Probabilistic Hydrologic Hazard Analysis

Best Practices Chapter II-2

12 Jun 2015

RECLAMATION
Managing Water in the West

US Army Corps of Engineers
BUILDING STRONG®

Outline

- Floods and Hydrologic Hazards – Why do we care?
- Some Hydrologic-Related Potential Failure Modes
- Risk Analysis and Hydrologic Loads
- What's a Hydrologic Hazard Curve?
- Hydrologic Hazards - Current Guidance
- Hydrologic Hazard Curve Estimation – Key Principles
  - Risk and Type of Decision
  - Interdisciplinary Teams
  - Data, Combinations, Extrapolation
  - Hydrologic Hazard Methods
  - Use of Multiple Methods and Weighting
  - Uncertainty of Estimates
- Example and Summary

Floods and Hydrologic Hazards:
Why do We Care?

Cedar Rapids, Iowa 2008

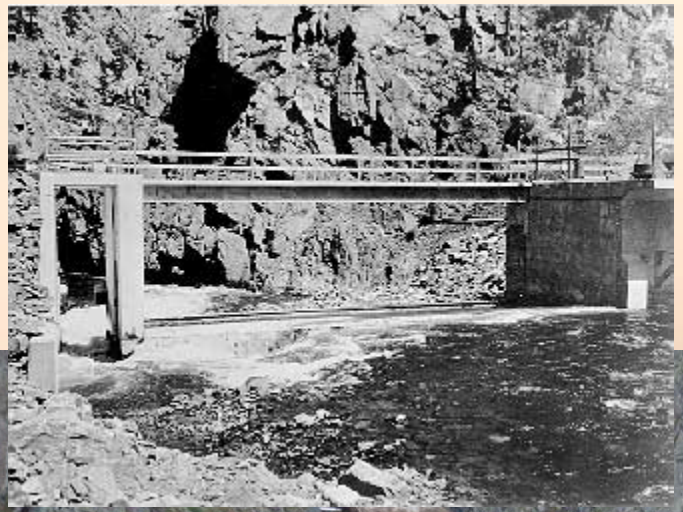
McConnell Drive at Hwy 36
Lyons, CO Sept 2013

Floods in the Big Thompson River, CO (Canyon Mouth) 07/31/1976; 09/13/2013

08/02/1976
Qp=31,000 ft^3/s

09/13/2013
Qp= ?
Substantially larger volume and duration

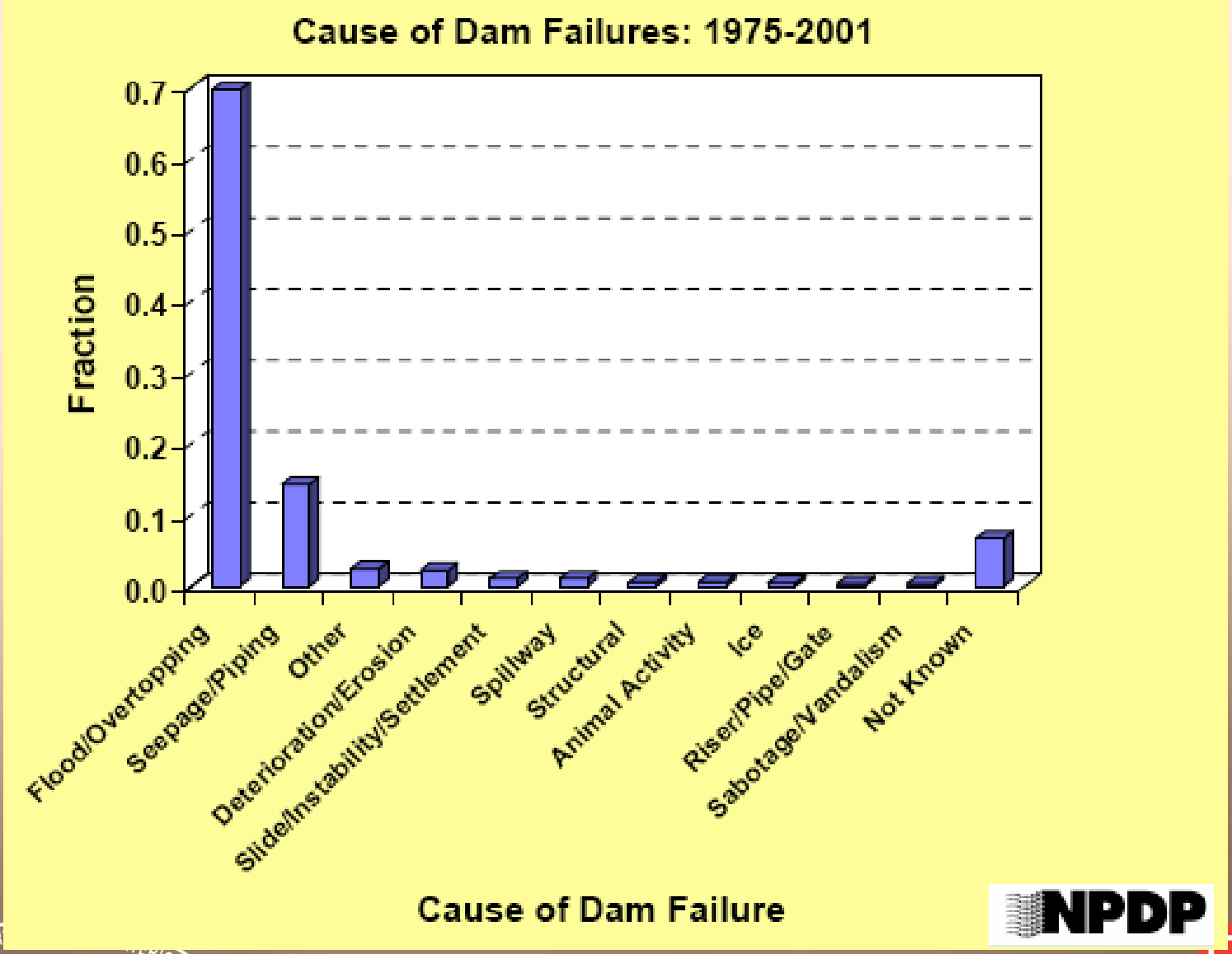
Dille Diversion Dam, Big Thompson River Flood of Sept 12-13, 2013



Some Example Hydrologic-Related Dam Failure Modes

- Overtopping
  - erosion of downstream toe, foundation or dam crest
- High Reservoir Levels
  - seepage through impervious core; piping and erosion
- Spillway Chute or Stilling Basin Failure
  - erosion, cavitation or overtopping
- Spillway Gate Mechanical Failure

Flood Overtopping Dam Failures



Lake Delhi Dam, Eastern Iowa
July 24, 2010 - 12:14 pm

Further Details in USACE/USBR Case Histories

Lake Delhi Dam, IA
July 24 – 12:15 pm

Lake Delhi Dam, IA - Full Breach

Hydrologic Loads and Risk Analysis for Dam Safety (Reclamation)

Annualized Failure Probability

$$f = P_l * P_{r|l}$$

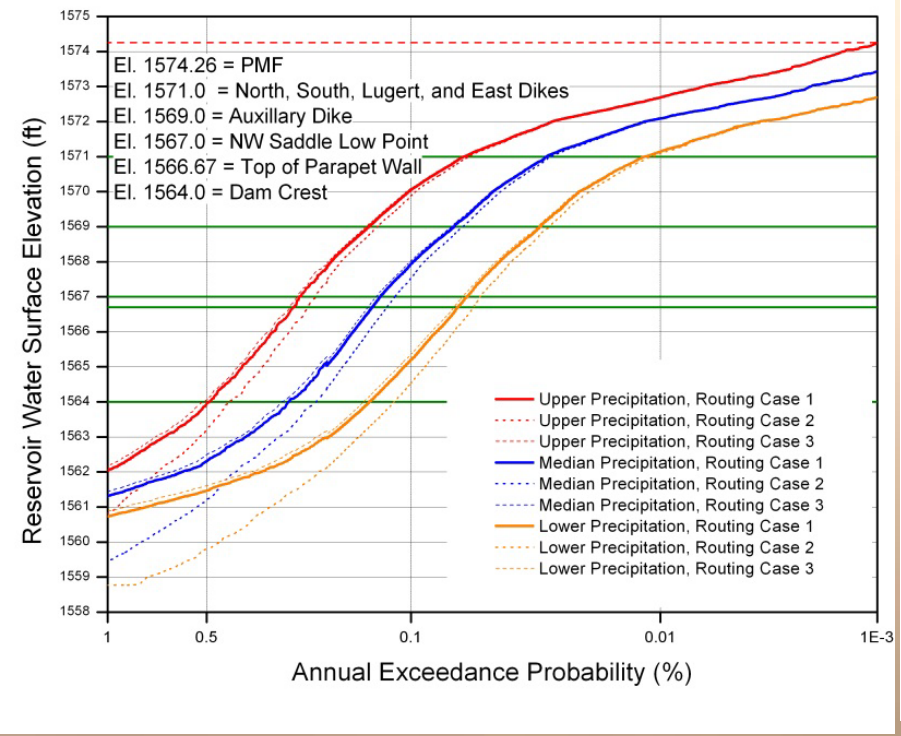
Risk: Annualized Life Loss

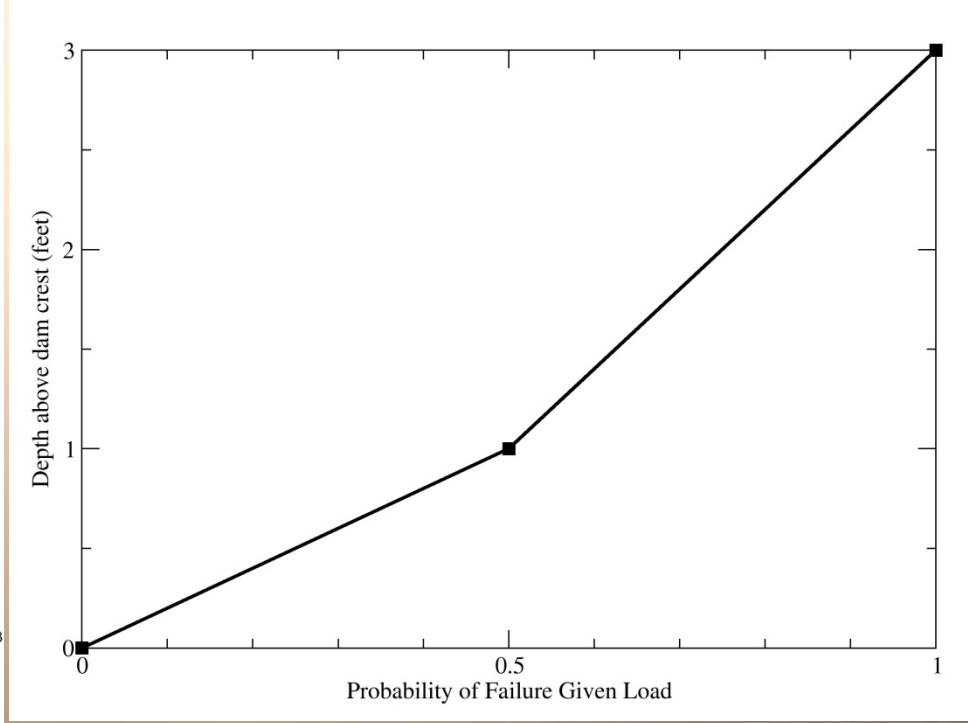
$$Risk = P_l * P_{r|l} * C$$

P_l = Probability of Load – ***Hydrologic Hazard Curve***

$P_{r|l}$ = Probability of Adverse Response Given Load
C = Consequences (or Loss of Life, N)

Risk Analysis for Dam Safety: Interaction of Load and Failure Probabilities





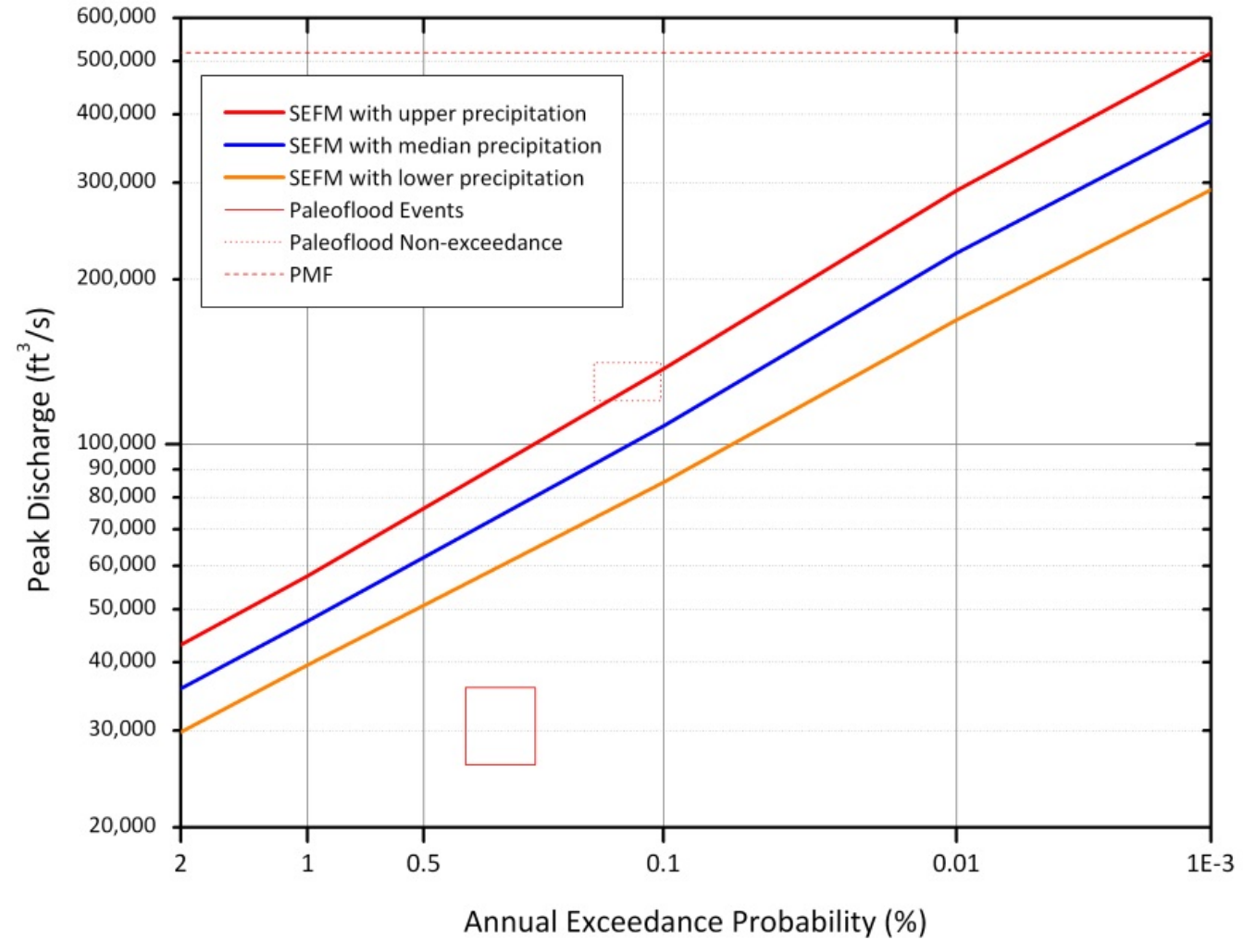
P_l = Probability of Load – ***Hydrologic Hazard Curve (Reservoir Elevation)***

$P_{r|l}$ = Probability of Response Given Load (Depth above Dam Crest)

Hydrologic Hazard Curve Definition

- 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 Reclamation)***
- 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) (overtopping, gates, spillway chute, etc.)

