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Managing Water in the West

Hydrologic Hazard Curve Methods for Dam Safety

15 Years of Progress, Development and Applications

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Bureau of Reclamation

Some Key HHA Concepts

- Hierarchy and Risk Process – Agency Specific
- Probability Estimates and Full Distributions needed, with Uncertainty
- PMF and Single (Point) Deterministic Flood Estimate No Longer Adequate – more information required
- Hydrologic Hazard Curves are the Load Input to Risk
  - Peak Flow and Volume Frequency Curves
  - 1/1,000 AEP to 1/10,000 AEP (typical for failure probability)
  - less than 1/10,000 AEP extrapolation!
- Hydrographs; Maximum Reservoir Levels
- HHA Methods vary; depend on study level
- Multiple HHA Methods Used and Combined

15-Year History of Estimating Hydrologic Hazards for Dam Safety

Pre 1997 Interpolation of the PMF probability (Much debate)

1997 to Present - Method Development/Applications

- Paleoflood Studies
- Stochastic Flood Modeling Studies, Meteorology

June 1997 - Logan Flood Workshop

- Blueprint for the Future – Characterizing Extreme Floods

July 2001 – Flood Hydrology and Paleoflood Cadre

June 2004 – Hydrologic Hazard Research Report

June 2006 – Hydrologic Hazard Guidelines

Ongoing – improvements to HHA tools, data sets, applications

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Reclamation Extreme Flood Workshop Logan, Utah June 16-20, 1997

NRC PFHA Workshop Participants
Jery Stedinger, Mel Schaefer
John England, David Bowles

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Hydrologic Hazard Curve Principles
Reclamation Flood Workshop

- Do Not Assign AEP to the PMF
- No Single Approach Describing Flood Hazards Over the Range of AEP Needed
- Greatest Gains From Incorporating Regional Precipitation, Streamflow, Paleoflood Data
- Honestly Represent Uncertainty
- Research and Development - 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

U.S. DEPARTMENT OF THE INTERIOR
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WATER RESOURCES MANAGEMENT.....FOR THE FUTURE
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November 1999

ftp://ftp.usbr.gov/jengland/Dam_Safety/LoganWorkshop.pdf

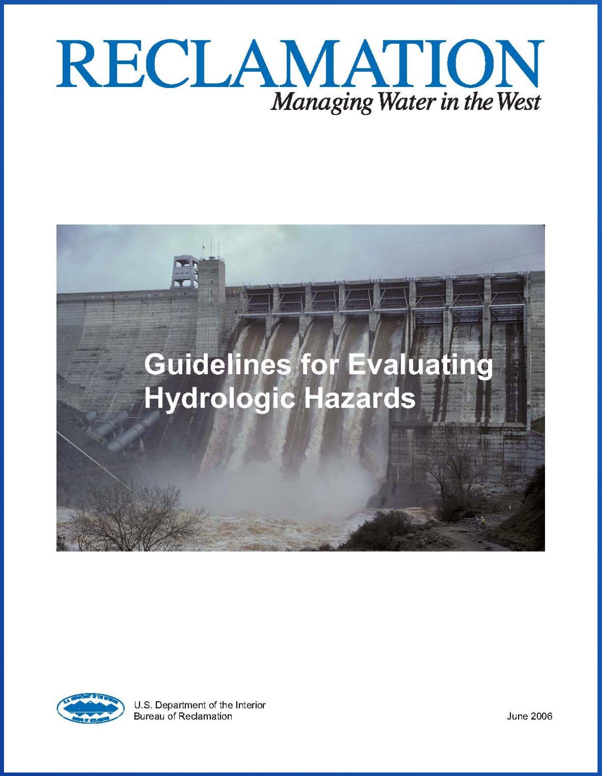
Development of New Flood Methods and Hydrologic Hazard Curves

- Paleoflood Studies
  - Bradbury Dam Investigations (1993-1996)
  - A.R. Bowman Dam Investigations (1995-1999)
- Stochastic Flood Modeling Studies
  - PMF Variability estimates at Bumping Lake Dam, WA (1995-1997)
  - Hydrologic Hazard estimates for Bowman Dam (1996-1998)
  - Hydrologic Hazard estimates at Seminoe and Glendo dams (1997-2000)
  - Many other studies completed 2001 – 2012 and ongoing

Hydrologic Hazard Guidelines

Guidelines Report provides details on the HHA methods and overall framework

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



June 2006 guidelines report

ftp://ftp.usbr.gov/jengland/Dam_Safety/Hydrologic_Hazard_Guidelines_final.pdf

Hydrologic Hazard Guidelines

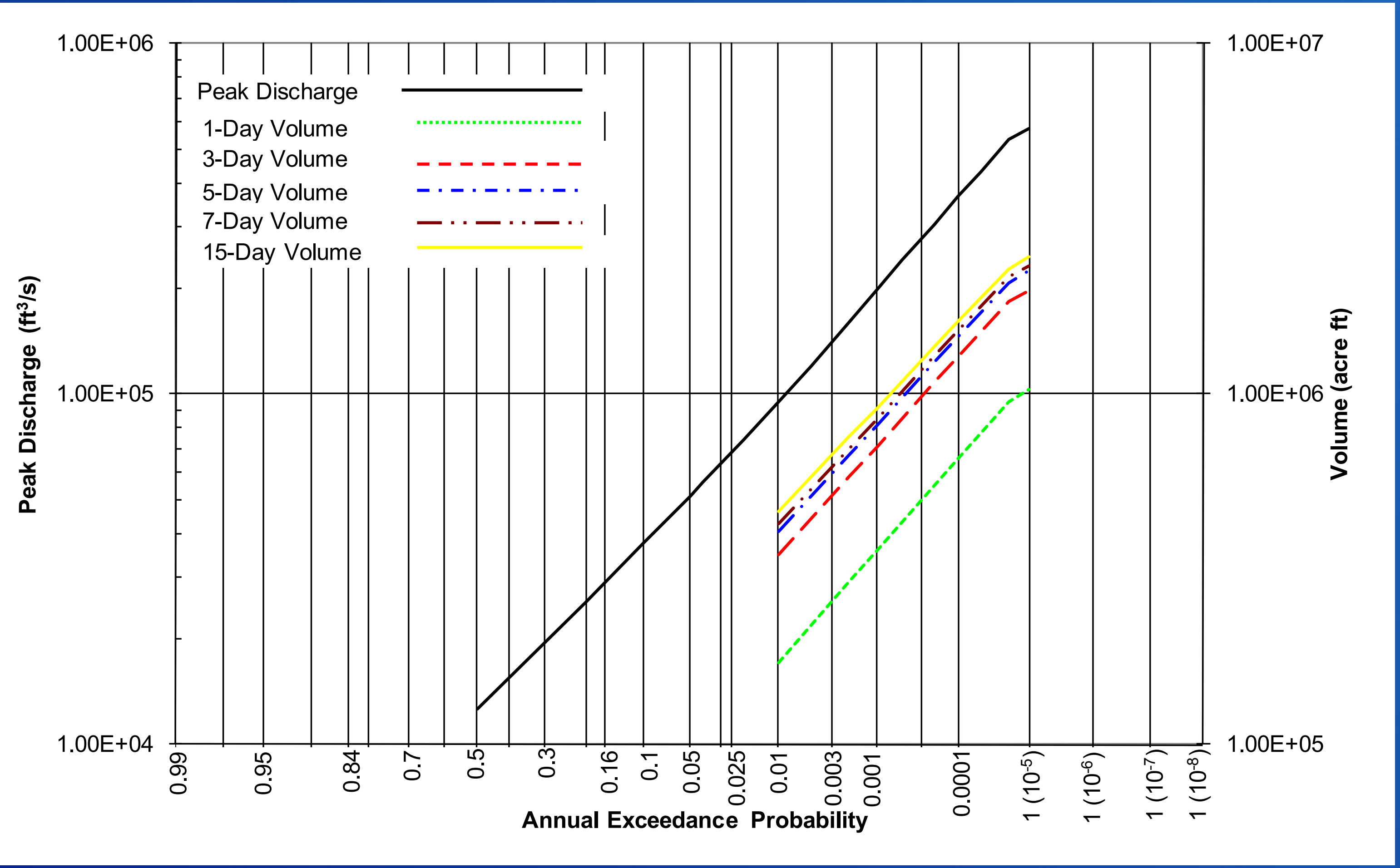
Methods (as of 2006) developed and used by Reclamation for flood loadings

