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Managing Water in the West

Extreme Flood Probability Estimation Methods for Dam Safety Hydrologic Risk Analysis used by Reclamation and USACE

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U.S. Department of the Interior
Bureau of Reclamation

Acknowledgments

Reclamation:

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Corps of Engineers:

Methods courtesy of:

Doug Clemetson (NWO)

Jeff Harris (HEC) and others

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Outline

- Overview of Extreme Flood Problem
- Probable Maximum Flood – Upper Limit
- Dam Safety Risk and Hydrologic Loadings
- Overview of Reclamation Flood Risk Methods
- Overview of USACE Flood Risk Methods
- Data and Paleoflood Data
- Reclamation Hydrologic Hazard Procedures
- Example Case: Folsom Dam, CA

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

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Rainbow Dam, Michigan 1986

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Rainbow Dam, Michigan 1986

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Rainbow Dam, Michigan 1986

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Rainbow Dam, Michigan 1986

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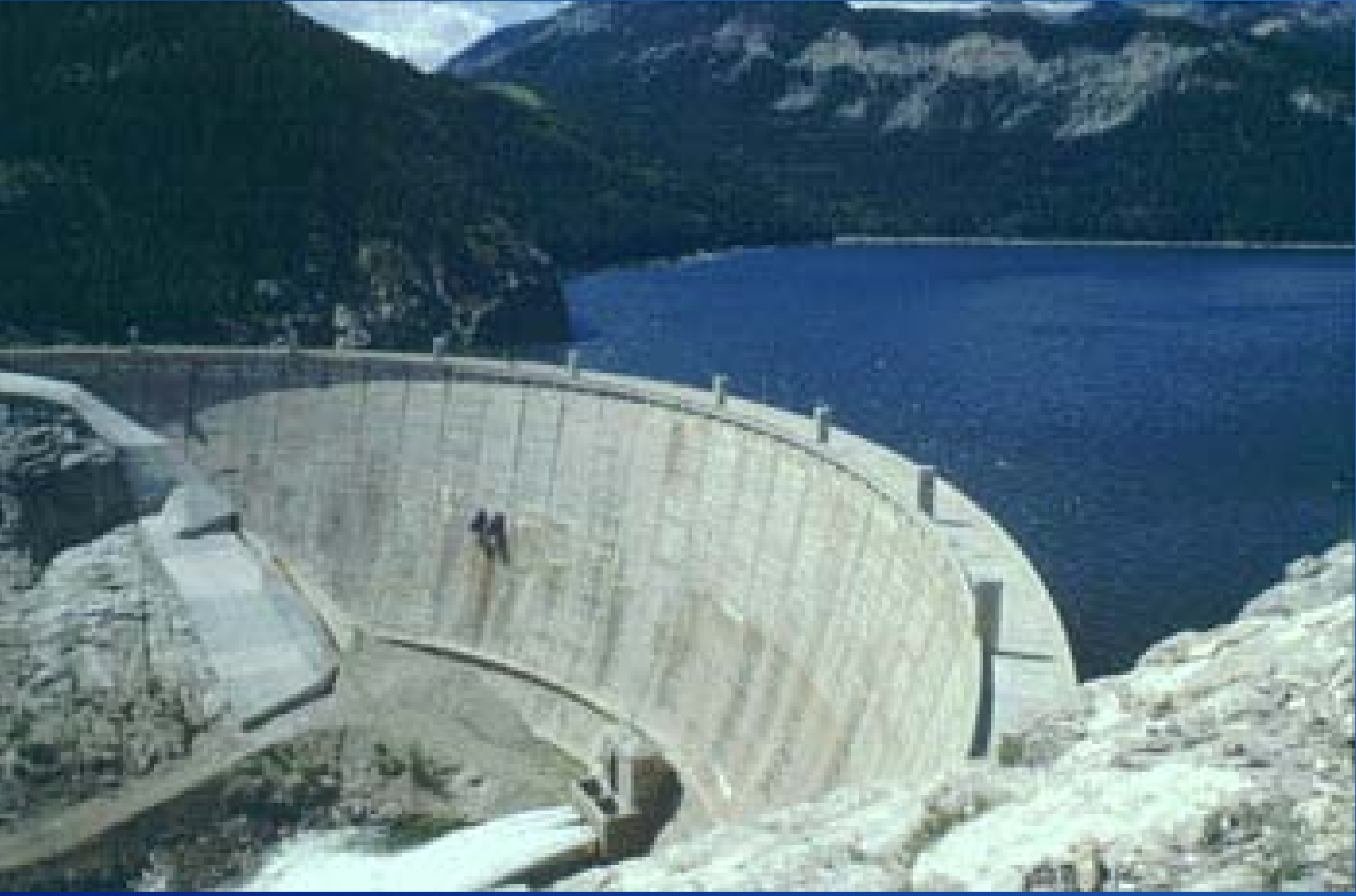

Gibson Dam, MT

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Gibson Dam, MT June 1964

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Gibson Dam, MT June 1964

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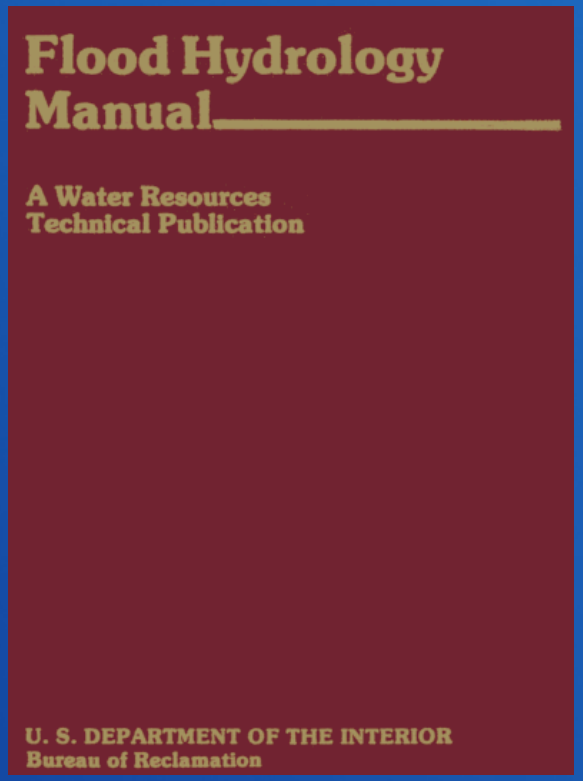
Probable Maximum Flood (PMF): Upper Design Flood Limit (USBR)

PMF: The 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 – Maximum Condition; NO Estimate of Risk

Reclamation uses the PMF as the upper limit of flood potential (maximum) at a site for storm durations defined by the PMP

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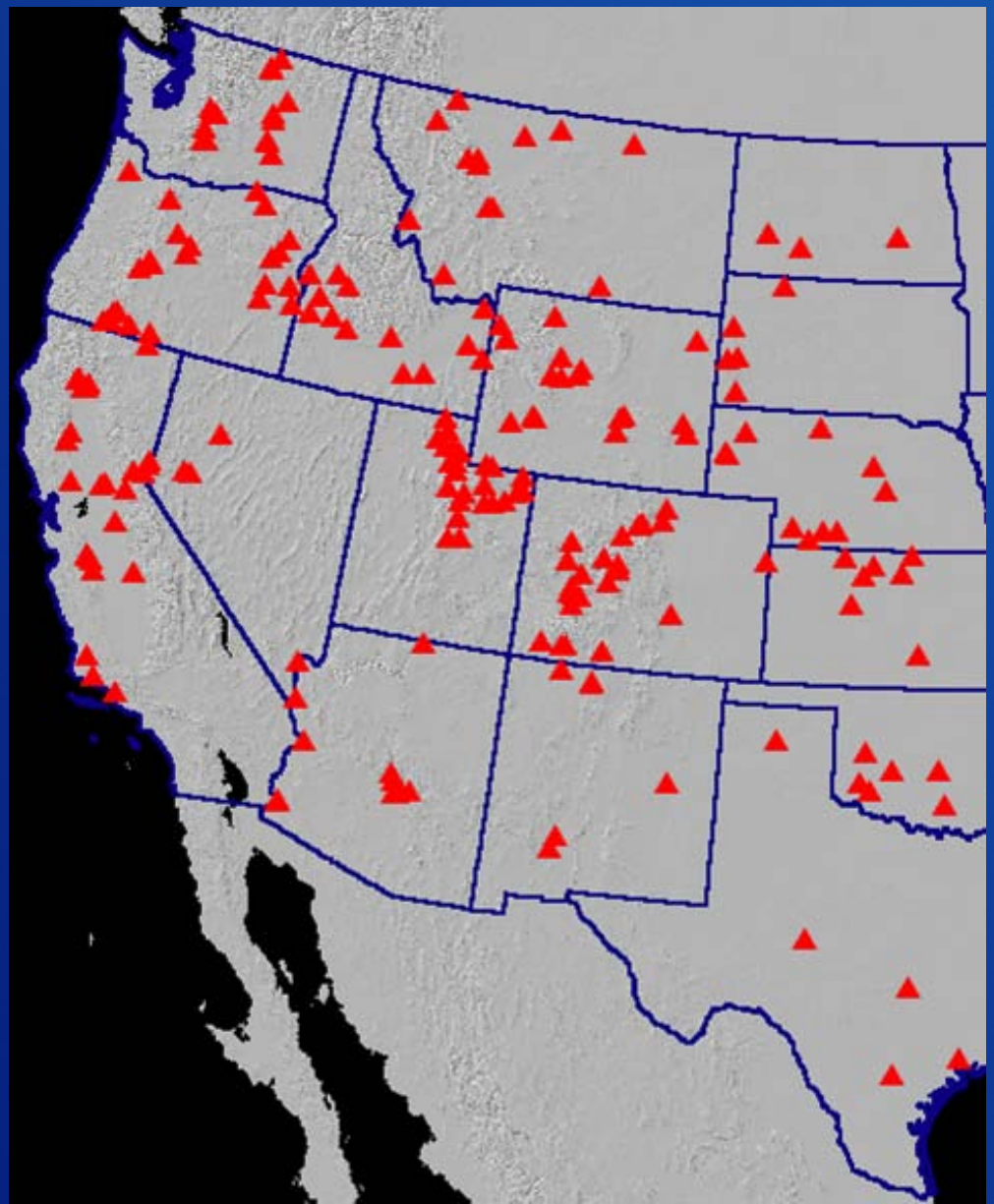
USBR Dam Safety Risk Analysis



- 300 large dams
- < 50% pass PMF

<u>Risk Guidelines</u>

- Annual Failure Probability: **0.0001**
- Estimated Risk – Annualized Loss of Life: **0.001**

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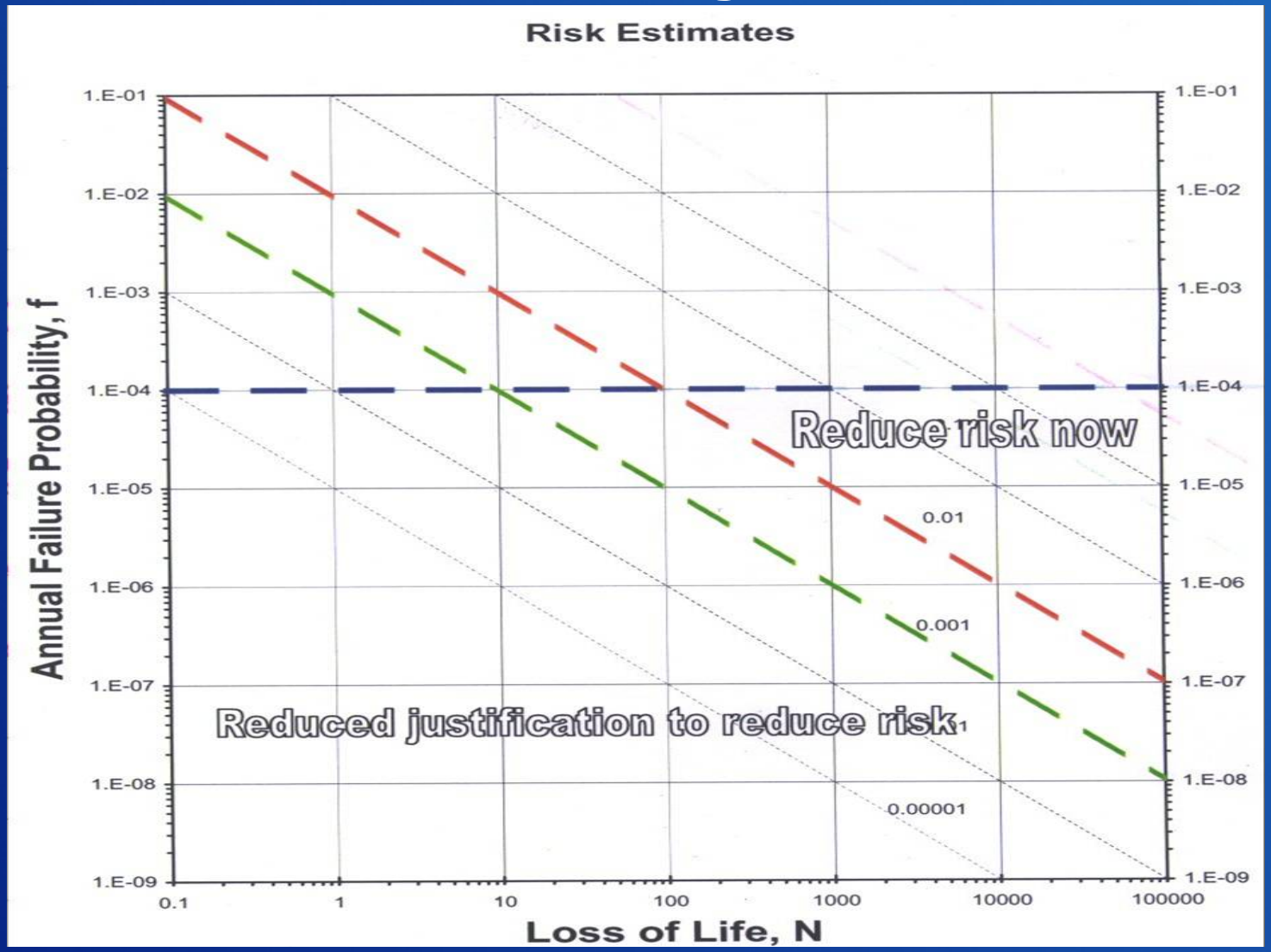
USBR Dam Safety Risk Criteria



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Hydrologic Loads and Risk Analysis

Annual Failure Probability f =

$$\begin{bmatrix}\text{Probability}\\ \text{of}\\ \text{Load}\end{bmatrix} * \begin{bmatrix}\text{Probability}\\ \text{of Adverse Response}\\ \text{Given Load}\end{bmatrix}$$

