# Annual Exceedance Probability of Extreme Events

David Jeff Harris, A.M. ASCE
Chief, Hydrology and Hydraulics Technology Division
Hydrologic Engineering Center
US Army Corps of Engineers
609 Second St.
Davis, CA 95616

Tel: 530-756-1104
E-mail: David.J.Harris@usace.army.mil
Web: www.hec.usace.army.mil

BIOGRAPHICAL SKETCH

| | |
|---|---|
| Education: | BS, Atmospheric Science, University of California, Davis, 1976 |
| Registration/Professional Affiliations: | Engineer-In-Training Certification, A.M. ASCE |
| Experience: | 3 years, Chief, Hydrology and Hydraulics Technology Division at the Hydrologic Engineering Center |
| | 4 years, Hydraulic Engineer, H&H Technology Division, Hydrologic Engineering Center |
| | 6 years, Hydraulic Engineer, Hydraulic Design Section, Sacramento District Corps of Engineers |
| | 18 years, Hydraulic Engineer, Hydrology Section, Sacramento District Corps of Engineers |
| Technical Subjects: | Surface water hydrology, river hydraulics, water resources planning, risk analysis, system optimization, flood damage computations, water control management and dam safety research. |

ABSTRACT

Jeff Harris[1] and, Gary Brunner[2]

[1]Chief, H&H Technology Division, Hydrologic Engineering Center, US Army Corps of Engineers

[2] Senior Technical Hydraulic Engineer, H&H Technology Division, Hydrologic Engineering Center, U.S. Army Corps of Engineers, Davis, CA

The Corps of Engineers is currently evaluating its portfolio of dams with regard to risk and related maintenance. A draft Engineer Technical Letter “Risk Analysis and Assessment for Dam Safety” is under review. This ETL describes processes that will be used for screening projects for planning of corrective actions. One of the contributing factors that must be uniformly evaluated across all projects is the development of inflow frequency curves (peak flow and volume frequency) that define the frequency curve in the mid-range events (1 in 500 to 1 in 3000) and then extend out to the probable maximum flood level. Currently, no extension method is uniformly accepted. Multiple methods exist to facilitate extension. The current effort being undertaken by the Hydrologic Engineering Center is to present these variety of methods and provide a recommended method for extension that can be applied to the Portfolio Risk Assessment (PRA) effort. This presentation will provide an overview of the current status of the extension methodology.

# Annual Exceedance Probability of Extreme Events

*June 2008*
*California Extreme Precipitation Symposium*

*US Army Corps of Engineers*
*Hydrologic Engineering Center*

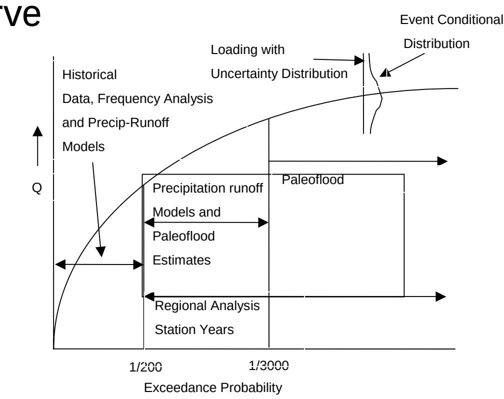
St. Francis Dam in Southern California failed in 1928. Designed by Mulholland. Over 100 died.