- ***Substantial Investment in Data, Tools, Software, Applications over past 15 years***
- Methods applied on Reclamation, BIA, NPS, USACE watersheds
  - available in various technical reports
- Multiple Methods used – combine results
- Paleoflood and Stochastic Rainfall-Runoff model based methods

Hydrologic Hazard Curve Definition

- A Hydrologic Hazard Curve is defined as a graph of peak flow and/or volume (for specified duration) versus Annual Exceedance Probability (AEP) ***(< 1 in 10,000 for Reclamation)***
- Hydrologic Hazard Curves may also depict Maximum Reservoir Elevation versus AEP
- AEP estimates are made for peak flows, runoff volumes and reservoir elevations to cover the range of values needed for risk-based dam safety decision making at specific facility
- Evaluate specific Potential Failure Modes (overtopping, gates, spillway chute, etc)

Hydrologic Hazard Curve



Portrays Flood Magnitude: Peak and Volume, and Exceedance Probabilities. Full distributions in the range of interest

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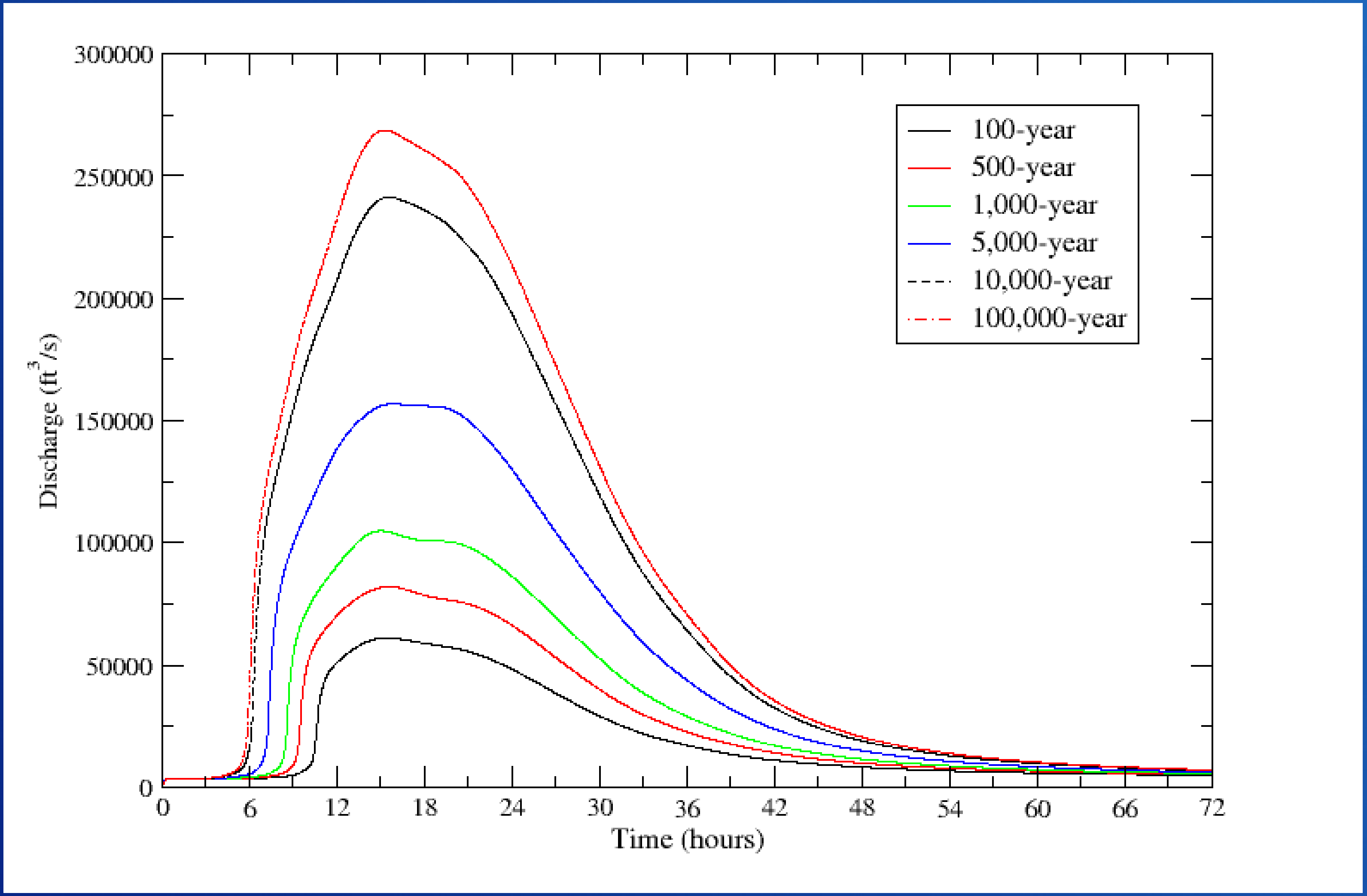
Example Extreme Flood Hydrographs