Hydrologic Loading Estimate

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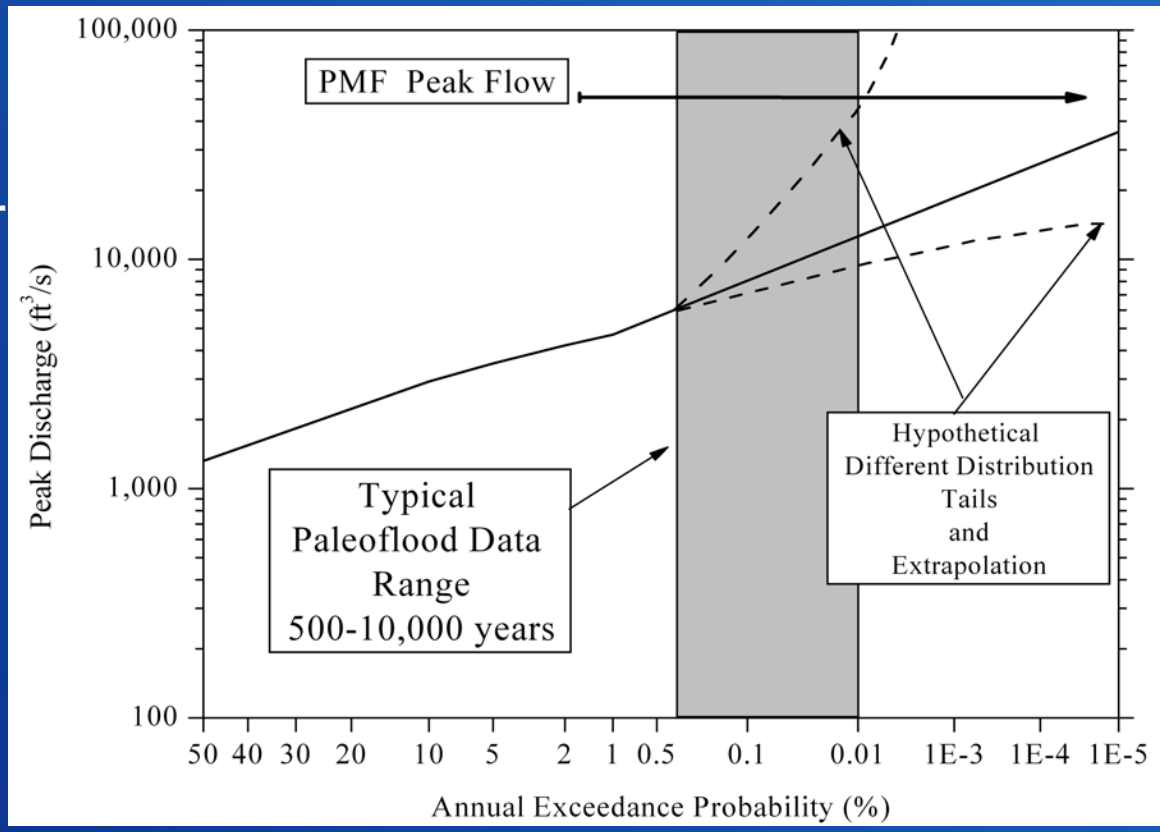
Hydrologic Risk Analysis Needs: Floods and Probability Estimates

- Peak Flow, Volume Frequency, Hydrographs, Reservoir Levels
- 1,000-year and 10,000-year (typical)
- up to 10,000,000-year Return Periods; extrapolation!



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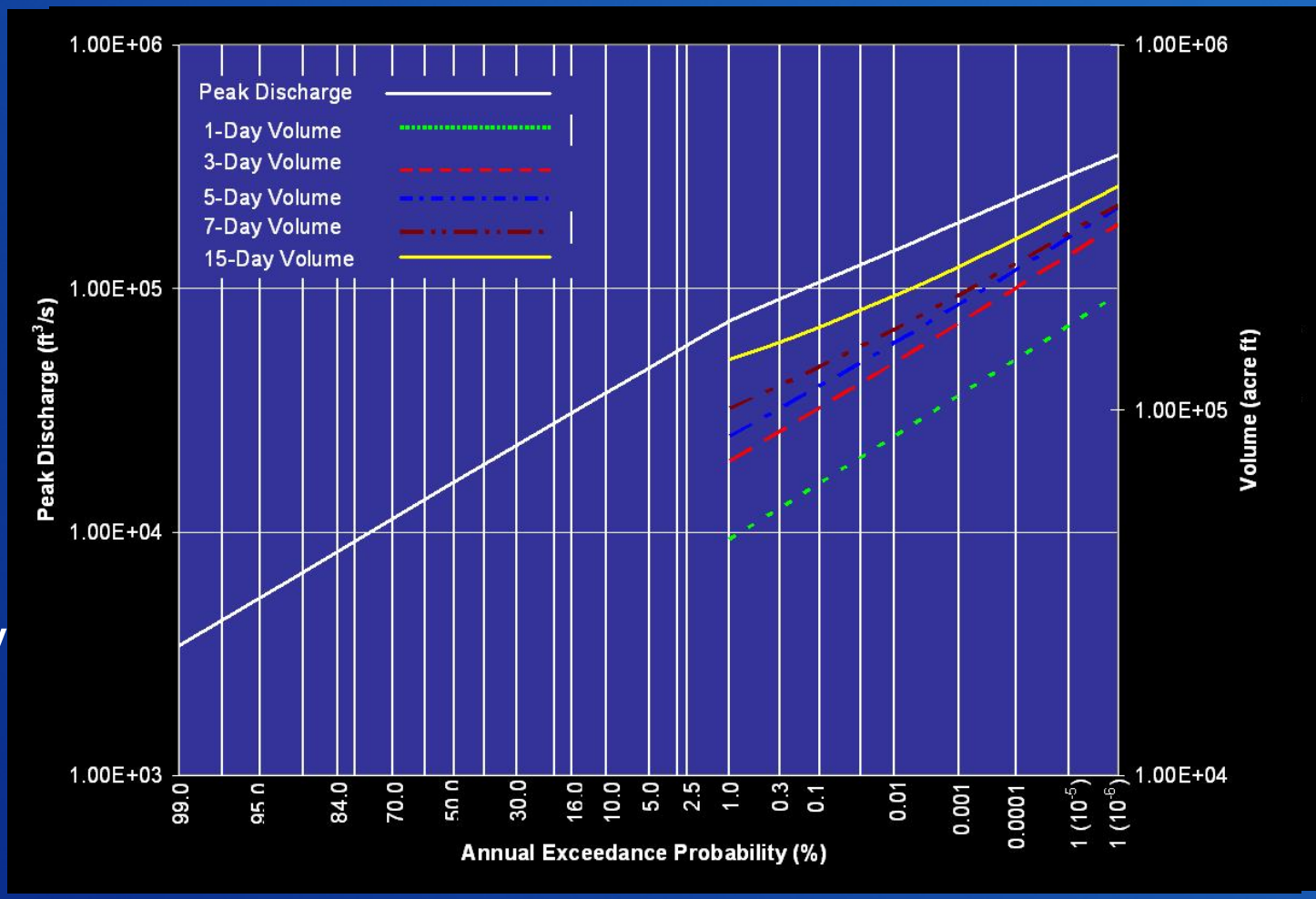
Hydrologic Hazard Curve

Portrays Flood Magnitude

Peak and Volume

or Reservoir Levels

and Probability



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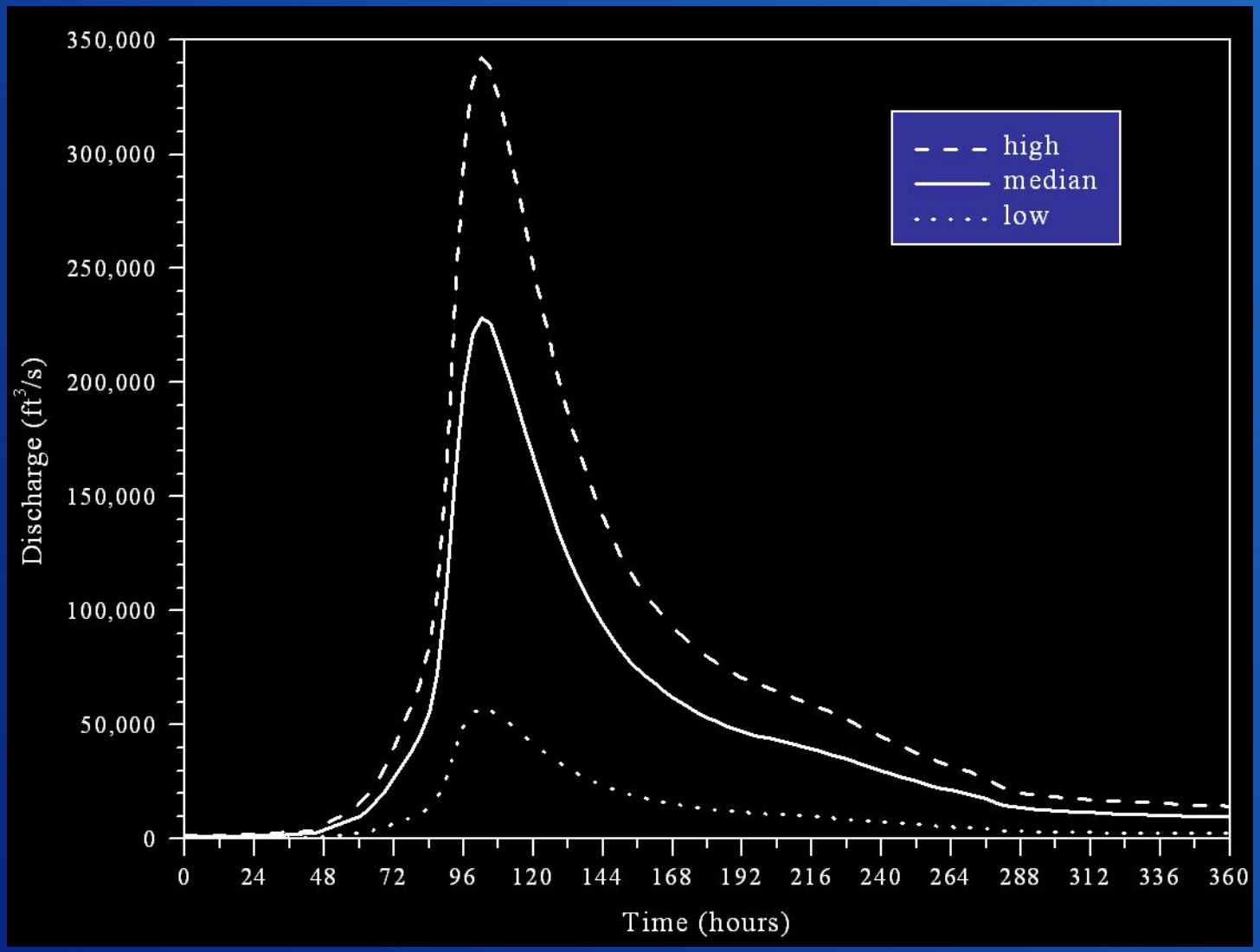
Example Extreme Flood Hydrographs



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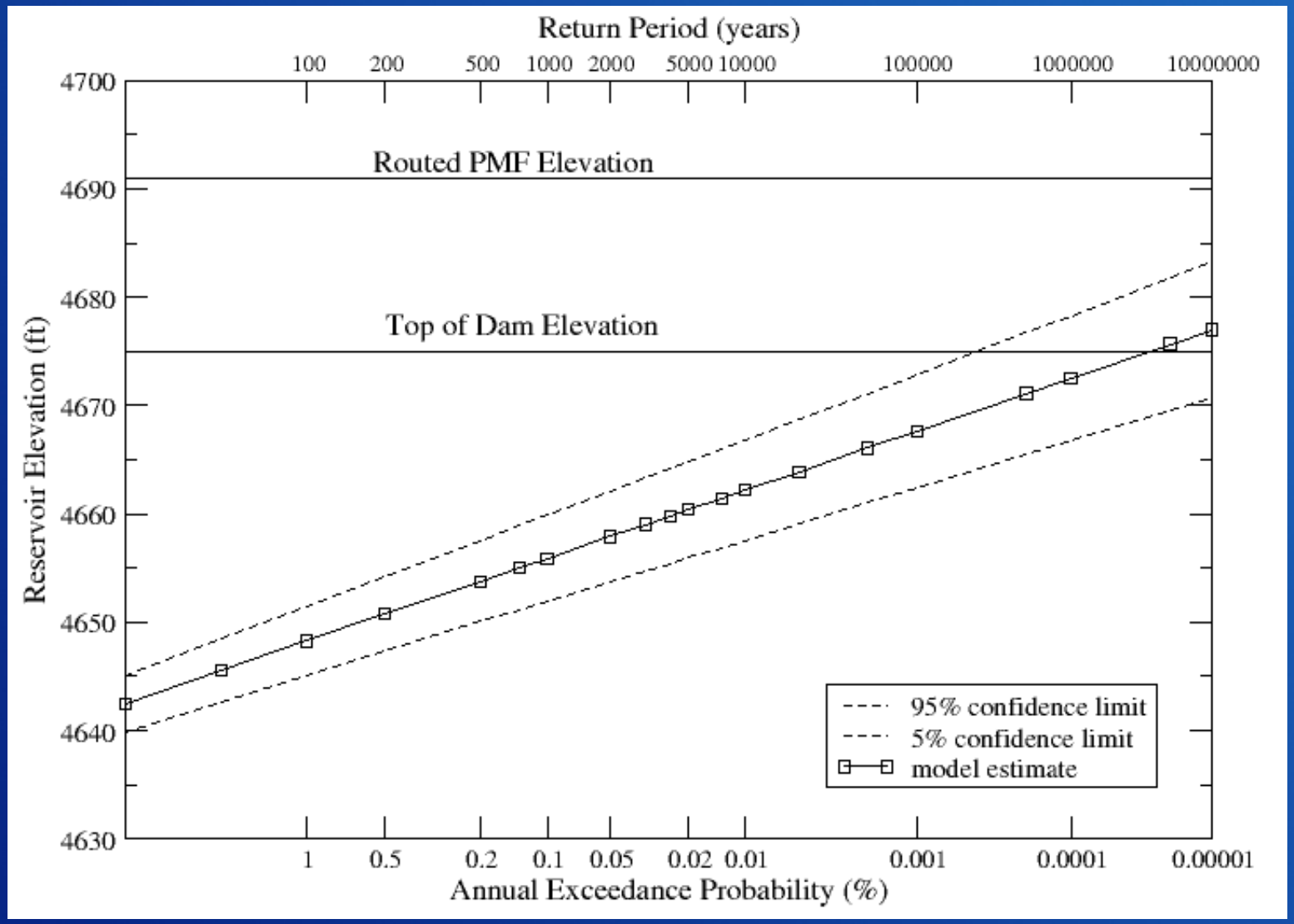
Reservoir Elevation Frequency Curve



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Reclamation Flood Hazard Methods

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June 2004

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Reclamation Hydrologic Hazard Curves: Extreme Flood Probability Estimation Methods

Statistical Streamflow Methods

- Flood Frequency Analysis with Historical/Paleoflood Data
- Hydrograph Scaling and Volumes

Rainfall/Runoff Methods

- GRADEX Method
- Australian Rainfall-Runoff Method
- Stochastic Event-Based Precipitation Runoff Modeling (SEFM)
- Stochastic Rainfall-Runoff Modeling with TREX

