2008)
  - ► Synthetic tracks have been acquired for New York City (Provided by Dr. Ning Lin at Princeton University)
    - Data derived from downscaling model.
    - Used for study: Physically based assessment of hurricane surge threat under climate change. *Nature Climate Change*, 14 Feb 2012.

ERDC

1.3.4.5 USBR Dam Breach Physical Modeling. Tony Wahl, USBR



Bureau of Reclamation

- U.S. Department of the Interior agency, founded 1902
- 600+ dams and reservoirs and 8000+ miles of canals provide irrigation, municipal and industrial water in western U.S.
- We deliver 10 trillion gallons per year to 10 million acres and 31 million people in the West
  - 60 percent of U.S. vegetables and 25% of fresh fruit and nuts

2 RECLAMATION

Dam Breach Research Interest

- Lead dam-safety agency for most DOI dams
  - National Park Service, Fish & Wildlife
- Leaders in the development of risk-based approaches to dam safety

3 RECLAMATION

USBR Hydraulics Lab History

- 1930 – first hydraulic models tested at joint USDA / USBR facility – Ft. Collins, CO
- 1947 – Labs from several locations consolidated at Denver Federal Center
- Since 1995 we have been interested in better dam breach models

4 RECLAMATION

Dam Breach Research...

- Breach parameter prediction equations and their uncertainties
- CEATI Dam Safety Interest Group
  - Development and evaluation of new dam breach models (WinDAM and HR BREACH / EMBREA)
  - Evaluated methods for measuring soil erodibility
- Canal breach physical models and numerical modeling

5 RECLAMATION

Canal Breach Research

- 8,000+ miles of canals
- Many reaches are now in urban areas

6

RECLAMATION

Truckee Canal, Fernley NV
January 5, 2008
Internal erosion through muskrat holes

Truckee Canal, Fernley NV - January 5, 2008

(*The 9th known failure in this canal's operating history*)

RECLAMATION

September 30, 2012 – CAP Canal near Bouse, AZ

Arizona Daily Star

CAP

Rupture in CAP puts water in desert

Concrete-lining break could be fixed in three weeks, officials say

OCTOBER 03, 2012 12:00 AM • TONY DAVIS ARIZONA DAILY STAR

The Central Arizona Project, Tucson's main drinking water source, is shut down after the first break in its concrete canal in the project's 27-year existence.

The canal rupture, spanning nearly 500 square feet and discovered early Sunday, could be repaired in less than three weeks but might take longer, depending on the cause, CAP officials said Tuesday.

The break allowed about 400 to 500 acre-feet, or 130 million to 160 million gallons, of Colorado River water to escape into a desert wash about 27 miles east of where the canal begins at Lake Havasu. The 336-mile-long CAP aqueduct ends at Pima Mine Road, 14 miles south of Tucson.

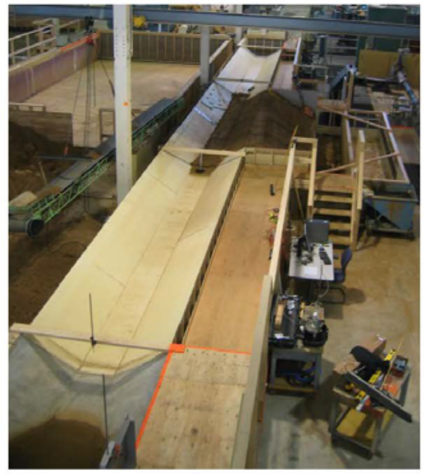
Internal erosion failure through uphill embankment…outflow restricted by culvert. Breach outflow into dry wash.

9

RECLAMATION

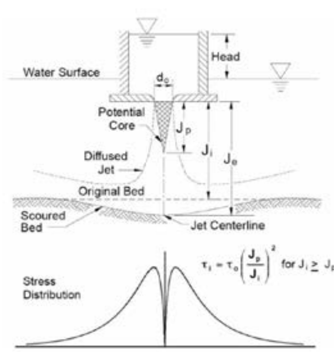
Canal Breach Modeling, 2010-2013

- **Physical models (4)**
  - Breaching processes
  - Effects of varying erodibility and initial conditions
- **HEC-RAS unsteady flow modeling**
  - Canal dynamics
  - How do limited conveyance and limited volume of a canal affect the breach outflow hydrograph?



10 RECLAMATION

Submerged Jet Test - Erodibility



11 RECLAMATION

Canal Breach Research Summary

- Four physical model tests were run
  - Wide range of erodibilities
- Created a spreadsheet model that predicts canal breach outflow hydrographs
- Now working to develop a procedure and guidance that can be used in our agency to assess and rank risks for our canal inventory
- Fourth test added geophysical instruments to detect internal erosion

12 RECLAMATION

Current Research

- Dam Safety Office is funding additional breach tests in a new facility
  - Continue studying breach processes
  - Additional testing of geophysical techniques for detecting internal erosion
- NRC: breaching of rockfill embankments
- USACE is also funding separate study focused on initiation of internal erosion through embankment cracks

13 RECLAMATION

New Dam Breach Test Facility

- 13-ft wide, 3-ft high embankment
- Inclined acrylic abutment
- Large tailbox to contain breach outflow

- Facility completed October 2014
- First test June 25, 2015

14

RECLAMATION

Test 1

- Homogeneous silty sand, internal erosion triggered at mid-depth
- k_d=5.5 ft/hr/psf 10 cm^3/(N-s) τ_c=0.0015 psf 0.07 Pa (Very erodible)

Test 1 – Downstream View

First Test

- **Objectives**
  - Shakedown of new facility
  - Test photogrammetry and geophysics techniques
- **General success**
  - Need to improve some flow and water level measurement issues
  - Photogrammetry worked well viewing through acrylic abutment
- **Observations of flow dynamics in "pipe" entrance were very interesting**

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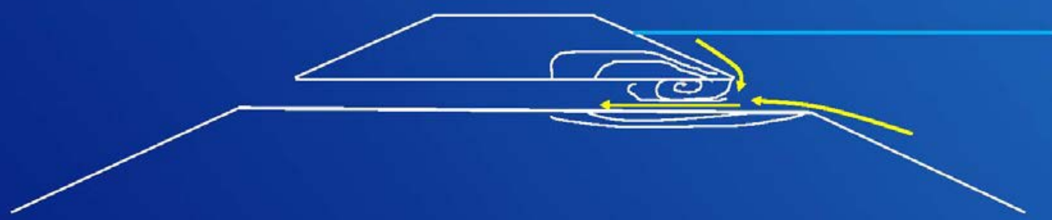
RECLAMATION

Flow at pipe entrance



RECLAMATION

18

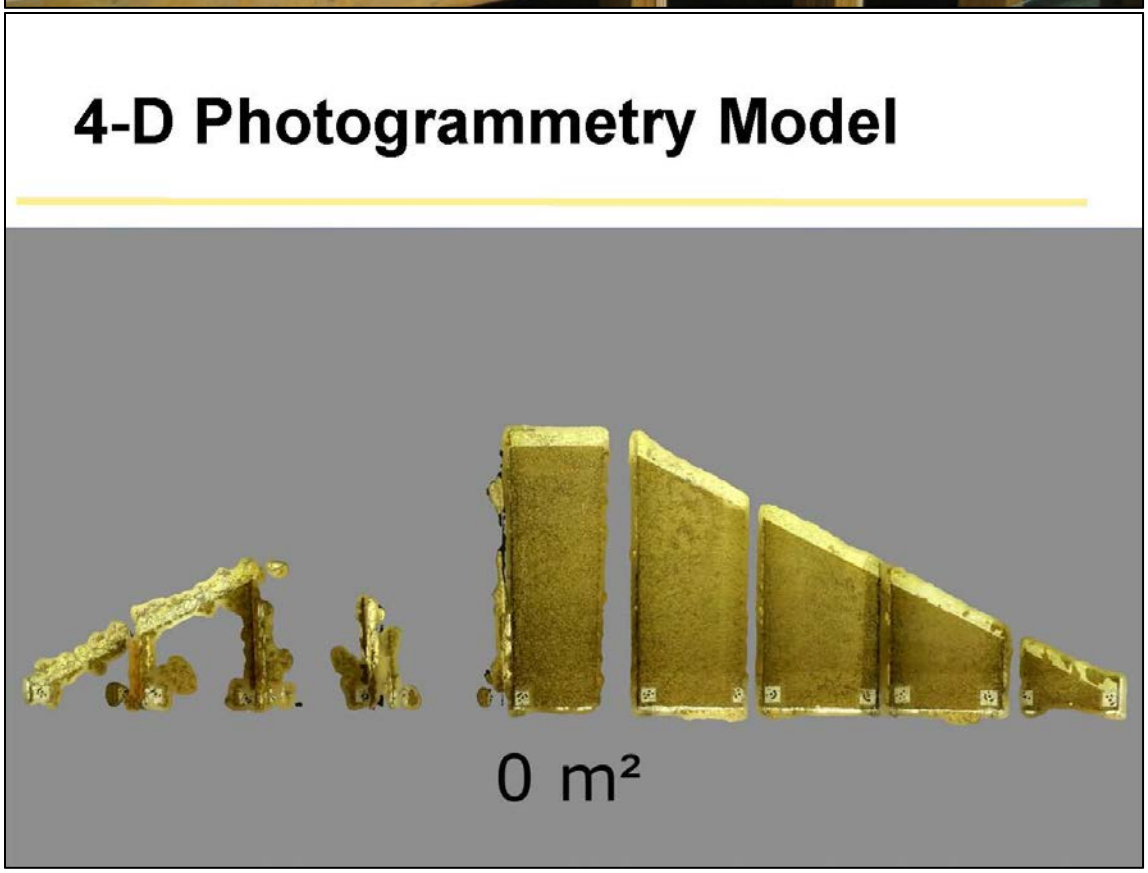
Video clip...

- **Show here the video time-lapse of still photographs from camera position #5**
  - **Presently having trouble getting Powerpoint to accept this file**
  - **(show in separate application)**

RECLAMATION

19


RIGIDLAM LVL


4-D Photogrammetry Model
0 m²

Upcoming Work

- Planning to model test 1 numerically with beta version of WinDAM C and with EMBREA
  - WinDAM C is a physically-based dam breach model from USDA
  - EMBREA is latest version of HR BREACH (HR Wallingford)
  - Flow measurement data from test 1 was not as good as we wanted, but we can still make some comparisons to breach development rate
- Next physical test is planned to be rockfill dam

22

RECLAMATION

Dynamic Similitude

- Our tests do not represent any specific prototype structure at a specific scale ratio
- Our embankments are large enough that we have similar erosion processes to prototypes
  - Some geotechnical processes are not perfectly modeled (e.g., mass collapse of side slopes) because our soils have similar strength as a prototype (should have lower strength)

23

RECLAMATION

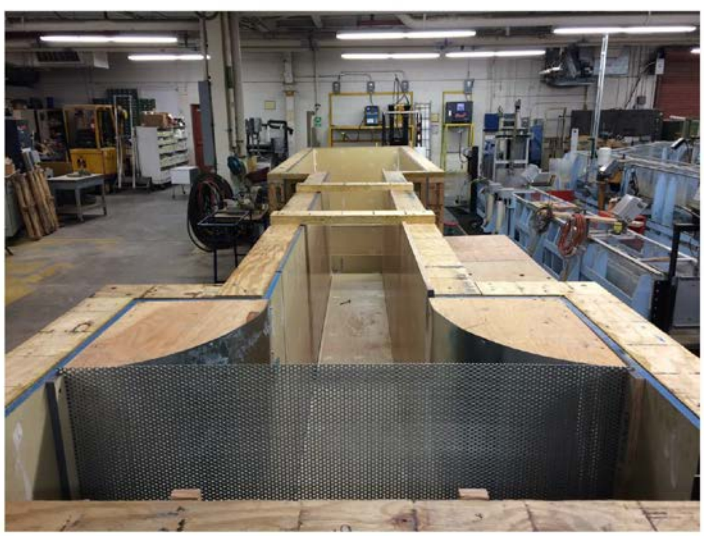
Dynamic Similitude

- In a typical Froude-scaled model, time is compressed by L_r
  - For example, in a 1:16 scale model, events should take place in ¼ of prototype time
  - But, this only applies to erosion rates if erodibility parameters are also scaled in accordance with Froude scaling laws
    - Rate coefficient higher by $L_r^{1/2}$ and τ_c lower by L_r
  - Our tests are representative of the Froude-scaled performance of prototypes that contain stronger materials