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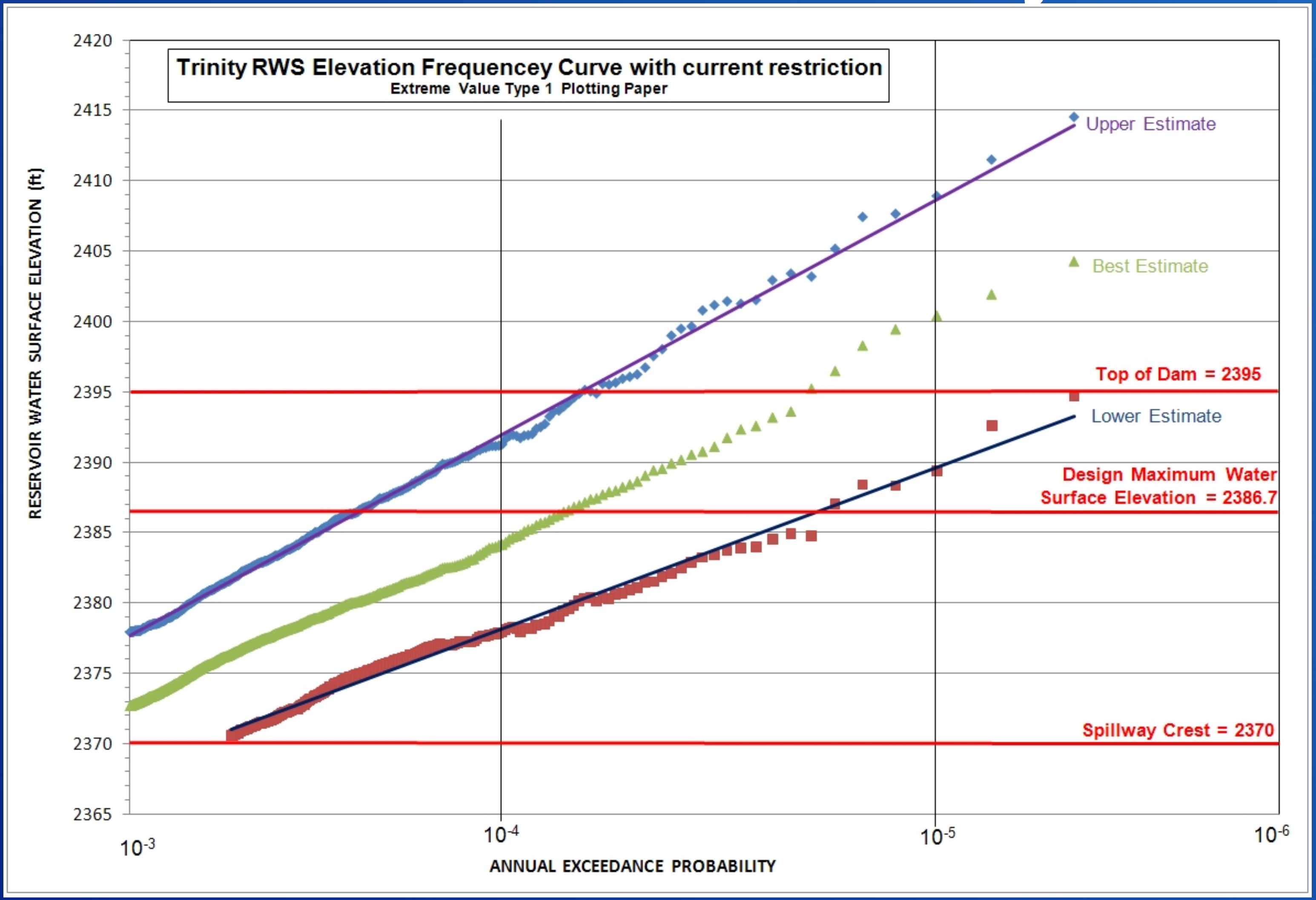
Hydrologic Hazard Reservoir Frequency Curve with Uncertainty



evaluate reservoir restriction, Trinity Dam

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Hydrologic Hazard Data

Some key sources and types

- 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

Further Details: Panels 3 and 6

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)