Swain et al. 2004, 2006

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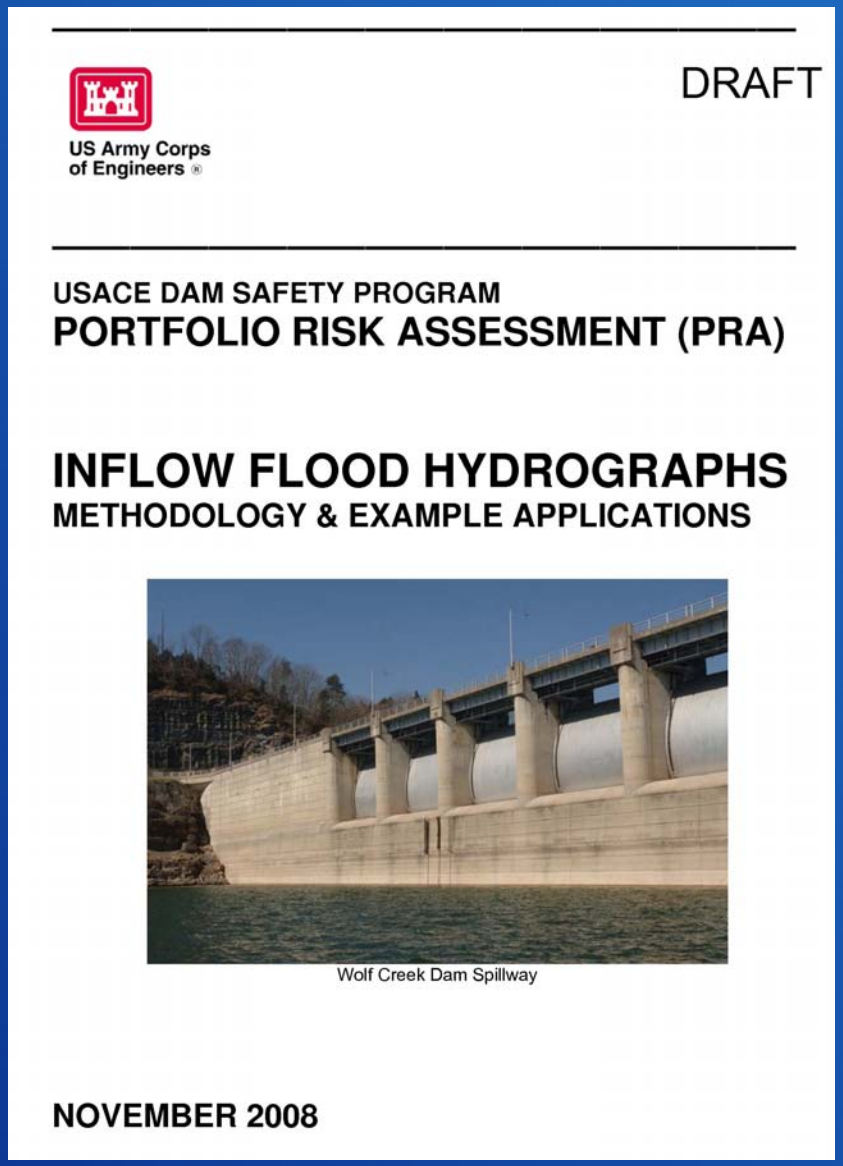
USACE Flood Hazard Methods



DRAFT

US Army Corps of Engineers ®

USACE DAM SAFETY PROGRAM

PORTFOLIO RISK ASSESSMENT (PRA)

INFLOW FLOOD HYDROGRAPHS

METHODOLOGY & EXAMPLE APPLICATIONS

Wolf Creek Dam Spillway

NOVEMBER 2008

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USACE Flood Hazard Methods

Table 1-1. Matrix of Methods

	SPRA	PA	IE
Pool-Frequency Curve	Use Existing Curve from Water Control Manual or Design Memorandum (extrapolate as necessary)	Historic Data + Rainfall-Runoff OR Balanced Hydrographs	Historic Data WITH P-O-R Simulation + Rainfall-Runoff AND/OR Balanced Hydrographs
Inflow Floods Hydrographs	PMF	Rainfall-Runoff OR Factor PMF based on Volume Frequency	Rainfall-Runoff OR Balanced Hydrographs + P-O-R Simulation
PMF Frequency	$1*10^{-4}$	Extreme Event Analysis or Volume Probability	Extreme Event Analysis
Antecedent Pool	From PMF routing	Interpolate from PMF routing and Calibrated Spillway Crest Flood or Top of Gates Flood	Interpolate from PMF and Calibrated Spillway Crest Flood or Top of Gates Flood
Downstream Flow Conditions	Use Median Flow (50% exceedance from flow duration curve)	Residual Rainfall with Watershed Model or Residual Rainfall Depth Adjusted Inflow Hydrograph	Residual Rainfall with Watershed Model

SPRA: Screening for Portfolio Risk Analysis (Phase I)
PA: Periodic Assessment (Phase II)
IE: Issue Evaluation (Phase III)

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USACE Flood Hazard Methods

8.3 Description of Techniques

Several techniques have been used recently to assign probabilities to rare floods all the way out to the magnitude of the PMF. Each of these methodologies are generally used in conjunction with gaged frequency analysis as a way of extending the gaged frequency curves out to events more rare than gaged data analysis would normally warrant. The following is a list of methods that have been selected for evaluation for inclusion in the PRA for Corps dams:

1. Extension of Gaged Frequency Curves with Historic/Paleoflood information
2. Hydrologic Modeling using frequency based storm events
3. The GRADEX Method
4. Stochastic Event Flood Model (SEFM)
5. Regional Probability of the PMF

Reclamation Hydrologic Hazard Curve Methods

Method of Analysis and Modeling	Hydrologic Hazard Curve Product	Risk Analysis/Design Level[1]	Level of Effort[2]
Flood frequency analysis (FFA) with historical/paleoflood data - Graphical method - EMA - FLDFRQ3	flood frequency	CFR, IE, CAS, FD	Low
Hydrograph Scaling and Volumes	hydrographs and volumes; based on flood frequency	CFR, IE, CAS, FD	Low
GRADEX Method	volume frequency; hydrographs	IE, CAS, FD	Moderate
Australian Rainfall-Runoff Method	flood frequency and hydrographs; based on rainfall frequency and PMP	IE, CAS, FD	Moderate
Stochastic Event-Based Precipitation Runoff Modeling with SEFM	flood frequency; hydrographs; volume frequency; reservoir elevation frequency	CAS, FD	High
Stochastic Rainfall-Runoff Modeling with TREX	flood frequency; hydrographs; reservoir elevation frequency	CAS, FD	High

[1]CFR: Comprehensive Facility Review; IE: Issue Evaluation; CAS: Corrective Action Study; FD: Final Design

[2]Low: 10-20 staff days; Moderate: 21-75 staff days; High: more than 75 staff days

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Hydrologic Hazard Characterization

- Make use of prior studies (PMF, FFA, 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

Hydrologic Hazard Data

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 (1999)

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Extreme Flood Probability Estimation Methods: FFA and Hydrographs

- Paleoflood **DATA** Collection
  - stratigraphy; macrobotanical analysis
  - radiocarbon dating/calibration
  - hydraulic modeling: 1D or 2D
- Flood Frequency Analysis
  - Bayesian MLE: O'Connell et al. 2002 WRR
  - Expected Moments: England et al. 2003 WRR
- Hydrograph Scaling
  - Rainfall-runoff (PMF), Statistical scaling

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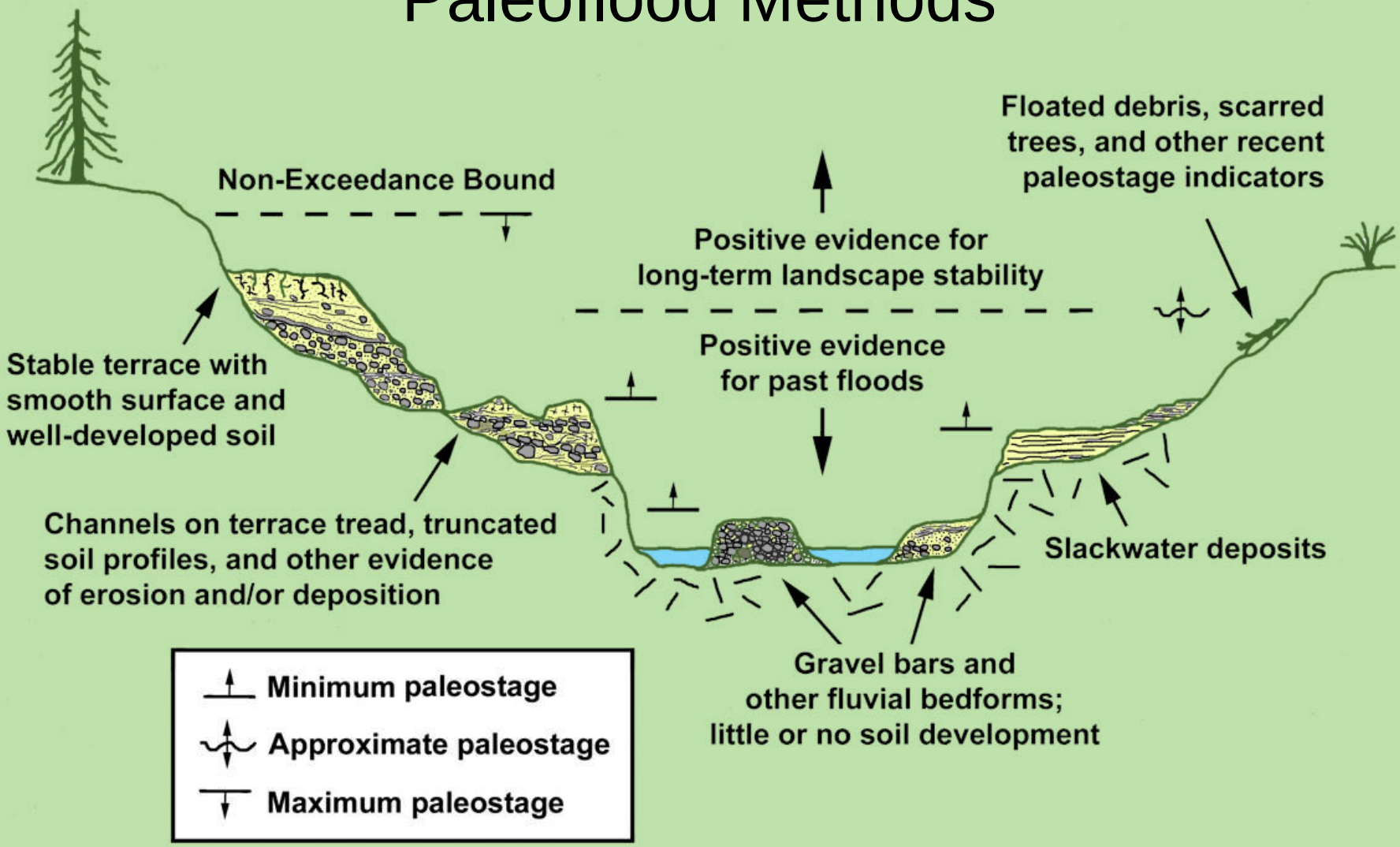
Paleoflood Data Collection

- Direct record of extreme floods in basin
- Record extension – significantly extend the peak-flow records within the watershed and region
- Individual paleofloods, e.g. Slackwater Deposit (SWD)
- Place limits on flood experience over time (paleoflood bound)
- Independent data for rainfall-runoff model validation

Paleoflood Methods



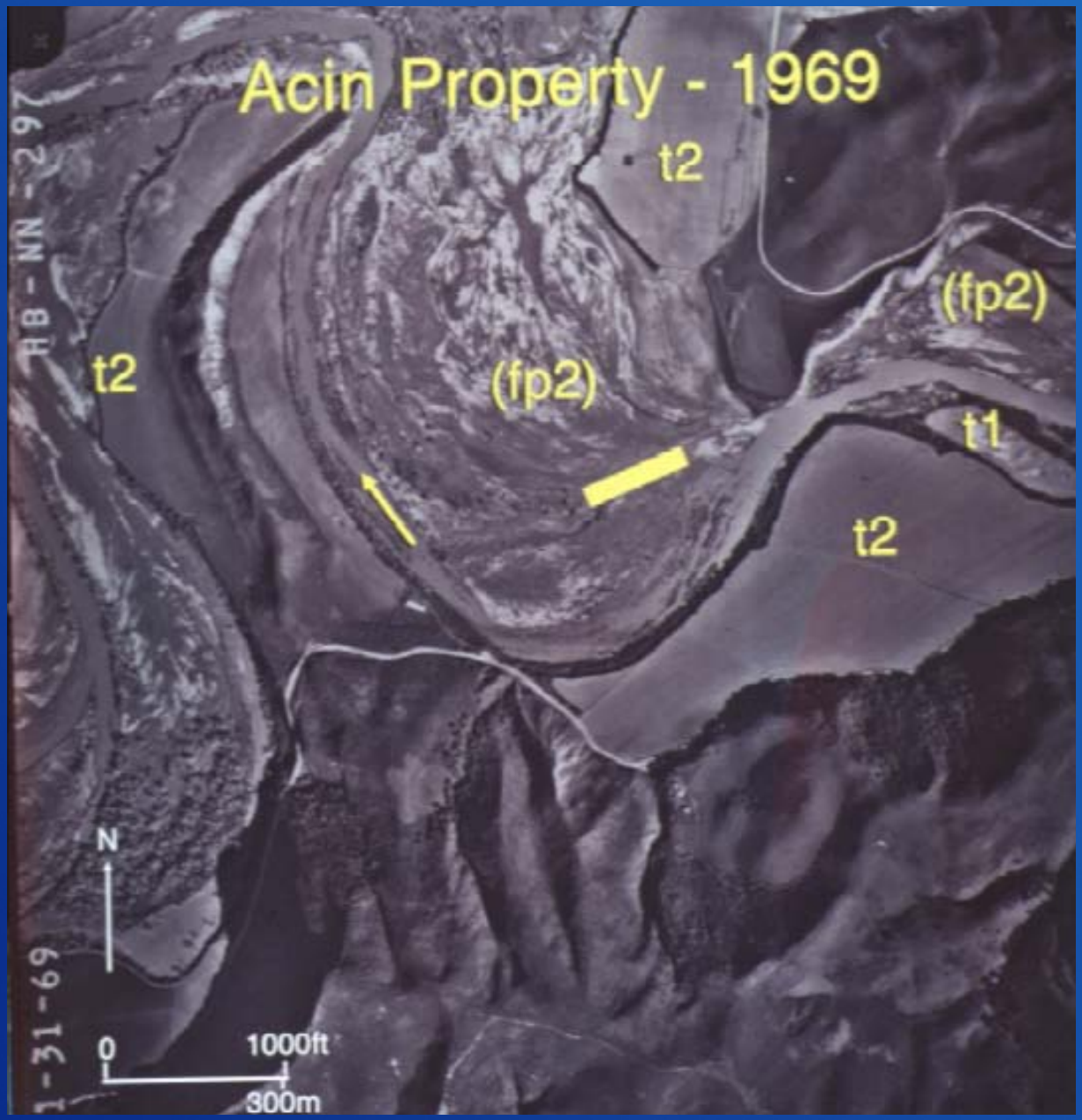
House et al. (2002) AGU Paleoflood Monograph

Flood Modified Surfaces

1969

Santa Ynez R.