24

RECLAMATION

Related Work - Cracked Embankment Erosion Test (CEET) facility funded by USACE



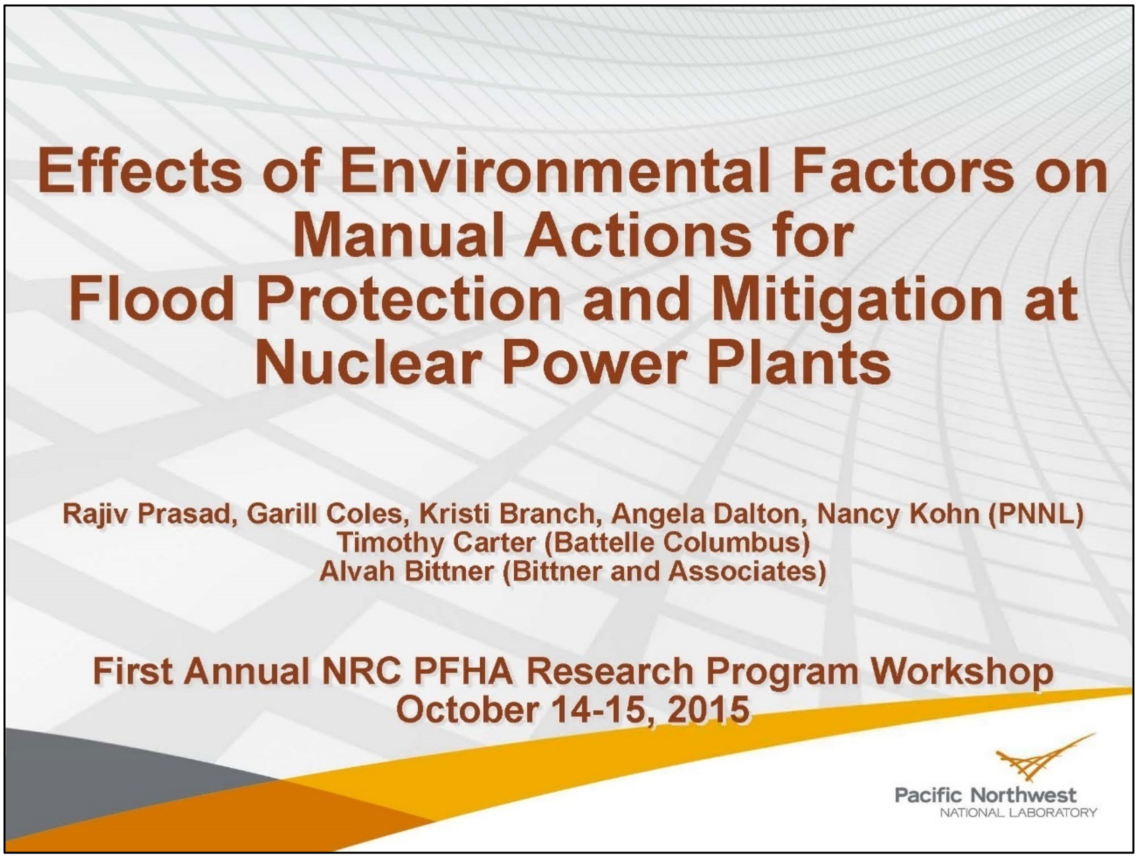
RECLAMATION

RECLAMATION

1.3.5 Day 2: Session V: Plant Response to Flooding Events

The final technical session switched from a focus on flooding hazard assessment to NRC-funded research related to evaluating risk from flooding hazards (i.e., reliability of flood protection features and nuclear power plant responses to flooding events). A team from PNNL, Battelle, and B&A presented its work to develop a framework for assessing the impacts of environmental conditions on manual actions for flood protection or mitigation. Researchers from Idaho National Laboratory (INL) discussed efforts to develop site-specific “flood hazard information digests” to support rapid assessment of risk significance for flooding events. Other INL researchers presented a dynamic probabilistic risk assessment framework to assess plant risk from flooding using a local intense precipitation event test case. Finally, NRC staff presented the outline of a proposed project to develop a protocol for assessing the reliability of nuclear power plant flood penetration seals.

1.3.5.1 Effects of Environmental Factors on Flood Protection and Mitigation Manual Actions. Rajiv Prasad, Garill Coles, Kristi Branch, Angela Dalton and Nancy Kohn, PNNL; Timothy Carter, BCO; and Alvah Bittner, B&A



Overview

- Effects of environmental factors on manual actions for flood protection and mitigation at nuclear power plants
  - Duration: 9/22/2014 – 9/30/2016
  - Key PNNL staff: Kristi Branch, Garill Coles, Angela Dalton, Nancy Kohn, Rajiv Prasad
  - Key Collaborators: Timothy Carter (BCO), Alvah Bittner (Bittner and Associates)
  - Key NRC staff: Valerie Barnes, Joseph Kanney, Jacob Philip
- Project scope
  - Review technical literature on effects of environmental conditions on human performance
  - An extension of NUREG/CR-5680, The Impact of Environmental Conditions on Human Performance, Volumes 1 and 2 (1994)
  - Consider environmental conditions that could occur during a flood and the manual actions taken to prepare/respond

2

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Key Concepts

- Key concepts
  - Consider flooding events that trigger manual actions (MAs)
    - A range of flood-causing mechanisms (FCMs) and their combinations
  - Consider environmental factors (EFs), environmental conditions (ECs), and MAs
  - Develop a framework to assess the impact of ECs on MAs
    - Characterization of MAs
    - Characterization of potential ECs
    - Characterization of impacts of ECs on MAs
  - Site-specific application of the framework
    - Accounting for site-specific FCMs
    - Accounting for site-specific ECs coincident with floods
    - Accounting for effects of site-specific topography and facility layout
    - Evaluating effects of (site-specific) ECs on (site-specific) MAs

3

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Literature being reviewed

- Characterization – Extent
  - Touches on all flood-related ECs
  - Comprehensively attends to manual handling tasks
  - Addresses operational vs. lab orientation
- Characterization – Nature
  - Integrated literature reviews and meta-analyses as frames for individual research studies
  - Emergence of brain imagery and directed cognitive task mixes as means to understand associated impacts on performance
  - Emphasis on operational applications
- Characterization – Ongoing process
  - Integrative review of current and still growing document-base
  - Identification of the most informative and useful framework (e.g., Classical Pictorial Overlays, and/or Pro-IMPACT, and/or other?)

4

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Literature Being Reviewed

- Sources
  - Military
  - Industrial
  - Flood response
  - Emergency response
  - Human Factors Engineering
  - Academic studies
  - Meta-Analyses
  - General studies
  - Aviation
  - Oil and Gas
  - Maritime
  - Foundry
  - Commercial Truck Drivers

5

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Definitions

- **Environmental factor (EF)**
  - An environmental phenomenon (e.g., from weather) that could exist during a flood of interest with a potential to affect human performance.
- **Environmental condition (EC)**
  - The condition of an environmental factor at the time a manual action is being performed.
- **Flood of interest**
  - A flood resulting from an event that would trigger initiation of flood-protection procedures at a nuclear power plant.
- **Primary EC**
  - An EC that does not require any other condition in order to affect performance. Examples: heat, cold
- **Secondary EC**
  - An EC that would not occur without one or more primary ECs. Examples: slippery surface, mud

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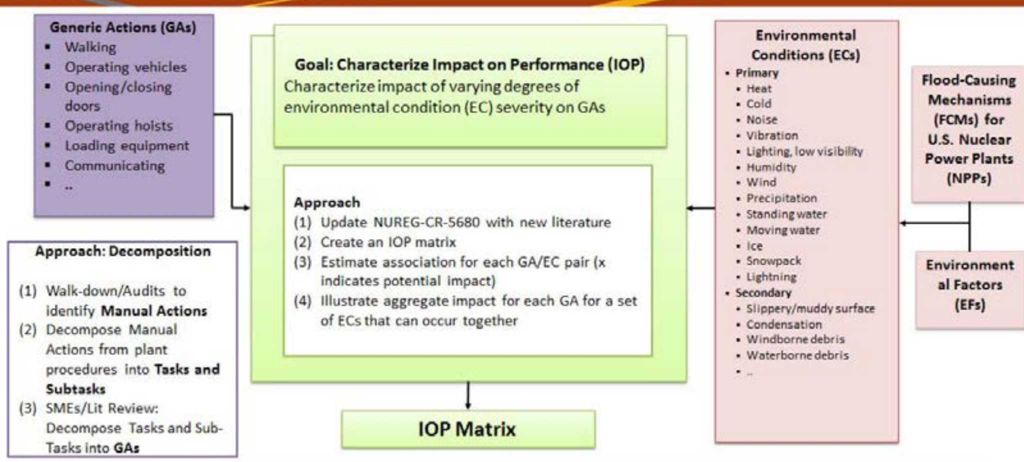
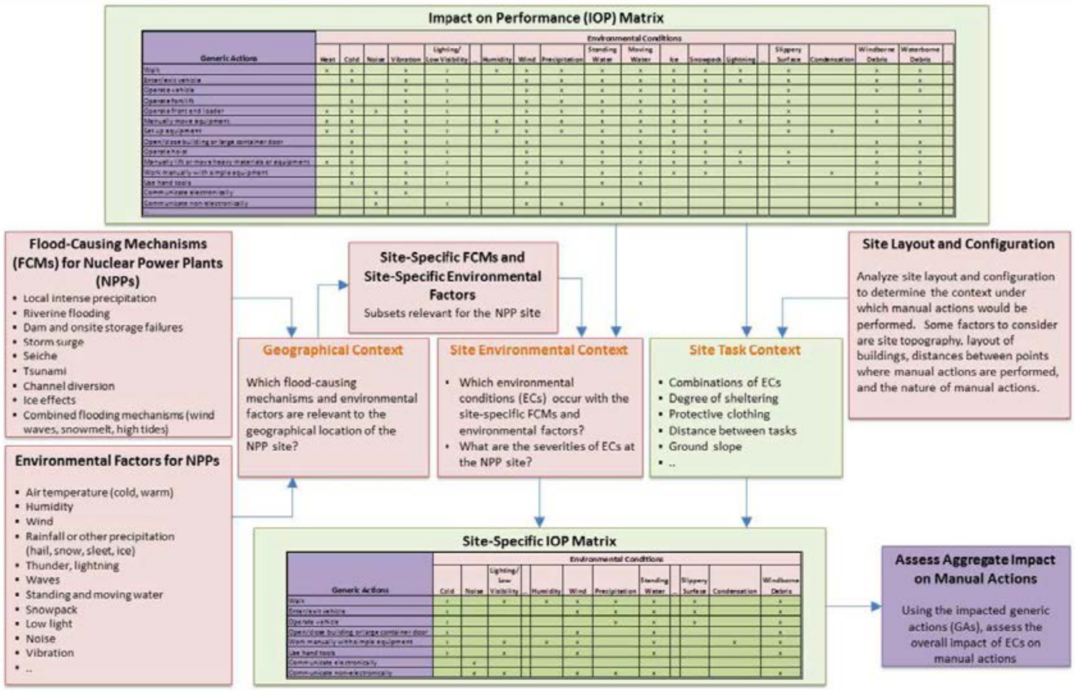
The Framework



Generic Actions	Heat	Cold	Noise	Vibration	Lighting/ Low Visibility	..	Humidity	Wind	Precipitation	Standing Water	Moving Water	Ice	Snowpack	Lightning	..	Slippery Surface	Condensation	Windborne Debris	Waterborne Debris	..
	Environmental Conditions																			
Walk	x	x		x	x		x	x	x	x	x	x	x	x		x		x	x	
Enter/exit vehicle		x		x	x			x	x	x	x	x	x	x		x		x	x	
Operate vehicle				x	x			x	x	x	x	x	x			x		x	x	
Operate forklift		x		x	x			x	x	x	x	x	x			x				
Operate front end loader	x	x	x	x	x			x	x	x	x	x	x			x		x	x	
Manually move equipment	x	x		x	x		x	x	x	x	x	x	x	x		x		x	x	
Set up equipment	x	x		x	x		x	x	x	x	x	x	x			x	x			
Open/close building or large container door		x		x	x			x		x	x	x	x					x	x	
Operate hoist		x		x	x			x		x	x	x	x	x		x		x	x	
Manually lift or move heavy materials or equipment	x	x		x	x			x	x	x	x	x	x	x		x		x	x	
Work manually with simple equipment		x		x	x			x		x	x	x	x				x	x	x	
Use hand tools		x		x	x			x		x	x							x	x	
Communicate electronically			x	x																
Communicate non-electronically			x		x			x	x	x	x							x	x	

RY

Site-Specific Application of the Framework



Identifying Environmental Conditions Associated with Floods of Interest

- Considered a range of flood-causing mechanisms, including combinations
  - NUREG-0800, ANSI/ANS-2.8-1992, NUREG/CR-7046
- Developed a list of EFs
  - List retains the five EFs considered in NUREG/CR-5680: heat, cold, noise, vibration, lighting
  - Additional EFs generally related to meteorological phenomena: precipitation, wind, humidity, ice, standing or moving water, snow
  - May or may not co-occur with floods of interest at a site
- Developed a list of ECs
  - Considered effects that EFs would cause during floods of interest
    - Example: during a local intense precipitation event, a site could develop standing and moving water
    - Deep standing water or rapidly moving water can affect performance

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Environmental Conditions

Flood-Causing Mechanisms	Environmental Factors that Could Co-Occur with Floods of Interest	Environmental Conditions that Could Affect Manual Actions
		Primary Environmental Conditions
Local Intense Precipitation	Cold	Cold
Streams and Rivers	Heat	Heat
Dam or water-storage structure failure	Humidity	Relative Humidity
Storm surges and seiches	Precipitation (rain, sleet, hail, snow)	Precipitation Type and Intensity
Tsunamis	Wind	Wind Velocity
Ice dams or jams	Thunder	Noise Level
Channel diversion or migration	Lightning	Water Depth
	Standing water	Water Velocity
Conditions Contributing to Combinations of Flooding Mechanisms	Moving water	Vibration Frequency and Intensity
	Waves	Lighting Level / Low Visibility
Concurrent wind-induced wave activity	Outdoor light level	Presence of Ice
Antecedent or subsequent precipitation	Ice	Snow Depth
Snowpack	Snow	Presence of Lightning
Dam failure concurrent with riverine flood		**Secondary Environmental Conditions**
Earthquakes		Slippery/muddy surfaces
Concurrent high tides		Condensation
		Windborne debris
		Waterborne debris