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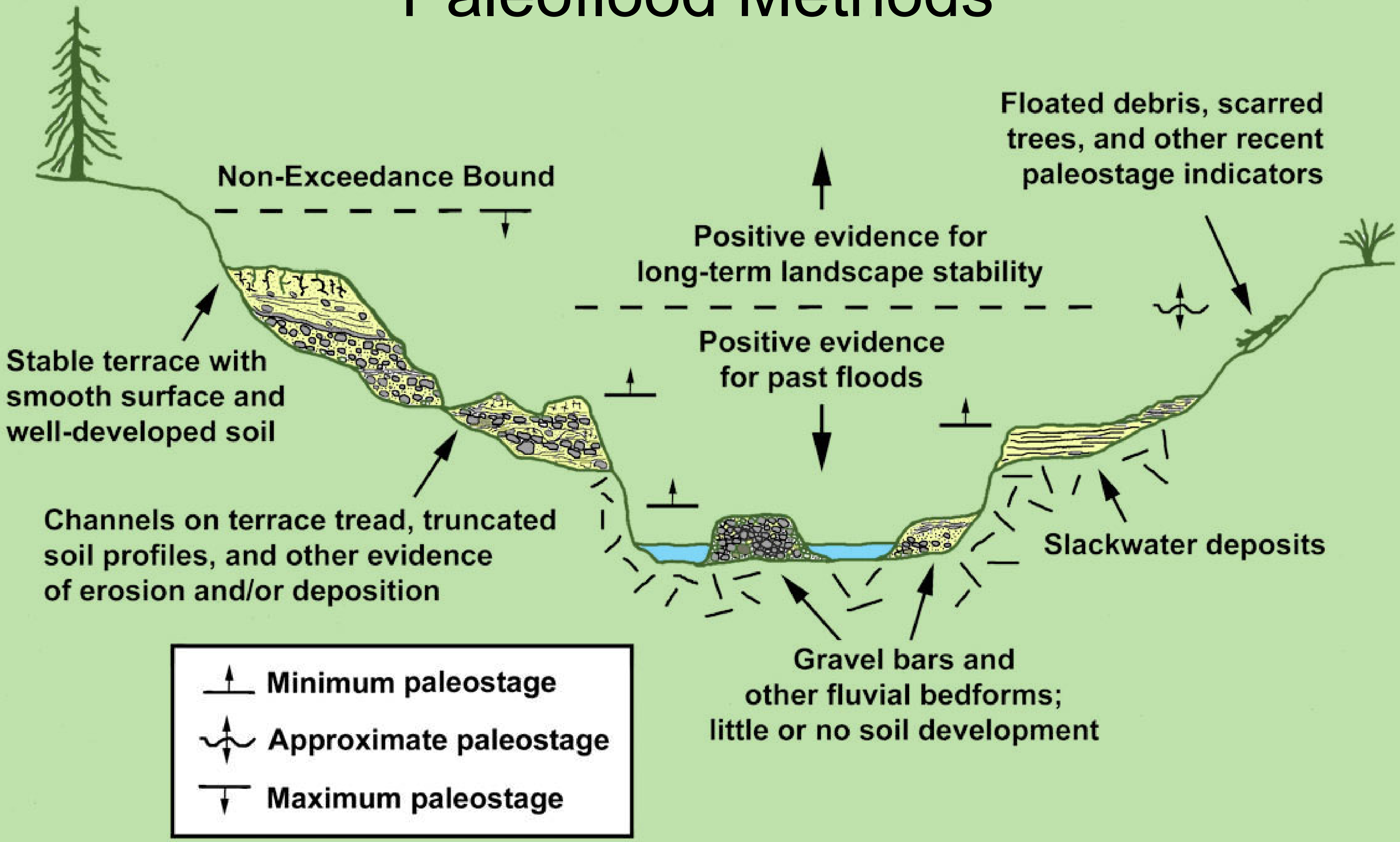
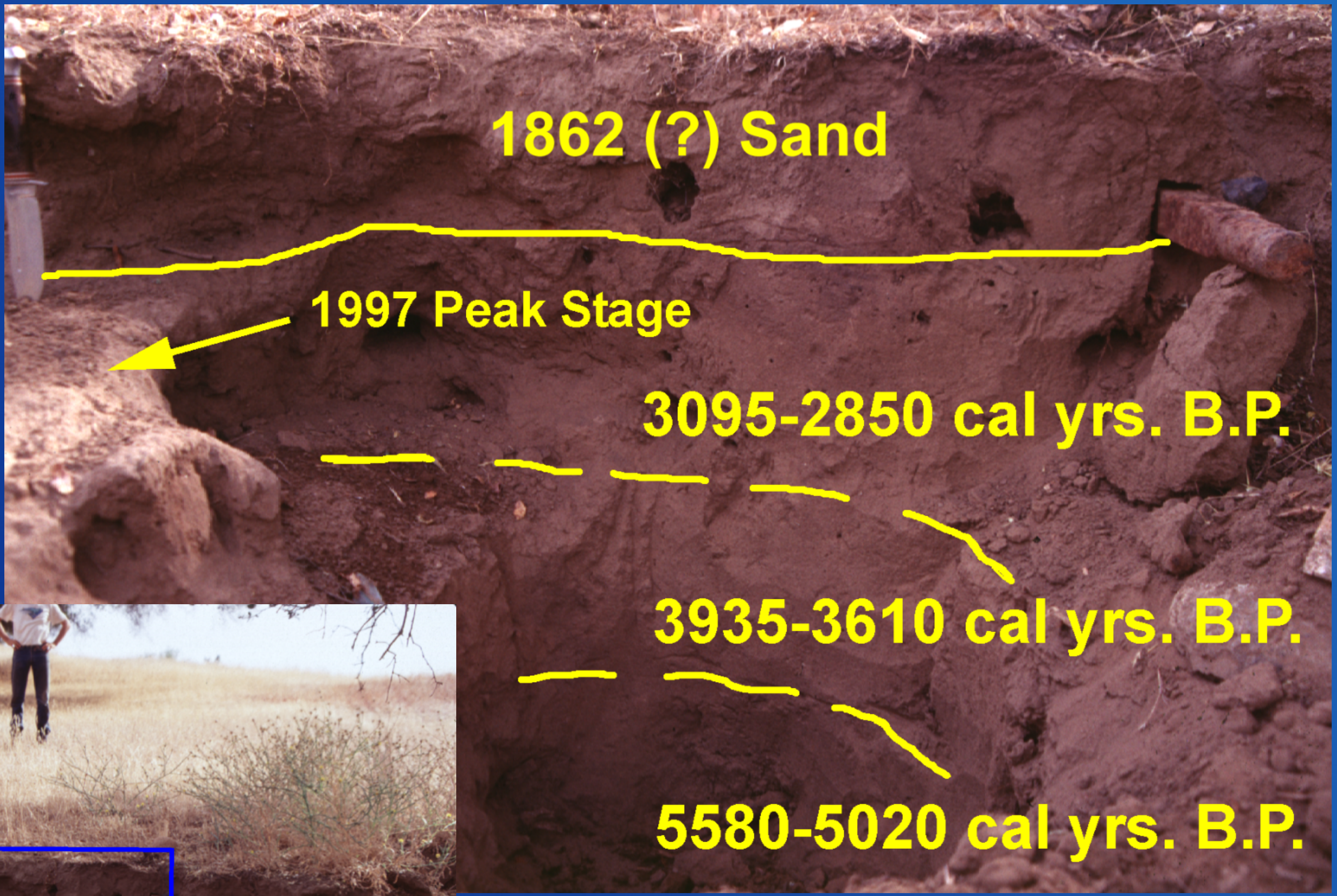
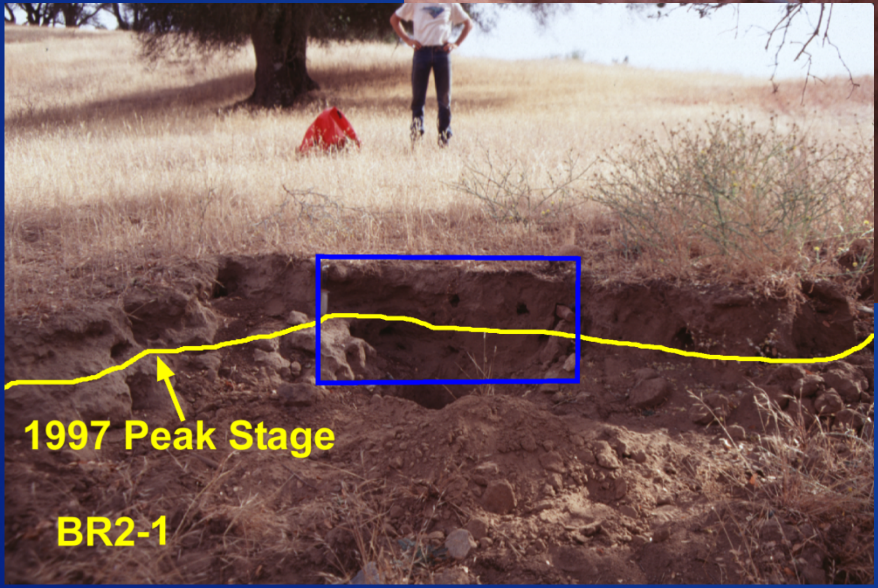
Paleoflood Methods



House et al. (2002) AGU Paleoflood Monograph





South Fork American near Lotus

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Hydrologic Hazard Curve Principles

- Data - focus on past (paleoflood) and present (recent) data
  - –Future climate projections assessed/used project by project – study and decision dependent
- Flood Hazards Estimated using Interdisciplinary Teams
- Flood Models, Relationships and Tools developed in-house by Reclamation and collaborators
- Uncertainty of Estimates is Quantified

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HHA Principles: Integrated Teams

HHA 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

HHA Principles: Multiple Methods

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

- Streamflow-based peak-flow frequency with historical and paleoflood data (EMA, FLDFRQ3)
- Stochastic rainfall-runoff modeling, such as SEFM 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

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HHA Principles

Expand Data and Information in the Hydrologic Hazard analysis and Hydrologic Hazard Curve

- 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

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Hydrologic Hazard Curves: Extreme Flood Probability Estimation Methods

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

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

NRC (1988) Estimating Probabilities of Extreme Floods

Hydrologic Hazard Methods

Class	Method of Analysis and Modeling	Level of Effort[2]
Streamflow-based statistics	Graphical Flood Frequency	Low
Streamflow-based statistics	EMA	Low/Moderate
Streamflow-based statistics	FLDFRQ3	Low/Moderate
Streamflow-based statistics	Hydrograph Scaling	Low
Rainfall-based statistics and Runoff Transfer	GRADEX	Moderate
Rainfall-based statistics and Rainfall-Runoff	Australian Rainfall-Runoff	Moderate
Rainfall-based statistics and Rainfall-Runoff	NWS SAC-SMA	Moderate
Rainfall-based statistics and Rainfall-Runoff	SEFM	High
Rainfall-based statistics and Rainfall-Runoff	TREX	High

[2]Low: 10-20 staff days; Moderate: 21-100 staff days; High: more than 100 staff days

Hydrologic Hazard Methods

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

Hydrologic Hazard Methods
Streamflow-Based Statistics

FLDFRQ3 Overview

- At-site peak-flow frequency
- Uses lots of different types of historical and paleoflood information, as well as uncertainties of each data type
- Bayesian Maximum Likelihood used for parameter estimation, with confidence intervals estimated by numerical grid integration
- user can choose a 3-parameter frequency distribution: LP3, P3, GEV, GLO, GPA, GNO
- statistically efficient

references/details in O'Connell (1999); O'Connell et al. (2002)