Southern California



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Flood Stratigraphy (buried road)

1969

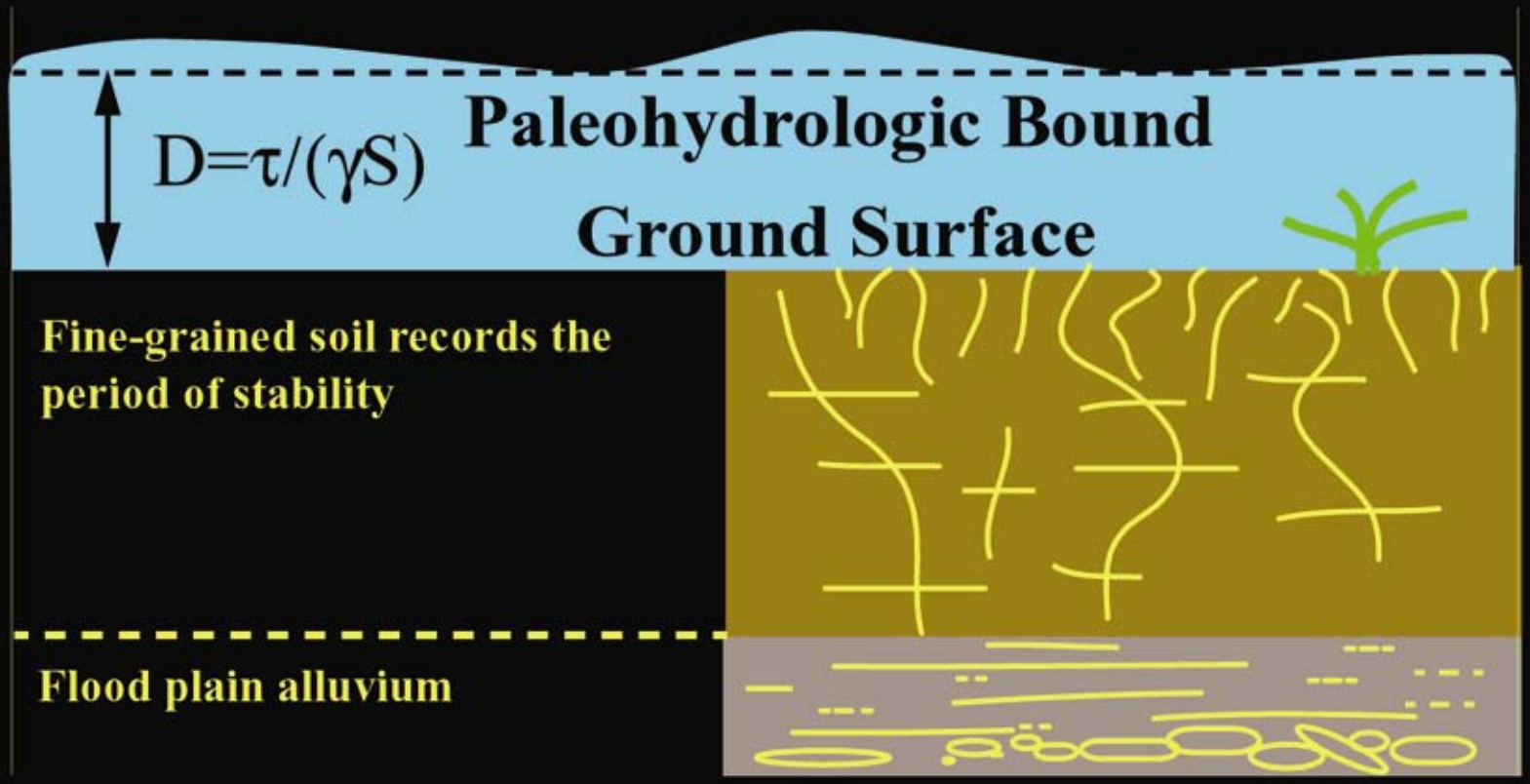
Santa Ynez R.

Southern California

ATION

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

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Limits of Floods

Medicine Bow River near Hanna, Wyoming - 7500 year old stable terrace

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Stable Surface – Limit on Floods

North Platte River near Rawlins, Wyoming

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Botanical Extreme Flood Evidence: Winter 1861 or 1862 flood
Crooked River, Oregon

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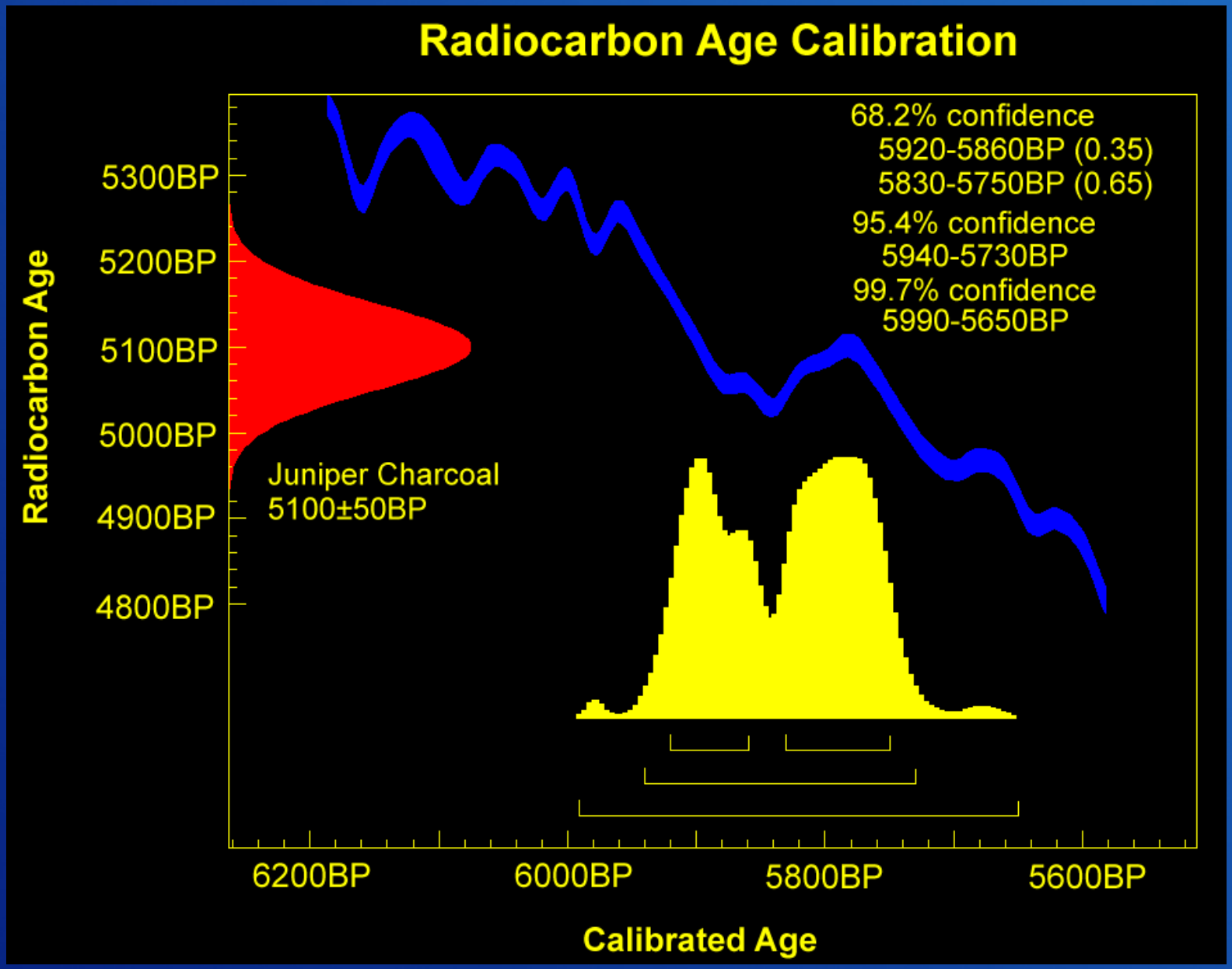
Soils Stratigraphy and Age Estimates (Radiocarbon)

Birkeland (1999)
soils techniques



Stuiver et al. (1998)

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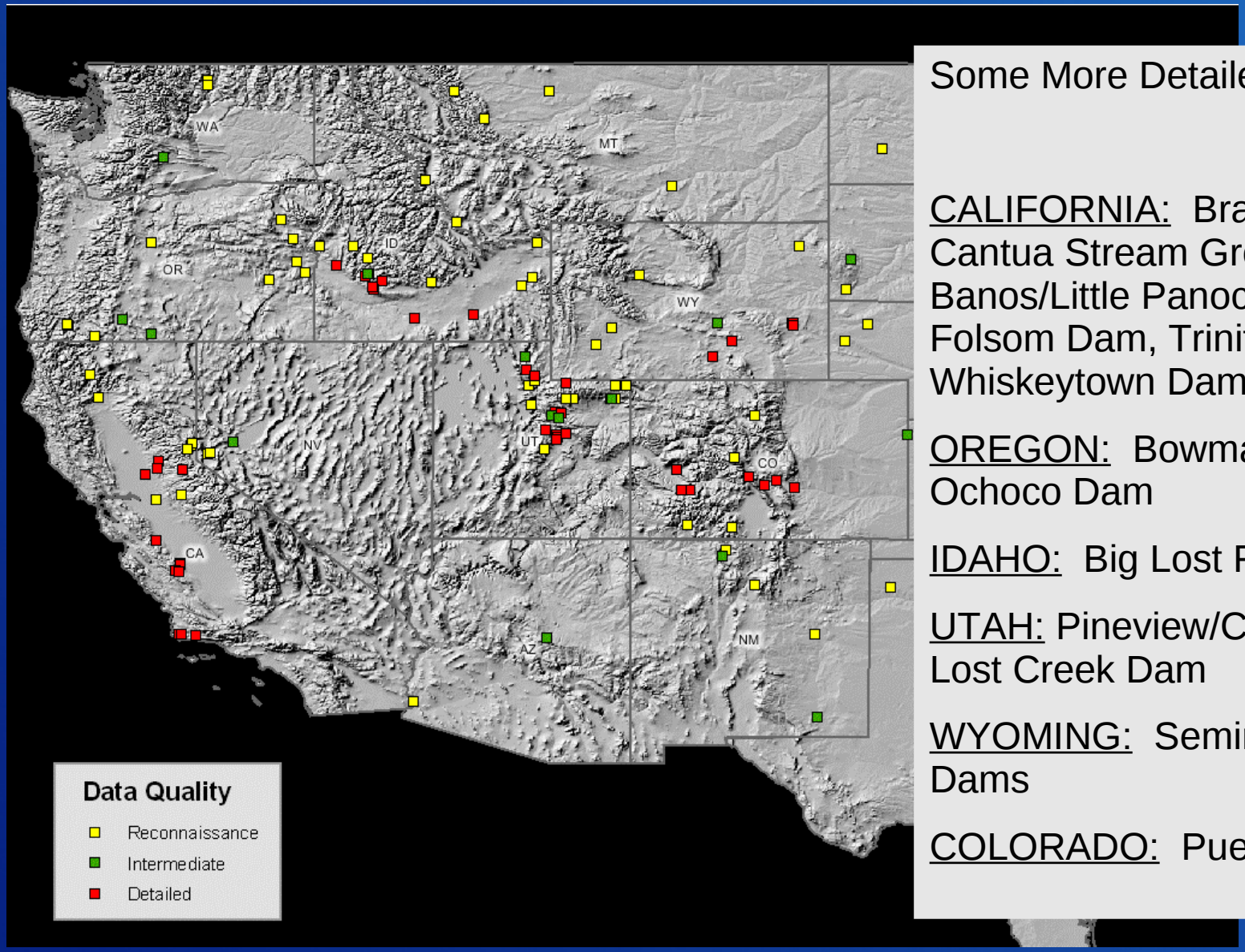
USBR Paleoflood Sites: Western U.S.



Some More Detailed Study Sites

CALIFORNIA: Bradbury Dam, Cantua Stream Group, Los Banos/Little Panoche Dams, Folsom Dam, Trinity Dam, Whiskeytown Dam, Friant Dam