# Topics

- Introduction
- Problem
- Techniques
- Sample
- Additional Applications

# Introduction

- Curve Extension
  - Mid range curve
  - AEP of PMF



## Problem

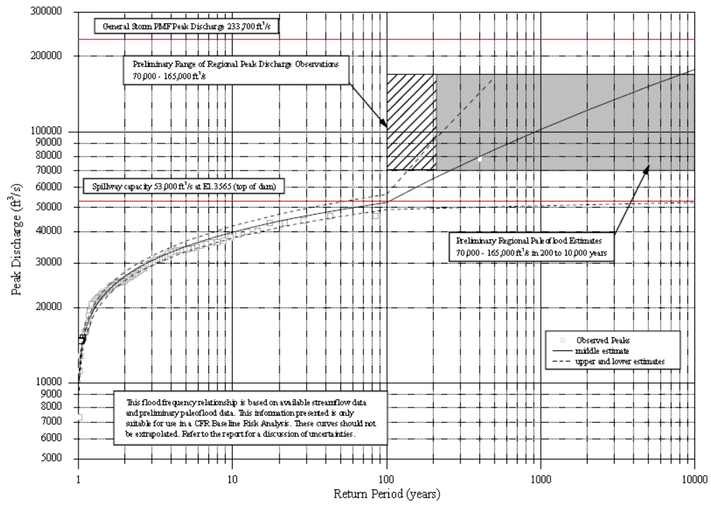
- No single accepted approach for extension method
- No single accepted approach for AEP of PMF

## Proposal

- Combine Techniques
  - Extension of Gaged Freq-Curves with Historic/Paleoflood
  - Hydrologic Modeling using Frequency Based Storms
  - GRADEX
  - Stochastic Event Flood Model (SEFM)
  - Regional Probability
  - Just Assign It

# Paleoflood

- Record Extension



# Paleoflood Challenges

- West of Rockies
- Debris Impacts
- Stationarity

There are several things which could impact a paleo estimate. They are listed. Picture of White River Bridge in Oregon after November 2006 flood.  Photo by Doug Jones, Mt. Hood National Forest.

# Hydrologic Modeling

- Model Calibrated to Historic Events
- Rainfall-runoff computations
  - NOAA Atlas Update
    - Up to 1 in 1,000
    - Only certain regions
  - TP-40
    - 1 in 100 (Can be extrapolated)
  - Regional Analysis
    - Station Years
    - Apply to Short Historic Record Areas
  - Local Studies
- Calibrate to Frequency Curve

Hydrologic models (e.g. HEC-HMS) can be used to develop frequency curves or extend gaged frequency curves. Generally, at projects such as Corps dams, gaged inflow records of reasonable length are available for performing statistical frequency analysis using Log Pearson III techniques. The hydrologic model can be calibrated to historic storm events and the gaged frequency curve for the frequency range in which the gaged data are deemed most appropriate. The curve can then be extended by running storm events for frequencies outside the gaged data range (i.e. 100, 200, 500, 1000 yr events ).

Frequency based precipitation data can be obtained from the National Weather Service. Currently, for many states, the NWS has frequency based storm estimates out to the 1000 yr return period (NOAA Atlas 14). For those states that are not covered by NOAA Atlas 14, frequency precipitation estimates are only available up to the 100 yr event from NOAA. For more rare precipitation events, the user would need to look for local studies that have been performed on regional precipitation data within the region of interest, or a regional precipitation-frequency study would need to be performed.

In areas where gaged data are very limited (i.e. less than 20 years of record), then the use of a hydrologic model with regionally based precipitation estimates (NWS, Precipitation Frequency Data) is a viable method for developing frequency curves out to the 1000 yr event range. A general procedure is to develop the hydrologic model by estimating parameters based on physical information (Terrain Data, Land use, Soils Data, etc…); calibrate the model to any significant events that are available in the short gaged record history; then apply frequency based rainfall events from the 2 to 1000 yr frequency to the model. The model parameters should be adjusted to get best estimates of peak flows and runoff volumes, but not to produce estimates that would be upper bounds. Computed values from the model can be used as mean estimates in developing the flow frequency curve. Uncertainty bands can be generated by performing sensitivity analysis of all the relevant model parameters (developing high, low, and mean values for all of the parameters), and predicting upper and lower bounds of the flow estimates.