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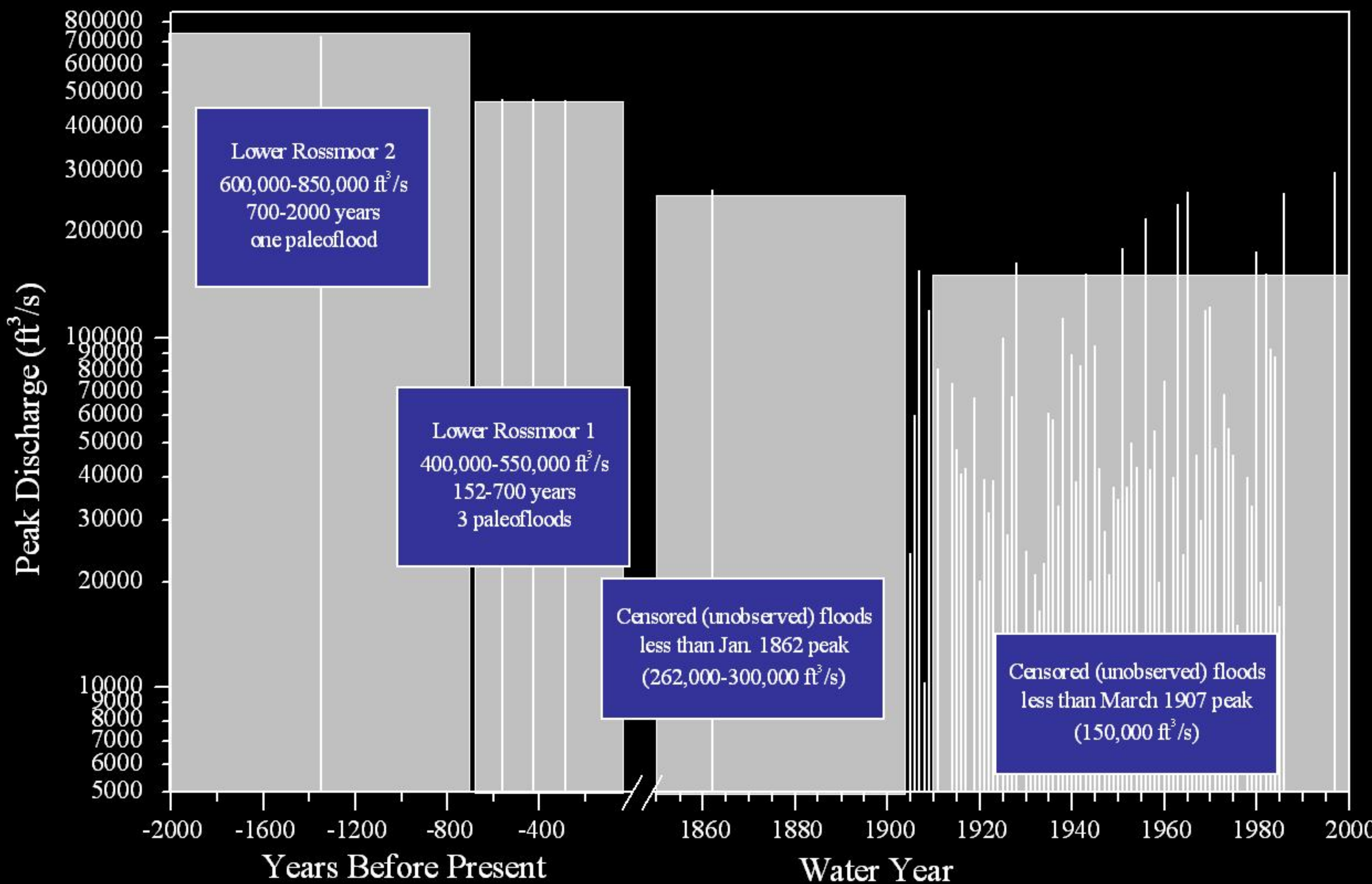
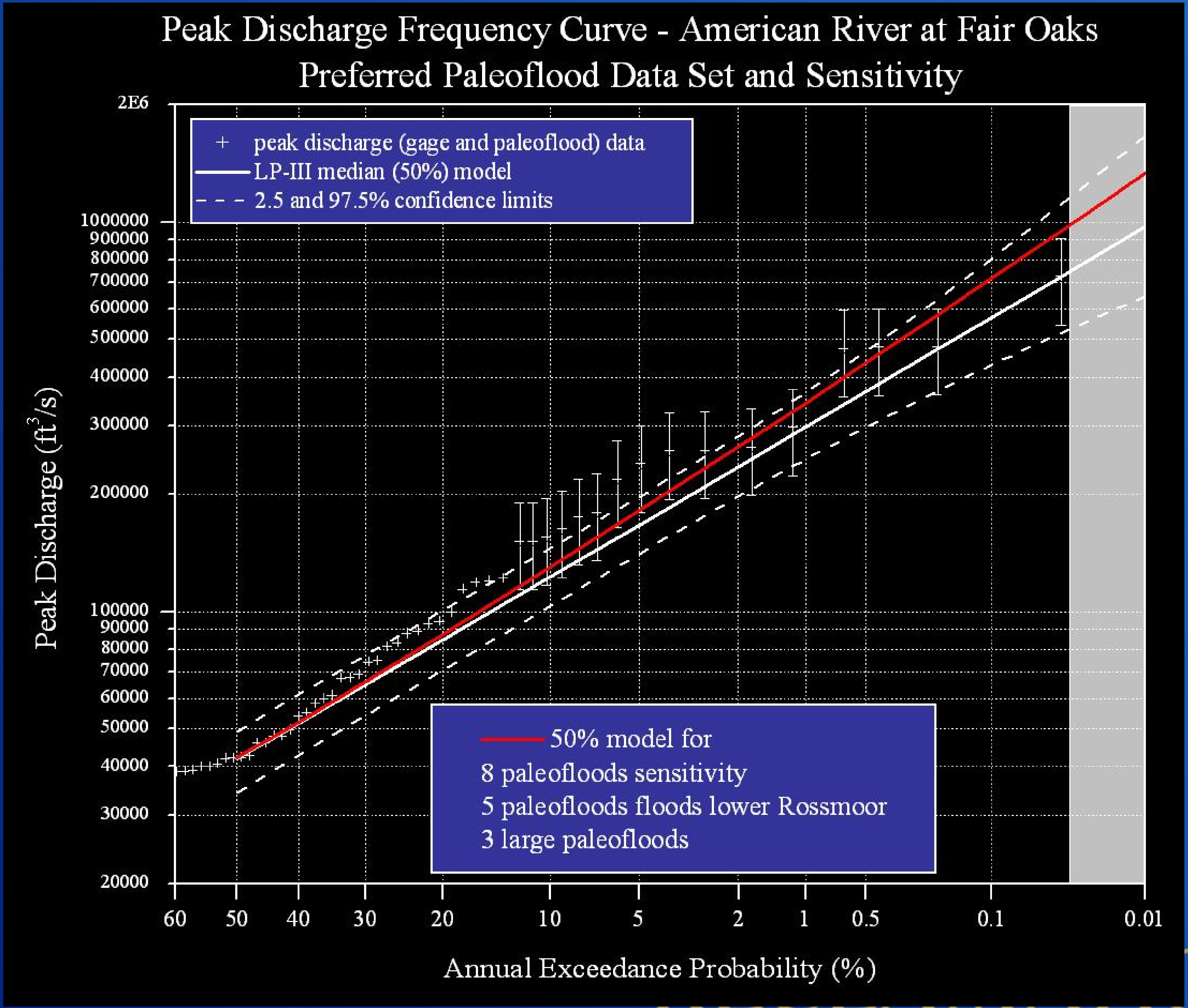
Approximate Unregulated Peak Discharge and Preferred Paleoflood Estimates
American River at Fair Oaks