OREGON: Bowman Dam, Ochoco Dam

IDAHO: Big Lost River

UTAH: Pineview/Causey Dams, Lost Creek Dam

WYOMING: Seminoe/ Glendo Dams

COLORADO: Pueblo Dam

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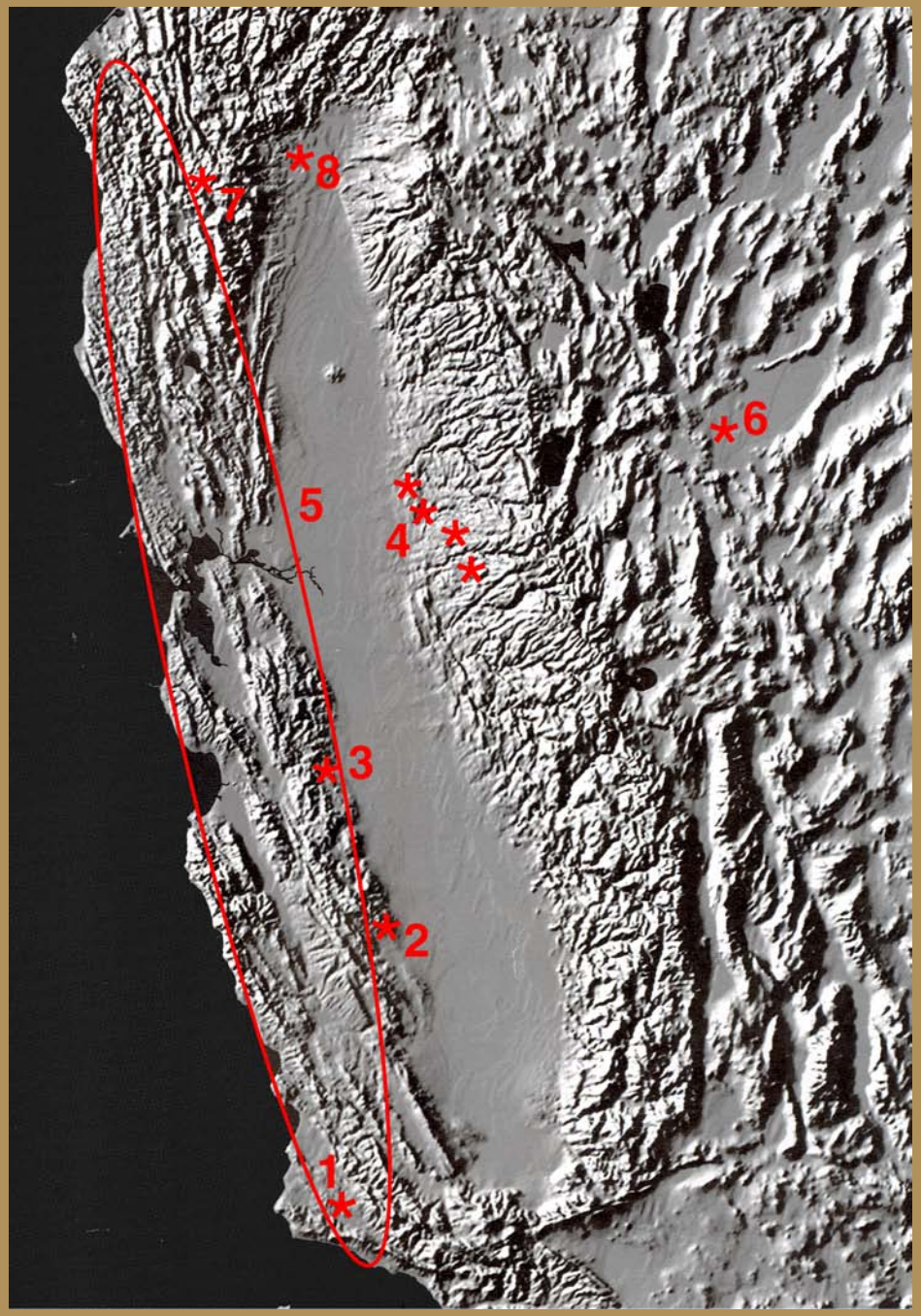
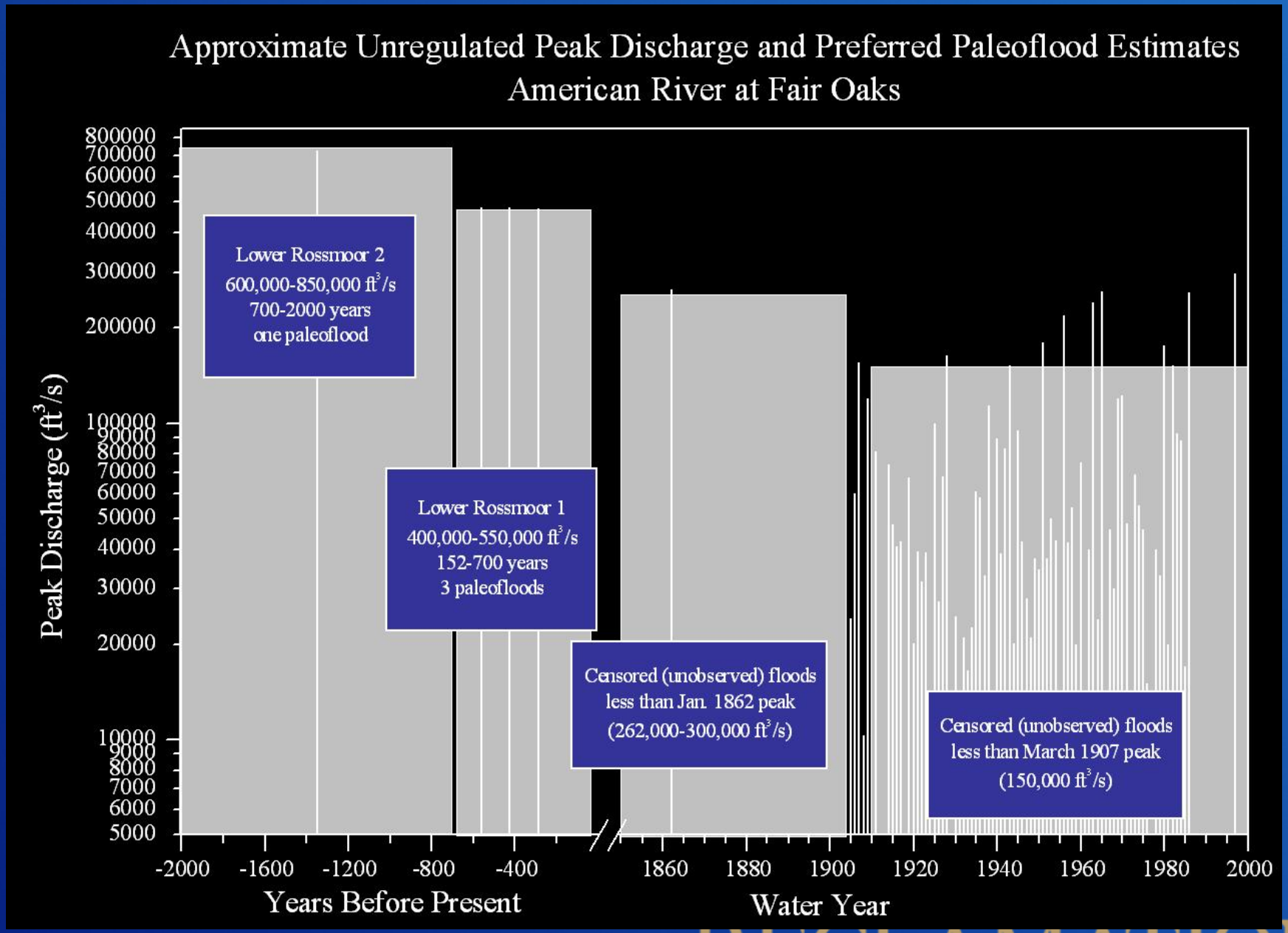
Studies in California

1. Santa Ynez River
2. Cantua Stream Group
3. Los Banos Creek
4. Central Sierra Nevada
5. Coast Range Extreme Precipitation
6. Carson River
7. Trinity River
8. Upper Sacramento River





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Extreme Flood Probability Estimation Methods: Rainfall-Runoff

- Flood Frequency Analysis with Historical/Paleoflood Data
- Hydrograph Scaling and Volumes
- GRADEX Method
- Australian Rainfall-Runoff Method
- Stochastic Event-Based Precipitation Runoff Modeling (SEFM)
- Stochastic Rainfall-Runoff Modeling with TREX

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
2. Introduction of more ‘structure’ into models
3. Focus of extremes or ‘tails’ as opposed to or even to the exclusion of central characteristics

NRC (1988) Estimating Probabilities of Extreme Floods

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Extreme Flood Probabilities

- 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.

after NRC (1988)

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Extreme Flood Probabilities

Method	Rainfall	Runoff
GRADEX	regional rainfall frequency & exponential tail	transfer function
Australian	PMP probability estimate and point rainfall frequency	Unit Hydrograph
SEFM	lmoment-based regional rainfall frequency	Unit Hydrograph; variable parameters and inputs
TREX	stochastic storm transposition with DAD catalog	2D distributed

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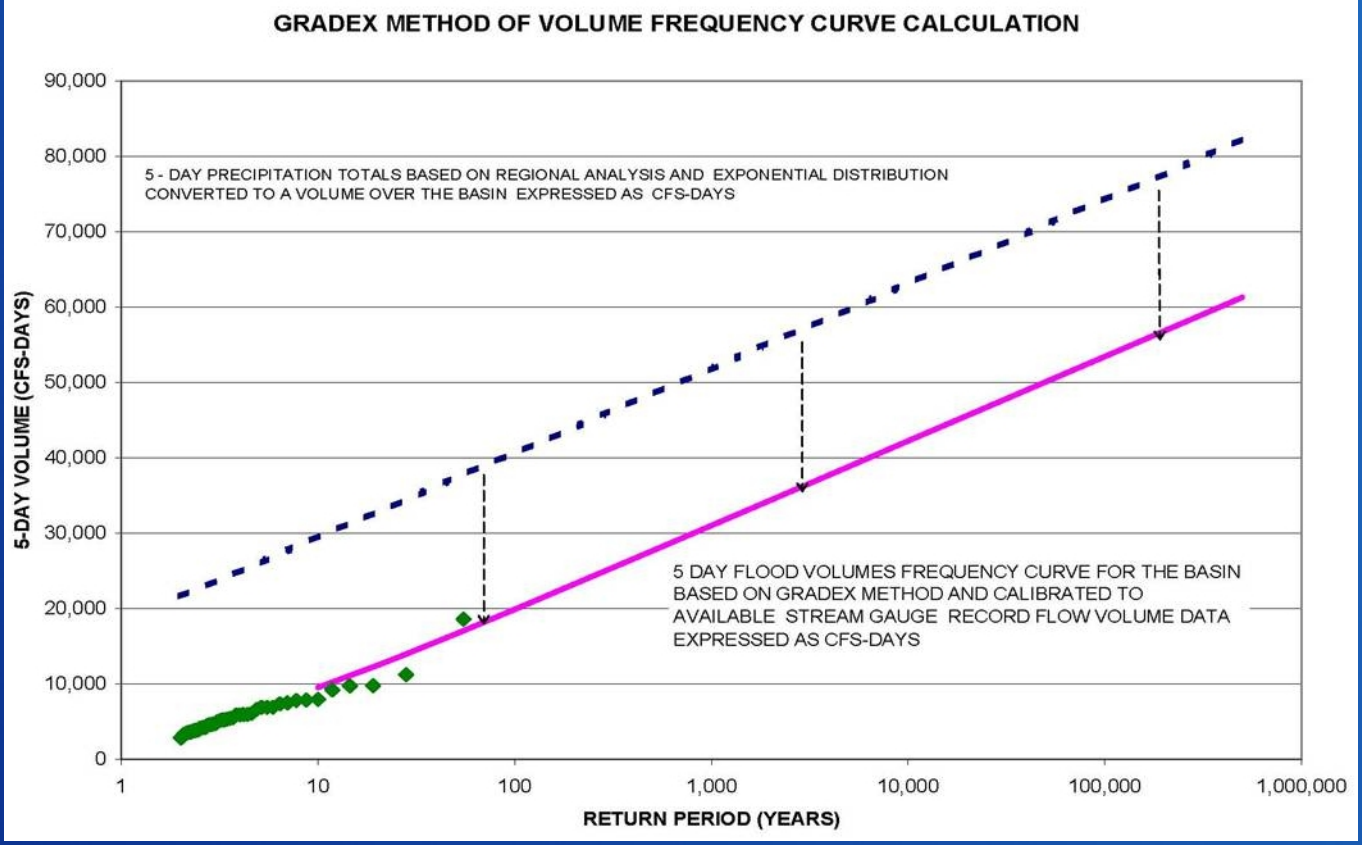
Gradex Method Assumptions

Watershed at saturation; increase in precipitation tends to produce equivalent increase in runoff volume



Upper tail of the flood volume distribution is exponential with the same scale parameter as the upper tail of the rainfall volume.

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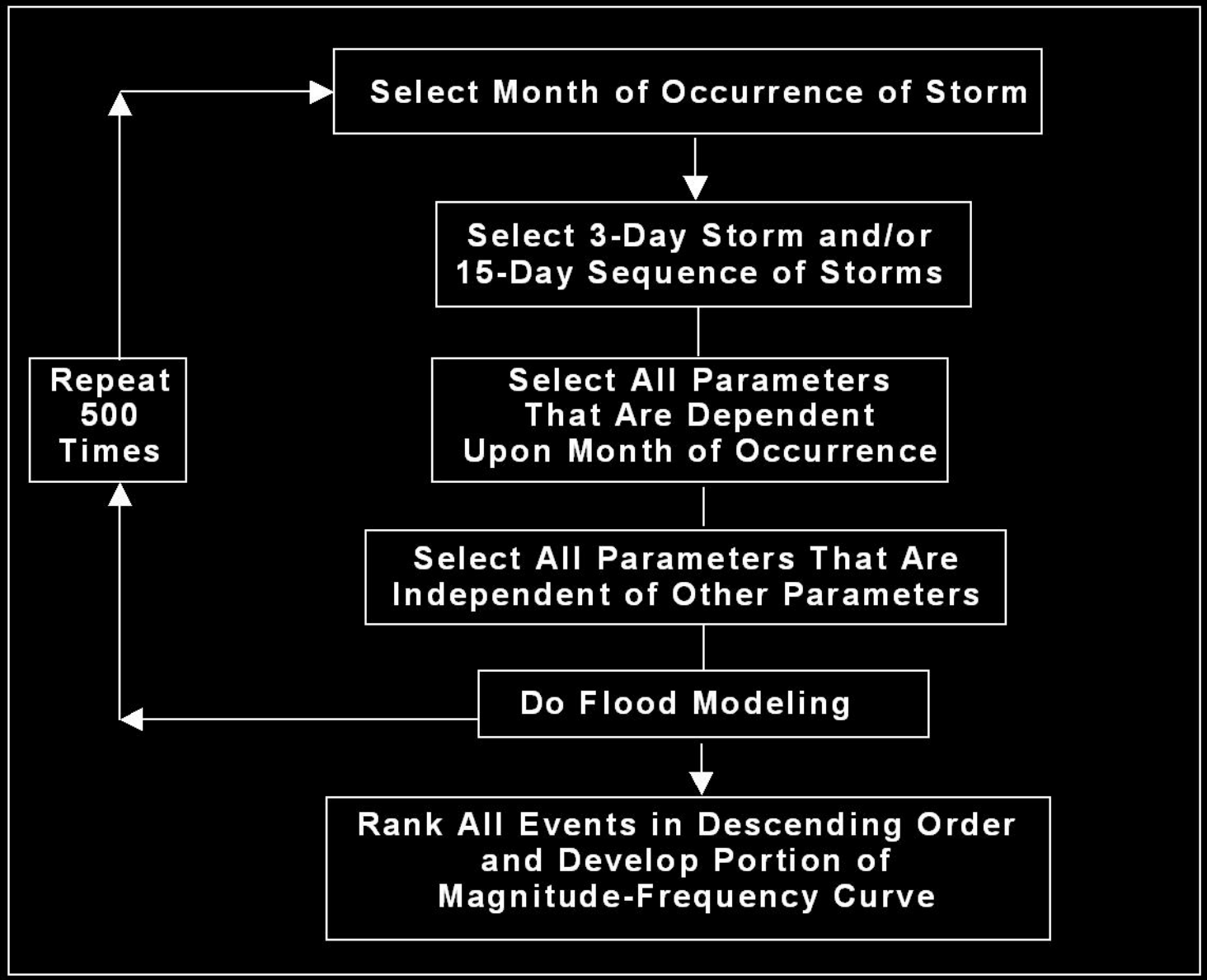
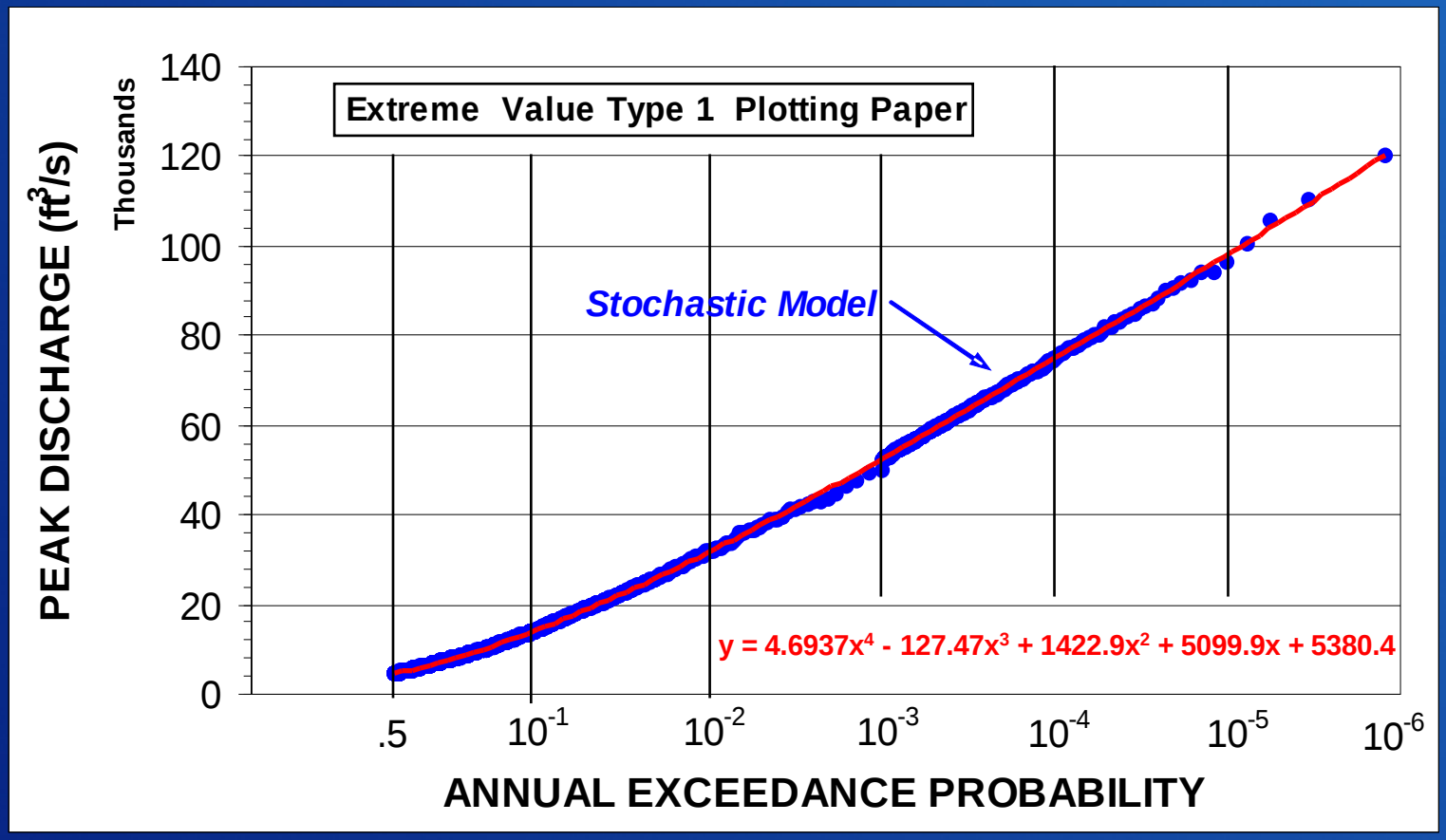
Stochastic Event-Based Rainfall-Runoff Model (SEFM) Key Elements