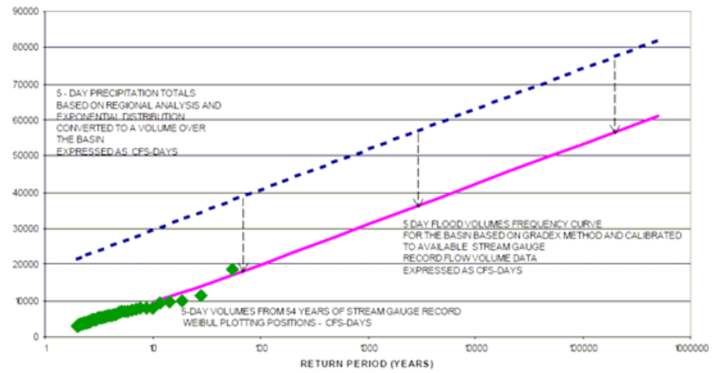
The more typical case in the Corps of Engineers is to utilize hydrologic models for extending gaged frequency curves out to the 1000 yr event. When a gaged frequency curve exists, and there is high confidence in that curve for the more frequent events, then a hydrologic model can still be developed as described in the previous paragraph. However, after the model is calibrated to all of the relevant historical events, and the frequency based rainfall events are applied, the model should be further calibrated to match the gaged frequency curve over the range of frequencies in which the gaged data are assumed to be the most appropriate. An example of this is shown in Figure 2. As stated in the previous paragraph, the adjustment of model parameters to best fit low to high events should be based on producing mean estimates, not conservative estimates. Uncertainty bands around model results can be produced with parameter sensitivity analysis as described previously. Additionally, calibration to the gaged frequency curve may require one model parameter set for low flows (e.g. 2 – 20yr), another for mid range events (e.g. 20 – 100 yr) and a third for the more rare events (e.g. 100 – 1000 yr). This third parameter set is basically assuming that the ground is saturated and that the runoff characteristics of the model are the same for the rare events. The break point of return period in which to change model parameters will be watershed specific, so the numbers shown above are only an example.

# Hydrologic Modeling Challenges

- More reliable in frequent events
- Involves extrapolation
- Model calibrated to smaller events
- Runoff Freq = Precip Freq

## GRADEX

- USBR
  - Select Duration
  - Compute slope (Grade X) of regional precip data
  - Apply slope to recorded flow data to extend




The GRADEX technique is a methodology for extending volume frequency curves from the 200 to 500 yr range out to values in the range of the PMF. The methodology was first introduced by Guillot and Duband (1967, 1993), and later refined by Mauro Da Chunha Naghettini (1994) for his Ph.D. degree at the University of Colorado. In simple terms, the GRADEX methodology is based on computing a slope (Grade X) of the regional precipitation frequency data, then applying that same slope to the runoff volume frequency curve for extending it out into the future. The basic concept is that the runoff volume frequency curve should be parallel to the rainfall volume frequency curve once you get up to the rare events in the 200 to 500 year range and larger. This assumes that during large events, the ground is saturated, and runoff properties are reaching an upper limit, such that any increased volume of precipitation will produce a corresponding increase in flood runoff volume.

# GRADEX

- Applied to three USBR Dams
- 2 DOS programs
- Precipitation analysis program
  - Critical Duration
  - All gages in similar meteorological region
  - Full period, continuous record
- GRADEX program
  - Gage physical information (elevation, DA, etc....)
  - Observed data statistics (mean, skew)
  - Reference return period (ie; .01 event)

The U.S. Bureau of Reclamation (USBR) has applied the GRADEX method recently to a few of their Dam sites. This work has been performed by Mr. Ken Bullard of their Denver, CO office. Mr. Bullard has developed two computer programs to assist him in applying the GRADEX methodology. Both programs are written in FORTRAN and are DOS based in that the user develops a text input file, runs the program, which produces a text output file. Neither of the two programs have user documentation, as they were developed for internal use in applying the methodology to USBR dam sites.

The first computer program is used to analyze the regional precipitation data in the study area. The user must gather daily precipitation records for all of the relevant gages in the region of interest. Records must be gathered for the full period of record of the gages, and the gaged record must be continuous. The user is required to first estimate a critical duration for the watershed above the dam (i.e. 1day, 2day, 3day, etc…). The critical duration is a function of the size of the watershed, the meteorology, runoff characteristics, and available flood storage volume of the reservoir. The software analyses each gaged record individually. The software takes the daily time series of precipitation events, does a moving average based on the critical duration, and computes the top events equal in number to the number of years of record.