Peak Discharge Frequency Curve - American River at Fair Oaks
Preferred Paleoflood Data Set and Sensitivity
+ peak discharge (gage and paleoflood) data
LP-III median (50%) model
2.5 and 97.5% confidence limits
50% model for
8 paleofloods sensitivity
5 paleofloods floods lower Rossmoor
3 large paleofloods
Peak Discharge (ft³/s)
2E6
1000000
900000
800000
700000
600000
500000
400000
300000
200000
100000
90000
80000
70000
60000
50000
40000
30000
20000
60
50
40
30
20
10
5
2
1
0.5
0.1
0.01
Annual Exceedance Probability (%)

Hydrologic Hazard Methods
Rainfall-Runoff

- construct a space-time extreme rainfall model (rainfall probability biggest factor)
- generate several large storms from model
- model “deterministic” rainfall-runoff transformation
- produce approximate probability statements for resultant large flood peaks and hydrographs.
- can use similar rainfall and runoff tools as PMF techniques

after NRC (1988)

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Australian Rainfall-Runoff Method

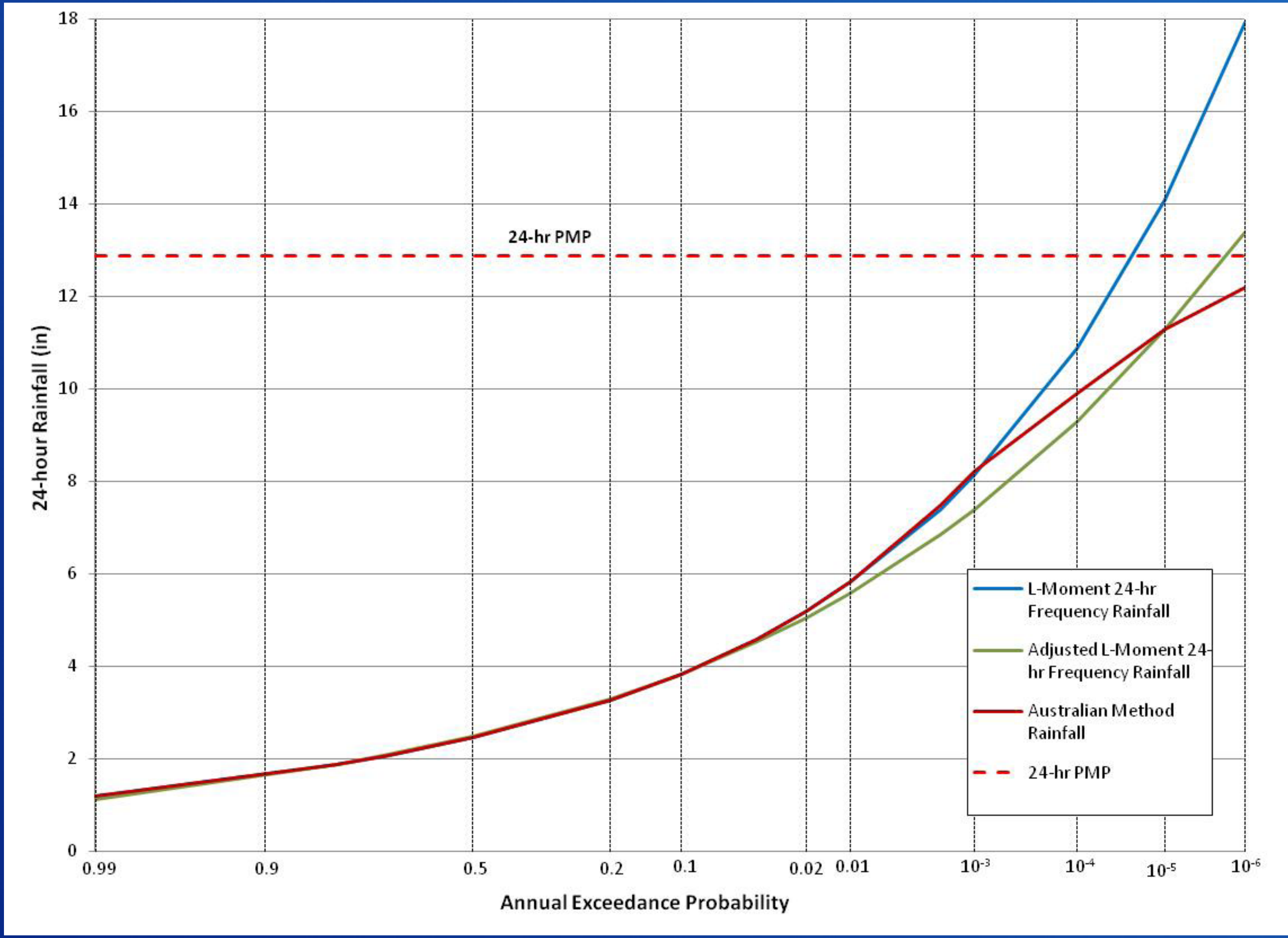
Use ARR rainfall/PMP probability concepts

Customize ARR concepts on spatial/temporal patterns, runoff models, loss rates and sensitivity by Reclamation

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

Australian Rainfall-Runoff

Example combining L-Moments regional precip frequency (Kappa distribution) with AEP of PMP (10^{-7})