- Regional Rainfall Frequency using L-Moments
- Hydrometeorological Parameters Treated as Variables
- Utilize 3-Day Storms and 15-Day Sequence of Storms
- Runoff Computed using HRU Approach with UH
- Perform Monte Carlo Simulations to Examine Combinations Favorable to Large Floods



Stochastic Simulation Flow Chart

Stochastic Event Flood Model
Peak Flow Frequency, Whiskeytown Dam



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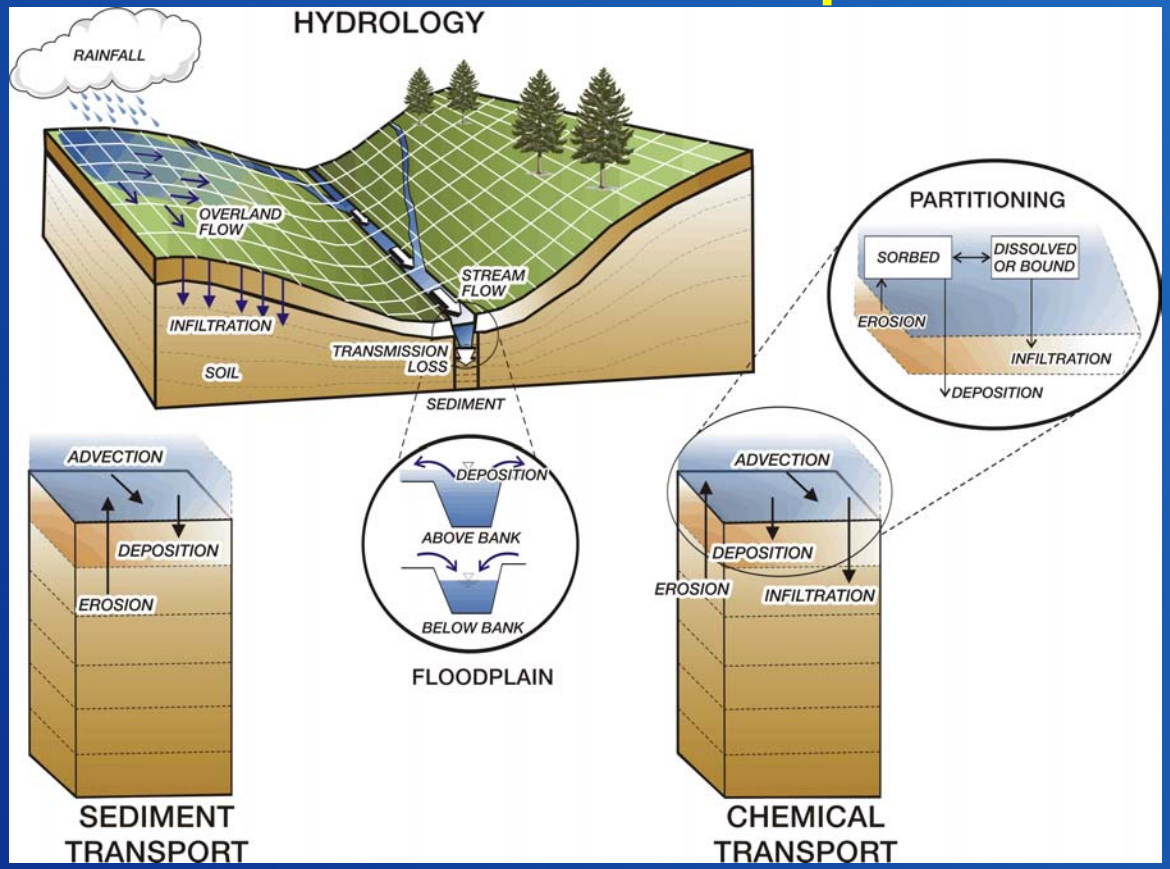
Two-Dimensional Physically-Based Flood Frequency Modeling with TREX

TREX: Two-Dimensional Runoff Erosion and Export Model



Velleux et al. 2006 ES&T
England et al. 2007 J. Hydrol.

Velleux et al. 2008 STOTEN

http://www.engr.colostate.edu/%7Epierre/ce_old/Projects/TREX%20Web%20Pages/TREX-Home.html

ftp://ftp.usbr.gov/jengland/TREX

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TREX: Hydrology Components

- Hortonian (infiltration excess) Runoff (events)
- Green/Ampt Infiltration
- 2-D Diffusive Wave Overland Flow Routing
- 1-D Diffusive Wave Channel Routing
- 8D Channel Network Topology
- Channel Mesh Generator – Spatial Width, Depth
- Extreme Storms with Ellipse and Depth-Area Duration
- Explicit Initial Soil Saturation Se
- Link Model with Stochastic Storm Transposition

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Stochastic Storm Transposition

$$G^a(d) = p_a(\bar{d}_c \geq d) = \hat{p}_s \sum_{j=1}^{N_s} \hat{p}_j(\bar{d}_c \geq d)\left(\frac{A_{eff,j}}{A_{tr}}\right)$$

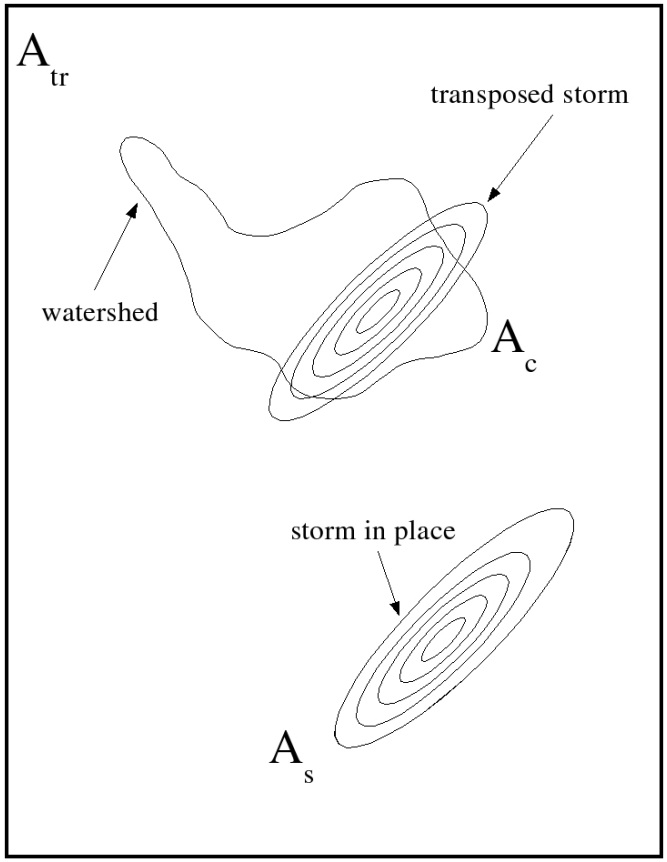
Idea: space-for-time substitution

- DAD extreme storm catalog

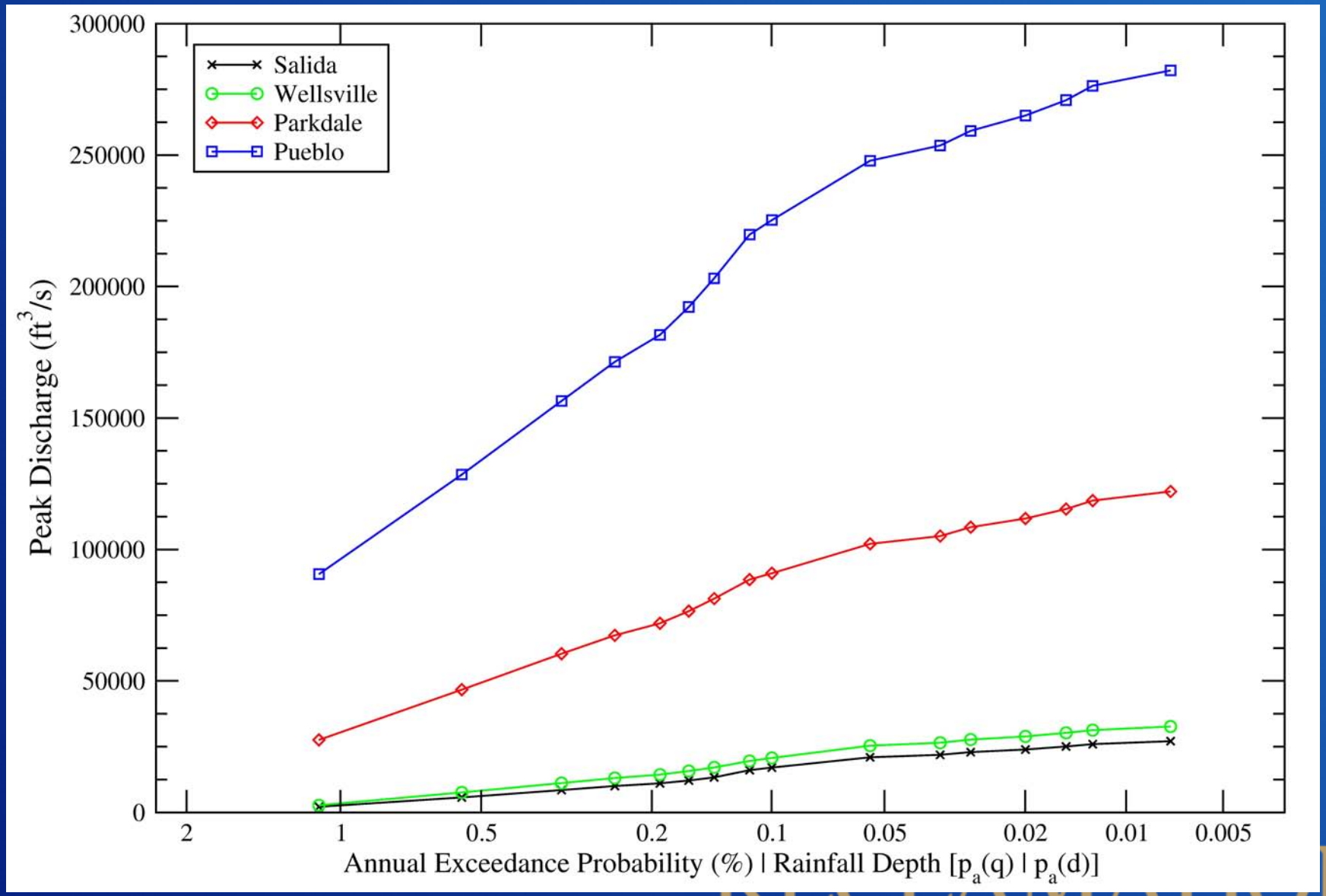
Basin-Average Rainfall for Time Δt

Joint Probability: reduce extrapolation

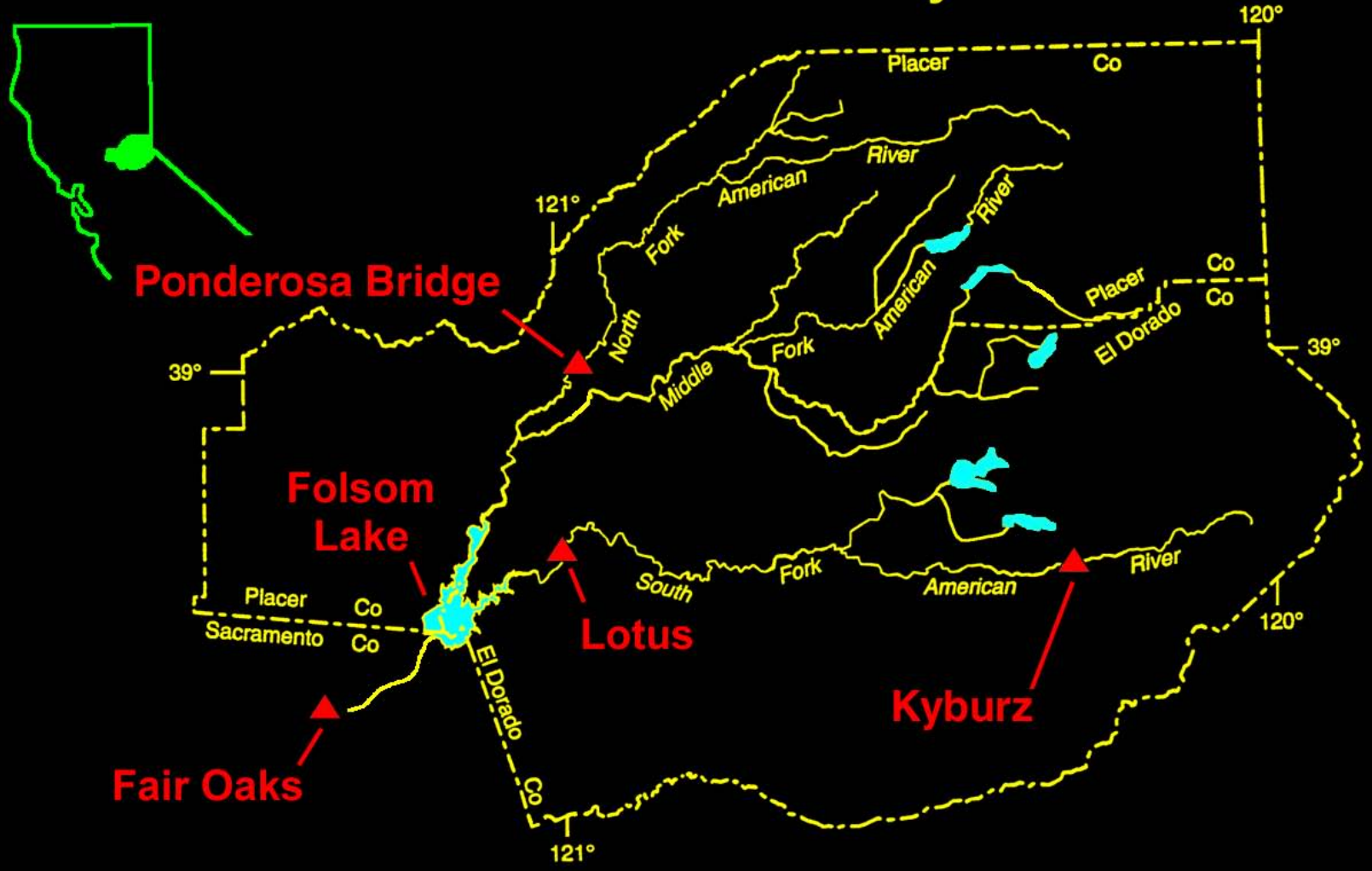
- Extreme storms occurring in transposition region → extreme storm probability
- Extreme storm causing a depth exceedance over catchment of interest → transposition probability