So for example, if a gage has 50 years of record, and the critical duration is 2 days, the program will find the largest 50 two day precipitation events in the historic record. The threshold precipitation value, statistics, and the top 10 percent of the events are then used as input data into the GRADEX computer program. Additional input required for the GRADEX program is mean annual precipitation for each gage, elevation of the gage, drainage area of the basin, critical runoff duration, mean basin elevation, mean annual precipitation for the watershed, and statistics about the flow duration frequency curve computed for the observed runoff data (Qmean, Qref, return period of the reference flow). The GRADEX computer program will then compute a slope for the regional precipitation and apply that to the volume frequency data provided. The output is a volume–duration frequency curve that starts at the reference flow and reference return period entered (ex. 100 yr), and goes out to the 1,000,000 year return period.

# GRADEX Challenges

- Not widely applied
- Involves extrapolation
- No user documentation
- Knowledge base is one person at Reclamation

# SEFM

- Monte Carlo analysis
  - Simulate several thousand annual maxima
  - Regional Precipitation
    - Station Years
  - Physically Based
  - Rainfall-Runoff model

This is a stochastic event model that is being used to extend gaged frequency curves. This method is generally used to extend a frequency curve out to the 200 to 500 year return interval range. However, one could also use it as a way to make an estimate all the way to a PMF level event. The U.S. Bureau of Reclamation is currently working to apply this technique to their projects.

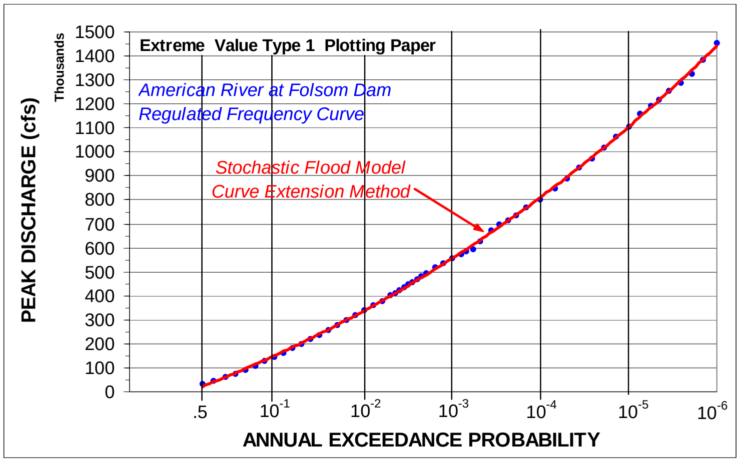
The concept employed with this technique is the simulation of several thousands of years of annual flood maxima. This is accomplished using a deterministic, single event, flood runoff model. Most of the prior work has been done using HEC-1; however, contemporary applications may require implementation of HEC-HMS. One proposal to be discussed is to automate this process as much as possible within the HEC-HMS program. Hydro meteorological parameters are treated as variable. Monte Carlo sampling procedures are used to allow climatic and storm descriptive parameters to vary in accordance with season and historical observations. The simulation of any annual flood contains a set of climatic and storm parameters selected via the Monte Carlo technique that collectively preserve any dependencies between the parameters that are contained in the historical record.