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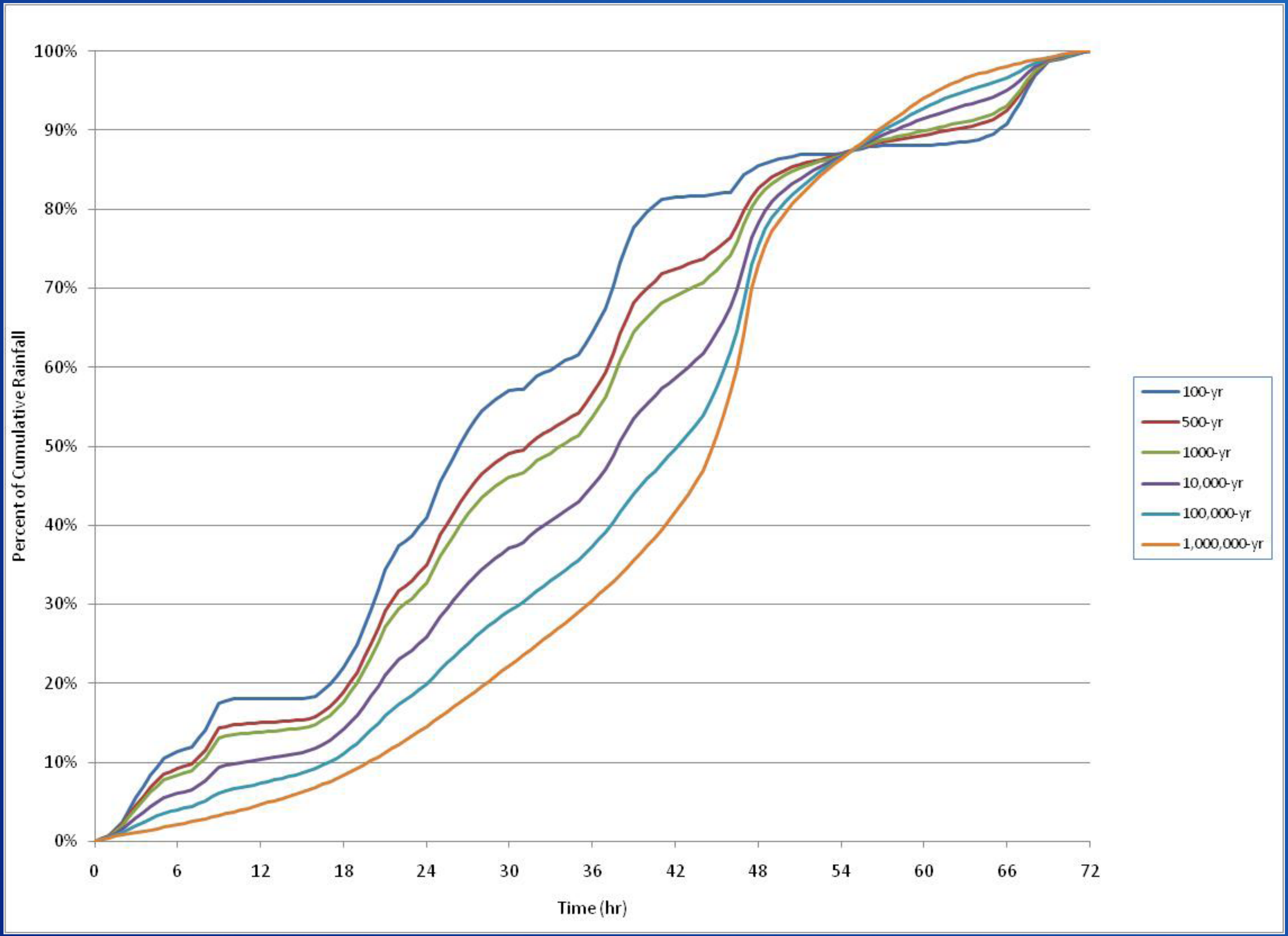
Australian Rainfall-Runoff

Example varying temporal pattern



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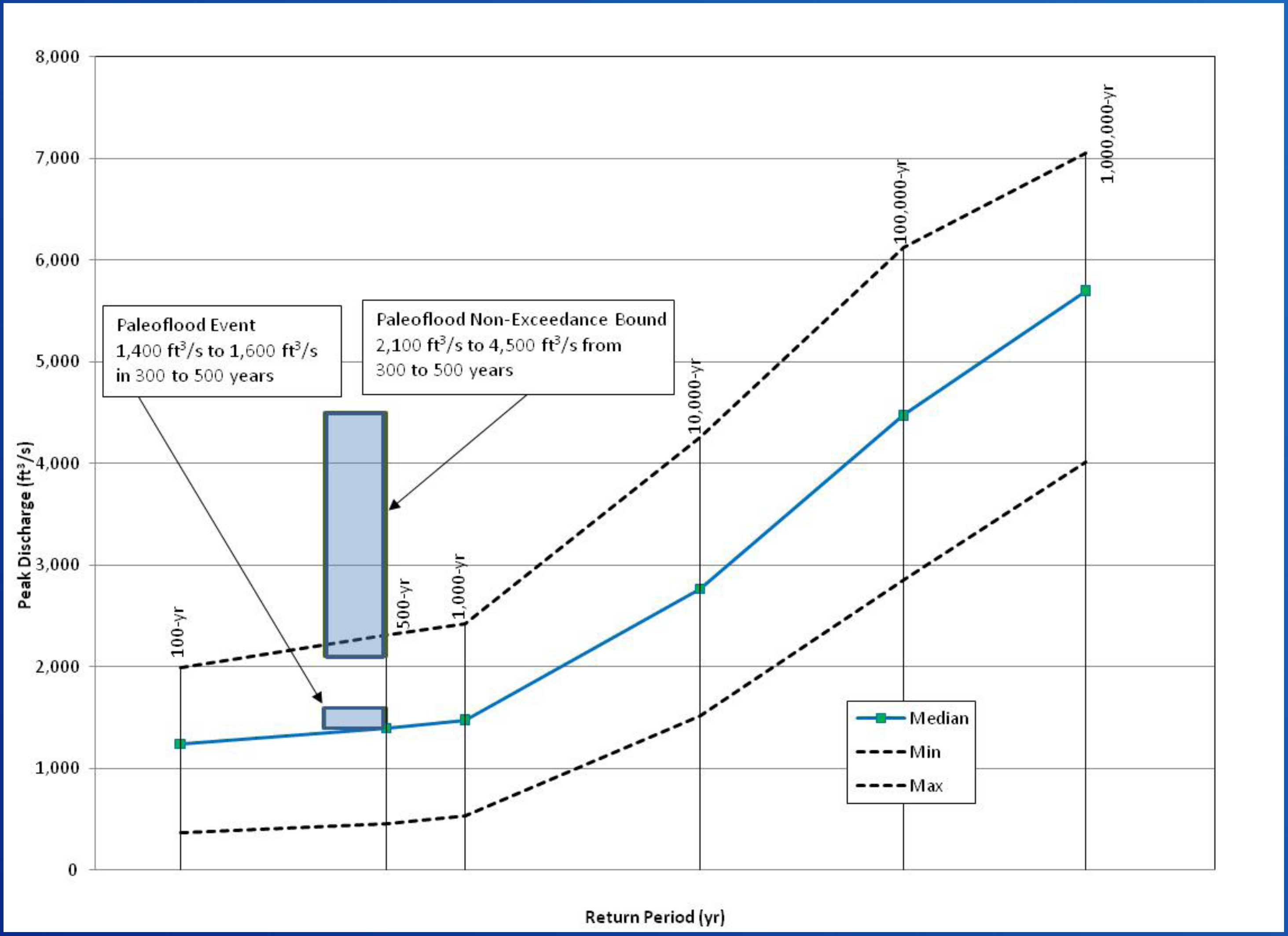
Australian Rainfall-Runoff

Example with HEC-1 and varying:
-loss rate
-lag coefficient
-temporal pattern
-upper and lower rainfall estimates