TREX Flood Frequency



American River Basin Study Sites



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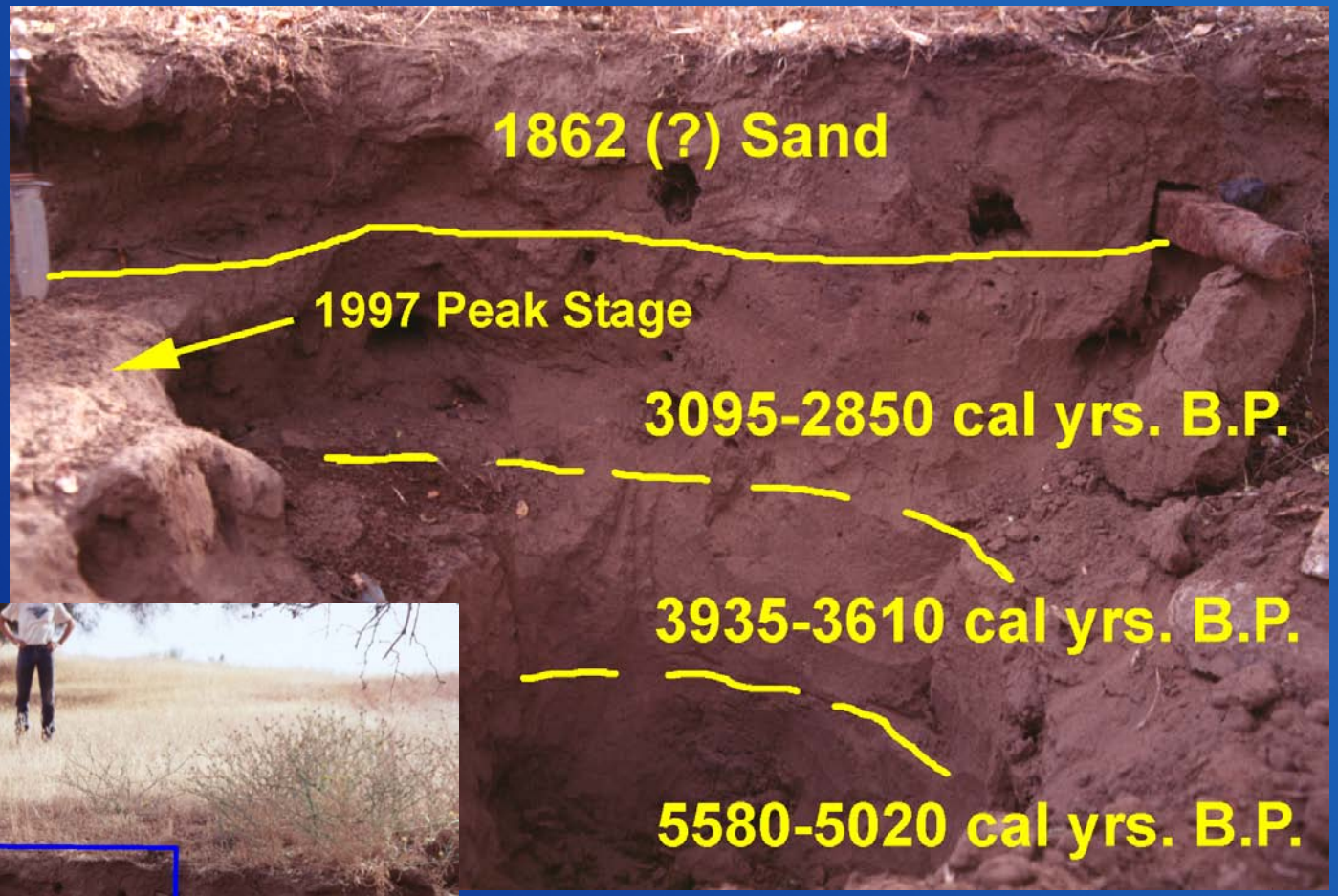

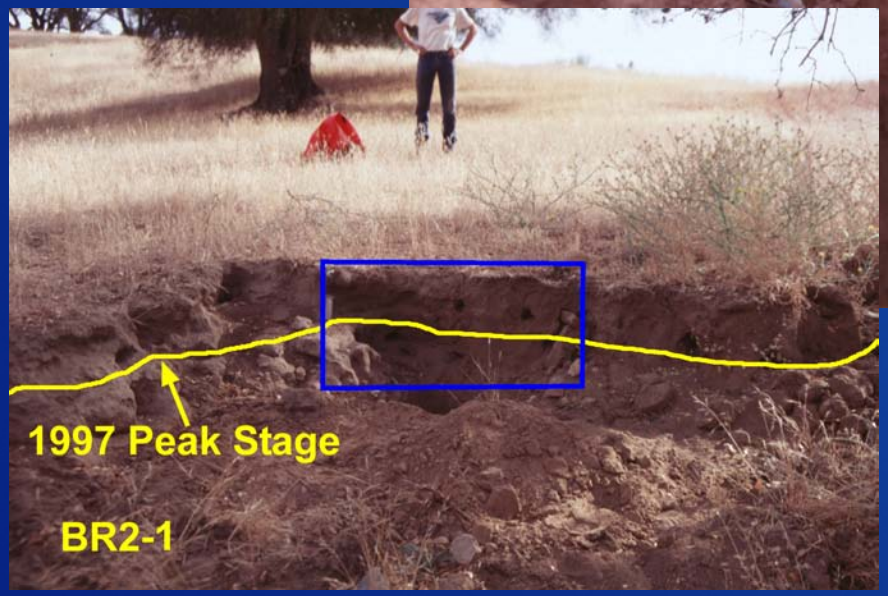

South Fork American near Lotus

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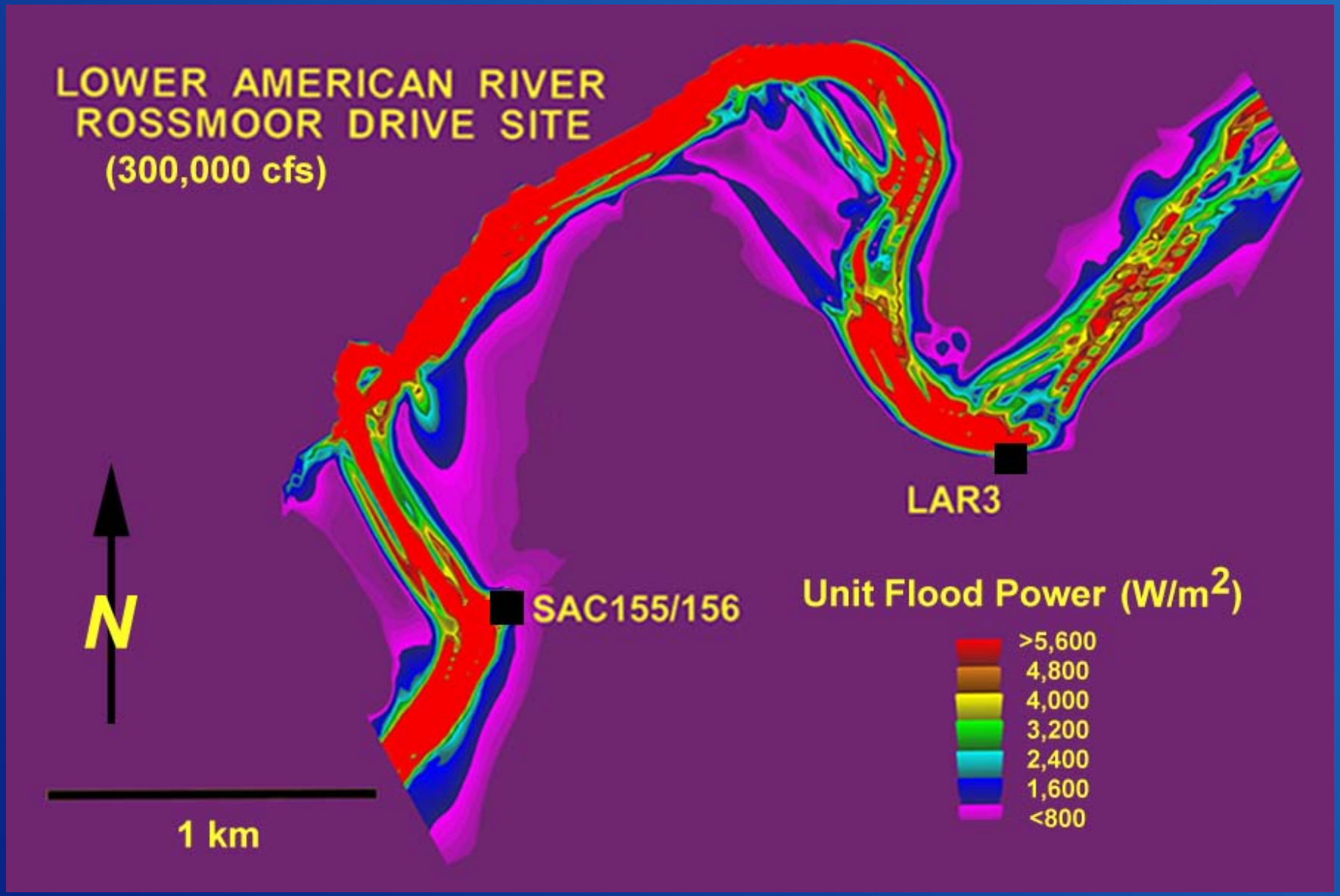

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Number of Floods	Preferred Age (years A.D. or years ago)	Age Uncertainty (years ago)	Preferred Discharge (ft^3/s)	Discharge Uncertainty Range (ft^3/s)
North Fork American River at Ponderosa Bridge (North Fork Dam)				
1997 flood	1997 A.D.	None	64,800	58,000 - 71,000*
Bound	10,000	None	None	240,000 - 360,000
South Fork American River near Kyburz				
1997 flood	1997 A.D.	None	25,000	20,000 - 30,000*
Paleofloods ($\geq$2-5)	$\leq$650 years	None	35,000	32,000 - 49,000
Paleofloods ($\geq$1)	None	650-1125	None	67,000 - 81,000
Paleofloods ($\geq$1)	None	1380-1650	None	67,000 - 81,000
South Fork American River near Lotus				
1997 flood	1997 A.D.	None	90,000	72,000-108,000*
1862 flood	1862 A.D.	None	90,000	72,000-108,000
Paleofloods ($\leq$3)	None	152-1000	212,000	170,000 - 254,000
Paleofloods ($\geq$1)	None	1000-1600	212,000	170,000 - 254,000
Lower American River at Fair Oaks				
1862 flood	1862 A.D.	None	265,000	212,000 - 318,000*
Paleofloods ($\geq$3)	None	152-700	None	400,000 - 550,000
Paleofloods ($\geq$1)	None	700-2000	None	600,000-850,000

*The range in peak discharge is based on an assessment of peak discharge uncertainty at the nearby gaging station by Meyer (1998).