The hydro meteorological inputs and their dependencies represent the detailed mechanics of flood generation. The table below, prepared for an SEFM application to Folsom Dam in California, indicates the complexity of the system parameters that are recognized by this method. This method can include historical uncertainties in project operation. For example, the historical review of the operation of Folsom Dam revealed that it is typically below the maximum allowable storage level based on end-of-month conditions

# SEFM

- Inputs (Folsom Dam Specific)
  - Seasonality
  - Storm Magnitude (Related to critical duration)
  - Temporal and Spatial Storm Distribution
  - Temperature Temporal Pattern
  - Sea Level Temperature
  - Freezing Level
  - Antecedent Precipitation, Snowpack, Soil Moisture
  - Upstream Storage
  - Initial Stream flow

# SEFM


Extreme Value Type 1 Plotting Paper
American River at Folsom Dam
Regulated Frequency Curve
Stochastic Flood Model
Curve Extension Method
PEAK DISCHARGE (cfs)
Thousands
1500
1400
1300
1200
1100
1000
900
800
700
600
500
400
300
200
100
0
.5
$10^{-1}$
$10^{-2}$
$10^{-3}$
$10^{-4}$
$10^{-5}$
$10^{-6}$
ANNUAL EXCEEDANCE PROBABILITY

# SEFM Challenges

- Data intensive
- Detailed analysis
- Not for all locations
- Time, Cost issues

# Regional Probability

- AEP of PMF from regional precipitation
  - Ratio Historic Precipitation vs PMP
  - Include effects of
    - Regional weather patterns
    - Distance from moisture source
    - Orographic impacts

The regional probability method is a way of estimating the probability of the Probable Maximum Flood (PMF) from regional precipitation data. The method outlined below is based on scaling the probability of the PMF by comparing regional historical precipitation data to that of the Probable Maximum Precipitation (PMP), computing a historical to PMP precipitation ratio, then using that ratio to estimate a probability of the PMF within the established institutional range of probabilities. By utilizing regional precipitation data, this procedure would inherently include the effects of regional weather patterns, distance from moisture sources, orographic effects, etc. The method is easy to apply and would be a consistent procedure. In regions where historical precipitation has come close to the PMP, the method would yield a probability towards the more frequent end of the range. Likewise, in areas where historical precipitation is much lower than estimates of the PMP, the probability of the PMF would tend towards the less frequent end of the range.

# Regional Probability

- Steps
  - Establish institutional range (ie: $10^{-3}$ to $10^{-7}$)
  - Determine Critical Storm Duration (ie: 72-hr at Folsom)
  - Determine appropriate storm area
  - Determine max regional storm precip for desired duration
  - Use appropriate HMR to compute PMP
  - Compute Ratio
  - Apply Equation

1. First the Corps must establish an institutionally assigned range of probabilities for the PMF

2. Determine the storm duration that is most critical to your watershed of interest (24 hr, 48 hr, or 72 hr). Also determine the storm area size critical to the watershed. This should be the same storm area size that was used in the determination of the basin average PMP for developing the PMF for the watershed.

3. Determine the historically maximum observed precipitation volume that has occurred within the region of interest, for the storm area size and duration of interest. The region of interest would most likely extend into neighboring basins of similar hydrologic and meteorological characteristics. The idea here is to find the largest storm that has occurred within the region, not limiting it to the basin of interest. One way to compute the maximum observed historical precipitation volume is to acquire maximum observed precipitation at all gages in the region of interest for the largest storms of record. Compute the area averaged (based on the selected storm area in step 2) maximum storm volume for the duration of interest (24, 48, or 72 hr). Other methods for obtaining maximum historical rainfall may be more appropriate depending on the area of the country you are in (such as using radar rainfall data, etc…).

4. Use standard National Weather Service (NWS) procedures for computing your basin average PMP from Hydrometeorological Report (HMR reports).

5. Compute the maximum historical precipitation to PMP ratio within the region of interest for the Dam being studied.

## Regional Probability

- Equation

$$AEP = 10^{-[(1-Ratio)\times Range + Min.Value]}$$

Ratio = Max historic storm precipitation divided by PMP for region of interest.
Range = Corps institutional range for probability of the PMF ($10^{-3}$ to $10^{-7}$)
Min Val = Minimum value of Corps institutional range.

Ratio approaches 1 = More frequent AEP
Ratio approaches 0 = Less frequent AEP

Calculate the probability of the PMF using above equation:

Where:

Ratio = Max historic storm precipitation divided by PMP for region of interest.