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Environmental Conditions

Flood-Causing Mechanisms	Environmental Factors that Could Co-Occur with Floods of Interest	Environmental Conditions that Could Affect Manual Actions
		Primary Environmental Conditions
Local Intense Precipitation	**Cold**	Cold
Streams and Rivers	**Heat**	**Heat**
Dam or water-storage structure failure	**Humidity**	**Relative Humidity**
Storm surges and seiches	**Precipitation (rain, sleet, hail, snow)**	**Precipitation Type and Intensity**
Tsunamis	**Wind**	**Wind Velocity**
Ice dams or jams	**Thunder**	**Noise Level**
Channel diversion or migration	**Lightning**	**Water Depth**
	Standing water	**Water Velocity**
Conditions Contributing to Combinations of Flooding Mechanisms	**Moving water**	Vibration Frequency and Intensity
	Waves	**Lighting Level / Low Visibility**
Concurrent wind-induced wave activity	Outdoor light	Presence of Ice
Antecedent or subsequent precipitation	Ice	Snow Depth
Snowpack	Snow	**Presence of Lightning**
Dam failure concurrent with riverine flood		**Secondary Environmental Conditions**
Earthquakes		**Slippery/muddy surfaces**
Concurrent high tides		**Condensation**
		Windborne debris
		Waterborne debris

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Combinations of Environmental Conditions

- Exposure to multiple ECs more likely than not
  - Combinations already considered in effects literature
    - Cold temperature + wind (wind chill)
    - Heat + humidity (heat index)
    - Noise + vibration
  - Other ECs could co-occur, e.g., heavy precipitation, strong wind, poor lighting or visibility, elevated noise, deep standing water
  - Combinations are topic of interest in ongoing literature review
    - Some challenges
      - Differences in terminology
      - Possible combined effects other than just additive
      - Changes in ECs over time as the manual action proceeds, importance of the changes

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12

Characterization of Manual Actions

- Manual actions are defined as actions taken away from the Main Control Room
- Key assumptions
  1. Differences between/among individuals are minimal
  2. Staffing levels are appropriate and adequate
  3. Procedures are established and appropriate
  4. Staff are provided with and know how to use necessary equipment
  5. Staff are trained
  6. Staff are fit for duty
- It is not within the project scope to attempt to measure or estimate the contribution associated with extreme situations or address fear, stress, and fatigue, or other physiological and psychological effects

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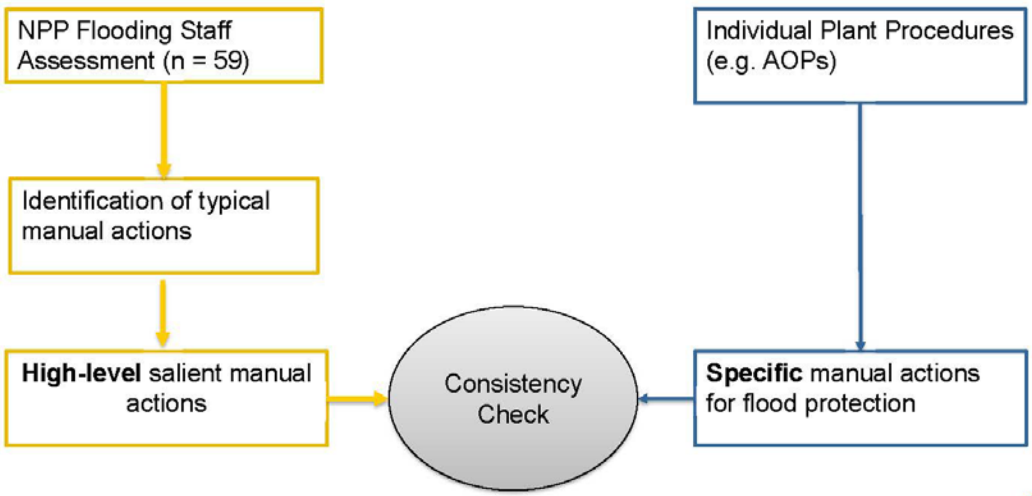
13

Characterization of Manual Actions

- To identify and describe typical manual actions performed at NPPs, a two-pronged approach was employed



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Characterization of Manual Actions

- Manual actions identified from staff assessments
  - Performed or partially performed outside facility
    - deploy sandbags and build berms
    - place flood barriers
    - close doors, gates, hatches, and manhole covers
    - secure drains, close valves, and seal openings
    - setup and operate portable pumps and sumps
    - equalize pressure (open doors, weight floor)
    - seal fuel vents and cover air intakes
    - monitor leakage, hazards, weather, and debris
  - Performed inside facility
    - de-energize and adjust electrical power
    - operate installed plant sump or pump systems
    - connect piping spool or electrical jumper

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Characterization of Manual Actions

- Manual actions identified from plant procedures
  - construct a sandbag barrier, berm, or levee around structure
  - plug or seal drains
  - remove or relocate equipment (e.g., fire equipment, security equipment)
  - stage diesel storage tanks or tankers
  - monitor and clear debris from traveling screen at the intake structure
  - bolt or weld steel plates over door openings
  - bolt or weld steel plates over floor drains, penetrations, and hatches
  - seal structural gaps
  - relocate, install, and operate diesel pump
  - relocate, install, and operate additional electric- or gas-driven sump pumps
  - route sump pump discharge lines
  - position or secure hatch cover
  - monitor water level
  - monitor intake screens for plugging
  - fill the lube oil dump tank with water
  - remove the drive motor and install a hand crank (e.g., traversing the rake)
  - provide diesel fuel and gasoline to power pumps
  - scarify or rip concrete and asphalt surfaces under levee
  - seal all conduits
  - plug manholes
  - rent/obtain watercraft
  - remove/block ventilation ducts
  - cap discharge line an drain line
  - secure two ladders
  - install electrical jumpers

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Decomposing Manual Actions

- Decomposition [of a manual action]
  - The analysis of a manual action into tasks, subtasks (if necessary), and generic actions for the purpose of assessing the impact of environmental conditions on human performance.
- Task [and subtasks]
  - One step of a manual action that has a distinct outcome or pre-determined objective contributing to accomplishment of the manual action. A task generally requires both motor and cognitive abilities.
  - Cues were taken from literature (Annett 2013) about level of detail
- Generic action (GA)
  - An individual component of a task or subtask that can be evaluated for impact on human performance. GAs are general in nature and function as “building blocks” used to determine the impact of ECs on the overall Manual Action.

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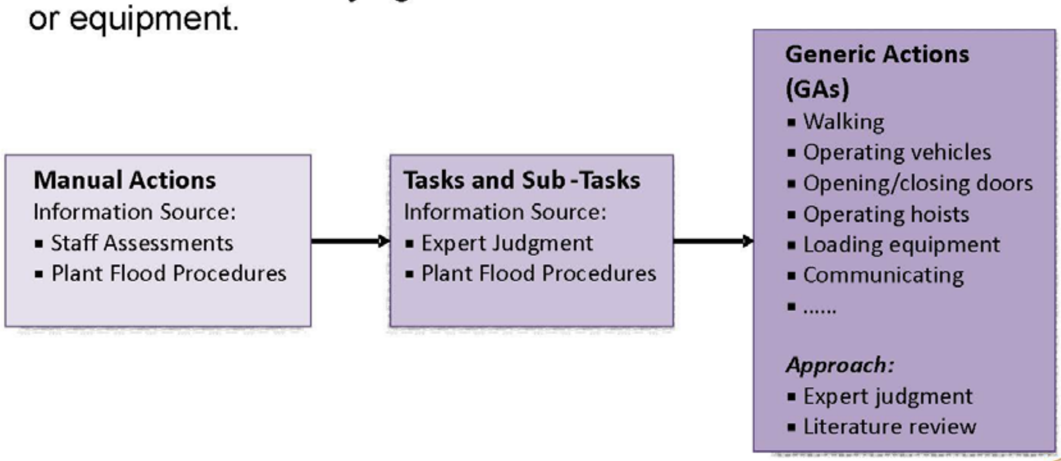
Decomposing Manual Actions

- Manual actions are often complex, consisting of multiple steps, involving sequential movements or a combination of motor and cognitive functions and processes, and requiring more than one task location and varying levels of automation and/or need for tools or equipment.



Decomposing Manual Actions

- Team initially tried to develop Elemental Actions based on basic physical movements – but reconsidered
  - In practice, the Elemental Actions approach quickly led to a complex aggregation of many repeated types of movements
  - Did not address cognitive aspects of the task
  - Many Manual Actions we discovered involved operating vehicles, which have clearly a significant cognitive element

Level 1	Manual Action	Installation of jumper to maintain power		
Level 2	Tasks	(1) De-energize	(2) Apply jumper	(3) Energize bus
Level 3	Elemental Actions	Walking	Walking	Walking
		Gripping	Gripping	Gripping
		Carrying	Carrying	Carrying
		Pushing	Twisting	Pulling

Decomposing Manual Actions

- Performed task decomposition exercises associated with three different Manual Actions
  - Installation of Portable Pump
  - Installation of Flood Barriers on Exterior Intake Structure Walls
  - Building Sandbag Berm Around the Service Water Strainer Pit
- Performed decomposition for one task associated with each Manual Action
  - Load and Unload Portable Pump
  - Fasten Barriers onto Exterior Walls
  - Filling Sandbags

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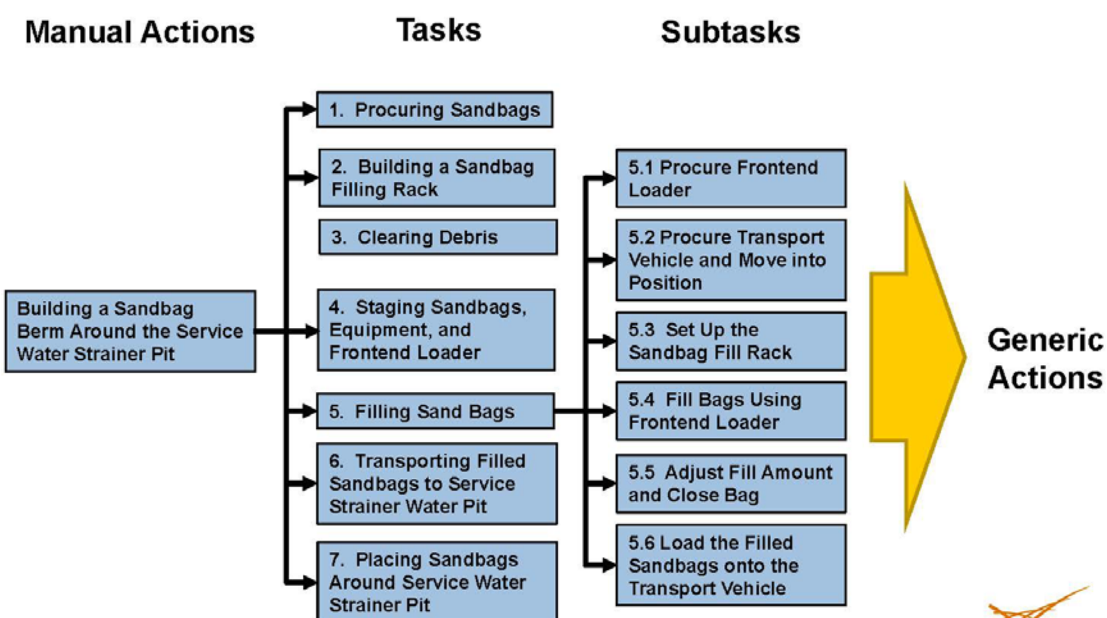
Decomposing Example – Sandbag Berm



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Decomposing Manual Actions

- The project team developed criteria to guide decomposition of Manual Actions into Generic Actions
  - GAs should be general in nature and function as "building blocks" that can be used for recomposing or decomposing other manual actions
  - GAs should be associated with accomplishing a functional objective (e.g., a step in a procedure)
  - GAs performed in an unsheltered location should be distinguished from those performed in a sheltered or semi-sheltered location
  - GAs that require a higher level of cognitive support should be distinguished from those not requiring a high level of cognitive support
  - GAs should be defined at a level for which the impact of EFs on human performance found in the literature can be applied.

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Decomposing Example – Filling Sandbags

Subtask 5.1 – Procure a Frontend Loader and Move It Into Position

Generic Action	Degree of Sheltering	High Level of Cognitive Support	Comments
Walk (to where the frontend loader is parked)	Unsheltered	No	• From an earlier task, a frontend loader has been procured and is available at the sand pile site. • Literature available for this action.
Climb into frontend loader	Unsheltered	No	• The frontend loader was assumed not to have an enclosed cab (though some frontend loaders do have enclosed cabs). • Literature available for this action.
Operate the frontend loader	Unsheltered	Yes	• Requires frontend loader operating experience. • Requires fine motor skills. • Weather could affect visibility, hearing, and skills required to operate the forklift. • Literature available for this action.

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Decomposing Example – Filling Sandbags

Subtask 5.2 – Procure Transport Vehicle And Move It Into Position

Generic Action	Degree of Sheltering	High Level of Cognitive Support	Comments
Walk (to the transport vehicle)	Unsheltered	No	• Transport vehicle located away from reactor building and equipment storage building. • Literature available for this action.
Enter transport vehicle	Unsheltered	No	• Requires fine motor skills to unlock and open vehicle. • Literature available for this action.
Operate the transport vehicle	Semi-sheltered	Yes	• Requires fine motor skills and a higher level of cognitive support. • Considered semi-sheltered because though the operator will be in the truck cab weather could affect visibility and hearing. • Literature available for this action.
Exit the transport vehicle	Semi-sheltered	No	• Literature available for this action.