Hydrologic Hazard: Peak Discharge

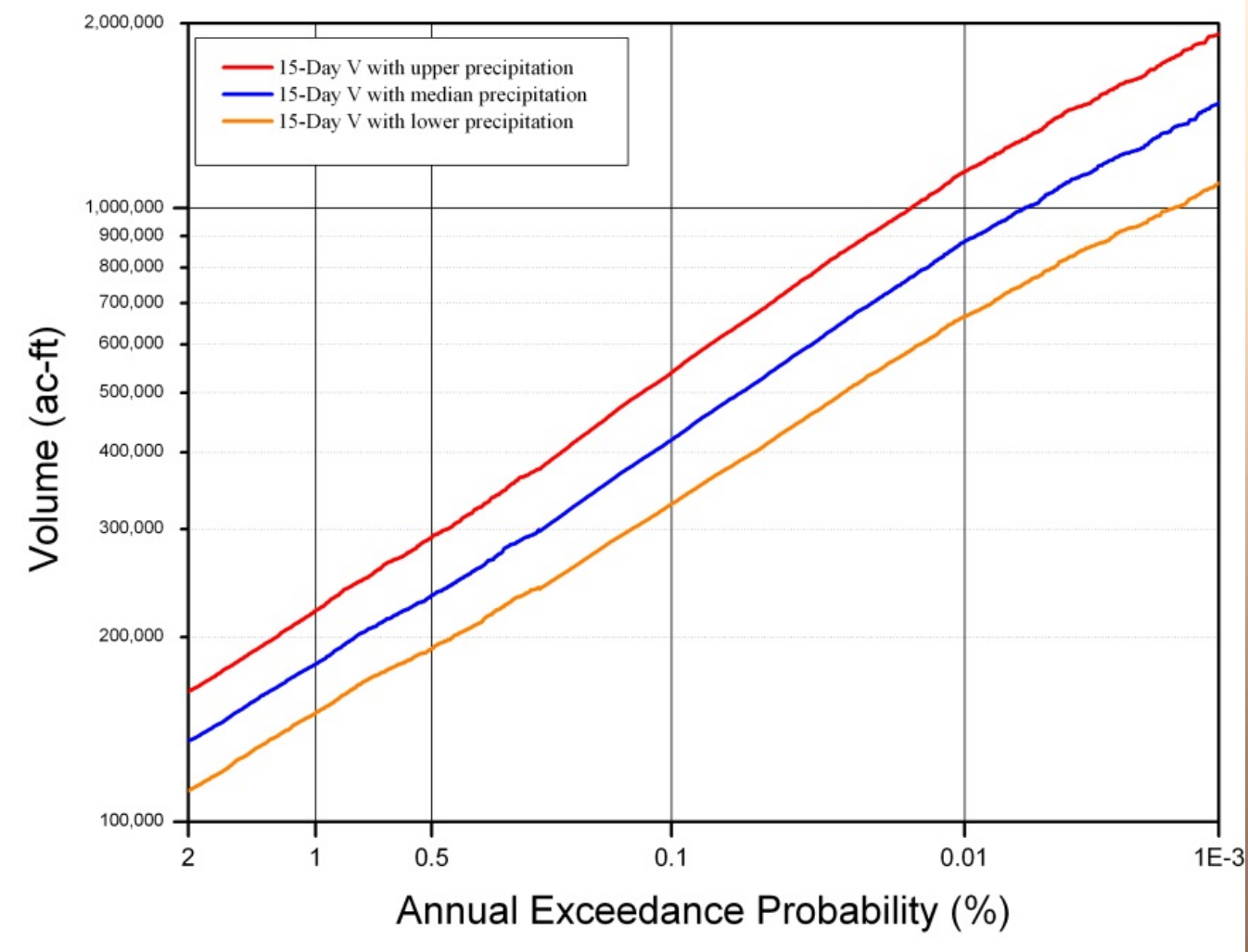


Red – 95th percentile precipitation

Blue – 50th percentile precipitation

Orange – 5th percentile precipitation

Hydrologic Hazard: 15-day volume

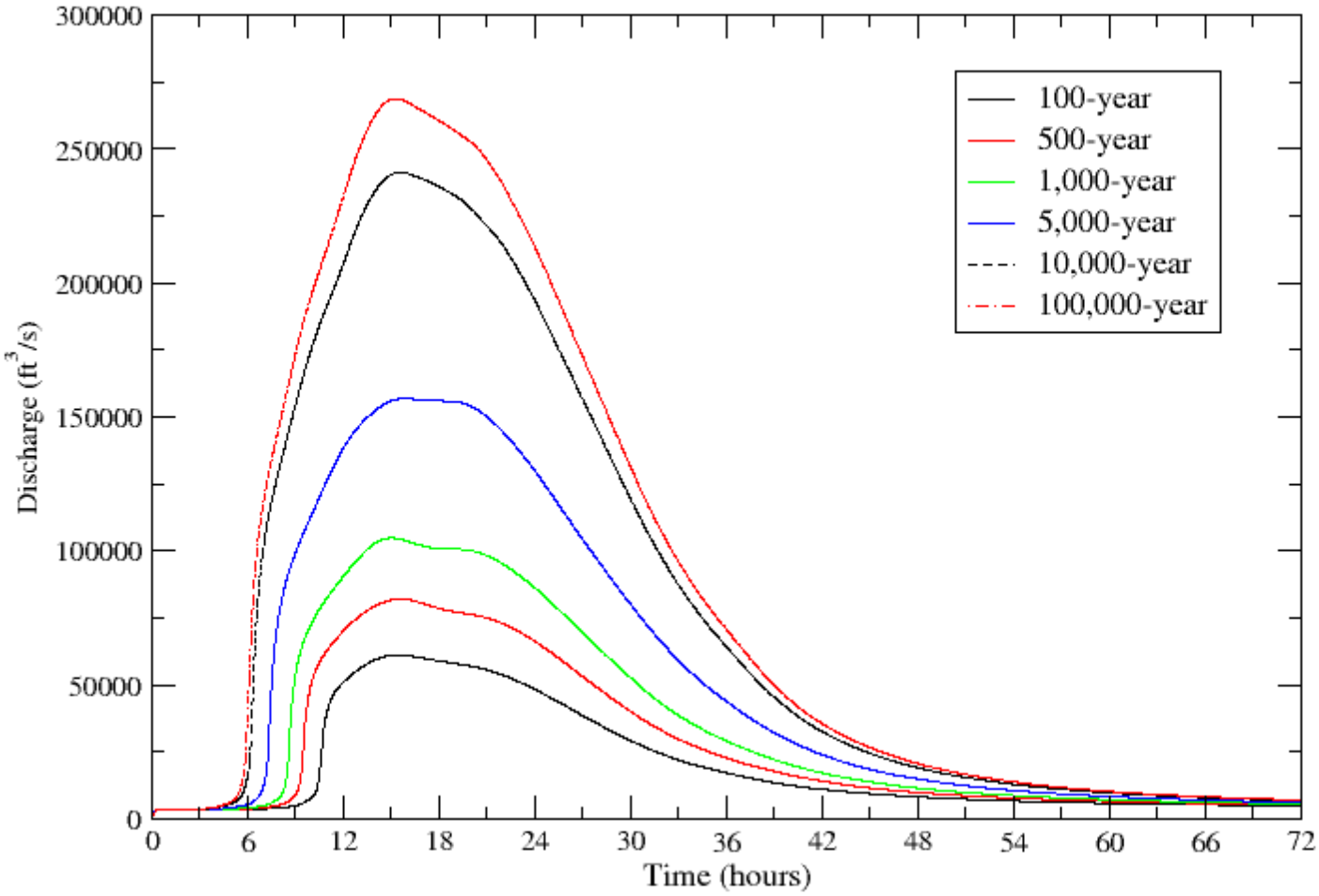


Red – 95th percentile precipitation

Blue – 50th percentile precipitation

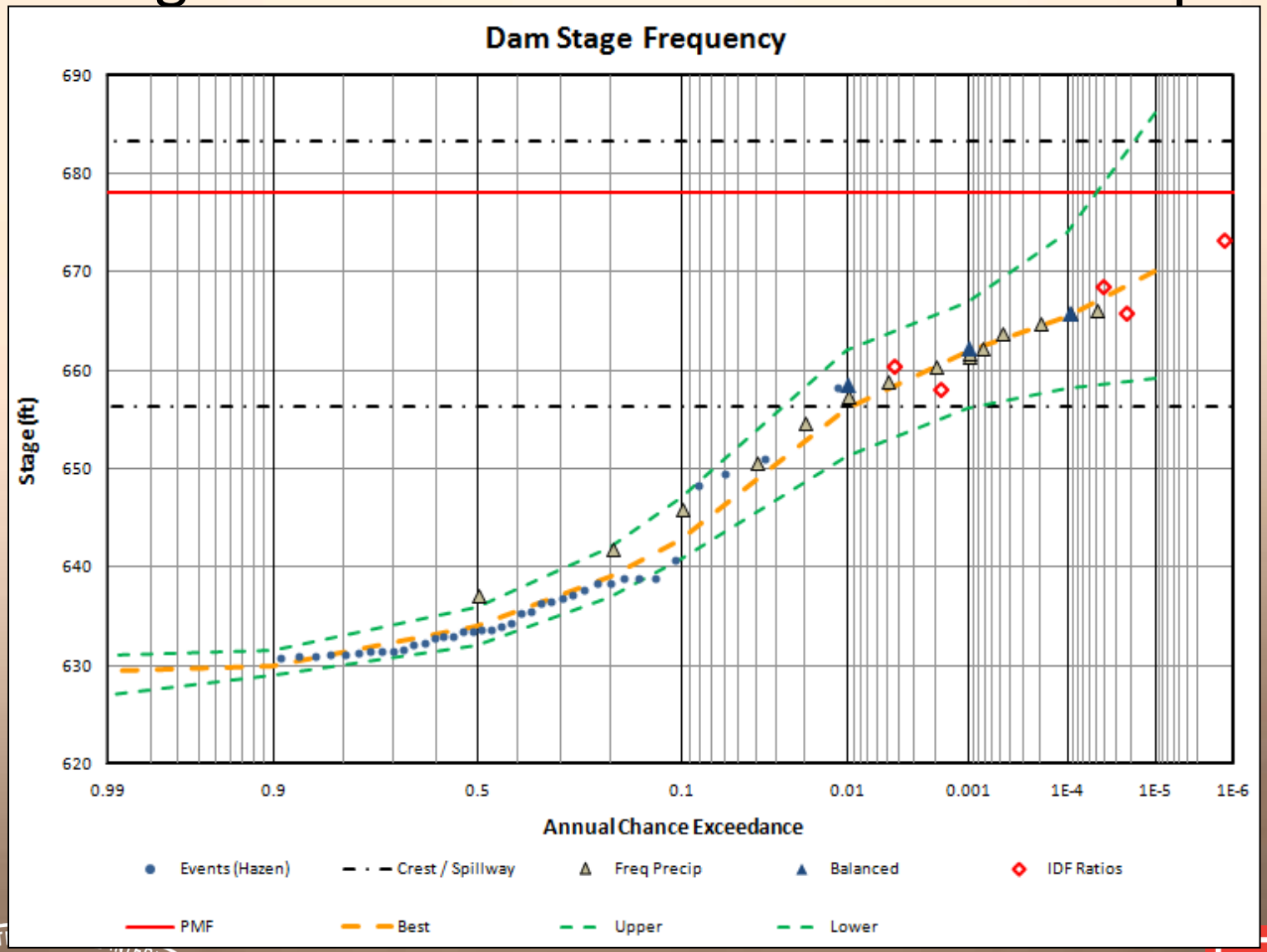
Orange – 5th percentile precipitation

Example Extreme Flood Hydrographs



Based on event (peak, *n*-day volume) probabilities

Hydrologic Hazard: Reservoir Elevation Frequency

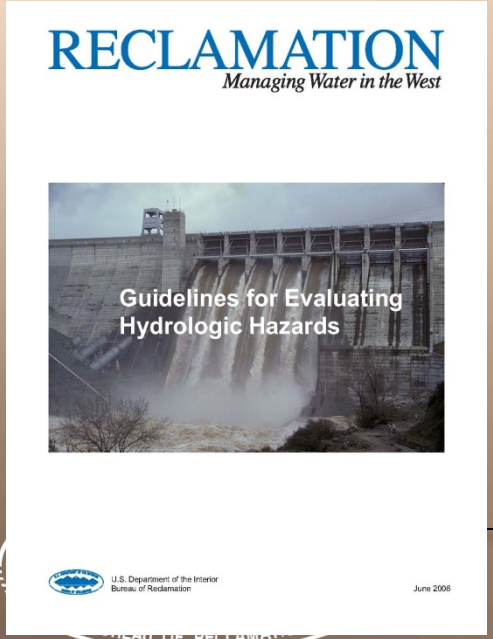


Stage frequency curve with uncertainty, can also be developed for levees

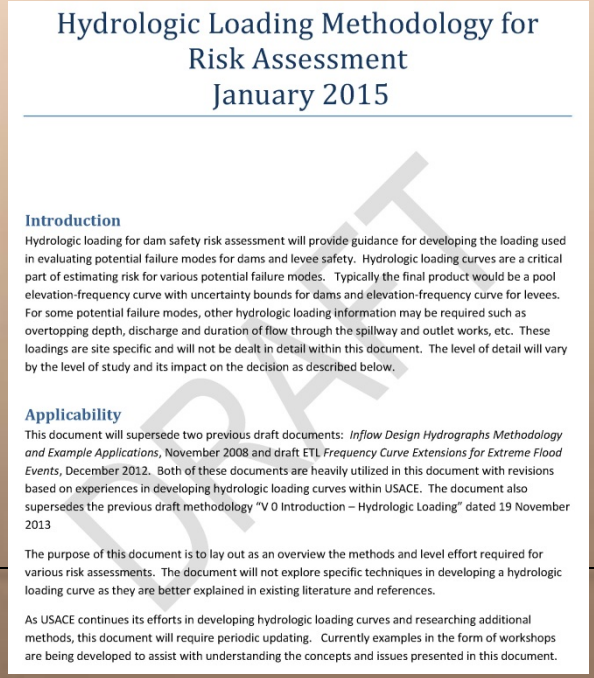
Current Guidance on Hydrologic Hazard Estimation

Reclamation, USACE and FERC implementing and using similar methods for hydrologic hazards; some technical details in these reports

Reclamation, 2006;
(under revision, 2015)



USACE, 2015
(under development)



Hydrologic Loading Methodology for Risk Assessment
January 2015

DRAFT

Introduction

Hydrologic loading for dam safety risk assessment will provide guidance for developing the loading used in evaluating potential failure modes for dams and levee safety. Hydrologic loading curves are a critical part of estimating risk for various potential failure modes. Typically the final product would be a pool elevation-frequency curve with uncertainty bounds for dams and elevation-frequency curve for levees. For some potential failure modes, other hydrologic loading information may be required such as overtopping depth, discharge and duration of flow through the spillway and outlet works, etc. These loadings are site specific and will not be dealt in detail within this document. The level of detail will vary by the level of study and its impact on the decision as described below.