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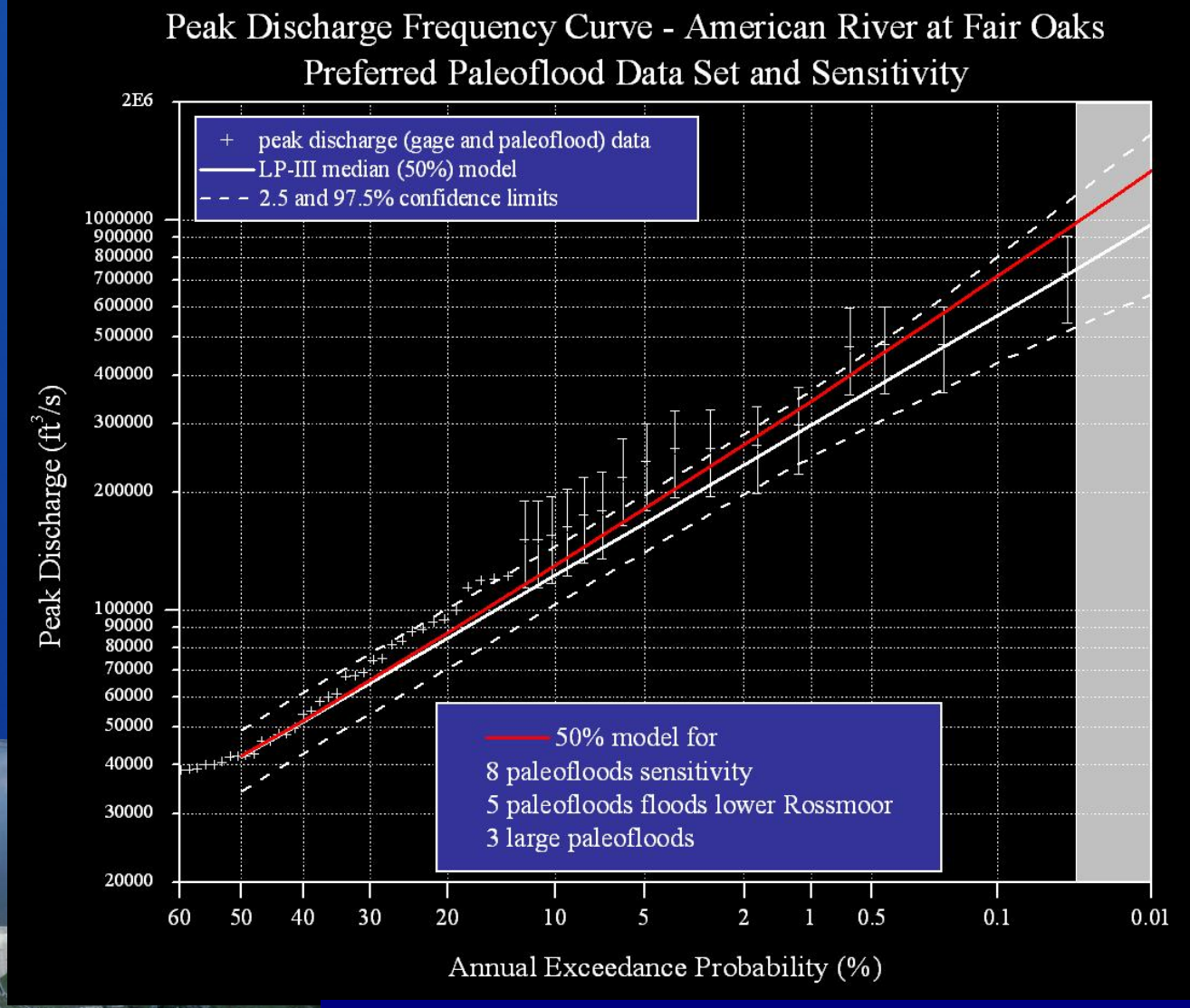
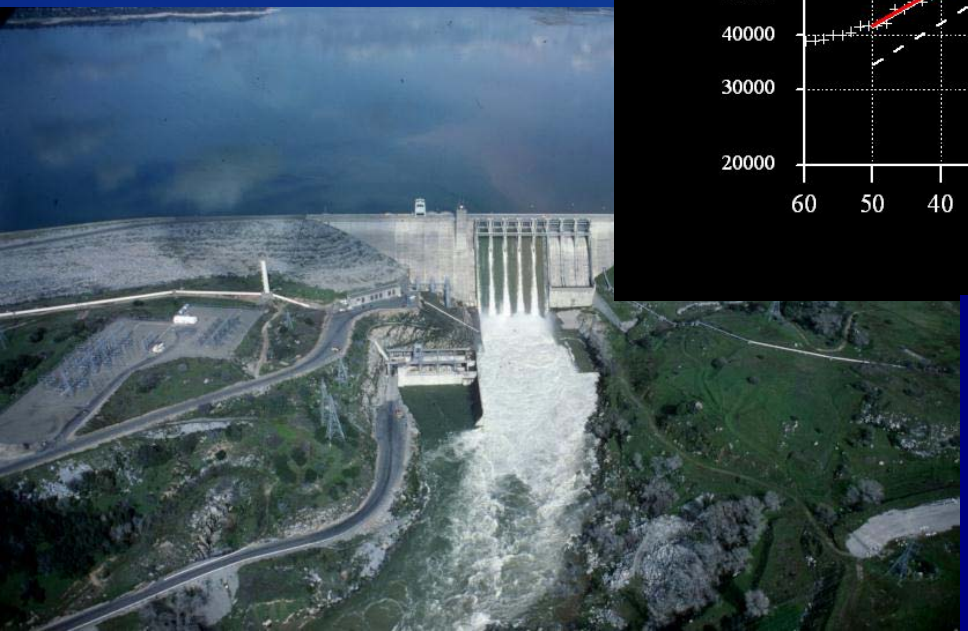
Several Paleofloods larger than gage record

PMF within frequency curve at 1/10,000





Conclusion: overtopping risk HIGH; modifications ongoing

Folsom Dam SEFM - USACE

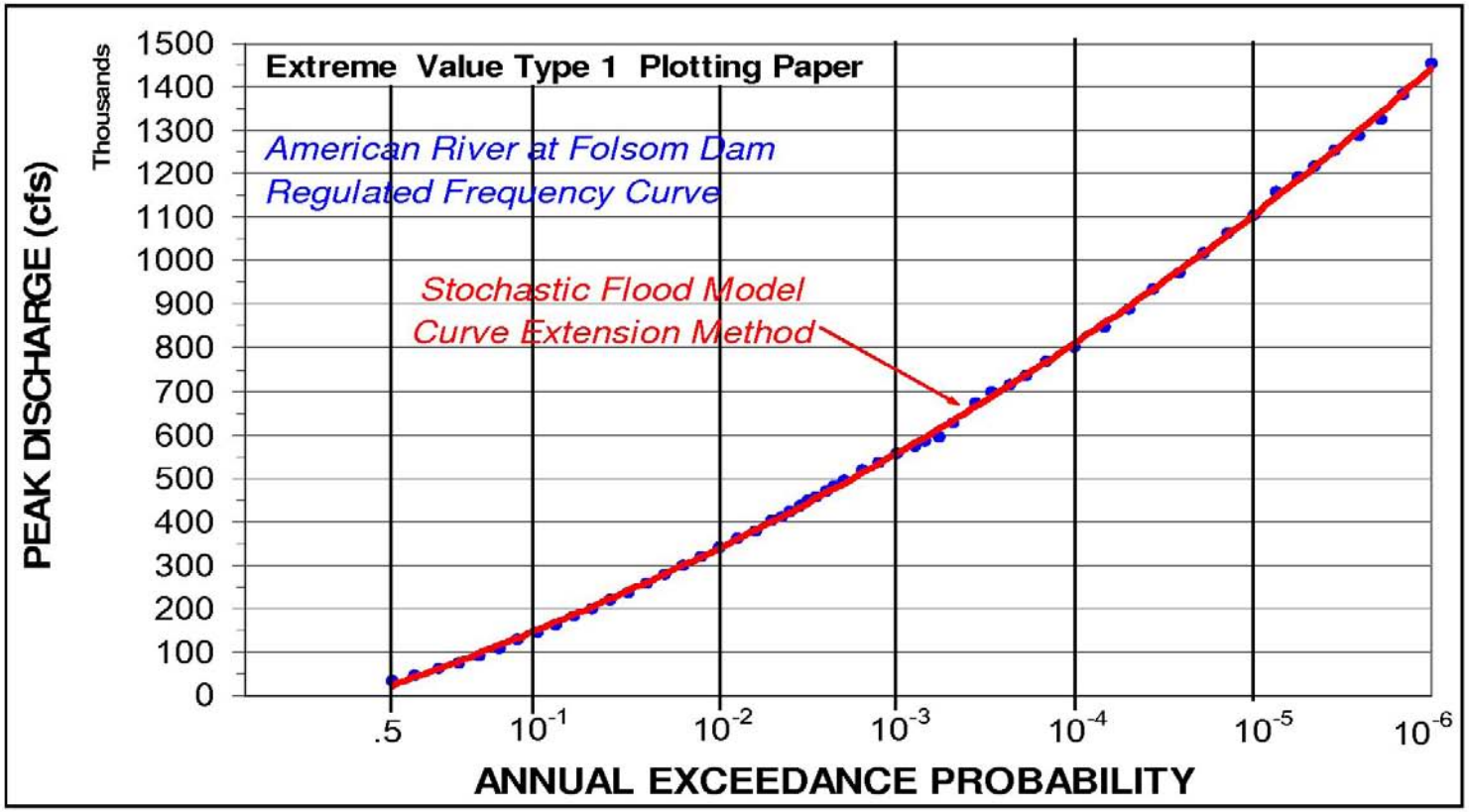


Figure 8-6. SEFM Model Results Extended to Probability of 10^{-6}

MGS Engineering Consultants

RECLAMATION

Folsom Dam USACE Weighted Methods

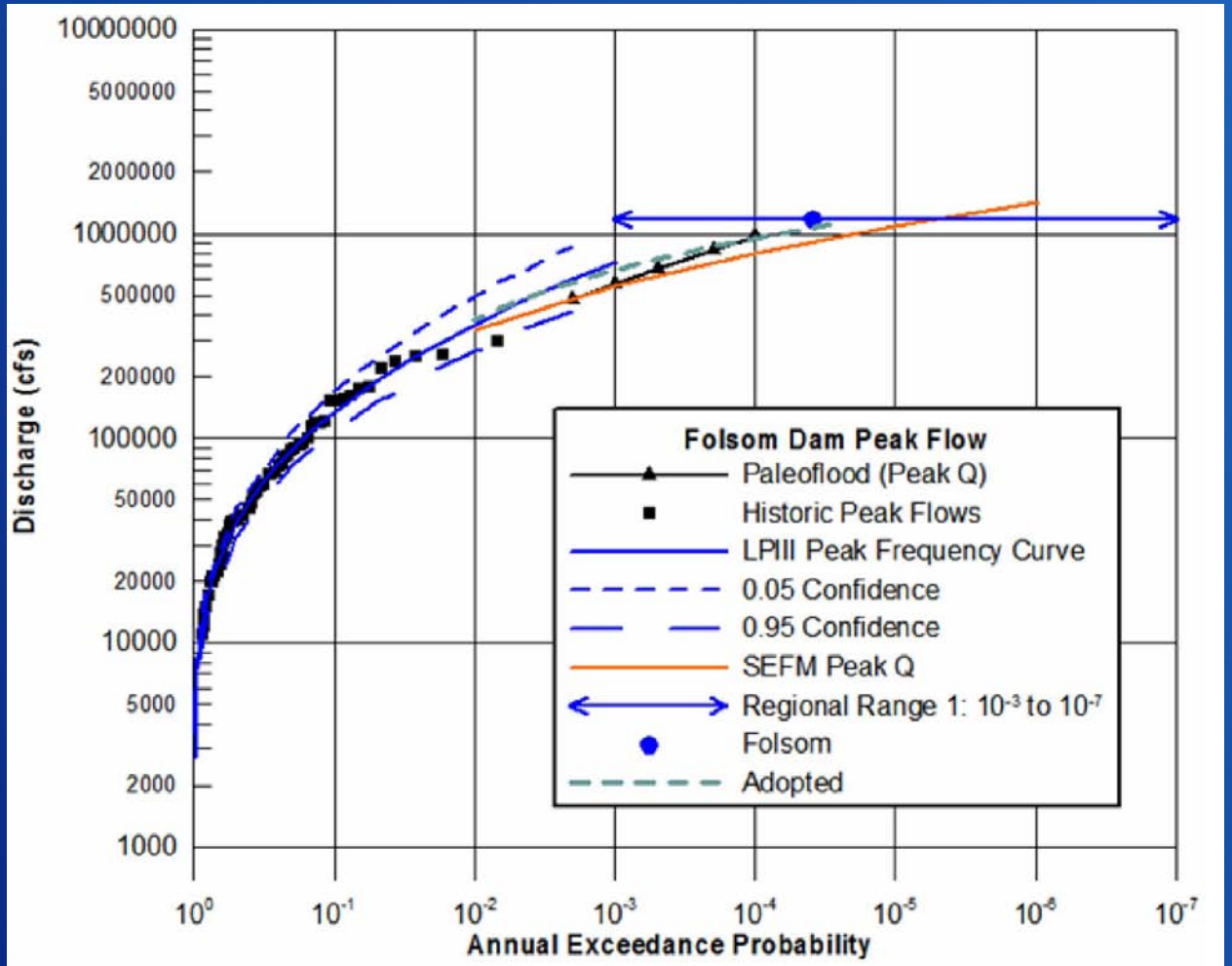


Figure 8-13. Peak Flow Frequencies with PMF Range 1

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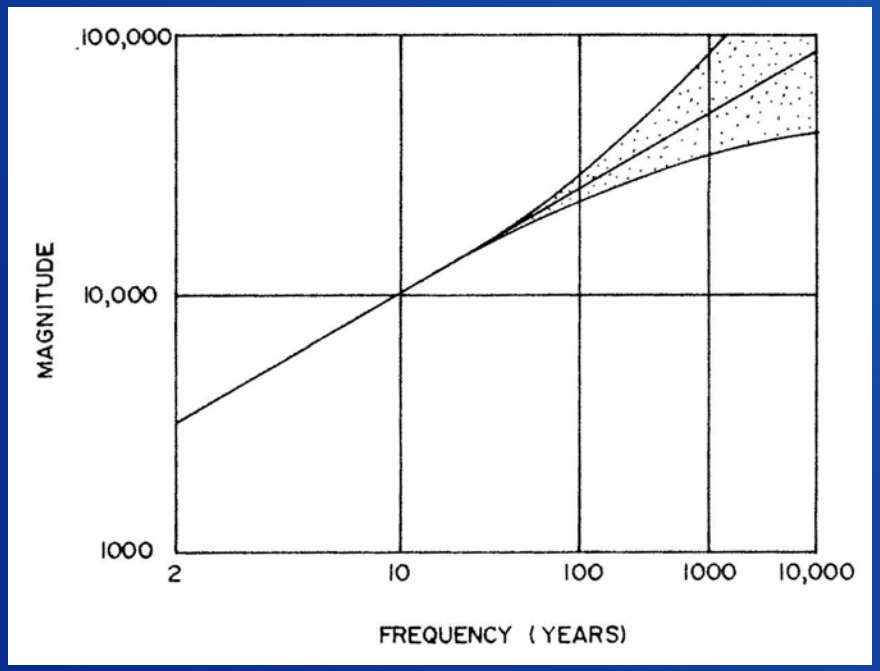
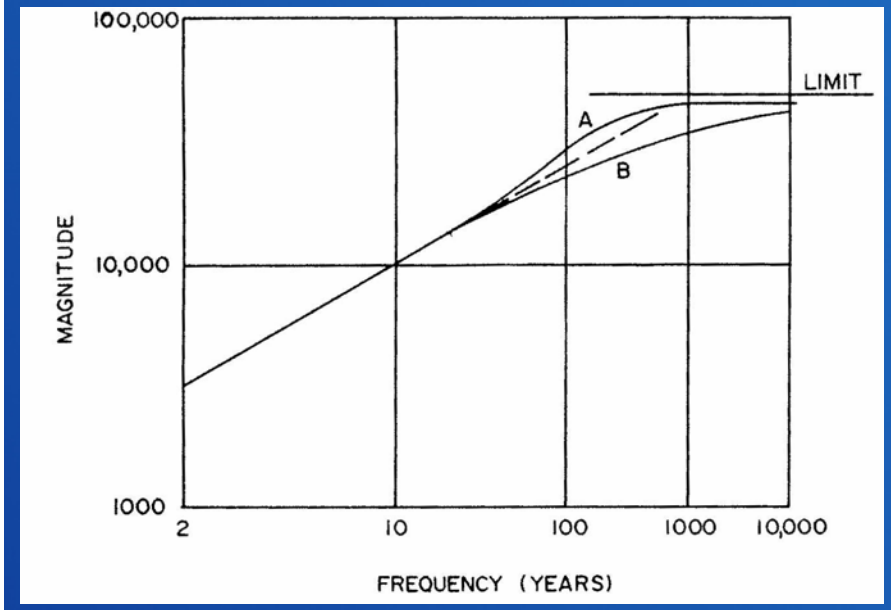
Hydrologic Hazard Summary

- Reclamation utilizes a suite of methods for estimating hydrologic hazard curves for dam safety
- USACE utilizes similar methods
- 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
- Results from multiple methods are combined
- PMF is utilized to represent the upper limit to hydrologic risk

Upper Bound to Rainfall and Floods?



Unlimited Magnitude--Frequency



Limited Magnitude--Frequency

Does it Exist? Operational Estimates? Hydrologic El Dorado?

Laursen, 1987

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