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Decomposing Example – Filling Sandbags

Subtask 5.3 – Set Up The Sandbag Fill Rack

Generic Action	Degree of Sheltering	High Level of Cognitive Support	Comments
Move equipment into position (i.e., set the fill rack into position)	Unsheltered	No	• Requires two operators to move the rack. • The primary motions would be gripping and lifting. • Literature available for this action.
Set up equipment (i.e., hang the sandbags on to the fill rack)	Unsheltered	No	• Literature available for this action.

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Decomposing Example – Filling Sandbags

Subtask 5.4 – Fill Bags Using Frontend Loader

Generic Action	Degree of Sheltering	High Level of Cognitive Support	Comments
Operate the frontend loader (i.e., drive the frontend loader to the sand pile)	Unsheltered	Yes	• The task involves driving the frontend loader and requires frontend loader operating experience. • Requires fine motor skills. • Weather could affect visibility, hearing, and skills required to operate the frontend loader. • Literature available for this action.
Operate the frontend loader (i.e., scoop sand into bucket)	Unsheltered	Yes	• The task involves operating the frontend loader controls to scoop a bucket of sand and requires frontend loader operating experience. • Requires frontend loader operating experience. • Requires fine motor skills. • Weather could affect visibility, hearing, and skills required to operate the forklift. • Blowing sand could be an issue. • Literature available for this action.
Operate the frontend loader (i.e., drive the frontend loader to the fill rack)	Unsheltered	Yes	• Requires fine motor skills. • Weather could affect visibility, hearing, and skills required to operate the frontend loader. • Literature available for this action.

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Decomposing Example – Filling Sandbags

Subtask 5.5 – Adjust Fill Amount Using Hand Tools And Close Bag

Generic Action	Degree of Sheltering	High Level of Cognitive Support	Comments
Use of hand tools (i.e., adjust amount of sand in sandbags) to appropriate amount	Unsheltered	No	• This task involves use of hand tools to level out or adjust the amount of sand in the sandbags. • Literature available for this action.
Manual work with simple equipment (i.e., take sandbags off of the fill rack)	Unsheltered	No	• This task involves manually gripping, lifting, carrying, and moving filled sandbags off of the fill rack. • Literature available for this action.
Manual work with simple equipment (i.e., tie off the sandbags)	Unsheltered	No	• This task involves manually using the tie strings at the top of the sandbag to tie off the bag. • Requires fine motor skills. • Literature available for this action.

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Decomposing Example – Filling Sandbags

Subtask 5.6 – Load The Filled Sandbags On The Transport Vehicle			
Generic Action	**Degree of Sheltering**	**High Level of Cognitive Support**	**Comments**
Manually load material (i.e., sandbags) onto transport vehicle	Unsheltered	No	• Involves gripping, lifting, and carrying sandbags to load onto the transport vehicle. • Literature available for this action.

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Decomposing Manual Actions

- Generic Actions based on the limited decomposition exercises
  - walk
  - enter or exit vehicles (transport vehicles, and light and heavy equipment)
  - operate a transport vehicle
  - operate forklift
  - operate frontend loader
  - manually move equipment
  - setup equipment
  - open building or large container door
  - operate powered hoist
  - manually lift and move heavy materials or equipment
  - work manually with simple equipment
  - use hand tools
  - communicate electronically
  - communicate non-electronically

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Relating Manual Actions to Performance

- Explore how GAs and performance are related to draw generalizable conclusions
- Understand how Environmental Factors impact performance
- Identify ways to measure performance

Manual Actions/ Generic Actions

- Decomposition exercises help identify pertinent MAs and GAs
- Need a systematic way to relate GAs to operator performance

Environmental Factors

- Research is needed to establish the relationship between EFs and the performance of specific GAs/MAs pertinent to flood protection

Individual's Performance

Taxonomy of Human Performance

- Behavior description
- Behavior requirements
- Ability requirements
- Task characteristics

Performance Abilities identified in previous research

- Attention
- Vision
- Psychomotor skill
- Manual dexterity
- Cognitive functions
- Mood and comfort

Next Steps

- Complete the literature review
  - Assemble and review additional literature
  - Review and evaluate Improved Performance Research Integration Tool (IMPRINT), a software program developed by U.S. Army Research Laboratory
  - Identify and review other pertinent assessment tools
- Conduct exercise for performance impact assessment
- Potentially collaborate with industry
- Develop final project report (NUREG/CR)

Next Steps - IMPRINT

- Improved Performance Research Integration Tool (IMPRINT)
  - The team has identified a software program developed by U.S. Army Research Laboratory to assist in the analysis of human performance
  - We are currently evaluating this software
  - Implemented using Micro-Saint Task Network Modeling Tool with ~30yrs use with manual, and other tasks (e.g., maintenance)
  - Environmental performance shaping factors used in the software are based on:
    - Decades of Army integrated literature reviews and
    - User defined modules
- General capabilities (amongst many) of interest to the project
  - Predict performance effects of environmental stressors
  - Provide mission simulation that models aggregate performance

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Next Steps - IMPRINT

- Particular IMPRINT features of interest to the project
  - Considers impact of stressors on performance time and accuracy
    - **heat, cold, noise, and vibration** are built in
  - Weights task priority
  - Considers a range of failure mode impacts
  - Weights 1) perception, 2) cognitive, 3) motor, and 3) communication importance to the human action (called “taxons” by the software)
  - User-defined Performance Shaping Factors can be input into IMPRINT

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Next Steps - Exercise

- The team plans to set up an exercise for relating manual actions to performance under Environmental Conditions.
- The exercise would
  - Lay out timeline and plant context for a Manual Action already decomposed into Generic Actions
  - Define or assume a set of Environmental Conditions
  - Try associate literature about human performance at the intersection of each Generic Action and each Environmental Condition
  - Identify workable impact metrics such as:
    - The increase in time needed to perform a Manual Action
    - The decrease in likelihood that a Manual Action can be performed in a given time
  - Identify the intersections where there is gap in the literature performance impact

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Next Steps – Collaboration with Industry (Potential)

- Potential collaboration topics
  - Help NRC/PNNL validate the results of ongoing efforts to "decompose" manual actions into more elemental/building-block "generic actions"
    - Identify any potentially incorrect assumptions by the NRC/PNNL research team about credited manual actions
    - Identify gaps in our understanding of site-specific topographic, layout, and logistics details that could impact performance of manual actions
  - Help NRC/PNNL validate ideas related to EFs and ECs coincident with floods of interest
    - Identify potentially incorrect assumptions by the NRC/PNNL research team
    - Identify gaps in our understanding of the manner in which EFs create secondary conditions that affect performance of manual actions
    - Identify likely combinations of EFs and ECs and their potential impacts on manual actions
  - Help NRC/PNNL better understand plant-specific actions credited in response to external flooding and the conditions under which those actions will be performed

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1.3.5.2 Flooding Information Digests. Kellie Kvarfordt and Curtis Smith, INL

Topics

- Research motivation
- Information Digest project overview
- Flood Digest Information Needs Workshop Recap
- Flood Digest Framework & Pilot Data
- Safety Portal concept
- Upcoming Pilot and Workshop

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Motivation

- "Flooding projects" are part of the NRC's Probabilistic Flood Hazard Assessment (PFHA) Research plan
- They will support development of a risk-informed analytical approaches for flood hazards
- Goal is to build upon
  - Recent advances in deterministic, probabilistic, and statistical modelling
  - New approaches to extreme precipitation events

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

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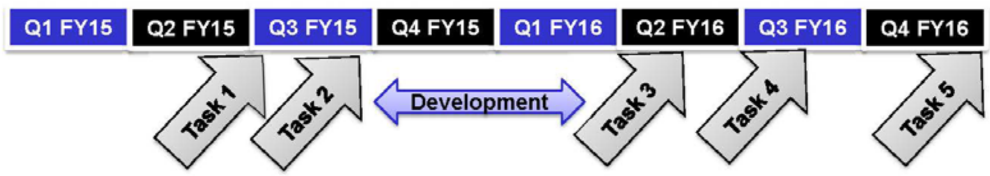
Information Digest project overview

- The project started September 2014 and concludes September 2016
  - NRC COR is Joseph Kanney
  - INL PI is Kellie Kvarfordt
- Project has five specific tasks
  - Task 1 - Flooding Hazard Information Needs Workshop
  - Task 2 - Existing Database Review and Work Plan Development
  - Task 3 - Database Design and Implementation
  - Task 4 - Database Pilot Demonstration
  - Task 5 - Knowledge Transfer



Information needs

- There is a need to better organize flooding information at operating reactor sites and improve its accessibility for NRC
- The types of information identified (by NRR/NRO staff) include
  - Flood hazard info from
    - NUREGs, FSARs, SERs, IPEEE submittals, SDP analyses
    - Post Fukushima flood hazard reevaluations
  - Precipitation frequency info
  - Flood frequency info
  - Hurricane landfall/intensity info
  - Flood protection and mitigation strategies info
    - Post Fukushima walkdowns

Flooding Information Needs Workshop (Held April 22, 2015)

- **Purpose**
  - To develop a description of the flooding hazard information needs that the flooding information digest must support
- **Objectives**
  - Provide input sufficient for INL to develop a work plan for designing and demonstrating the flooding ID architecture
  - Identify possible interfaces with other tools that SRA's use in SDP analyses (e.g. RASP handbook, external event SPAR models)
- **Participants**
  - RES/DRA
  - NRR/DRA
  - NRO/DSEA
  - Regional SRAs

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Flood Digest Content Needs

- Basic information about flood design basis, protection levels, procedures, etc. augmented with
  - Screening information
  - Plant relevancy to various flood hazard types
  - FAQs
- Help and guidance for using other tools and databases (such as NOAA and/or USGS)
  - Walk through steps to encourage use
  - Provide examples of usage
  - Include flowcharts and process diagrams to show users how to do certain things, especially technical activities
- For a particular analysis, what are the right questions to ask?

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Flood Digest Interfaces

- **<u>RASP Handbook</u>**
  - Volume 2 of new update (to be released this fall) will focus on external event "pinch points" (places where the modeling becomes difficult)
  - Flood Digest can link to the handbook, and also possibly supplement it with less controlled "desktop guides"

- **<u>SPAR Models</u>**
  - SRAs need a simple flooding model that fits into the SAPHIRE modeling world
    - Need site specific information (not too detailed)
    - Level-vs-time flood curve for different scenarios
  - As SPAR models enter the cloud, the flow of information can appear to be seamlessly tied together

Overall plan

- Our plan is to link the Flood Digest to INL Safety Portal, a cloud-based safety resource currently under development
  - https://safety.inl.gov/

- We will populate a cloud-based library with sample flood related documents from two plants
- Publish NRC information as produced (e.g., SER, SDPs, flood re-evaluation, walkdowns, etc)
- Link to applicable data, including NOAA, USGS and USACE, when possible

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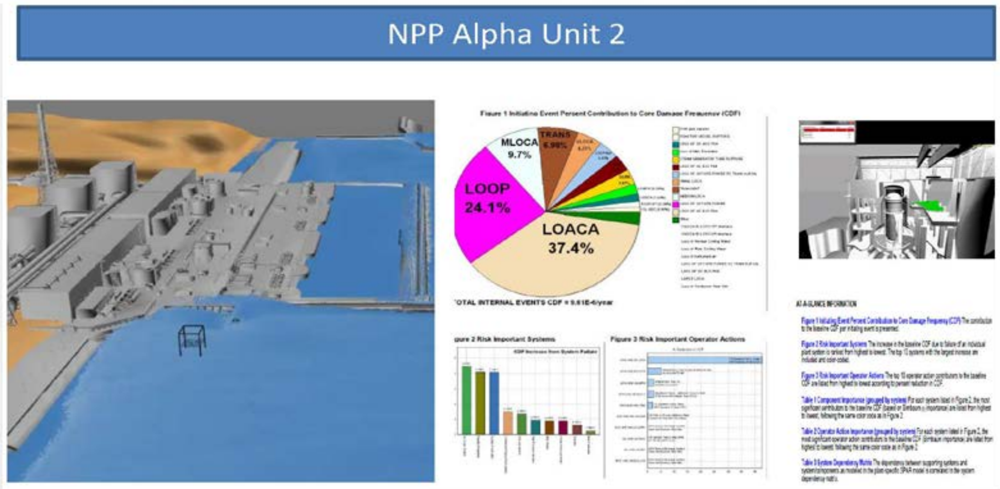
Plant Dashboard



The dashboard will provide both a snapshot of relevant information for a facility as well as provide a way to drill-down into more detailed information

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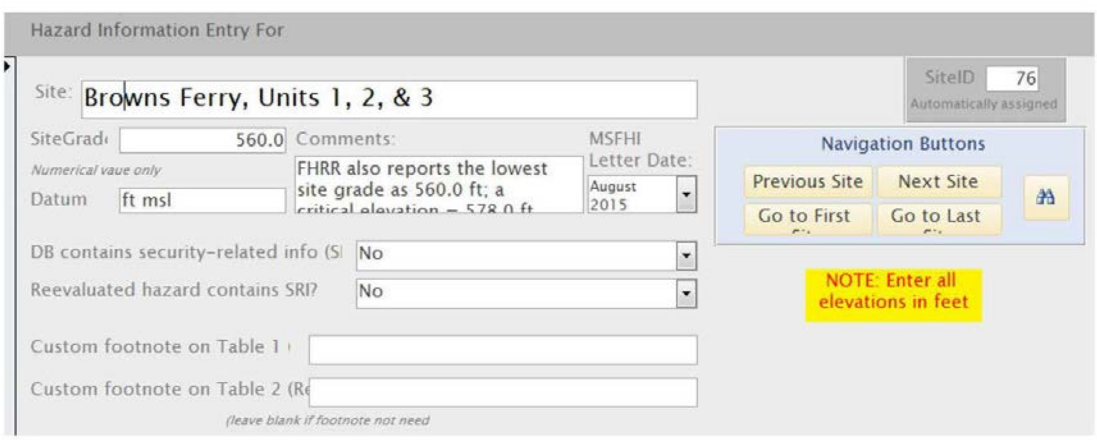
MSFHI Data