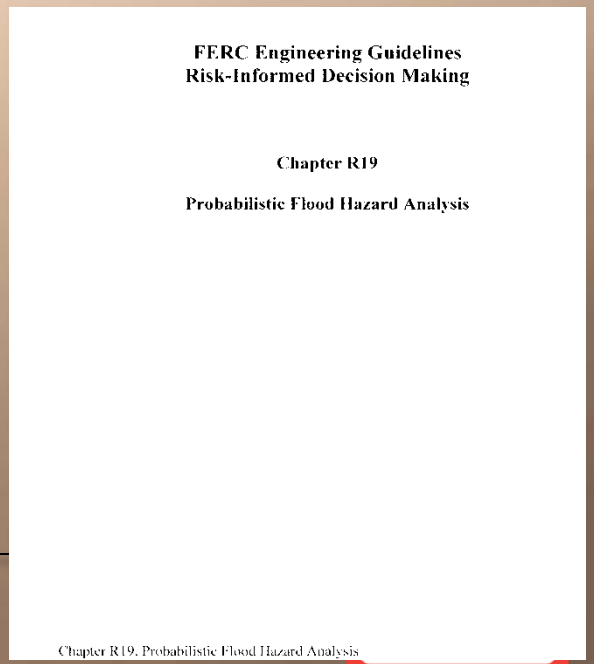
Applicability

This document will supersede two previous draft documents: *Inflow Design Hydrographs Methodology and Example Applications*, November 2008 and draft ETL *Frequency Curve Extensions for Extreme Flood Events*, December 2012. Both of these documents are heavily utilized in this document with revisions based on experiences in developing hydrologic loading curves within USACE. The document also supersedes the previous draft methodology "V 0 Introduction – Hydrologic Loading" dated 19 November 2013

The purpose of this document is to lay out as an overview the methods and level effort required for various risk assessments. The document will not explore specific techniques in developing a hydrologic loading curve as they are better explained in existing literature and references.

As USACE continues its efforts in developing hydrologic loading curves and researching additional methods, this document will require periodic updating. Currently examples in the form of workshops are being developed to assist with understanding the concepts and issues presented in this document.

FERC, 2014
draft for public



FERC Engineering Guidelines
Risk-Informed Decision Making

Chapter R19

Probabilistic Flood Hazard Analysis

Chapter R19, Probabilistic Flood Hazard Analysis

Hydrologic Hazards and Type of Risk Informed Decision

Hydrologic Hazard estimates are typically made for three levels of risk informed decisions. Data and methods depend on type of study:

- Periodic Assessments/Comprehensive Reviews
  - Screening-level/qualitative information used
- Issue Evaluation Studies
  - Increased regional data collection and level of detail
- Corrective Action/Dam Safety Modification Studies
  - Additional at-site data collection and modeling efforts

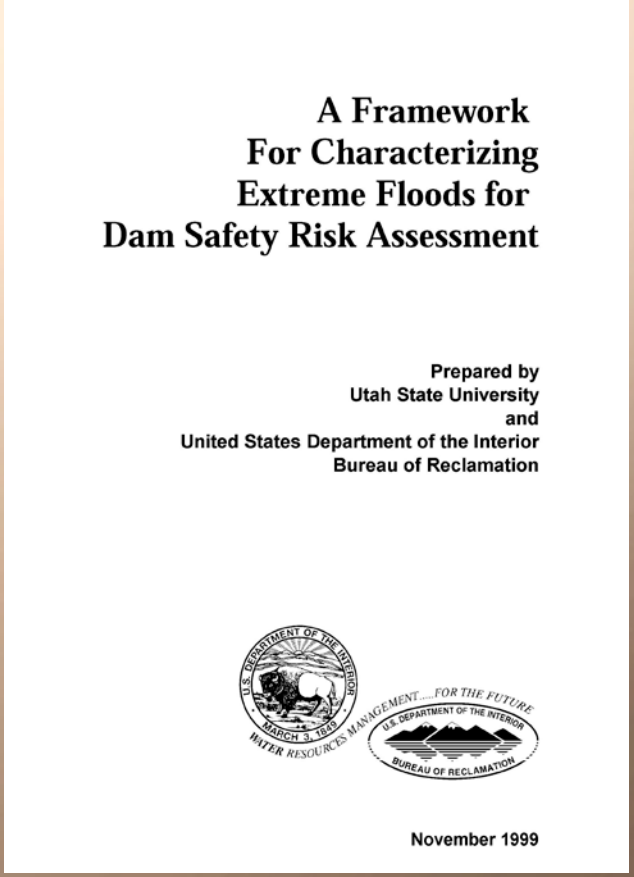
Hydrologic Hazard Principles Interdisciplinary Teams

Hydrologic Hazard Analysis requires interdisciplinary load specialist teams:

- Geologists/Geomorphologists – expertise in soils, stratigraphy, paleofloods
- Hydraulic Engineers – 2D river flow modeling for paleofloods
- Meteorologists – storm rainfall data, analyses, temporal and spatial patterns, statistics, extreme precipitation for runoff modeling
- Hydrologists and Hydraulic Engineers – flood frequency, flood statistics, rainfall-runoff modeling

Hydrologic Hazard Principles
Some Key Concepts

- Do Not Assign AEP to the PMF
- No Single Approach Describing Flood Hazards Over the Range of AEPs Needed – *Multiple Methods*
- Greatest Gains From Incorporating Regional Precipitation, Streamflow, Paleoflood Data – *Lots of Data*
- Honestly Represent Uncertainty – *Explicitly Quantify Uncertainty*
- Research and Development needed- Data/Methods


A Framework
For Characterizing
Extreme Floods for
Dam Safety Risk Assessment

Prepared by
Utah State University
and
United States Department of the Interior
Bureau of Reclamation

November 1999

Hydrologic Hazard Principles – Expand Data and Information Used

- Temporal Information: expand data in time
- Spatial Information: expand data in space
- Causal Information: utilize hydrological understanding of flood-producing factors

- 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

Merz and Bloschl (2008), WRR

Hydrologic Hazard Principles - Data

- Data - focus on past (paleoflood) and present (recent precipitation/streamflow) data
  - –Future climate projections assessed/used project by project – study and decision dependent – see CMIP5 Downscaled archive
- Extreme Storm Rainfall
  - point gages – NCDC
  - Depth-Area Duration storm catalog from USACE, Reclamation, NWS
  - MPE and MPR gridded precip (NWS)
- Extreme Flood Data
  - USGS stream gages: peaks, hydrographs
  - Historical information
  - Paleoflood data

Hydrologic Hazard Data
Types, Combinations, Extrapolation

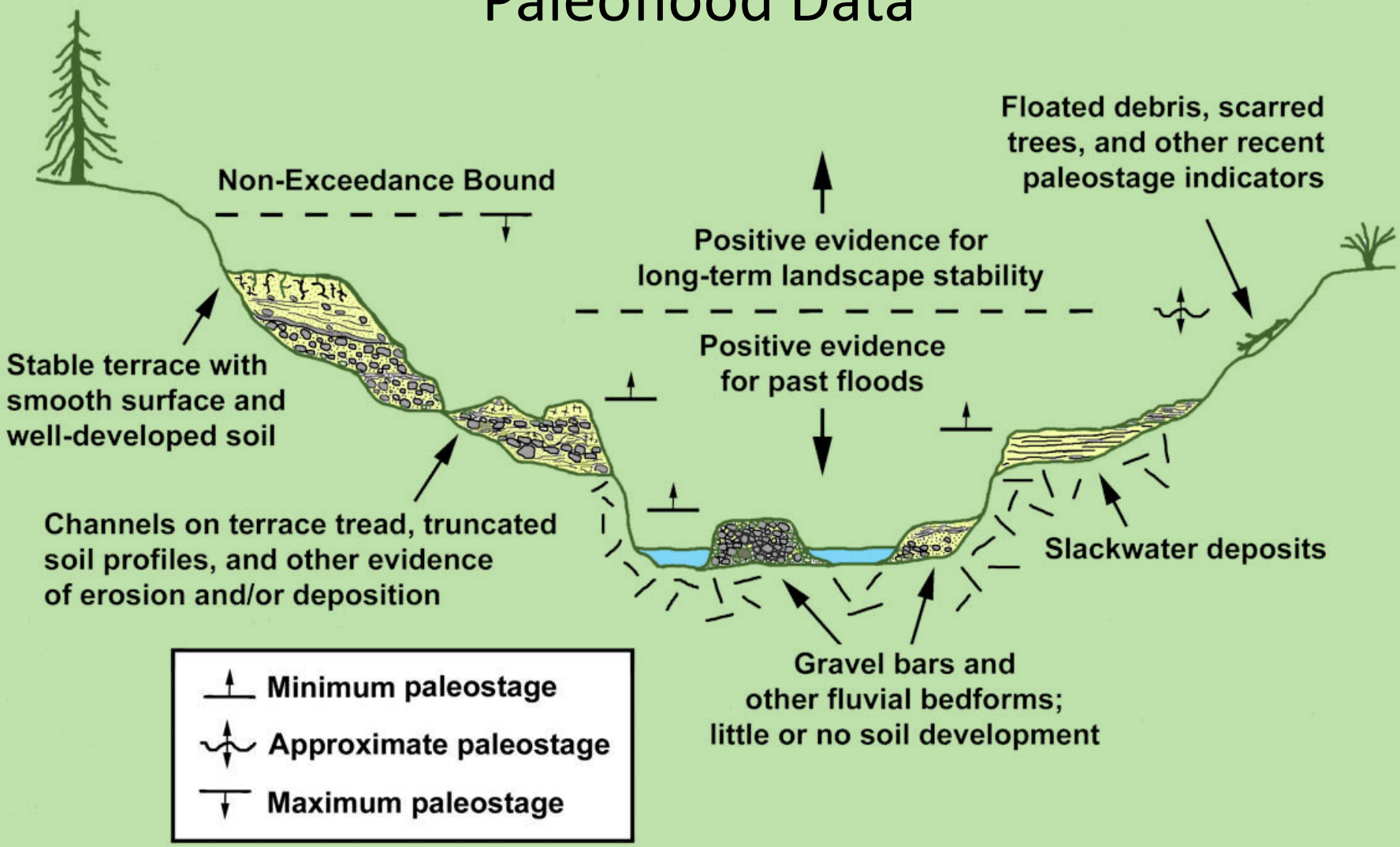
Type of data used for flood frequency analysis	Range of credible extrapolation for Annual Exceedance Probability	
	Typical	Optimal
At-site streamflow data	1 in 100	1 in 200
Regional streamflow data	1 in 500	1 in 1,000
At-site streamflow and at-site paleoflood data	1 in 4,000	1 in 10,000
Regional precipitation data	1 in 2,000	1 in 10,000
Regional streamflow and regional paleoflood data	1 in 15,000	1 in 40,000
Combinations of regional data sets and extrapolation	1 in 40,000	1 in 100,000

USBR - USU (1999), Swain et al. (2006)
Also in: Australian Rainfall-Runoff Book VI Extreme Floods (2001)