Range = Corps institutional range for probability of the PMF (10-3 to 10-7)

Min Val = Minimum value of Corps institutional range.

This equation will yield values close to 10-3 for areas that have experienced precipitation close to PMP values. Likewise, those areas that the historic precipitation is very low in comparison to the computed PMP values would have a PMF probability near the 10-7 value.

# Regional Probability

- 72-Hour Samples

$$AEP = 10^{-[(1-Ratio)\times Range + Min.Value]}$$

72-Hour Historic Precip = 14.05 inches
72-Hour PMP = 29.62 inches
Ratio = 14.05/29.62=.474

Range = 4 ($10^{-3}$ to $10^{-7}$)
Min Value = 3

AEP = $10^{-(0.526*4+3)}$ = $10^{-5.104}$ = 0.0000079 (1 in 126,000)

AEP = $10^{-(0.526*1.7+4.3)}$ = $10^{-5.194}$ = 0.0000064 (1 in 156,000) (Range $.5x10^{-4}$ to $10^{-6}$)

AEP = $10^{-(0.526*1+4)}$ = $10^{-4.526}$ = 0.0000298 (1 in 33,000) (Range $10^{-4}$ to $10^{-5}$)

# Regional Probability Challenges

- Requires institutional range
- Based on regional precipitation records
  - Generally short term
- Single Duration may not be appropriate
- Rain on Snow complexities
  - Not explicitly recognized
- Precipitation Gage Network
  - Density varies in US
- Climate variability impacts (All methods)

**Some limitations of this method are:**

1. It requires that an institutional range of possible AEP's for the PMF be identified.

2. Based primarily on regional historical precipitation records; which are relatively short for evaluation of the recurrence of such extreme floods.

3. Selection of a single (e.g., 24 hr.) duration may not be appropriate.

4. Complex rain on snow events are not explicitly recognized. However, basin average rainfall and snowmelt for historical events can be estimated.

5. Gage network density varies across the U.S.

6. Global meteorological change (climate variability) could affect future rainfall (this would affect any method presented).

# Application - Folsom Dam

- Adopted Curve
  - Graphical fit
  - Weighted based on confidence at each return interval
    - Table
  - Engineering Judgment
    - Group decision

# Adopted Curve

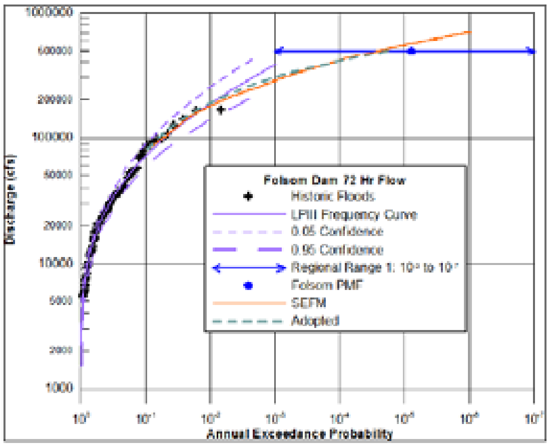
- Sample Table for weighting Peak Data

| Frequency | Historic Record | | Rainfall-Runoff | SEFM | | Gradex | Paleo | | Regional PMF | | Adopted |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Value | Weight | | Value | Weight | | Value | Weight | Frequency | Weight | Value |
| 2 | 30,000 | 1 | | | | | | | | | 30,000 |
| 5 | 80,000 | 1 | | | | | | | | | 80,000 |
| 10 | 140,000 | 1 | | | | | | | | | 140,000 |
| 25 | 170,000 | 1 | | | | | | | | | 170,000 |
| 50 | 250,000 | 1 | | | | | | | | | 250,000 |
| 100 | 350,000 | 1 | | | | | | | | | 350,000 |
| 200 | 420,000 | 0.5 | | 380,000 | 0.5 | | | | | | 400,000 |
| 500 | 580,000 | 0.4 | | 450,000 | 0.3 | | 450,000 | 0.3 | | | 502,000 |
| 1000 | 700,000 | 0.3 | | 550,000 | 0.35 | | 550,000 | 0.35 | | | 595,000 |
| 5000 | | | | 750,000 | 0.8 | | 850,000 | 0.2 | | | 770,000 |
| 10000 | | | | 820,000 | 0.9 | | 1,000,000 | 0.1 | | | 838,000 |
| 100000 | | | | | | | | | | | |
| 1000000 | | | | | | | | | | | |
| | | | | | | | | | | | |
| PMF | | | | 200,000 | 0.2 | | | | 25,000 | 0.8 | 60,000 |