* MSFHI database provided by NRO/DSEA (Shelby Bensi)

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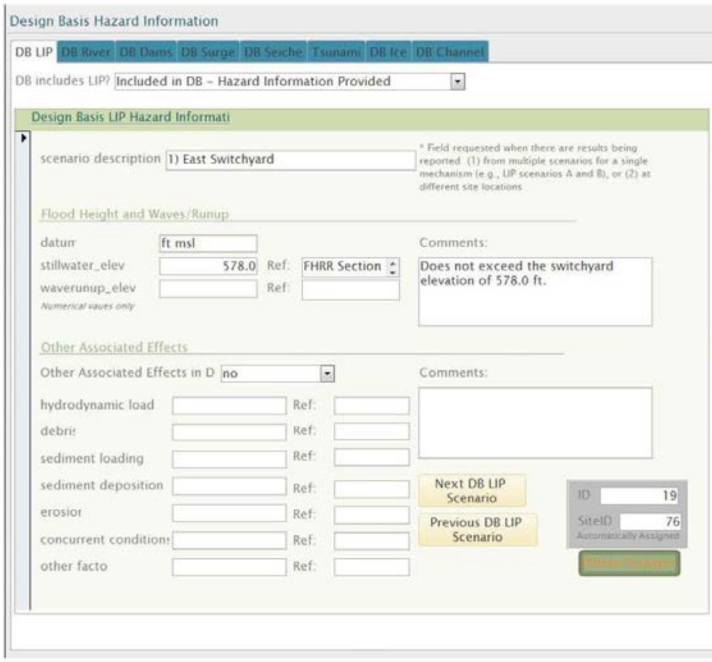
MSFHI Design Basis Info



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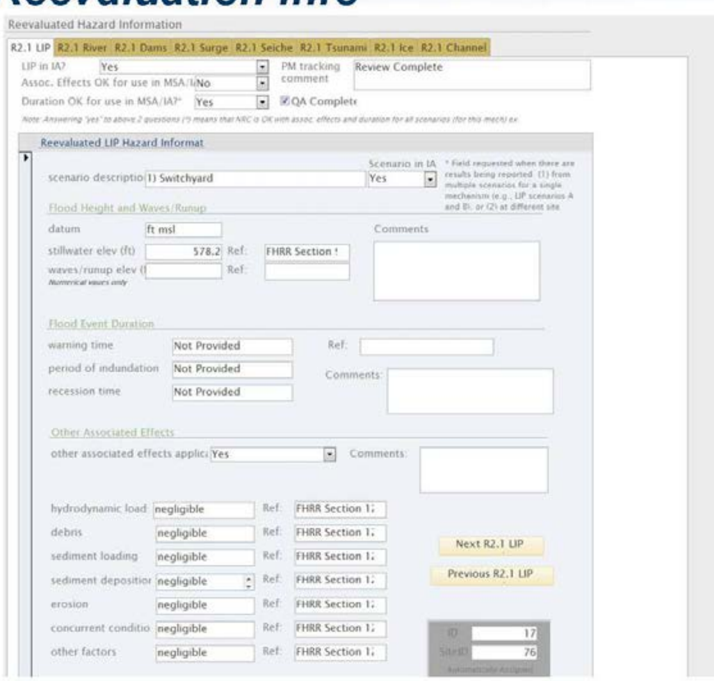
MSFHI Reevaluation Info



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SDP Pilot Documents Example

- *ANO Flooding Pictures*
  - Aux Or Turbine Building (60+ images)
  - Circ Water (2 images)
  - EDG Fuel Oil Vault (20+ images)
  - External Pictures (10+ images)
  - Intake SW Building (8 images)
  - PASS Room (7 images)
  - Turbine Building (15 images)
- *Licensee Documents*
  - 32-9207377-000_PMF Hydraulics.pdf
  - 32-9222517-000_Flood Frequency.pdf
  - LRE_Report_PRECIP_FINAL_20141019.pdf
  - N20090601102652055_ANO1-Flood.pdf
  - N20090601102857588_ANO_Flood_Elevation_Map.pdf
  - N20090601102904916_ANO_All-Hazards_Data.pdf
  - N20090612152304290_A-2001_Site_Layout.pdf
  - U1 Revised Flooding Report.pdf
  - U2 Revised Flooding Report.pdf
- *Post Reg Conference Material*
  - 2014010 EA-14-088 ANO Flooding To OENRR (3).docx
  - Action Response Summary Plant Response Timing.pdf
  - ANO Enforcement Conference Follow-up.docx
  - ANO flood results.xlsx
  - BT-Arkansas Nuclear One Flood Boundary Deficiencies Final Significance.docx
  - Final Analysis of Licensee Proposed Recovery Actions R3_FF.docx
  - Guidance for Step Sequence.pdf
  - MOV Hot Short Potential.docx
  - Response Use of Firewater Rev 2.pdf
  - Room Inspection for Potential Water Spray Due to Flood Barrier Deficiencies.docx
  - Unit 1 Packet for Supplying EFW with Service Water rev2.pdf
  - Unit 1 Packet for Supplying MFW.pdf
- *SDP Documents*
  - Arkansas Nuclear One Flood Boundary Deficiencies Final Significance_FF_KSee_2.docx
  - Final Letter.pdf
  - Preliminary Letter.pdf

* Pilot data provided by Fernando Ferrante from an SDP analysis

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Integrate Flood Digest into Safety Portal

https://safety.inl.gov/

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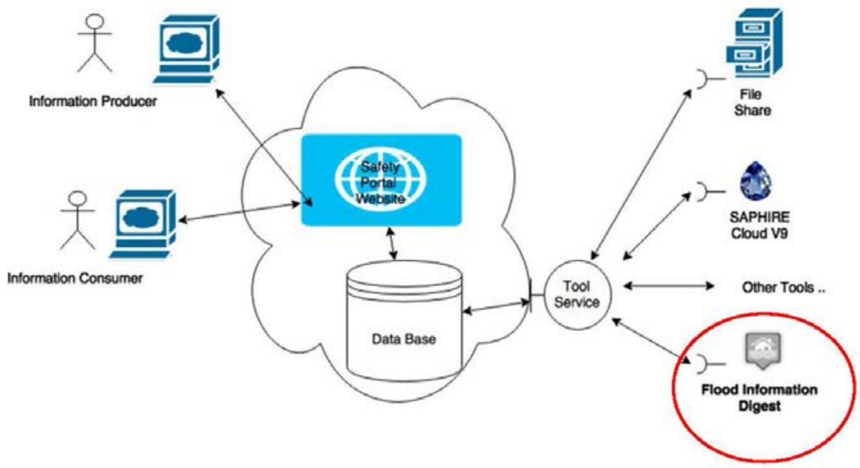
Safety Portal / Flood Digest Concept Diagram



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Safety Portal Features

- Serves as a ***resource*** for a growing set of safety related application tools and related data
- A ***collaboration focus*** where
  - Producers of information (e.g., analysts) can ***publish*** information and have control over who has access to that info
  - Users of information (e.g., analysts, reviewers, managers) can ***subscribe*** to information
    - Allows a focus on just needed tools and data
    - Yet still able to browse a complete collection of tools and data (as long as permission has been granted)
- A notification system for changes
- Loosely modeled after Google Drive

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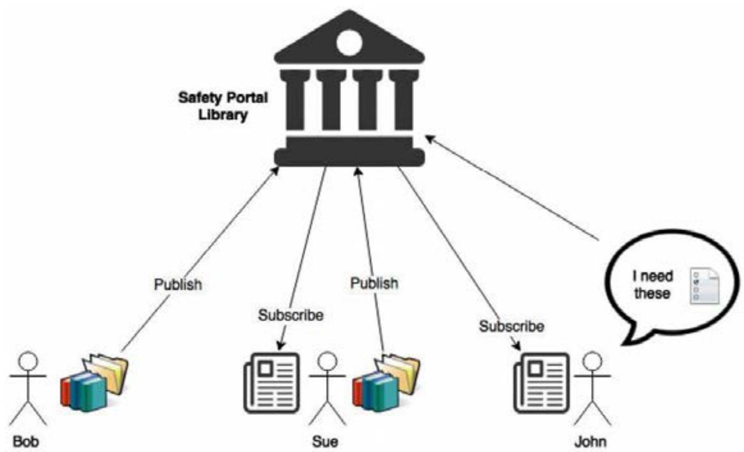
Publications and Subscriptions



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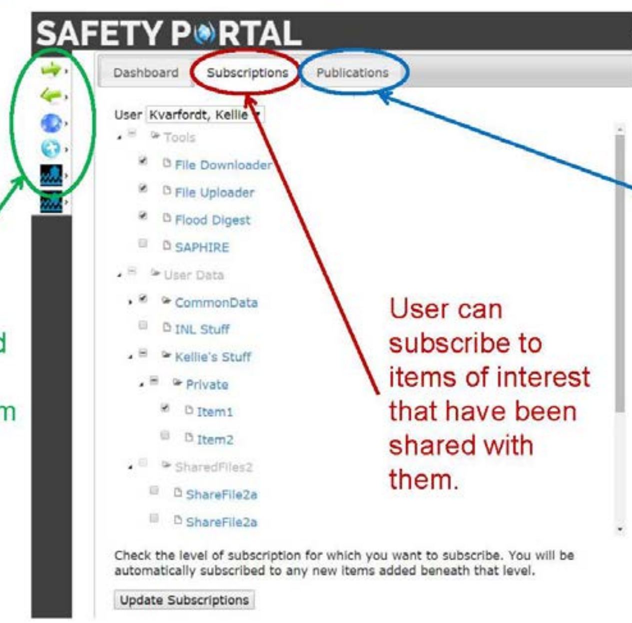
Safety Portal Subscriptions



All subscribed tools can launch from here.

User can subscribe to items of interest that have been shared with them.

User-owned publications can be selectively shared with groups or individuals.

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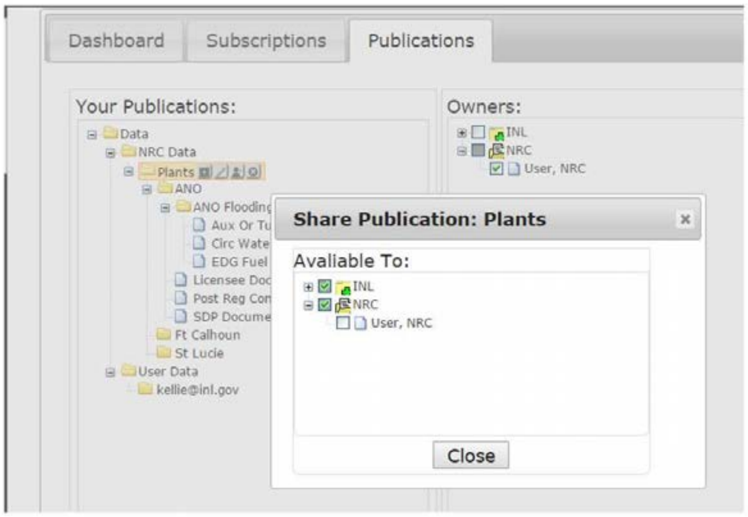
Sharing (Permissions)



Safety Portal Application Tool List

- ***Flooding Information Digest***
- A web-based version of SAPHIRE (in early development)
- A web-based wrapper for OpenBUGS
- 3D simulation tool
- 3D terrain mapping tool
- Other

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Flood Digest Pilot Period & Workshop

- Pilot database application planned to be available in June 2016, and tested throughout the summer
- NRC testers will be needed … Any volunteers?
  - Ideas are encouraged
  - Recent analysis? Examples?
- Following pilot test period, a September 2016 workshop will demonstrate and provide hands-on instruction
- Next steps
  - Populate the Flood Digest with additional data

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Summary

- Flood Information Digest will utilize the Safety Portal as a resource with a collaborative focus between producers and users of information
  - where users can tailor their information "feed" by subscribing to tools and topics of interest
- The Flood Information Digest will further organize, accumulate, and present a variety of relevant information
- **Feedback is welcome…**