Hydrologic Hazard Data – Peak Flows

Battle Creek, Shasta County, CA Dec. 22, 1964

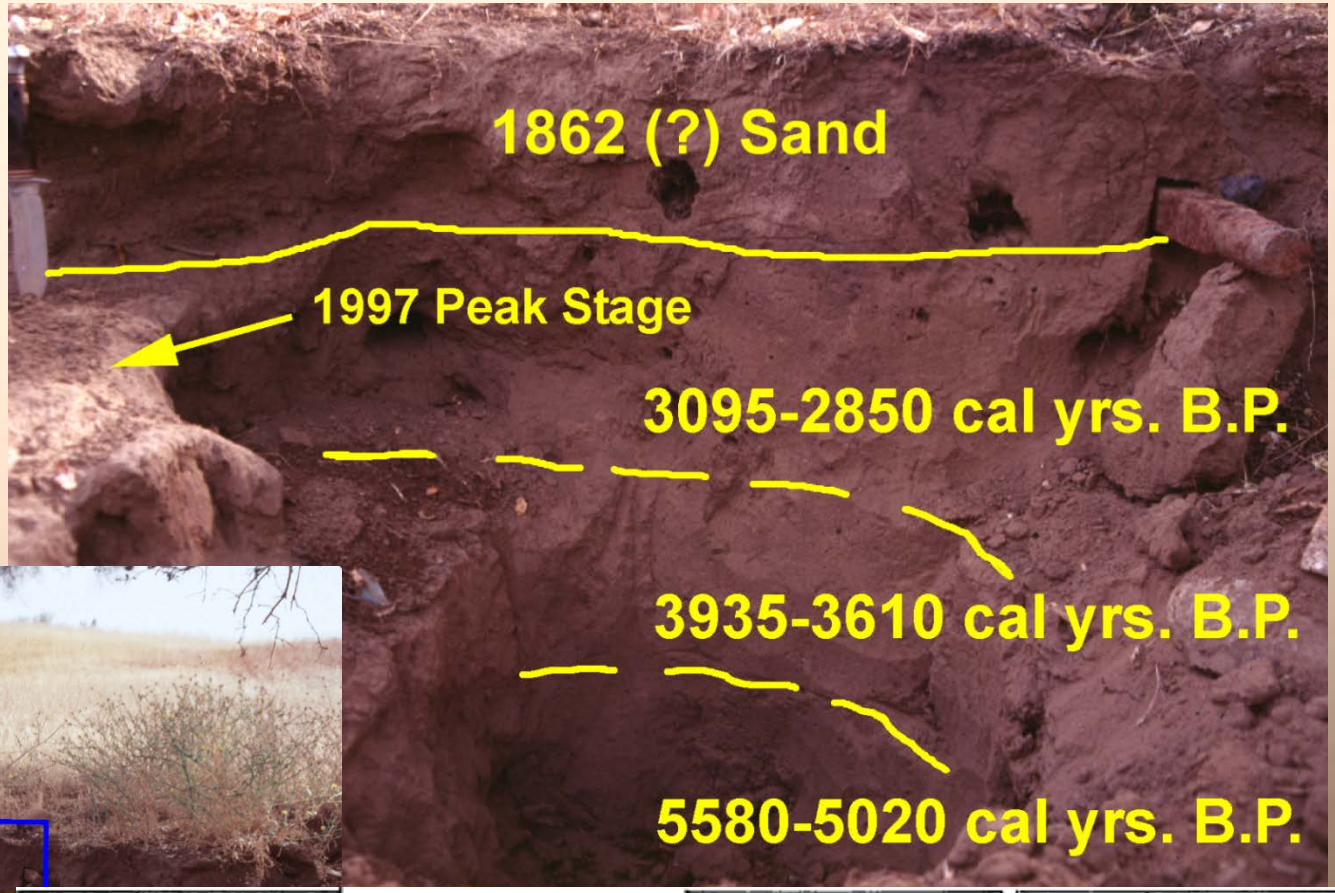
Paleoflood Data

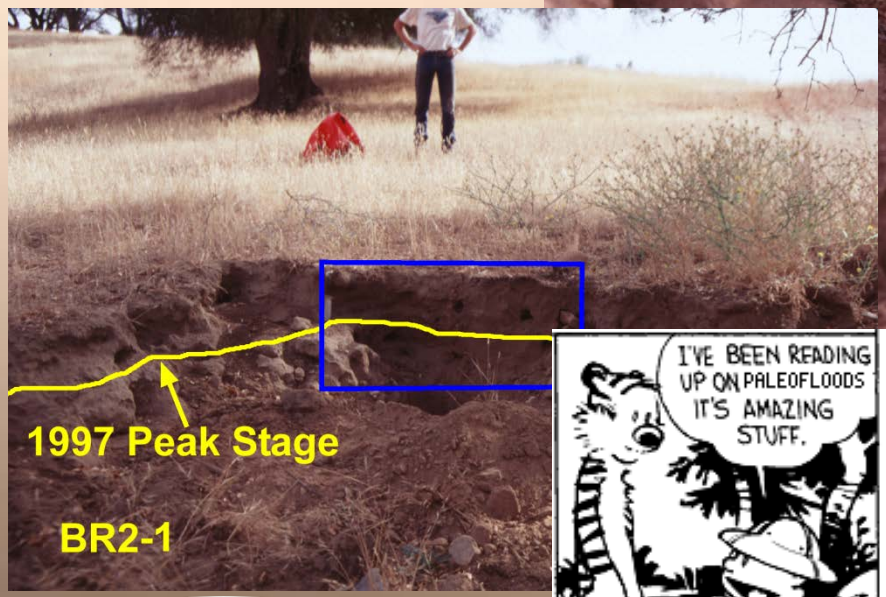


House et al. (2002) AGU Paleoflood Monograph

South Fork American River near Lotus Paleofloods

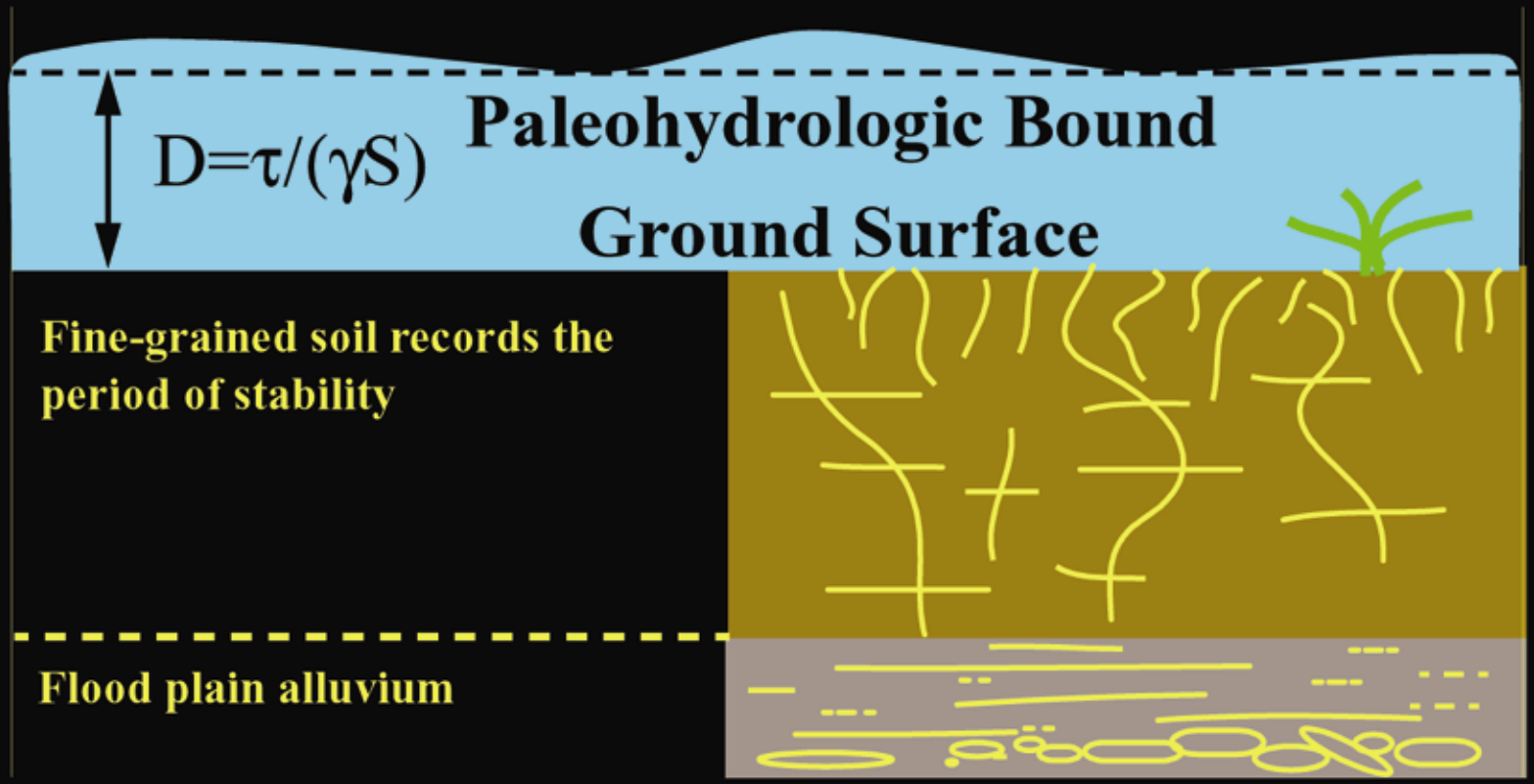
Example of crucial data used in Reclamation Folsom Dam Flood Hazard Analysis (2002)





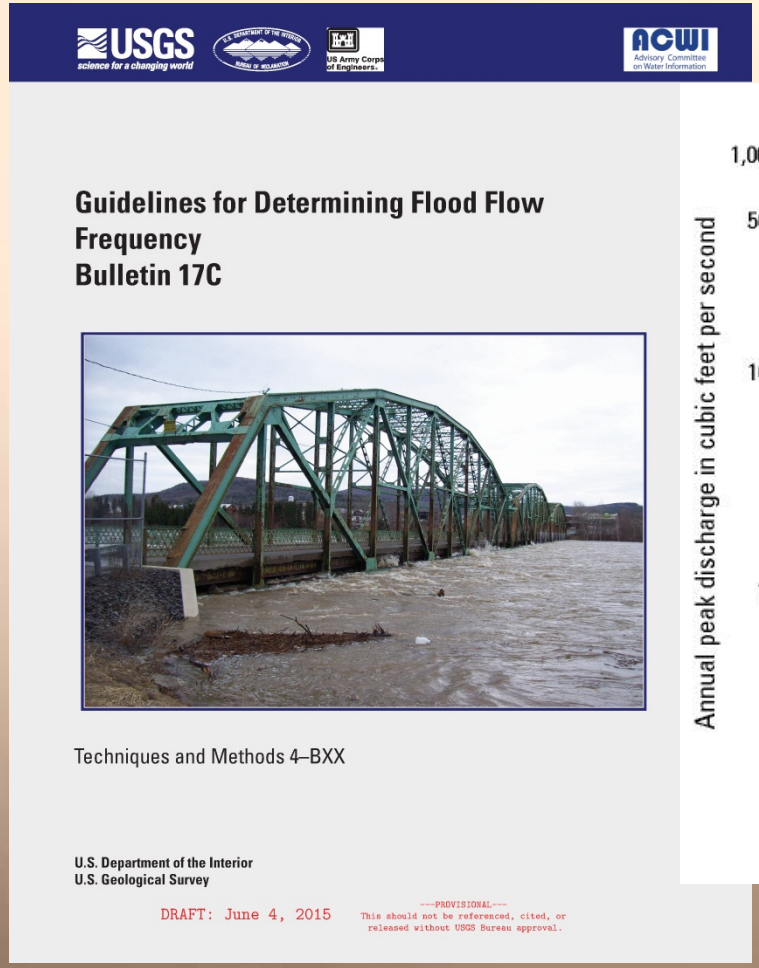
Paleohydrologic Bound

"A time interval during which a given discharge has not been exceeded"



Levish, D.R. (2002) in House et al.
AGU Paleoflood Monograph

Hydrologic Hazard – Peak Flow with Historical/Paleoflood data



Guidelines for Determining Flood Flow Frequency
Bulletin 17C

Techniques and Methods 4–BXX

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

DRAFT: June 4, 2015

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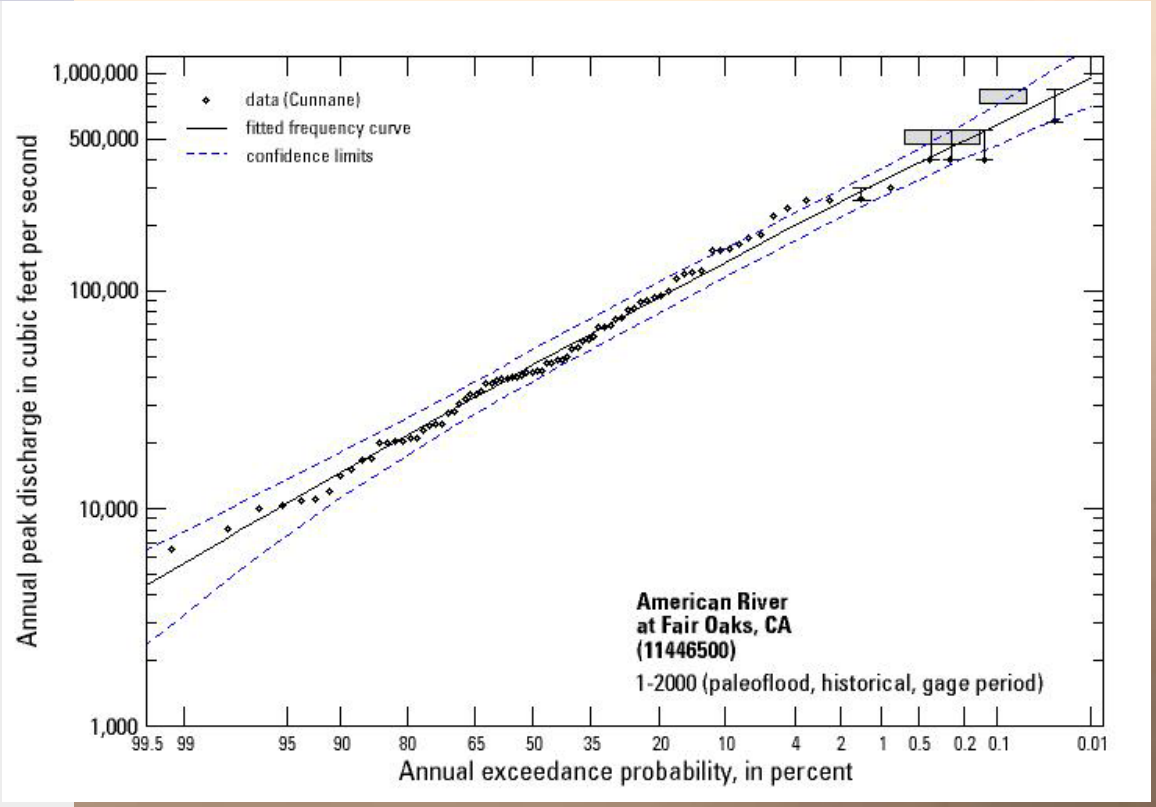
This should not be referenced, cited, or released without USGS Bureau approval.



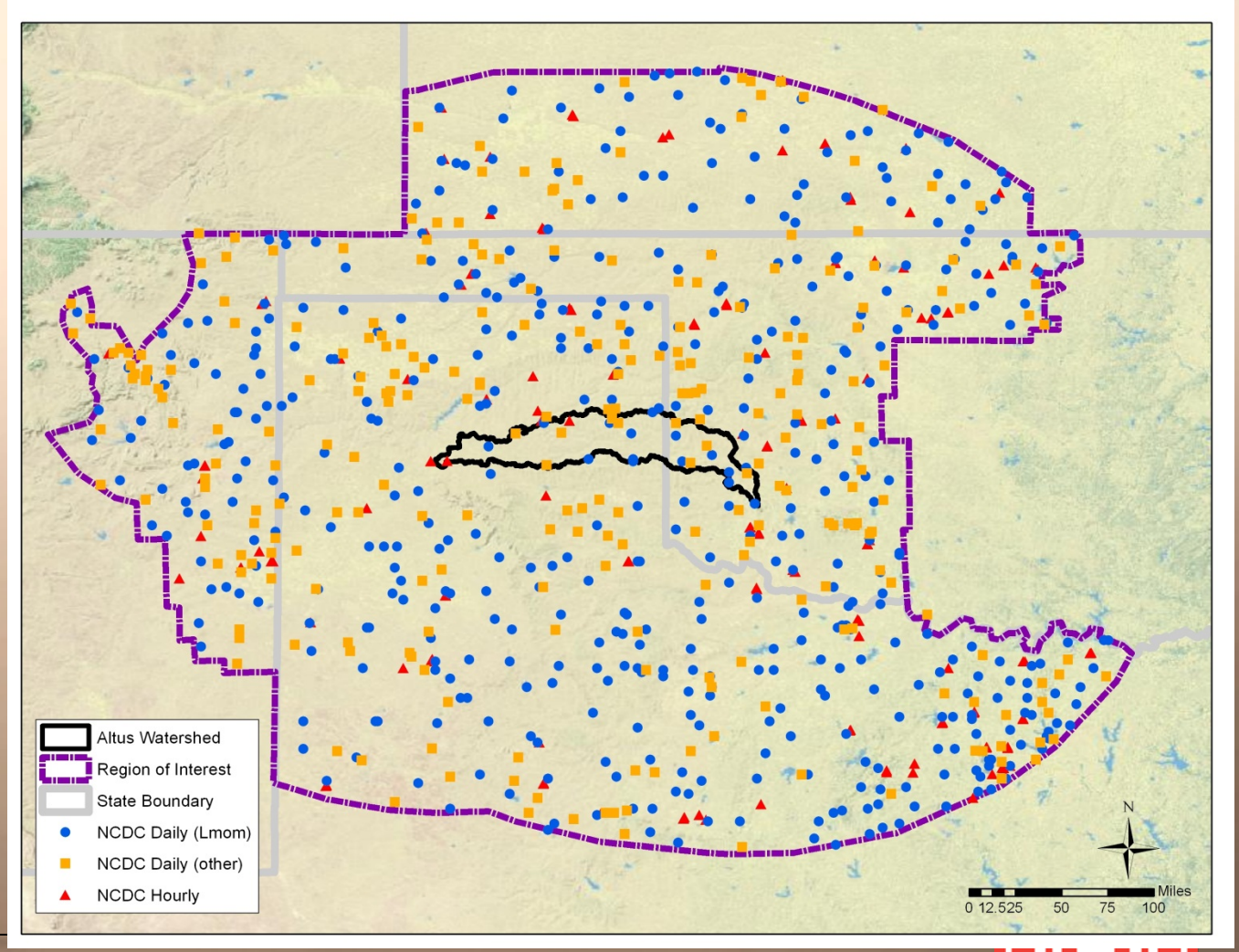
Bulletin 17C draft in review, June 2015

Hydrologic Hazard Data
Precipitation gages within Large Region

Spatial Information: expand data in space.