Note: Values in PMF row are frequencies

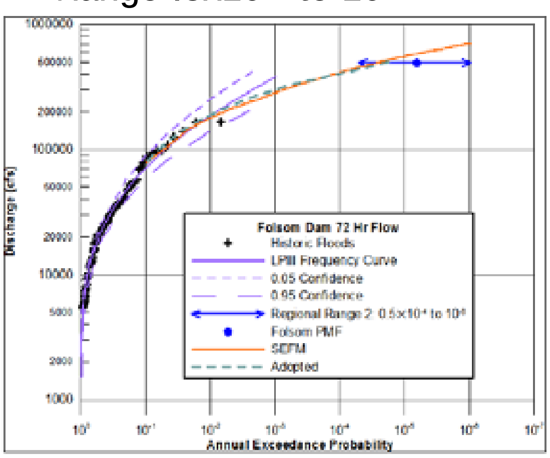
# Application - Folsom Dam

- Range $10^{-3}$ to $10^{-7}$



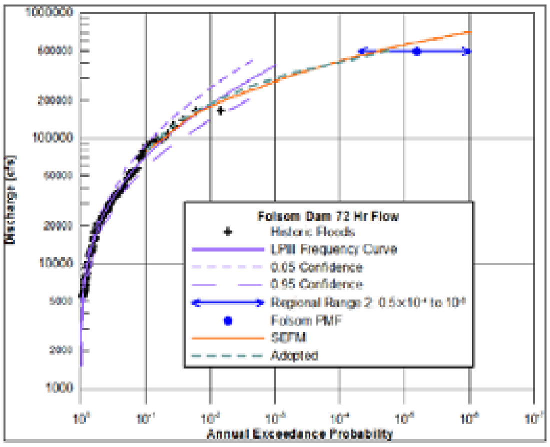

# Application - Folsom Dam

- Range $.5x10^{-4}$ to $10^{-6}$



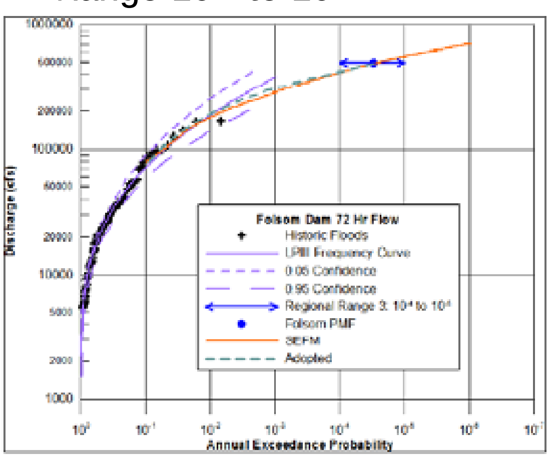
# Application - Folsom Dam

- Range .5x$10^{-4}$ to $10^{-6}$




# Application - Folsom Dam

- Range $10^{-4}$ to $10^{-5}$



# Recommendations

- Don't use any single method
- Utilize all methods appropriate for application and weighting
  - Significance of Dam
  - Time and funds
  - Data availability
- Possible Range - $10^{-3}$ to $10^{-7}$
  - $10^{-3}$ reflect areas that have experienced near PMP events
  - $10^{-7}$ reflect areas that have not come close to experiencing PMP events
  - Provides flexible range encompassing multiple professional opinions
  - Doesn't force into small range
    - 72-hr and 6-hr nearly same
    - Entire country almost same