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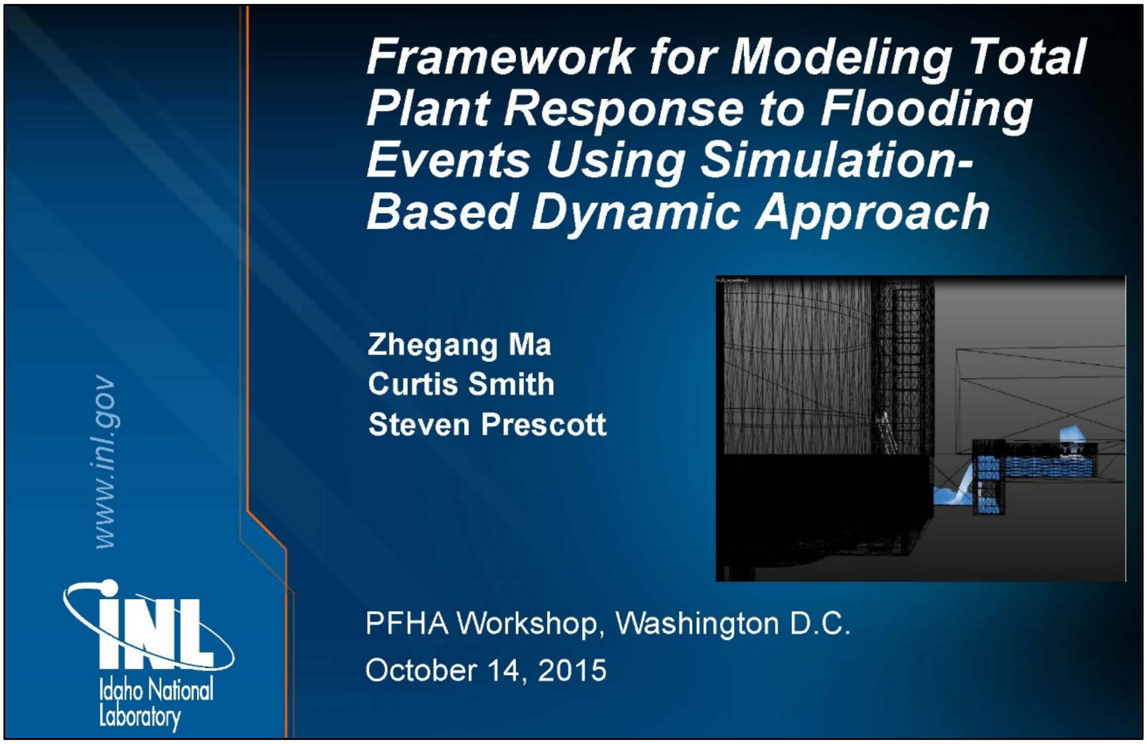
1.3.5.3 Framework for Modeling Total Plant Response to Flooding Events. Zhegang Ma and Curtis Smith, INL



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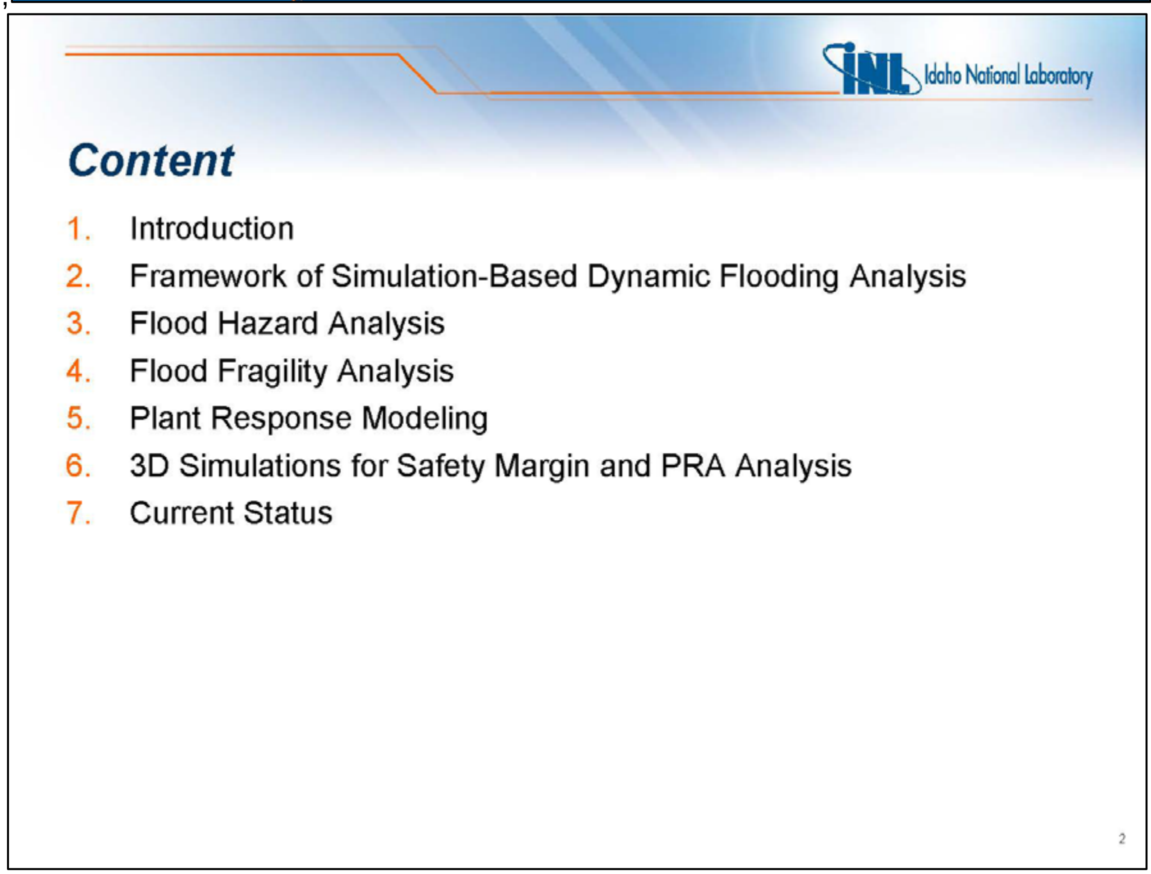

1. Introduction

- Recent lessons learned show that more detailed risk assessment of external flood hazards is warranted for operating nuclear power plants in U.S
  - Fukushima (2011)
  - Fort Calhoun (2011)
  - ANO (2013)
  - St. Lucie (2014)
  - ...
- The total plant response must be evaluated to ensure that flood protection features and procedures as well as flood mitigation measures are adequate to ensure plant safety
- Traditional methods using frequency analysis combined with static system event and fault trees are difficult to deal with some unique and challenging aspects presented by external flooding events

1. Introduction (cont.)

- Unique challenges for a comprehensive external flooding analysis:
  - Plant response is highly spatial- and time-dependent
  - Plant response is subject to the hydrological and hydraulic characteristics of the flood event
  - Flood protection may be a function of flooding levels (spatial)
  - Degree of flooding may influence the rate of stochastic or common cause failures (dynamic)
  - Response relies heavily on procedures and manual actions
  - Feasibility and reliability of actions can be impacted by the flooding (dynamic and spatial)
  - Duration of the flooding event can be quite long and onsite conditions may change throughout the event

1. Introduction (cont.)

- INL is exploring *Simulation-Based Dynamic Flooding Analysis (SBD-FA)* approaches to investigate total plant response to external flooding events
- This project is intended to demonstrate a proof-of-concept for the advanced representation of external flooding analysis
- A series of case studies will be envisioned to demonstrate the basic feasibility and to work out technical issues
  - This project uses a local intense precipitation (*LIP*) event as the study case

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1. Introduction (cont.)

- The project started September 2014
  - NRC COR is Joesph Kanney
  - INL PI is Curtis Smith
- Project has four specific tasks
  - Task 1 - Work Plan Development
  - Task 2 - Margins Assessment Approach for Local Intense Precipitation External Flooding Events
  - Task 3 - PRA Approach for Local Intense Precipitation External Flooding Events
  - Task 4 - Knowledge Transfer

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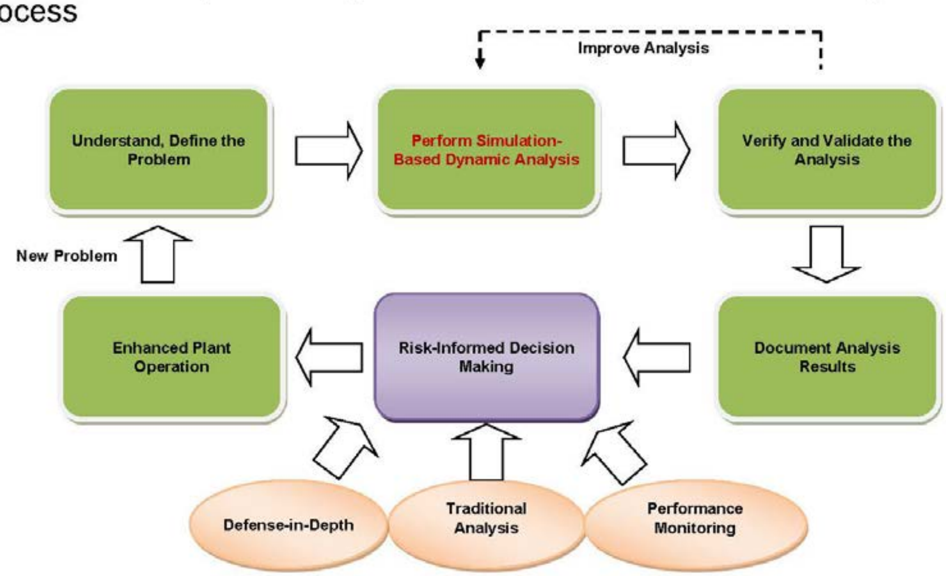
2. Framework of Simulation-Based Dynamic Flooding Analysis

- SBD-FA is an important step in the risk-informed decision making process



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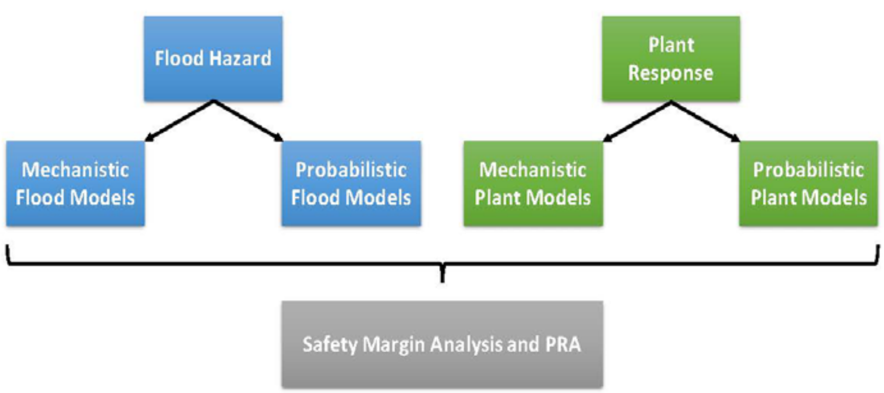
2. Framework (Cont.)

- Both mechanistic and probabilistic analyses are performed in the project
  - Mechanistic part: deterministic aspects
    - thermal-hydraulic simulator
  - Probabilistic part: stochastic and uncertain variables
    - parameter uncertainties and probability associated with timing of events



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- Task 1

  Perform External Flood ***Hazard*** Analysis

- Task 2

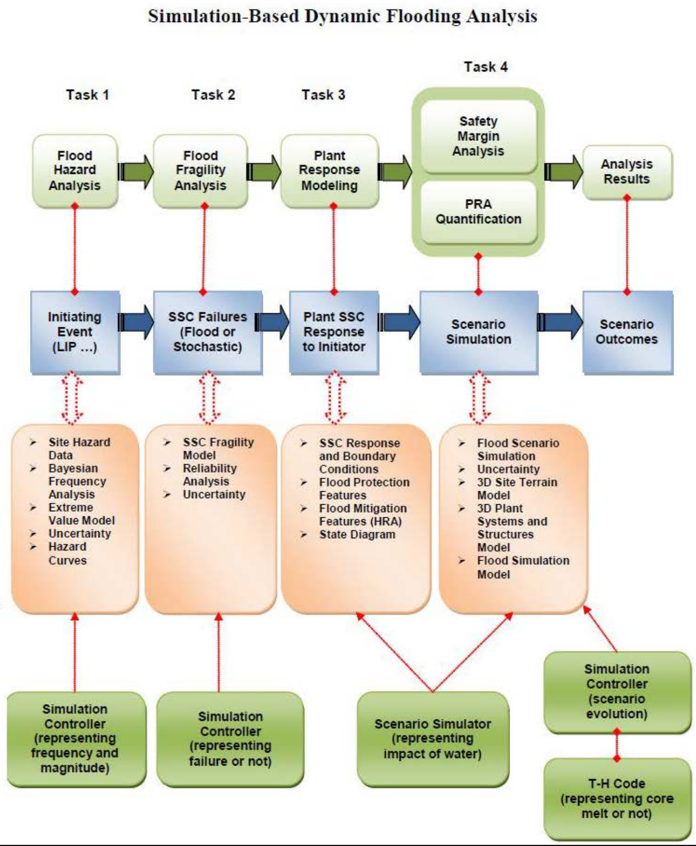
  Perform External Flood ***Fragility*** Analysis

- Task 3

  Develop External Flood Plant ***Response*** Model

- Task 4

  Perform Safety Margin or PRA ***Quantification*** Analysis



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3. Flood Hazard Analysis

- *Not the focus of this project, No detailed analysis*
- Assess available, historical site-specific data to develop hazard curves with uncertainties characterized
- Data sources such as National Oceanic and Atmospheric Administration (NOAA) Atlas 14
- Historical data is usually sufficient for observed return periods, but not for longer return periods.
- Generalized Extreme Value (GEV) model is used to extrapolate NOAA precipitation data and estimate the hazards for longer periods

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NOAA estimated and GEV model calculated precipitation frequencies for 24-hour duration

Precipitation Amount (inches)		Annual Exceedance Probability (1/years)								
		1/2	1/5	1/10	1/25	1/50	1/100	1/200	1/500	1/1000
NOAA Data	Mean	**4.40**	**6.03**	**7.38**	**9.33**	**10.90**	**12.60**	**14.40**	**17.00**	**19.00**
	5%	3.66	5.00	6.09	7.49	8.56	9.55	10.50	11.90	12.90
	95%	5.31	7.29	8.96	11.90	14.10	16.70	19.60	23.70	26.80
GEV Calculated	Mean	**4.29**	**6.12**	**7.47**	**9.36**	**10.90**	**12.55**	**14.34**	**16.93**	**19.08**
	5%	4.12	6.02	7.39	9.27	10.80	12.46	14.25	16.83	18.92
	95%	4.45	6.22	7.56	9.45	10.99	12.65	14.43	17.04	19.25
	Difference on Mean	-2.6%	1.5%	1.2%	0.3%	0.0%	-0.4%	-0.4%	-0.4%	0.4%