Example – precipitation gages from NCDC (possibly also NRCS SNOTEL) for regional precipitation frequency analysis (space-time substitution)

Altus Dam, OK HHA



Storm Catalog/ Analyses of Individual Extreme Events

Jan 1997

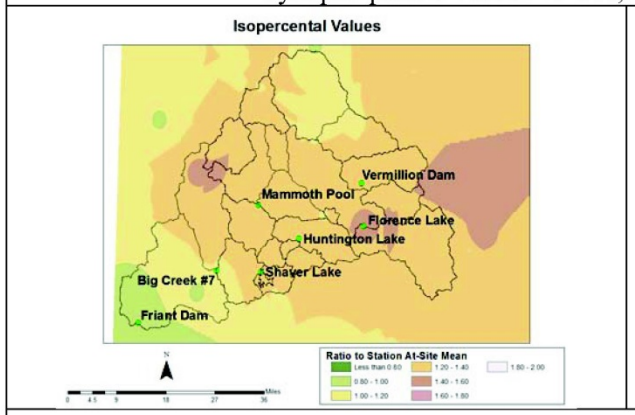
16 storms analyzed for Friant

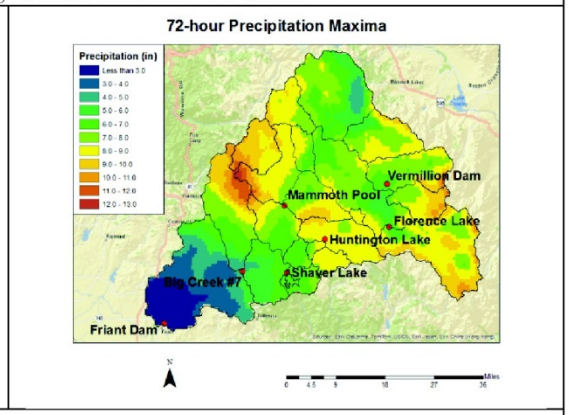
Wright et al (2013) Hydrologic Hazard report

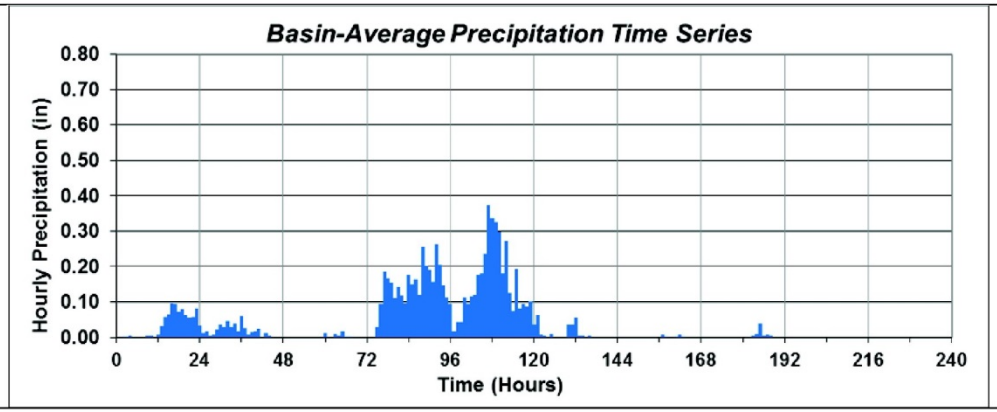
29 December 1996 – 7 January 1997

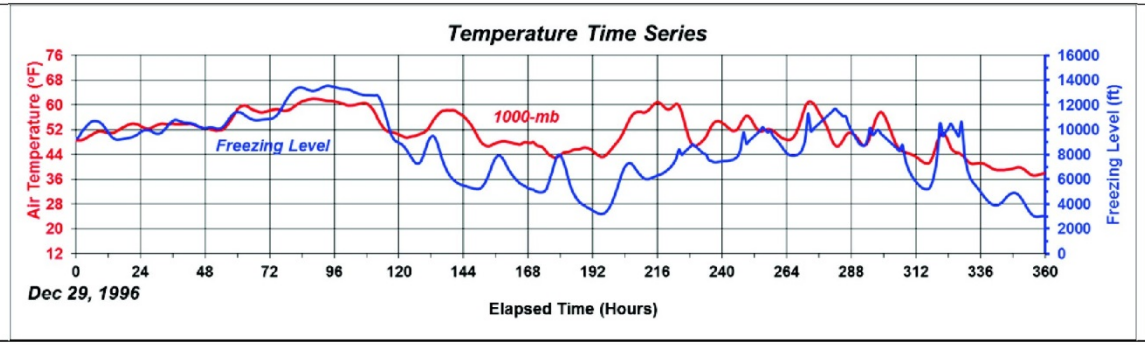
Synoptic set-up: Warm air advection associated with a weaker atmospheric river/jet from the central Pacific, precipitation ends with dry air advection

Synoptic period: Hours 48-144; Storm duration: 97 hours

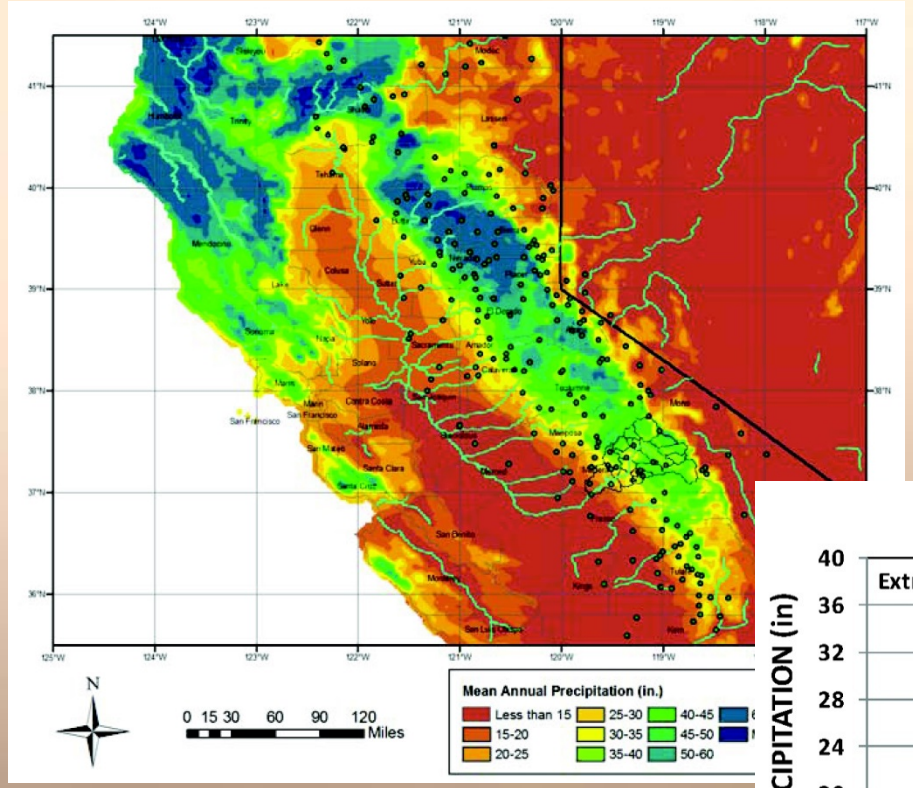




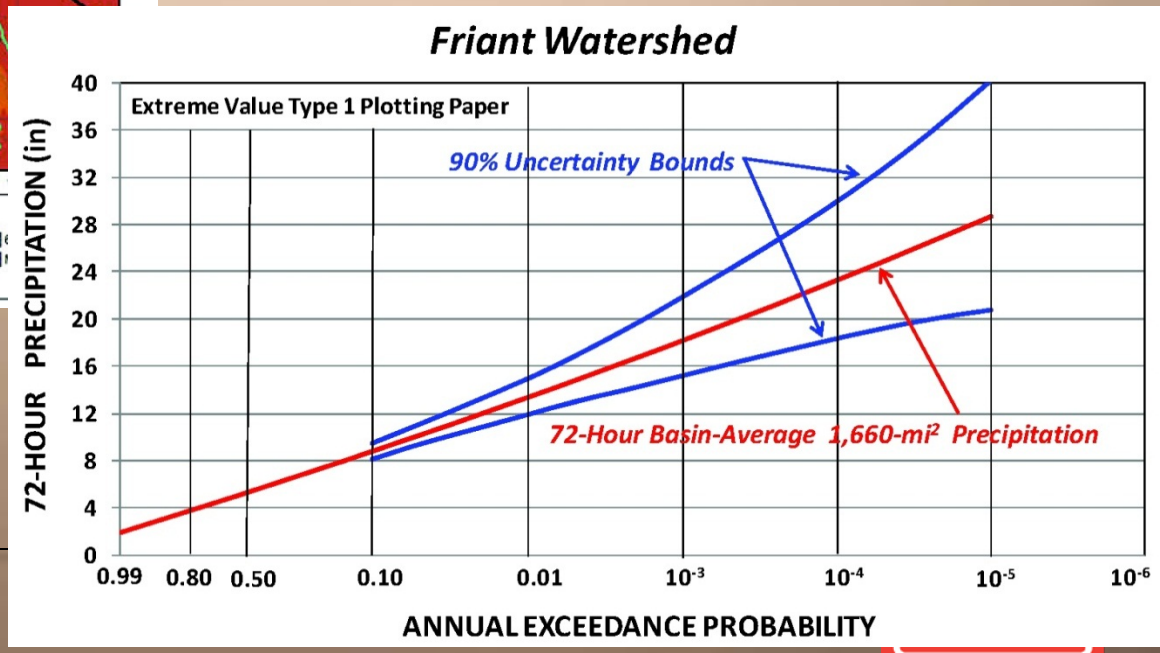




Basin-Average Precipitation Frequency with Uncertainty



key input to rainfall-runoff model



Data: large region;
272 gages used

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Hydrologic Hazard Methods

- Make use of prior studies and documents (PMF, FFA, WCM, etc.)
- Staged approach; balance study cost and solution cost
- Begin with initial characterization – streamflow and paleoflood frequency; scaled hydrographs
- Conduct other studies on an as needed basis
- Application of several methods will increase credibility and confidence in results

Probable Maximum Flood (PMF)

PMF: The estimated maximum runoff condition resulting from the most severe combination of hydrologic and meteorological conditions that are considered reasonably possible for the drainage basin under study.

- Design-Based Standard
- Based on (usually) conservative estimates
- No Estimate of ACE
- May represent the maximum, but it may not...
- Used to perform initial screening on overtopping risk

Hydrologic Hazard Methods – Two Main Classes

- Streamflow Statistics
  - Direct use of streamflow (peak/volume) data
  - Peak-flow frequency analysis
  - Volume frequency analysis
  - Hydrograph scaling
- Rainfall-Runoff Modeling
  - Extreme rainfall probabilities
  - Extreme storm spatial and temporal patterns
  - Runoff model calibrated to large floods
  - Monte-Carlo framework

Hydrologic Hazard Methods- Streamflow

Class	Method *(Agency)*	Method of Analysis and Modeling *(reference)*	Data Inputs	Assumptions	Level of Effort
Streamflow-based statistics	Graphical Flood Frequency *(USBR)*	Peak-flow frequency analysis with historical/paleoflood data - Graphical method (*Swain et al., 2004*)	Peak flow, reconnaissance paleofloods, PMF hydrograph	LogNormal flood frequency; PMF hydrograph represents volume	Low
Streamflow-based statistics	EMA-LP-III and Bulletin 17C USGS PeakFQ; HEC-SSP *(USACE and USBR)*	Peak-flow and volume frequency analysis with historical/paleoflood data - EMA (*Cohn et al., 1997; England et al., 2003; England et al., 2015*)	Peak flow, historical data, regional skews, detailed paleofloods	LP-III flood frequency distribution with moments and regional skew	Low to moderate
Streamflow-based statistics	FLDFRQ3 *(USACE and USBR)*	Peak-flow frequency analysis with historical/paleoflood data - FLDFRQ3 (*O'Connell et al., 2002*)	Peak flow, detailed paleofloods	Various flood frequency distributions with likelihood	Low to moderate
Streamflow-based statistics	Hydrograph Scaling *(USACE and USBR)*	Hydrograph Scaling and Volumes (*England, 2003*)	Hydrographs and volumes	Hydrographs represent extreme flood response; requires FFA for scaling	Low
Streamflow-based statistics	Streamflow Volume Stochastic Modeling (MCRAM)		Pool duration, volumes, and Hydrographs	Main inputs defined by distributions, volume-frequency observed hydrographs, and pool duration frequency	Moderate

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Hydrologic Hazard Methods: Rainfall-Runoff

Class	Method *(Agency)*	Method of Analysis and Modeling (*reference*)	Data Inputs	Assumptions	Level of Effort
Rainfall-based statistics and Runoff Transfer	GRADEX USACE and USBR	GRADEX Method (*Naghettini et al., 1996*)	Rainfall gages/regional statistics; streamflow volumes	Flood frequency same shape as rainfall frequency with exponential tail; saturated basin	Moderate
Rainfall-based statistics and Rainfall-Runoff	Australian Rainfall-Runoff *(USBR)*	Australian Rainfall-Runoff Method (*Nathan and Weinmann, 1999*)	PMP design storm; rainfall frequency; watershed parameters	Exceedance Probability of PMP; average watershed parameter values; runoff frequency same as rainfall frequency	Moderate
Rainfall-based statistics and Rainfall-Runoff	SEFM *(USBR)*	Stochastic Event-Based Precipitation Runoff Modeling with SEFM (*MGS,2005, MGS, 2009; Schaefer and Barker, 2002*)	Rainfall gages/ detailed regional rainfall frequency, watershed parameters, snowpack, reservoir data	Main inputs defined by distributions; unit hydrograph; rainfall frequency using GEV/L-moments	High
Rainfall-based statistics and Rainfall-Runoff	TREX *(USBR)*	Stochastic Rainfall-Runoff Modeling with TREX (*England et al., 2006, 2007, 2014*)	Regional extreme storm DAD data, watershed parameters, snowpack	Diffusive wave runoff; stochastic storm transposition rainfall frequency	High
Rainfall-based statistics and Rainfall-Runoff	HEC-WAT *(USACE and USBR)*	Watershed analysis tool coupling rainfall-runoff model (HEC-HMS), river routing (RAS), and reservoir operations for system-wide basin flood studies	Can be Regional extreme storm DAD data or meteorlogic extreme storm data, watershed parameters, snowpack	Main inputs defined by distributions; unit hydrograph; rainfall frequency using GEV/L-moments or weather generator	High

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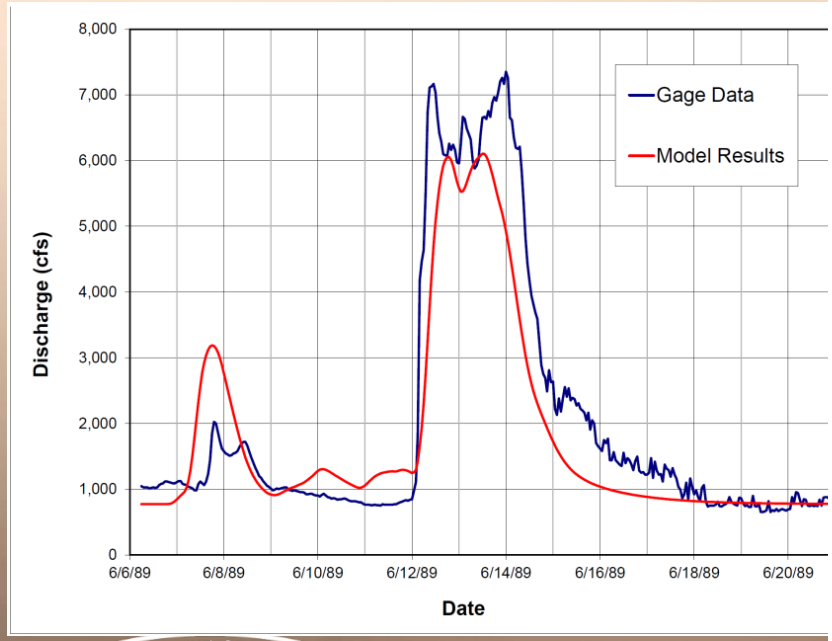
Hydrologic Hazard Principles: Multiple Methods and Weighting