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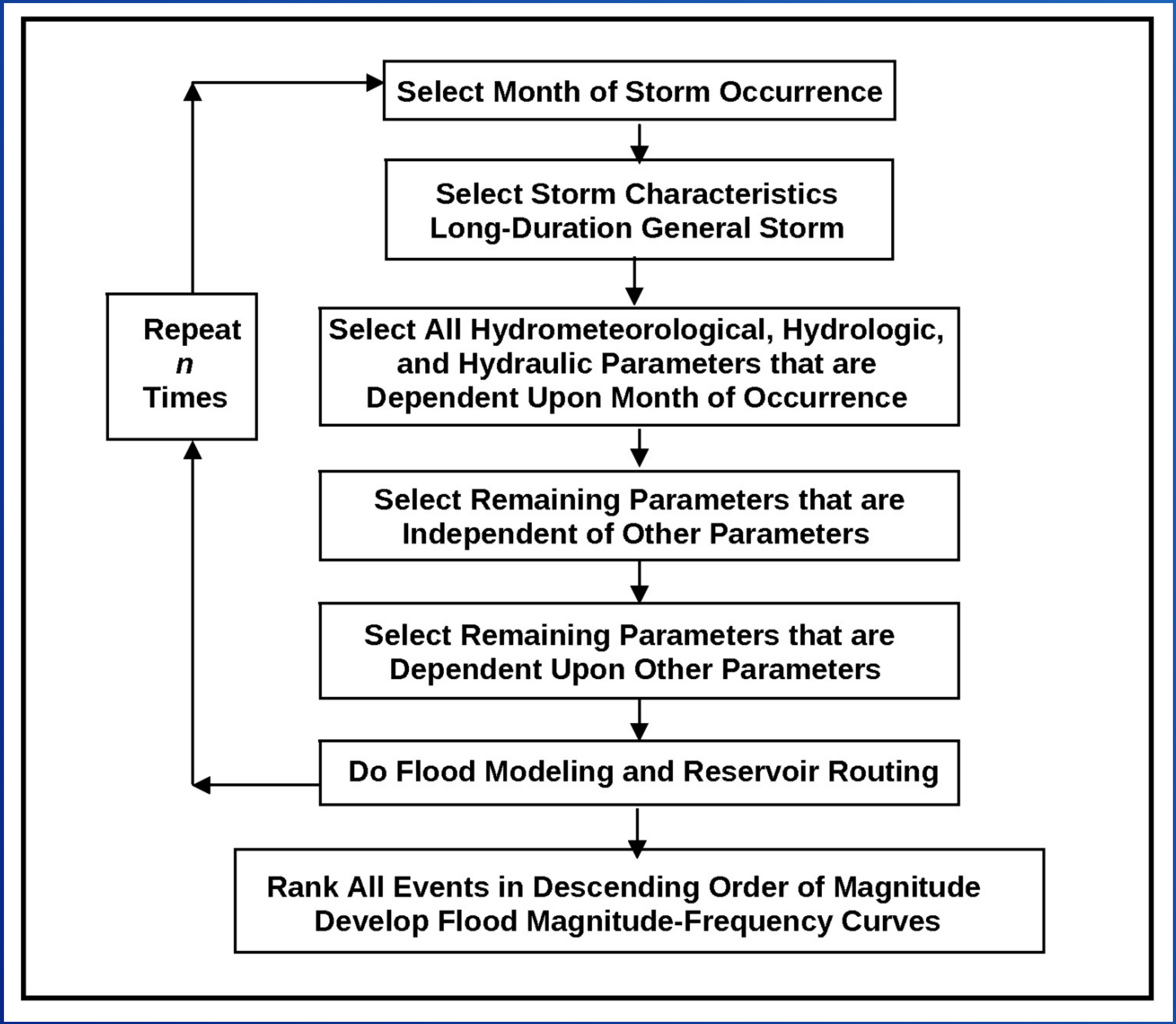
Stochastic Event-Based Rainfall-Runoff Model (SEFM) Key Elements

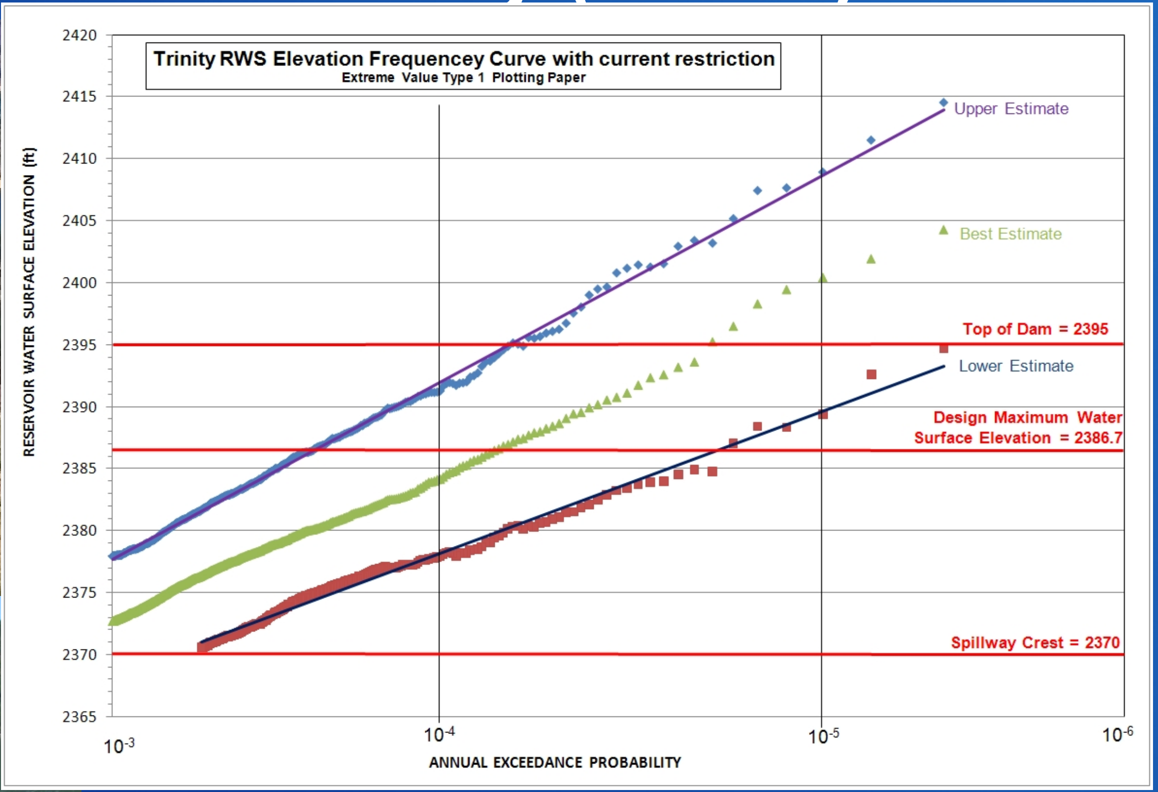
- Regional Rainfall Frequency using L-Moments
- Hydrometeorological parameters treated as random variables (snowpack , infiltration..)
- Utilize Storm Patterns and Sequence of Storms
- Runoff Computed using HRU Approach with Unit Hydrograph
- Perform Monte Carlo Simulations - Frequency Analysis on output;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

Details/Application: Panel 6

SEFM Simulation



Hydrologic Hazard Reservoir Frequency Curve with Uncertainty (SEFM)



evaluate reservoir restriction, Trinity Dam, CA
538 ft high (structural height) embankment

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Multiple Methods and Weighting

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

Reclamation HHA Ongoing R&D

- Paleoflood data collection
- Extreme storm data collection
- Gridded spatial and temporal extreme storms - orographics
- Extreme storm ingredients and NWP models (NCAR and NOAA-ESRL)
- Physics of extreme storms (WRF) with NOAA-ESRL
- Monte-Carlo reservoir routing
- NWS SAC-SMA stochastic runoff modeling framework
- Gridded SNODAS data assimilation
- NWS-RFS gridded, continuous models (NWS NWRFC, NCAR) (also considering NCAR WRF-Hydro)
- Climate change and flood extremes (statistics, rainfall-runoff)

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Questions/Comments?

Sacramento
Folsom JFP

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USACE

~$1.3B

HHA:
Paleofloods,
FLDFRQ3
SEFM
PMF

ftp://ftp.usbr.gov/jengland; jengland@usbr.gov