Precipitation Amount (inches)		Annual Exceedance Probability (1/years)								
		5.00E-04	2.00E-04	1.00E-04	5.00E-05	2.00E-05	1.00E-05	5.00E-06	2.00E-06	1.00E-06
NOAA Data	Mean	NA								
	5%	NA								
	95%	NA								
GEV Calculated	Mean	**21.41**	**24.80**	**27.60**	**30.65**	**35.07**	**38.74**	**42.71**	**48.49**	**53.29**
	5%	21.15	24.34	26.95	29.74	33.75	37.03	40.55	45.60	49.74
	95%	21.68	25.26	28.27	31.57	36.41	40.48	44.94	51.49	57.00
	Difference on Mean	NA								

3. Flood Hazard Analysis (Cont.)

- GEV model estimated precipitation results for shorter return periods are very close to the NOAA data, but with smaller uncertainty ranges
  - NOAA data is derived from the scattered observed "raw" precipitation measurement data
  - GEV model uses the NOAA derived data as the input
- Traditional flood analysis uses mean values as the initiating event frequencies
- Simulation based approach could use the full spectrum of the hazard curves

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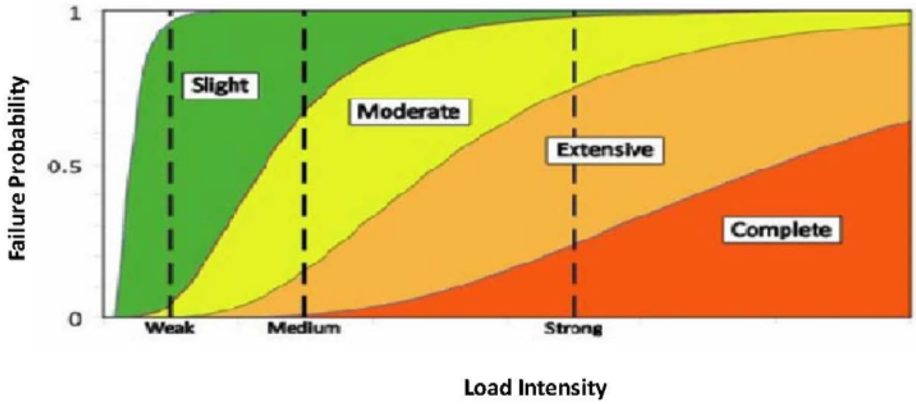
4. Flood Fragility Analysis

- *Not the focus of this project, No detailed analysis*
- The fragility of plant SSCs is evaluated as a function of the severity of the external flood
- Traditional analysis uses the concept of critical flood height
- Simulation based approach could use the full spectrum of the fragility curve associated with flood heights and inundation rates



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5. Plant Response Modeling

- Identify plant structures and components
  - Important to risk and susceptible to external flood hazards
- Identify flooding scenarios to be modeled
  - flood propagation paths, flood protection features, flood mitigation features, etc.
- Perform scenario-specific human reliability analysis
  - Feasibility and reliability of manual actions depending on flood progressing
- Develop plant response model
  - Incorporates plant-specific flood protection and mitigation features, time-dependent operator actions

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5. Plant Response Modeling (cont.)

- Traditional event tree/fault tree approach in a static PRA model is difficult to accurately represent component or system behavior and reliability of manual actions
- SBD-FA uses a new PRA technique, State-based PRA Modeling, accounts for both flood caused failures and random failures with *time based dependency and behavior*
  - The "State" represents and tracks the condition of a component in the model along with the time
  - Driven by "Events" and "Actions"

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5. Plant Response Modeling (cont.)

- At any given moment, the model is in a set of "States"
  - Each state can have "Actions" it performs upon entering that state, and "Events" that trigger an action or set of actions
- The set of "Current States" changes over time until a terminal state is reached
- Once a terminal state is reached, the "Current States" list is evaluated and logged as one iteration of the model
- After running many iterations, the model converges on a failure probability
  - Comparable to traditional static PRA results
- 3D simulation related variables, events, and actions are included in the model to account for the flood caused failures

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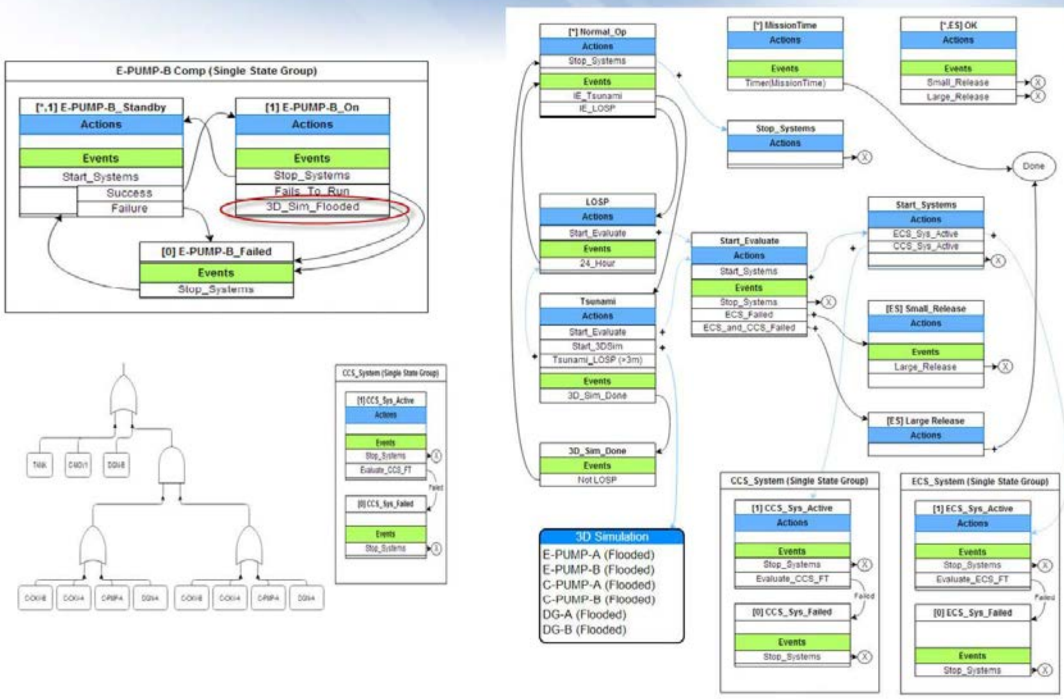

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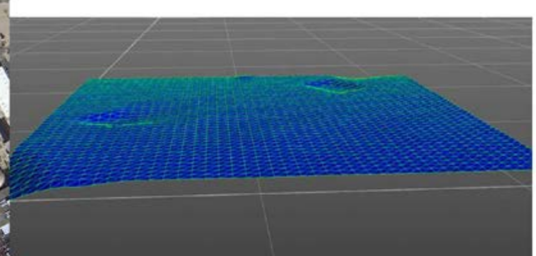
6. 3D Simulations for Safety Margin or PRA Analysis

6.1. Develop 3D terrain model that represents the topography of the site

- Web_Terrain_Mapper API was developed to retrieve site terrain information
  - Utilizing public available Google's Elevation API
  - Input the latitude, longitude, distance and resolution data
  - Output a geometry interchange file (.obj)



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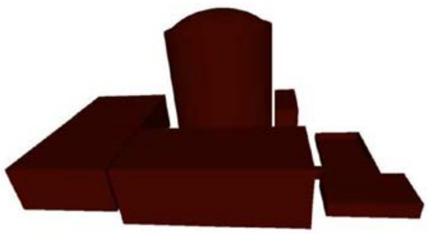
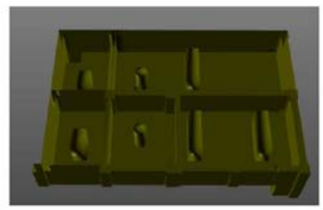
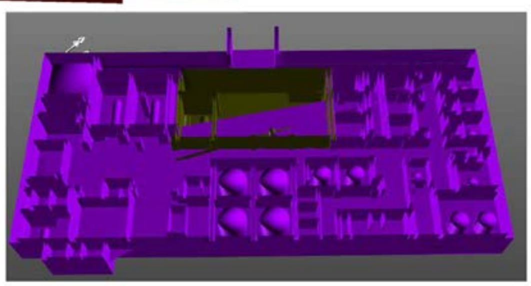
6. 3D Simulations (Cont.)

6.2. Develop 3D plant models that can be used for the simulations

- Develop or obtain applicable 3D plant models







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6. 3D Simulations (Cont.)

6.4. Perform Safety Margin Analysis *with State PRA Model and 3D Simulation Model*

- Identify and characterize the factors and controls that determine safety margin
- Run the State PRA Model and the 3D Simulation Model
  - Various hazard parameters and different values
- Thermal hydraulic calculations to evaluate the impact on the plant
  - T-H codes (MELCOR, MAAP) for plant response function

6.5. Perform PRA Analysis *with State PRA Model and 3D Simulation Model*

- Link 3D simulation model to State PRA model
  - Flood-caused unavailability feed to State PRA model
- Quantify State PRA Model
  - Integrating the external flood hazard, the external flood fragilities, and the system-analysis aspects
  - Monte Carlo Simulation – sampling full spectrum of hazard and fragility
  - Flood physical simulation

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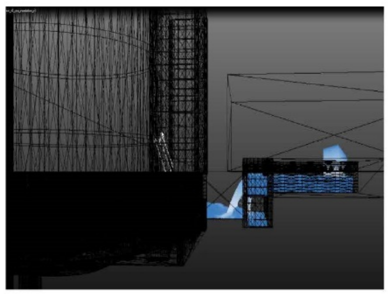
7. Current Analysis Status

- A previous LIP event occurred in a PWR plant was reviewed
- A typical 3D PWR plant model was developed
- Flooding scenarios to be simulated were developed
- The first stage of the State PRA Model (component random failures, system logic, accident sequences) was completed
  - tested against SAPHIRE/SPAR model
  - the results are promising
- Working to perform the 3D simulations



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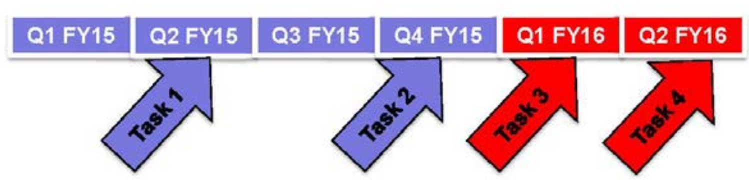
7. Current Project Status

- Task 1 - *Completed*
- Task 2 - *Completed*
- Task 3 – *December 2015*
- Task 4 – *March 2016*