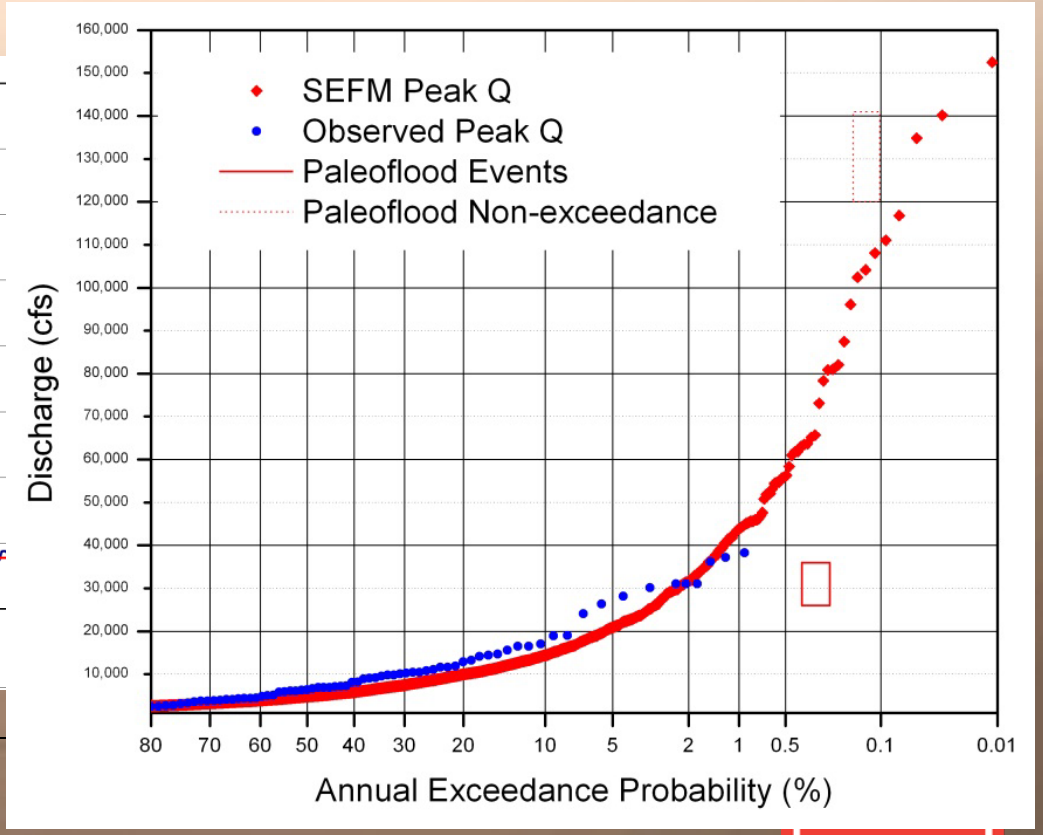
Development of Hydrologic Hazard Curves requires multiple methods, typically at least:

- Streamflow-based ***peak-flow frequency with historical and paleoflood data*** (such as EMA/LP-III, FLDFRQ3)
- ***Stochastic rainfall-runoff modeling***, such as SEFM or HEC-WAT using Monte-Carlo methods
- Data, information and models on peak flows, geomorphology, hydrometeorology, and flood hydrology can be integrated
- Because estimation of Hydrologic Hazard Curves involves substantial extrapolations, use of multiple methods and independent data sets provides more reliable results

Rainfall-Runoff Calibration and Weighting

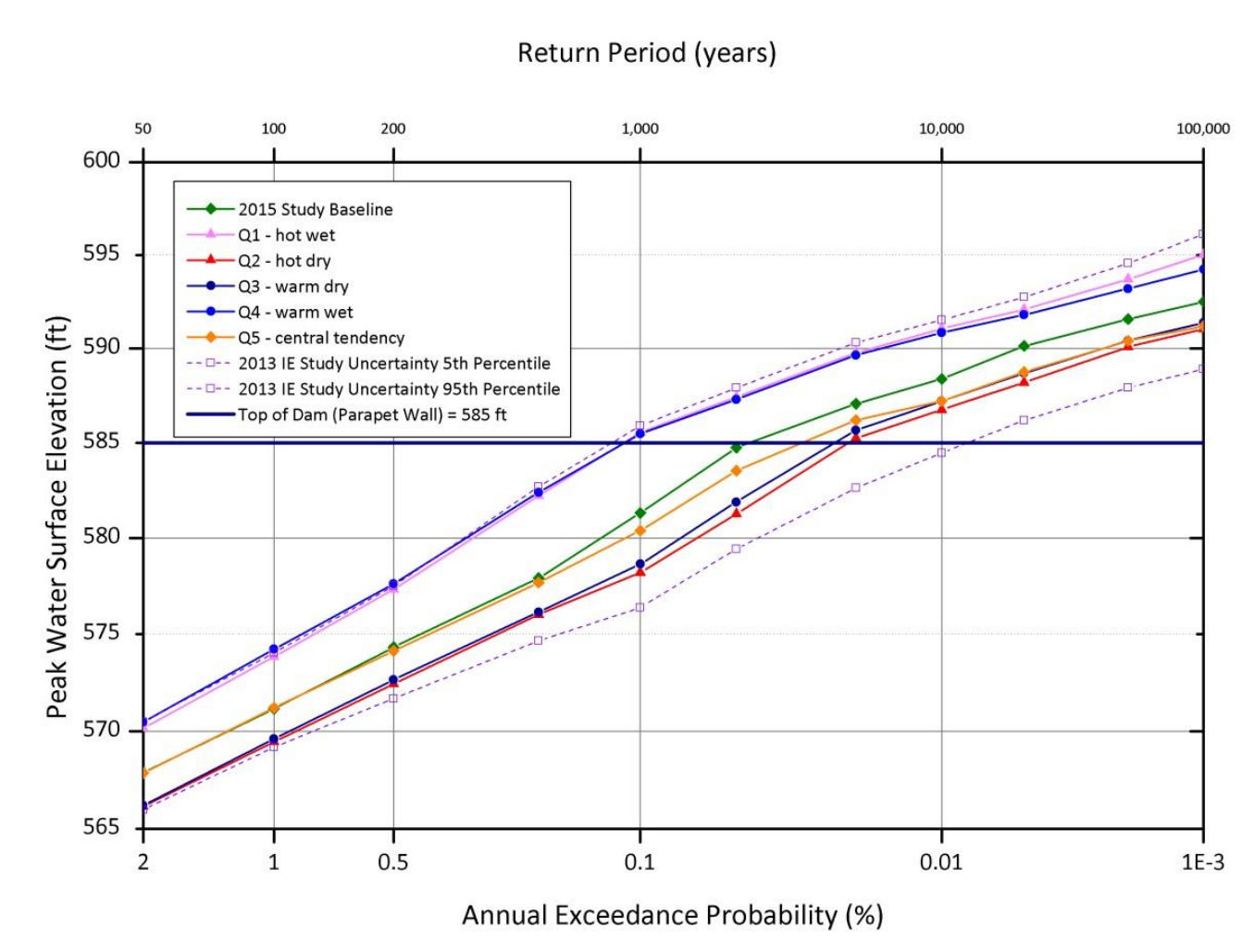
Calibrate model results to observed hydrographs and estimated frequency curves (peak/volume) to determine best model input parameters and distributions





Honestly Represent Uncertainty

- Uncertainty of peak flow frequency with paleofloods
- Uncertainty of basin-average rainfall frequency
- Variation in rainfall-runoff parameters and inputs
- Include future Climate projections



Climate change Pilot for Friant Dam

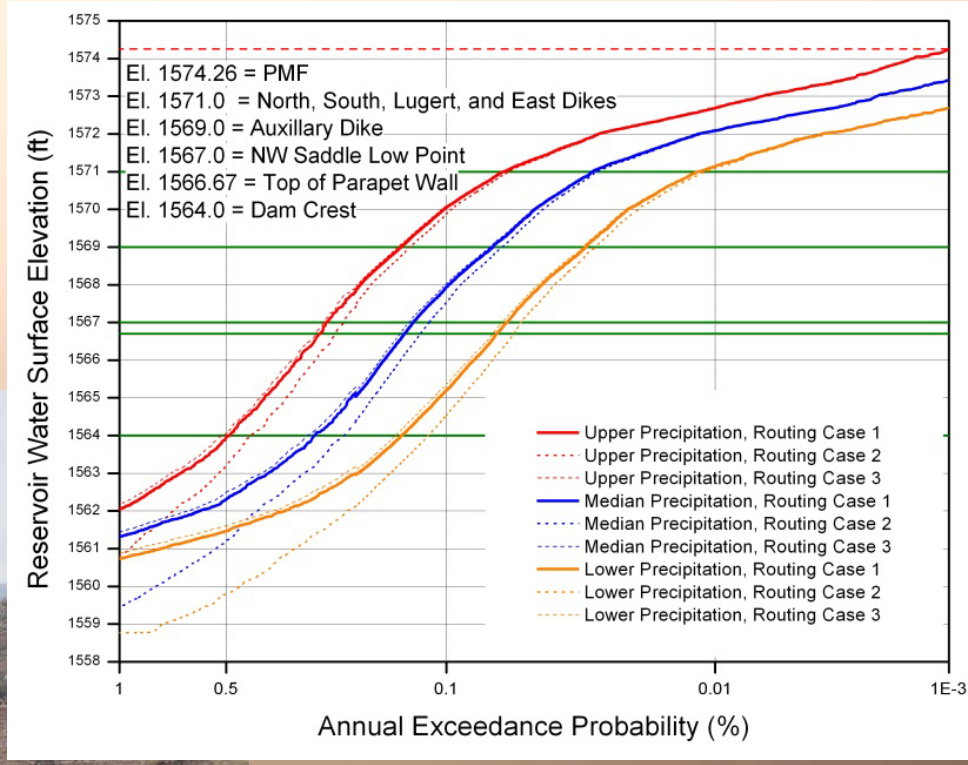
Issue Evaluation (IE) and Corrective Action (CAS) HHA "Typical" Studies

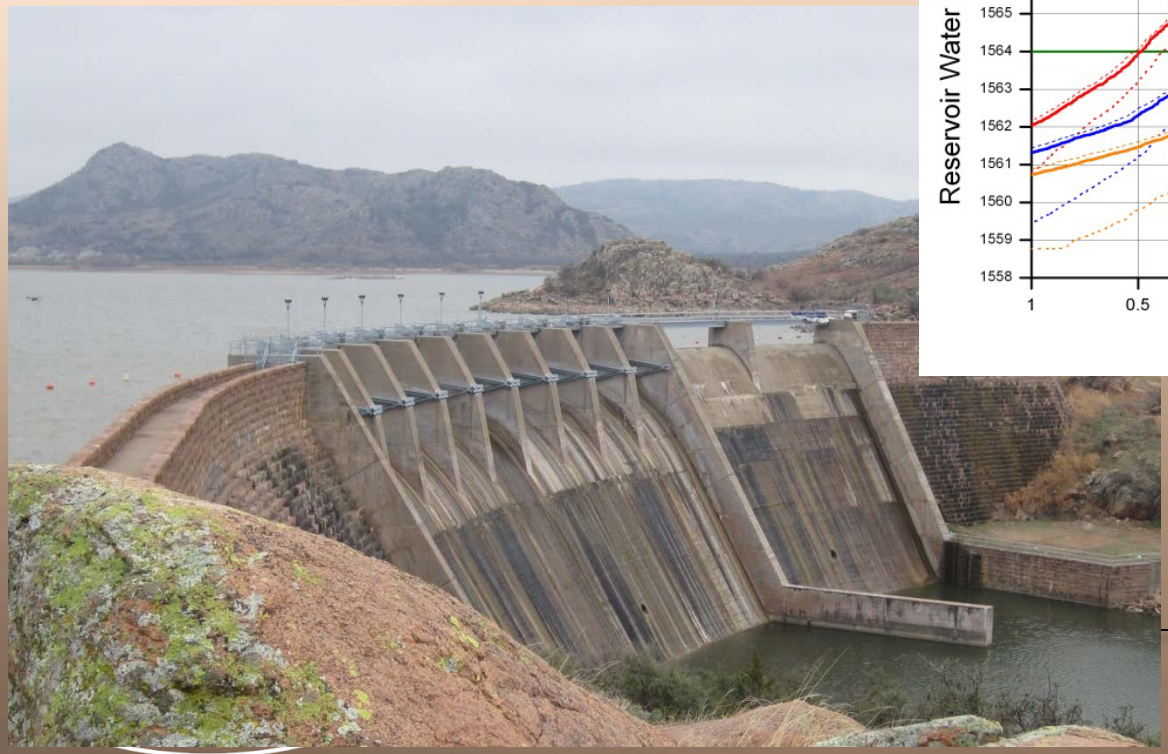
- Peak-flow Frequency with Paleoflood Data
- Rainfall-Runoff Modeling

- Ranges of frequency hydrographs &/or Res. Elev. Freq.
  - approximately describe ranges on values- not formal uncertainty
  - upper, lower estimates based on runoff model input variations, parameters or combinations, sensitivity
- Weights on peaks or hydrographs for risk analysis
  - may be equal weighting (e.g. several hydrographs for return period)
  - weighting may be provided to risk team
- Recommended initial reservoir elevation distributions
- Reservoir routing

Example HHA for CAS/DSMS: Altus Dam, OK Reservoir Frequency Curve with Uncertainty (SEFM)

Reclamation - Altus Dam, Oklahoma evaluate concrete gravity dam and dikes overtopping and risk for potential modification

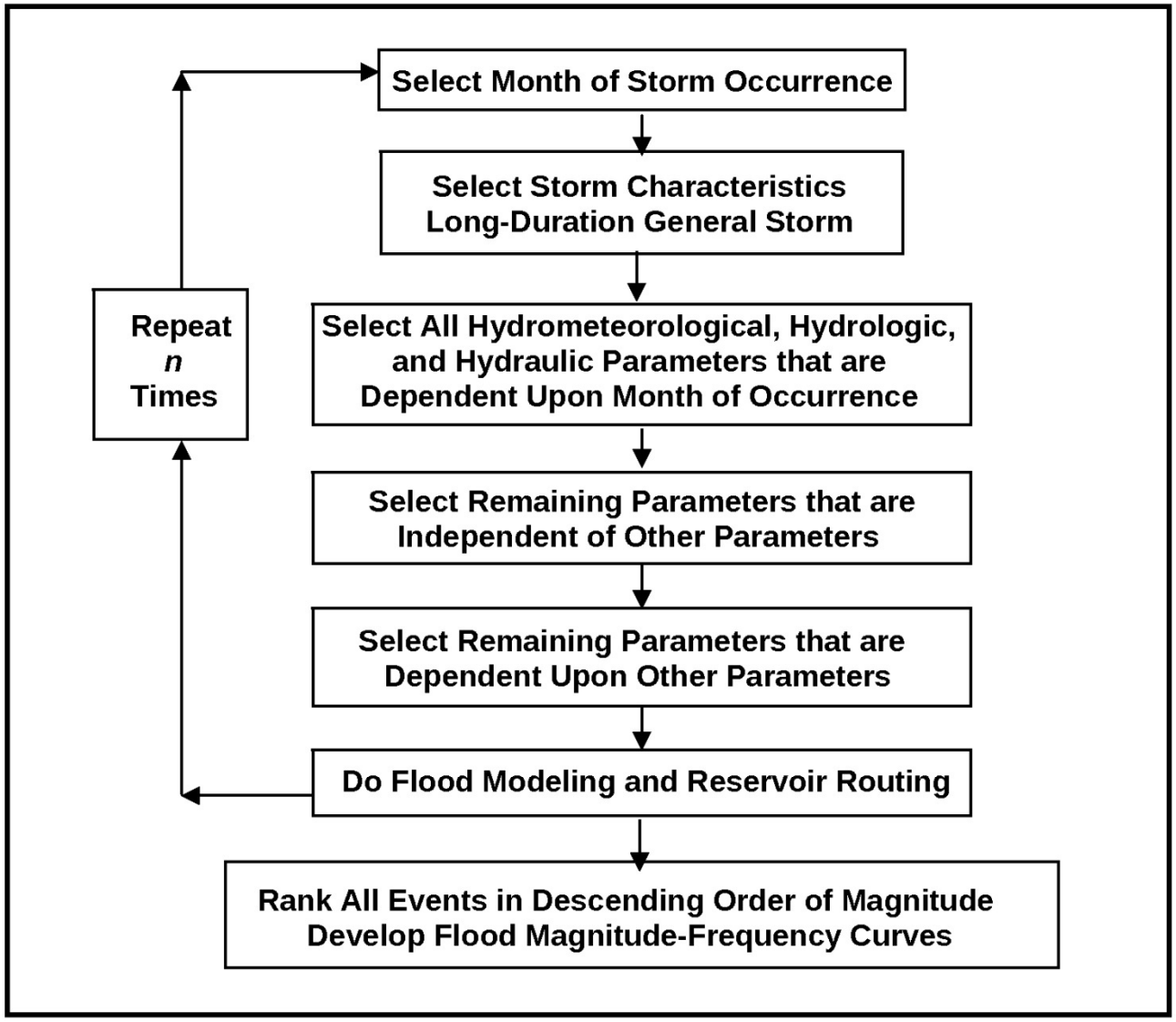




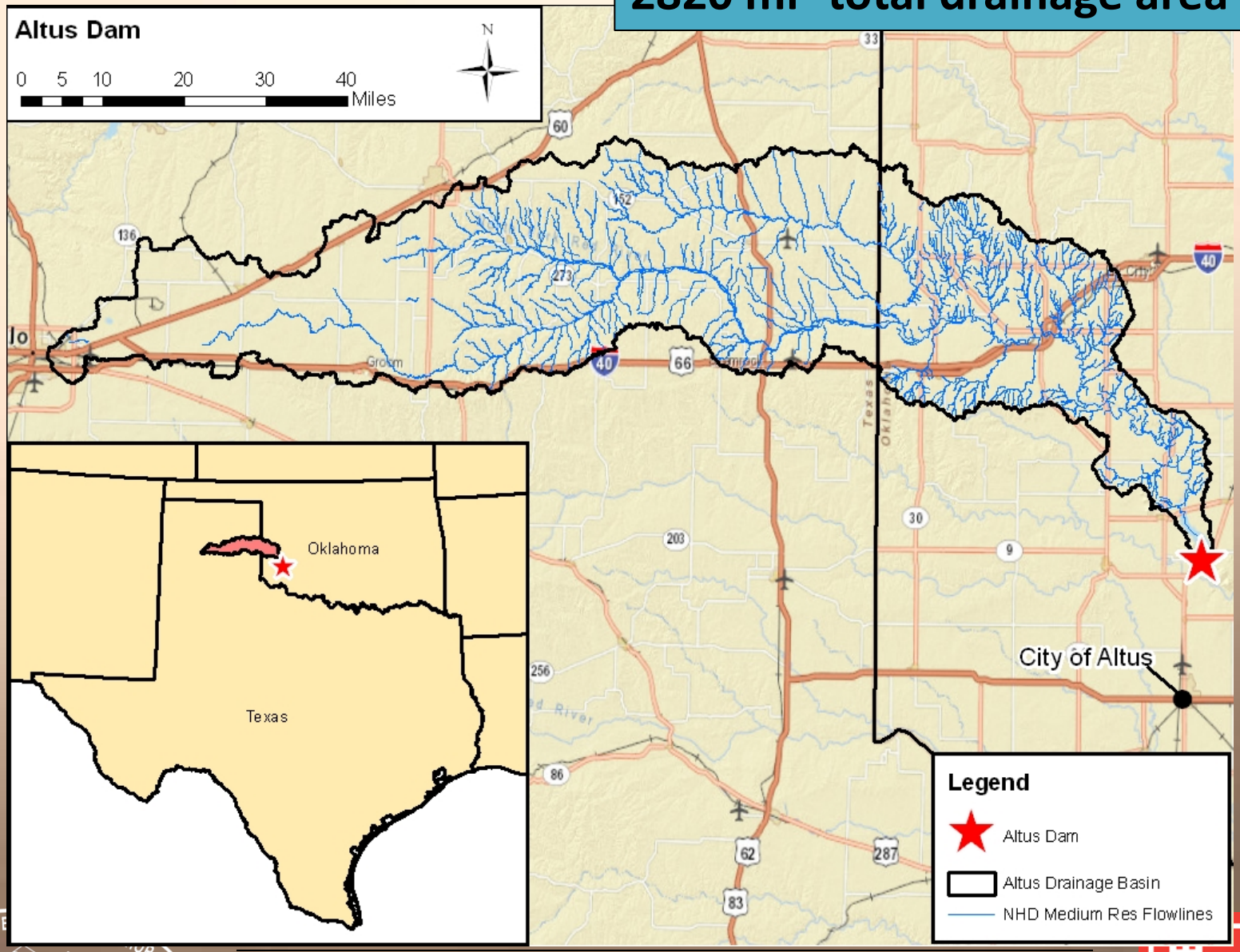
Stochastic Event-Based Rainfall-Runoff Model (SEFM) Key Elements

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

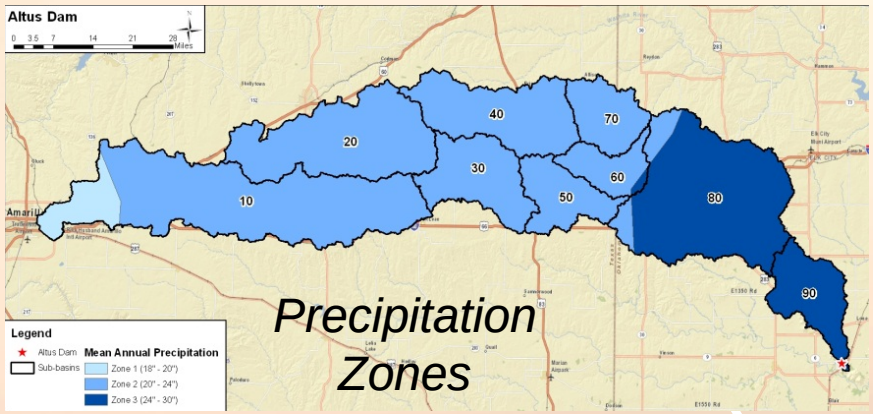
SEFM Simulation

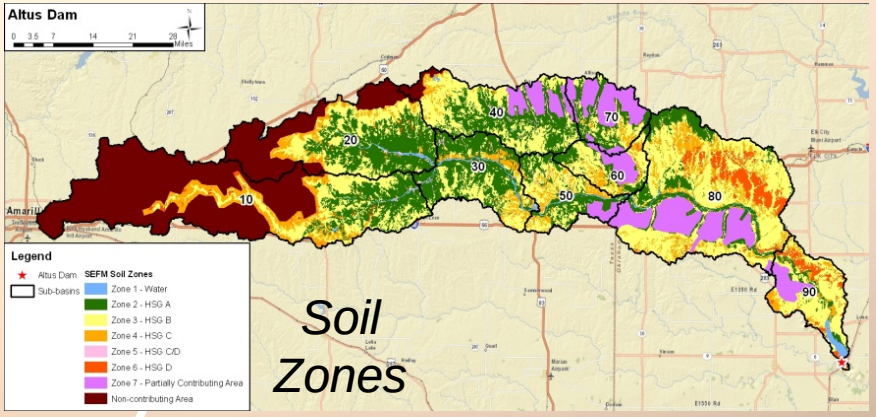


2820 mi² total drainage area



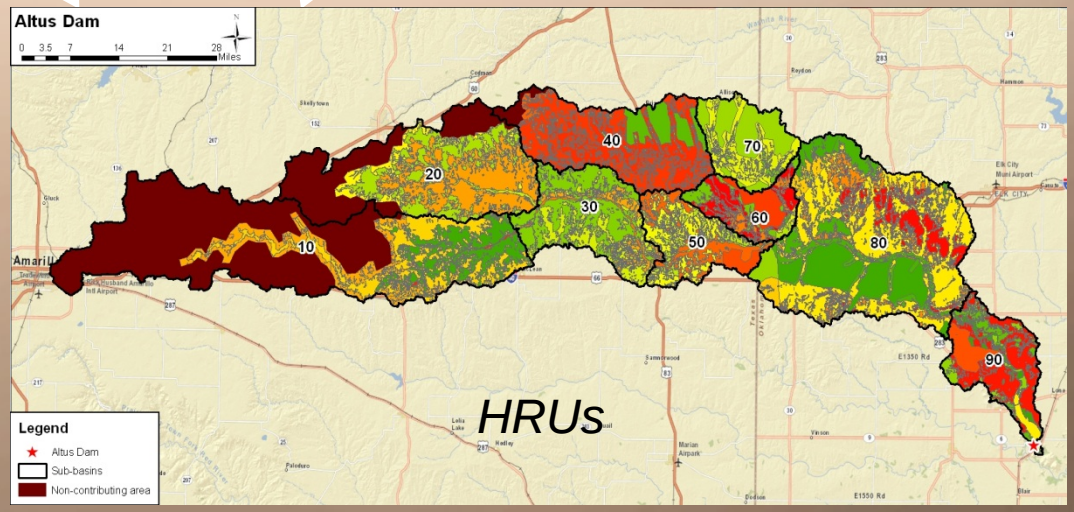
Hydrologic Runoff Units (HRUs)





Overlay (64 HRUs)

- **Precipitation zones (3)**
- **Soil zones (7)**
- **Elevation zones (1)**
- **Sub-basins (9)**



Meteorological Inputs

- Storm templates for each calibration storm
- Antecedent precipitation
- Evapotranspiration

Hydrological Inputs

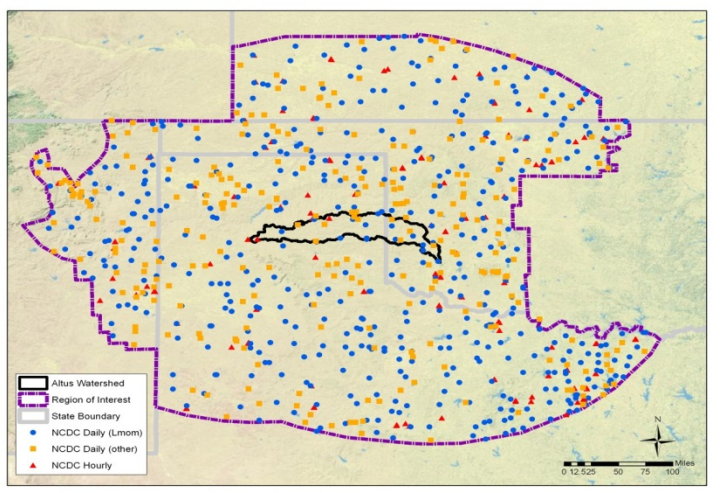
Streamflow observations for each calibration event

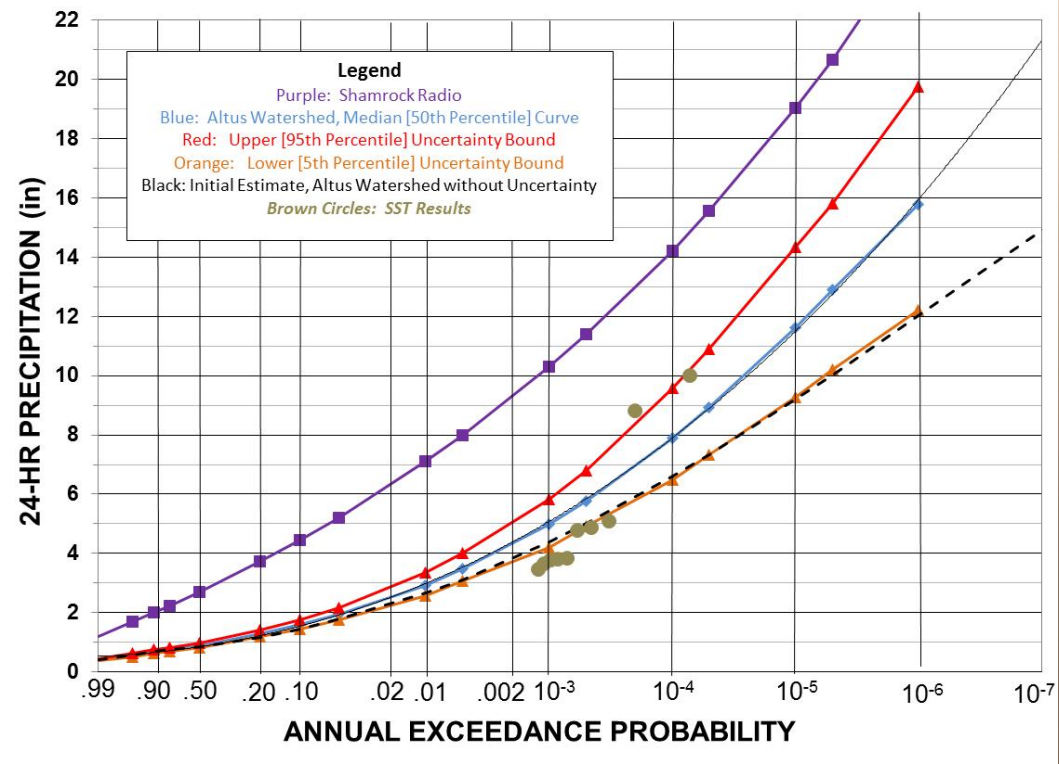
Provide range of parameters for calibration:

- Soil infiltration parameters
- Surface runoff unit hydrograph parameters
- Interflow unit hydrograph parameters