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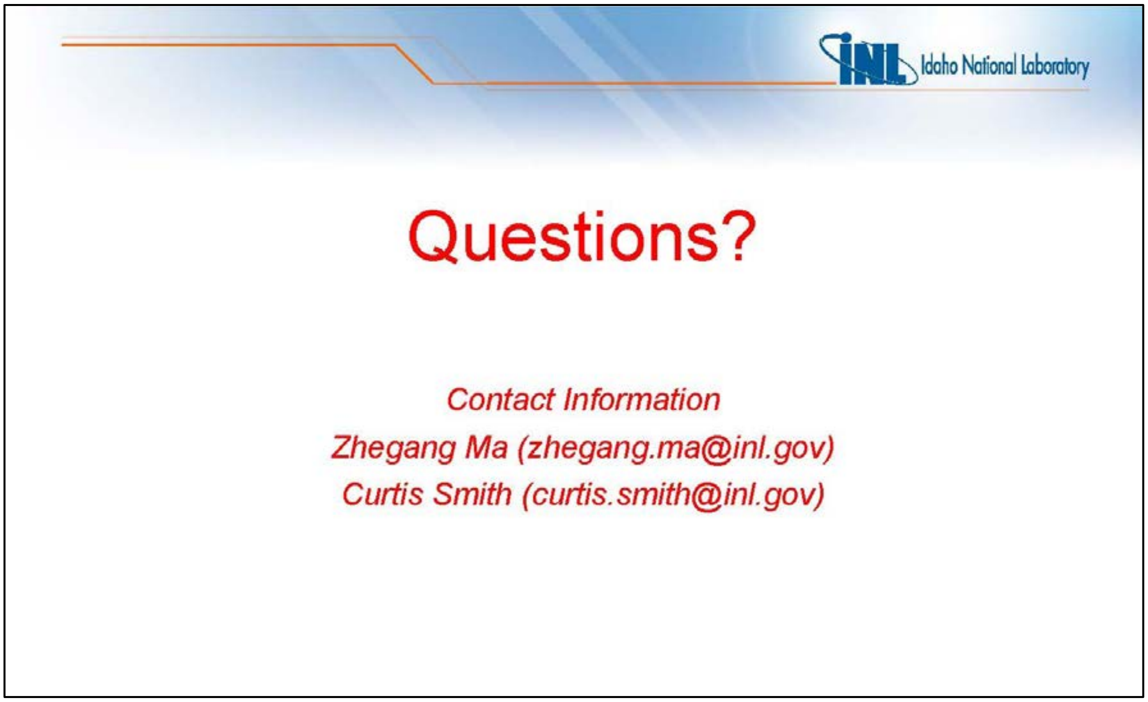
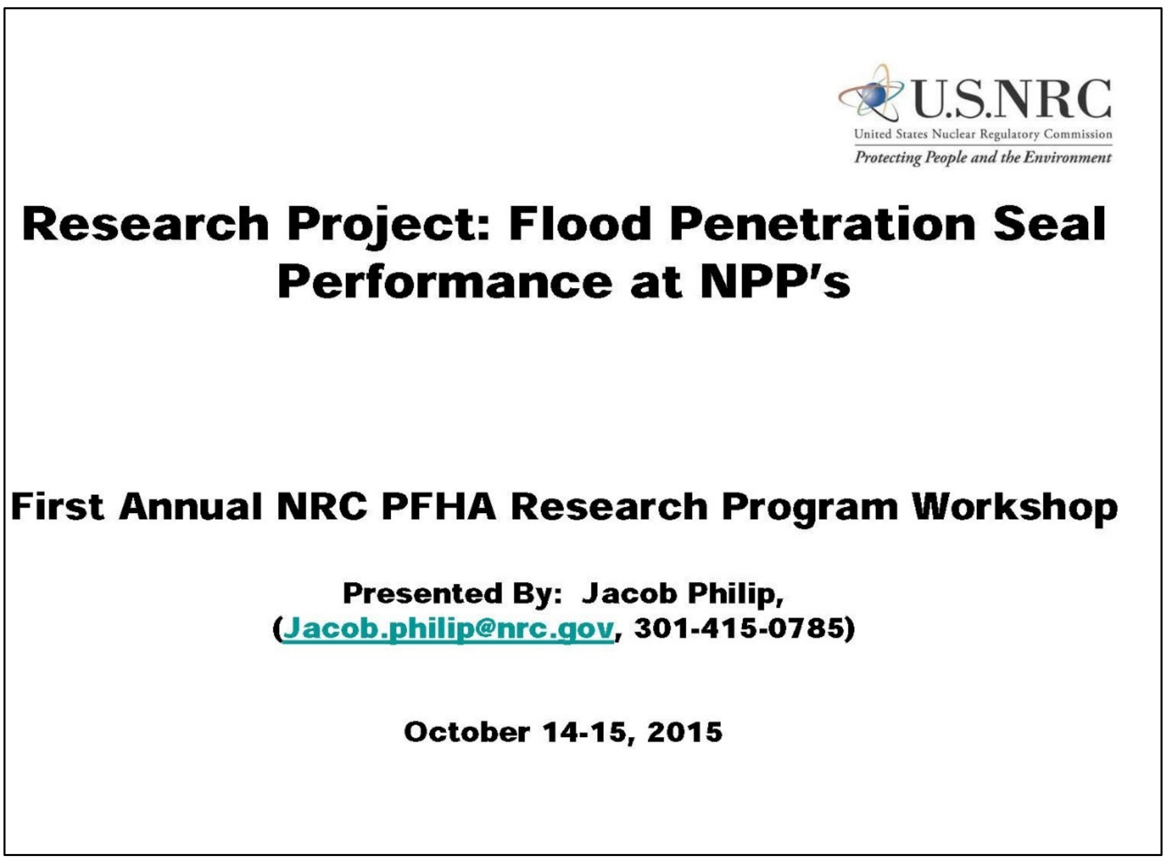


1.3.5.4 Performance of Penetration Seals. Jacob Philip, NRC



Background/Purpose:

- Penetrations in external (and internal walls) of safety related structures allow cables, conduits, cable trays, piping etc., to pass through the walls.
- Flood Seals for Penetrations (FSP) are used to seal these openings to ensure water tightness and integrity of wall penetrations.
- Currently there are no standard procedures and test methods or acceptance criteria for FSP's and their effectiveness to water pressure and other loads.
- PSF's may be subject to drying, cracking, vibrations of piping, hydrodynamic forces, debris loads, etc., during flood events.
- There is need to establish testing procedures, criteria and protocols to evaluate the effectiveness of FSP'.

2

Objectives:

- Establish testing procedures and protocols to evaluate the effectiveness and performance of intact and degraded FSP' at NPP's.
- Conduct a series of tests on intact and degraded seals to assess their effectiveness to water intrusion based on the developed testing strategy and protocols.

3

Scope of Work:

- Task 1
  - Identify and describe the various typical seal materials for FSP's used at NPP's (size, shape, substrate, configuration of penetrations, seal materials etc.)
  - Based on the review from above, develop testing procedures, acceptance criteria and protocols for testing the effectiveness of FSP's.
  - Prepare a letter report on Task 1 for NRC comments and approval.
- Task 2
  - Based on Task 1, develop a testing plan to conduct a series of tests on typical intact and degraded seals to assess their effectiveness and performance.
  - Implement testing plan after discussions with and approval of the NRC project manager.
- Task 3
  - Prepare a final NUREG/CR report detailing the research conducted under Tasks 1 and 2.

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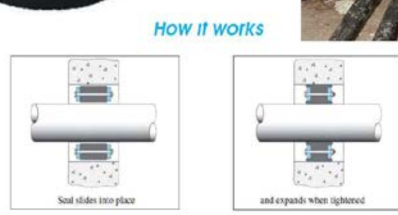
Some Examples of Generic Seal Configurations for Penetrations:



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1.4 Summary

This report transmits the agenda and slides from presentations given at the 1st Annual NRC Probabilistic Flood Hazard Assessment Research Workshop held at NRC Headquarters in Rockville, MD, on October 14–15, 2015. Participants in this workshop included NRC technical staff and management, NRC contractors, and staff from other Federal agencies.

The NRC had the following objectives for the workshop:

- Inform NRO and NRR management and staff on the progress of the PFHA Research Program.

- Solicit feedback from NRO and NRR management and staff on current and proposed research activities.

- Allow RES contractors to do the following:

  - Interact with NRO and NRR staff to get a better understanding of NRO and NRR needs and priorities.

  - Interact with each other to gain a better understanding of how the participants' individual project(s) fit into the larger program.

- Inform partner Federal agencies on NRC PFHA research activities.

The 2-day workshop began with an overview of the RES PFHA Research Program, followed by presentations by NRO and NRR staff to give user office perspectives on research needs and priorities as to flood hazard assessment and analysis of risks from flooding. The balance of the workshop consisted of five technical sessions, during which the NRC staff and contractors gave presentations that described the individual research projects in the PFHA Research Program.

The five technical sessions covered the following topics:

(1) program overview
(2) climate
(3) precipitation
(4) riverine and coastal flooding processes
(5) plant response to flooding events

The workshop included substantial discussion after each presentation and during an open discussion session at the conclusion of the workshop. The NRC met its overall workshop objectives of soliciting feedback from user office staff and management, promoting interaction and collaboration between projects, and informing partner Federal agencies.

These proceedings include the following:

- Section 2.2: Workshop Agenda
- Section 2.3: Proceedings
- Section 2.4: Summary
- Section 2.5: Workshop Participants

1.5 Workshop Participants

U.S. Nuclear Regulatory Commission (U.S. NRC)

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Hosung Ahn
Rasool Anooshehpoor
Michelle Bensi
Rudolph Bernhard
Jill Caverly
Christopher Cook
Valerie Barnes
Mark Fuhrmann
Ian Gifford
Mohammad Haque
Brandon Hartle
Barbara Hayes
Joseph Kanney
Michelle Kichline
Cheng Yuan
Louise Lund
Mark McBride
Asimios Malliakos
Jeff Mitman
Thomas Nicholson
Marie Pohida
Malcom Patterson
Jacob Philip
Kevin Quinlan
Mehdi Reisi Fard
Mohamed Shams
Warren Sharp
Nebiyu Tiruneh
Juan Uribe
Thomas Weaver
Sunil Weerakkody
Elena Yegorova

U.S. Army Corps of Engineers (USACE)

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Meredith Carr
Victor Gonzalez
David Margo
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Brian Skahill
Norberto Nadal-Caraballo

Federal Energy Regulatory Commission (FERC)

Ken Fearon
Paul Shannon

U.S. Bureau of Reclamation (USBR)

Joseph Wright
David Keeney
Tony Wahl

U.S. Geological Survey (USGS)

Timothy Cohn
William Asquith

National Weather Service (NWS)

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Michael St. Laurent

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Kellie Kvarfordt
Curtis Smith

Pacific Northwest National Laboratory (PNNL)

Garill Coles
Ruby Leung
Philip Meyer
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University of California at Davis (UC)

Kei Ishida
Levent Kavvas
Mathieu Mure-Ravaud

U.S. Department of Energy (DOE)

Sharon Jasim-Hanif

Coppersmith Consulting, Inc. (CCI)

Kevin Coppersmith

Fire Risk Management, Inc. (FRM)

William (Mark) Cummings

5 SUMMARY AND CONCLUSIONS

5.1 Summary

This report has presented agendas, presentations and discussion summaries for the first four NRC Annual PFHA Research Workshops (2015-2019). These proceedings include presentation abstracts and slides and a summary of the question and answer sessions. The first workshop was limited to NRC technical staff and management, NRC contractors, and staff from other Federal agencies. The three workshops that followed were meetings attended by members of the public; NRC technical staff, management, and contractors; and staff from other Federal agencies. Public attendees over the course of the workshops included industry groups, industry members, consultants, independent laboratories, academic institutions, and the press. Members of the public were invited to speak at the workshops. The fourth workshop included more invited speakers from the public than from the NRC and the NRC's contractors.

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

5.2 Conclusions

As reflected in these proceedings PFHA is a very active area of research at NRC and its international counterparts, as well as other Federal agencies, industry and academia. Readers of this report will have been exposed to current technical issues, research efforts, and accomplishments in this area within the NRC and the wider research community.

The NRC projects discussed in these proceedings represent the main efforts in the first phase (technical-basis phase) of NRC's PFHA Research Program. This technical-basis phase is nearly complete, and the NRC has initiated a second phase (pilot project phase) that is a syntheses of various technical basis results and lessons learned to demonstrate development of realistic flood hazard curves for several key flooding phenomena scenarios (site-scale, riverine and coastal flooding). The third phase (development of selected guidance documents) is an area of active discussion between RES and NRC User Offices. NRC staff looks forward to further public engagement regarding the second and third phases of the PFHA research program in future PFHA Research Workshops.

ACKNOWLEDGEMENTS

These workshops were planned and executed by an organizing committee in the U.S. Nuclear Regulatory Commission's (NRC's) Office of Nuclear Regulatory Research (RES), Division of Risk Analysis, Fire and External Hazards Analysis Branch, and with the assistance of many NRC staff.

Organizing Committees

1st Workshop, October 14–15, 2015: Joseph Kanney and William Ott.

2nd Workshop, January 23–25, 2017: *Co-Chairs*: Meredith Carr, Joseph Kanney; *Members:* Thomas Aird, Thomas Nicholson, MarkHenry Salley; *Workshop Facilitator:* Kenneth Hamburger

3rd Workshop, December 4–5, 2017: *Chair:* Joseph Kanney, *Members:* Thomas Aird, Meredith Carr, Thomas Nicholson, MarkHenry Salley; *Workshop Facilitator*: Kenneth Hamburger

4th Workshop, April 30–May 2, 2019: *Co-Chairs:* Meredith Carr, Elena Yegorova; *Members:* Joseph Kanney, Thomas Aird, Mark Fuhrmann, MarkHenry Salley; *Workshop Facilitator:* Kenneth Hamburger

Many NRC support offices contributed to all of the workshops and these proceedings. The organizing committee would like to highlight the efforts of the RES administrative staff; the RES Program Management, Policy Development and Analysis Branch; and the audiovisual, security, print shop, and editorial staff. The organizers appreciated office and division direction and support from Jennene Littlejohn, William Ott, MarkHenry Salley, Mark Thaggard, Michael Cheok, Richard Correia, Mike Weber, and Ray Furstenau. Michelle Bensi, Mehdi Reisi-Fard, Christopher Cook, and Andrew Campbell provided guidance and support from the NRC Office of New Reactors and the Office of Nuclear Reactor Regulation. The organizers thank the Electric Power Research Institute (EPRI) for assisting with planning, contributions, and organizing several speakers. EPRI personnel who participated in the organization of the workshops include John Weglian, Hasan Charkas, and Marko Randelovic.

During the workshops, Tammie Rivera assisted with planning and organized the registration area during the conference. David Stroup and Don Algama assisted with room organization. Notes were studiously scribed by Mark Fuhrmann, David Stroup, Nebiyu Tiruneh, Michelle Bensi, Hosung Ahn, Gabriel Taylor, Brad Harvey, Kevin Quinlan, Steve Breithaupt, Mike Lee, Jeff Wood, and organizing committee members. The organizers appreciate the assistance during the conference of audiovisual, security, and other support staff. The organizers thank the panelists, the technical presenters, and poster presenters for their contributions; Thomas Aird and Mark Fuhrmann for performing a colleague review of this document; and the Probabilistic Flood Hazard Assessment Research Group for transcript reviews.

Members of the Probabilistic Flood Hazard Assessment Research Group:
MarkHenry Salley (Branch Chief), Joseph Kanney (Technical Lead), Thomas Aird, Meredith Carr, Mark Fuhrmann, Jacob Philip, Elena Yegorova, and Thomas Nicholson (Senior Technical Advisor)

APPENDIX A: SUBJECT INDEX

APPENDIX B: INDEX OF CONTRIBUTORS

This index includes authors, co-authors, panelists, poster authors and self-identified participants from the audience who spoke in question and answer or panel discussions.

APPENDIX C: INDEX OF PARTICIPATING AGENCIES AND ORGANIZATIONS