Altus Dam

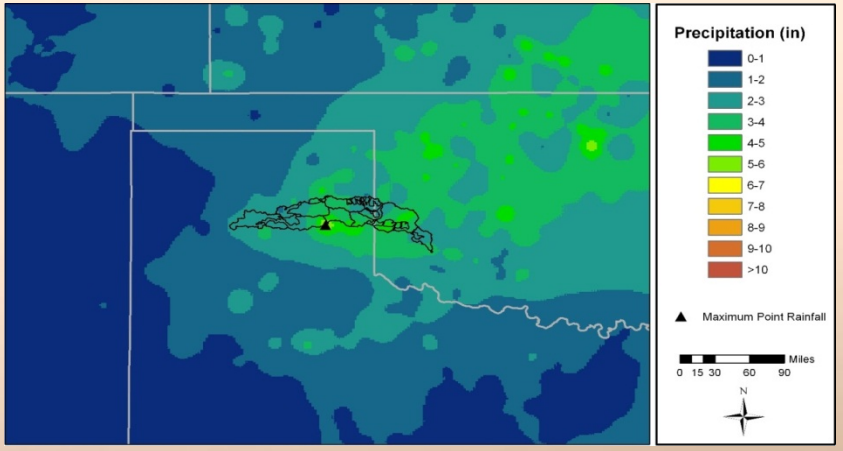
Precipitation frequency from L-moments

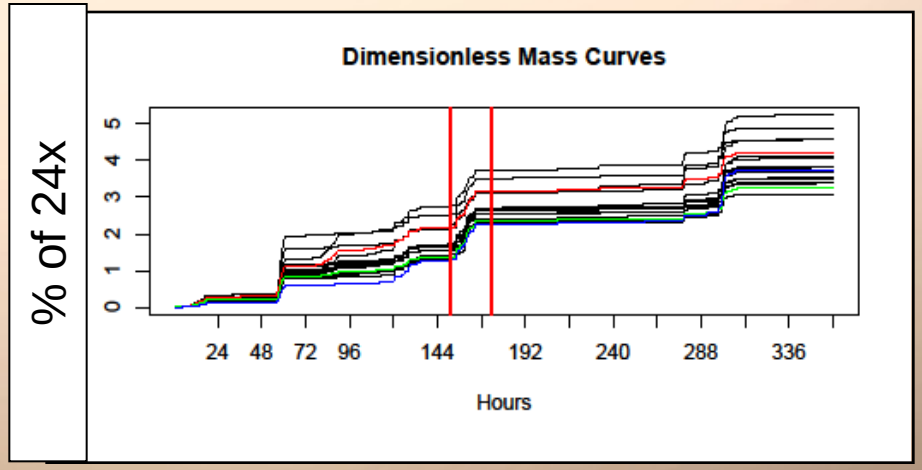


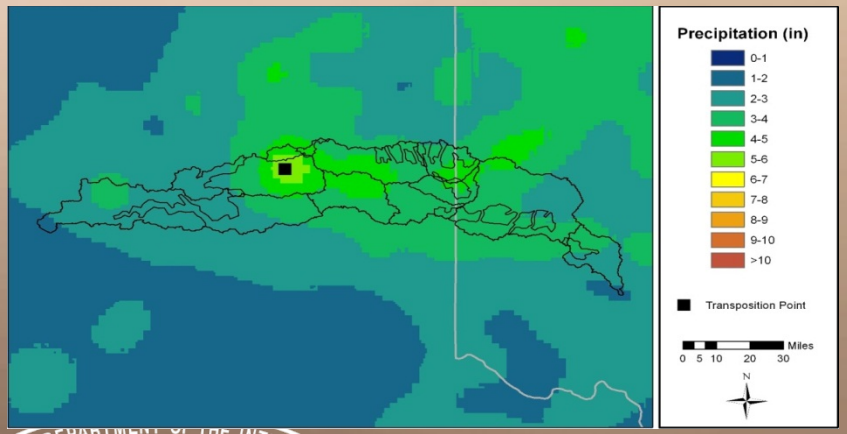


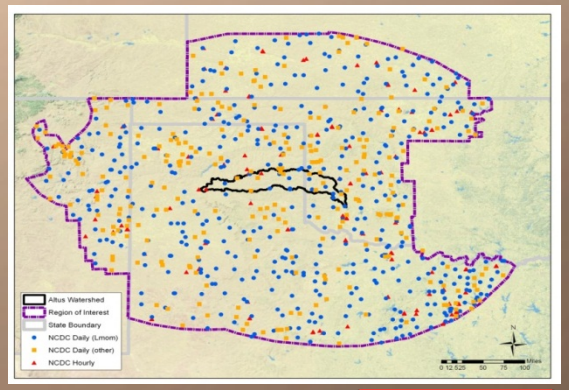
Altus Dam

Storm spatial patterns



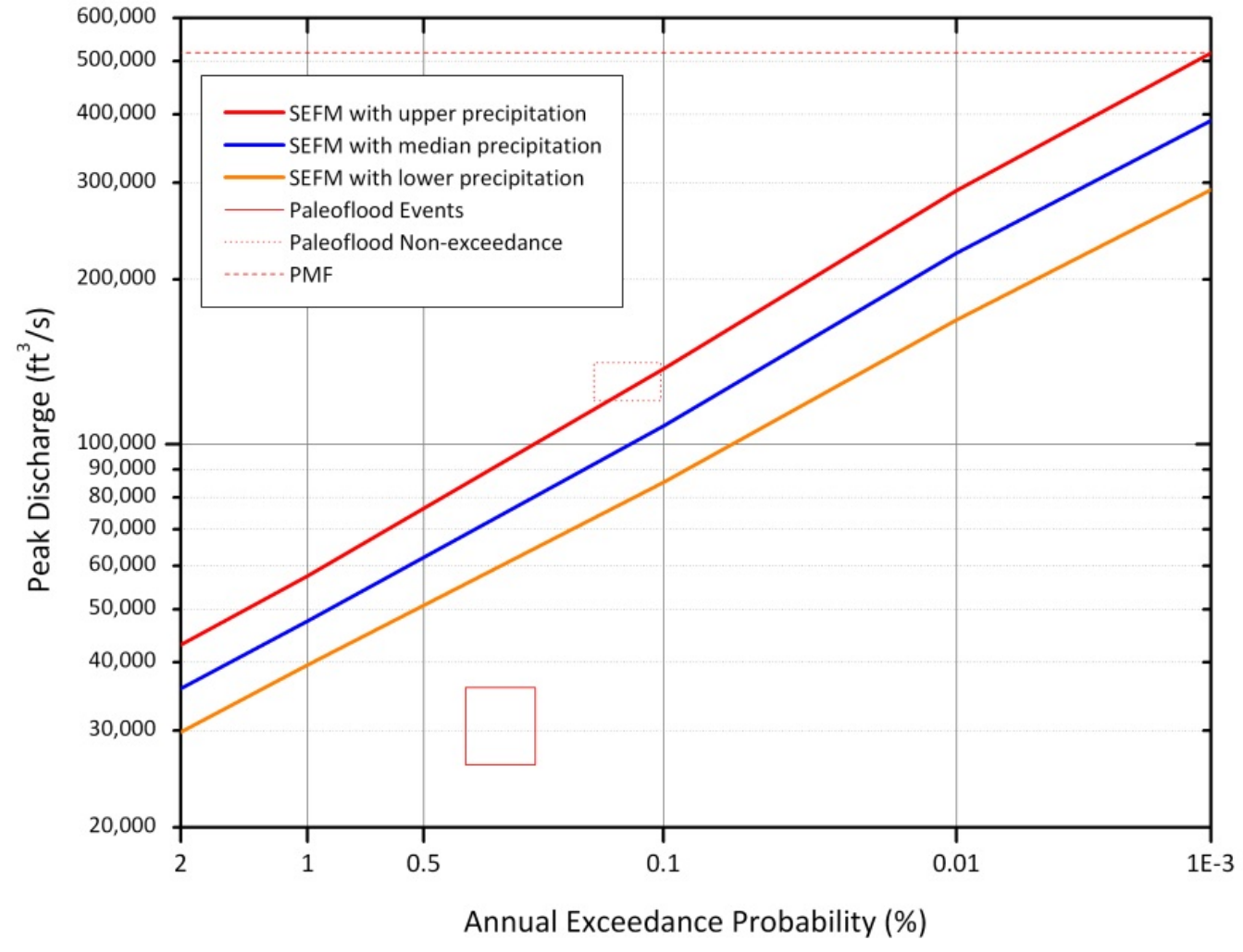






May 22, 1972 event

Peak Discharge frequency curves

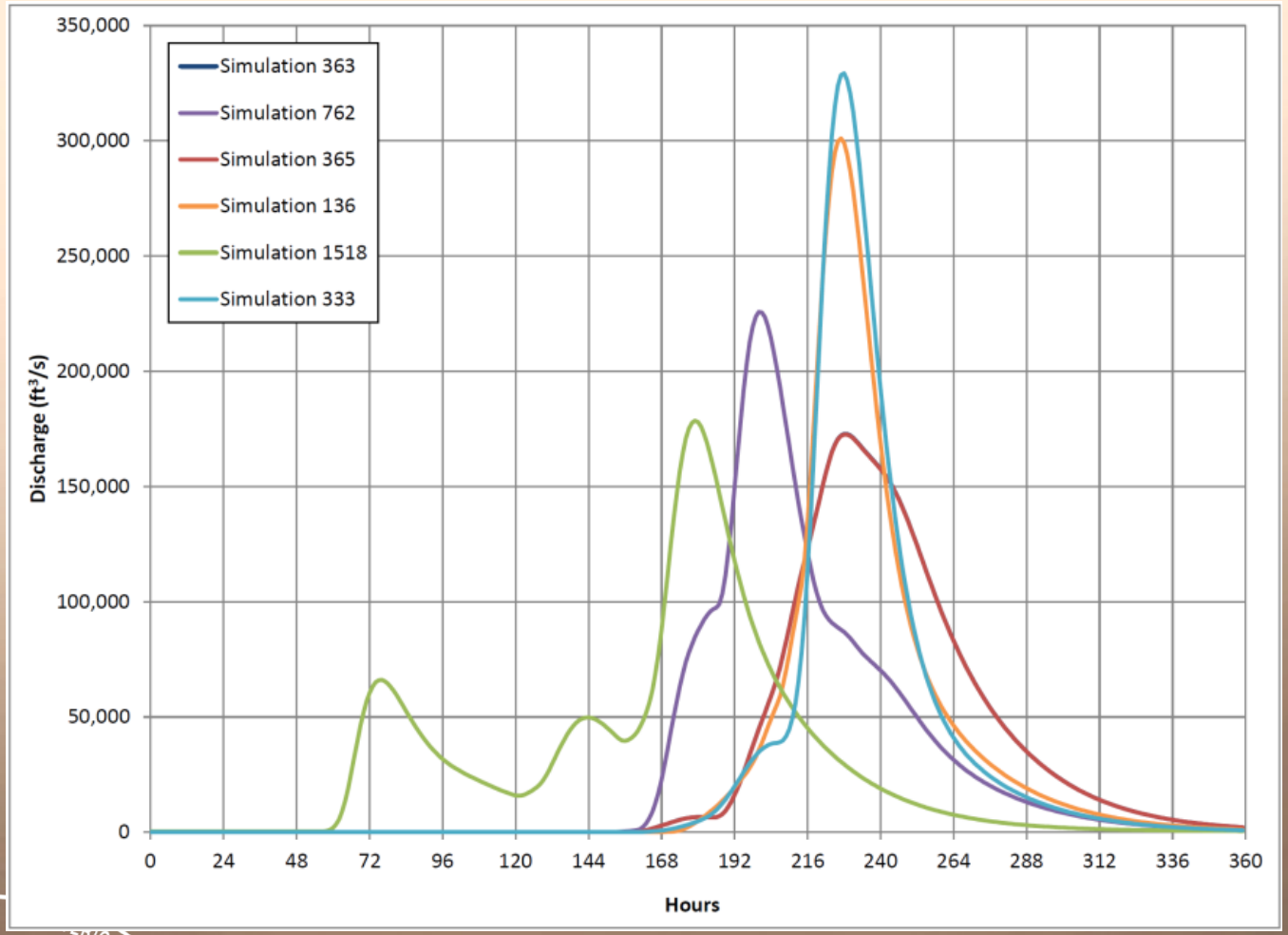


Red – 95th percentile precipitation

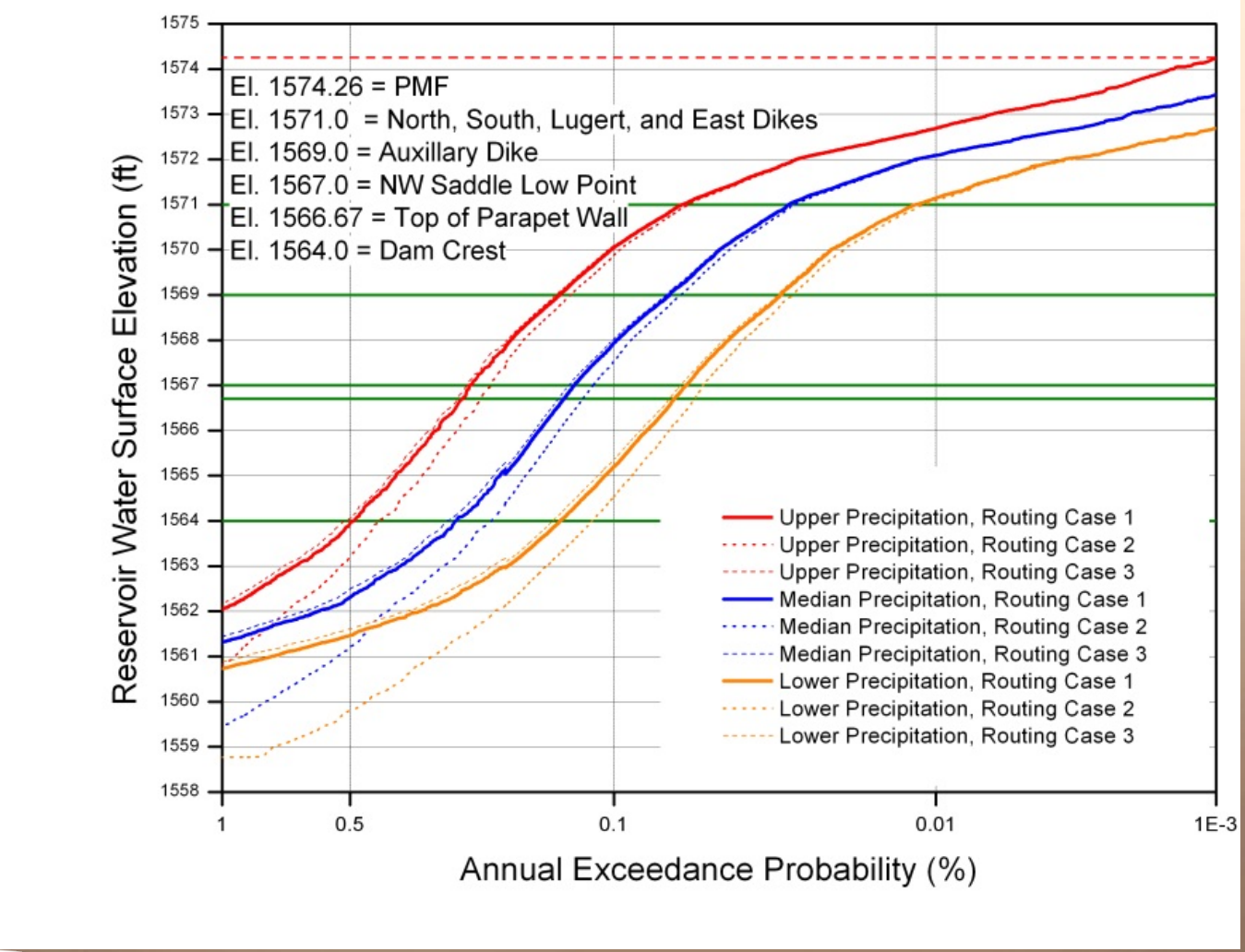
Blue – 50th percentile precipitation

Orange – 5th percentile precipitation

10,000-yr Hydrographs based on Volume



Reservoir elevation frequency curves



Red – 95th percentile precipitation

Blue – 50th percentile precipitation

Orange – 5th percentile precipitation

Hydrologic Hazard Summary

- Uses a suite of methods for estimating hydrologic hazard curves for dam safety
- Combining streamflow, paleoflood and rainfall data allows more confidence in extrapolated flood frequency curves
- The procedure relies on extracting information from existing studies and available data
- Initial hydrologic hazard estimate can usually be accomplished using existing data
- IE/IES and CAS/DSMS require new data collection, analysis and synthesis

Final Hydrologic Hazard Curve

- The amount of effort expended on analyzing a hydrologic hazard is dependent on the nature of the risk problem and level of decision needed
- When multiple methods are used, best estimate is based on sound physical and scientific reasoning for weighting or combining results, with uncertainty
- Initial characterization is replaced by more detailed studies

Questions?

Folsom Joint Federal Project Sacramento, CA

Reclamation and USACE Partnership

New spillway for improved flood control