Development of F-N Curves for Public Safety Risks Associated with Dam Failures in the U.S.

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Objective

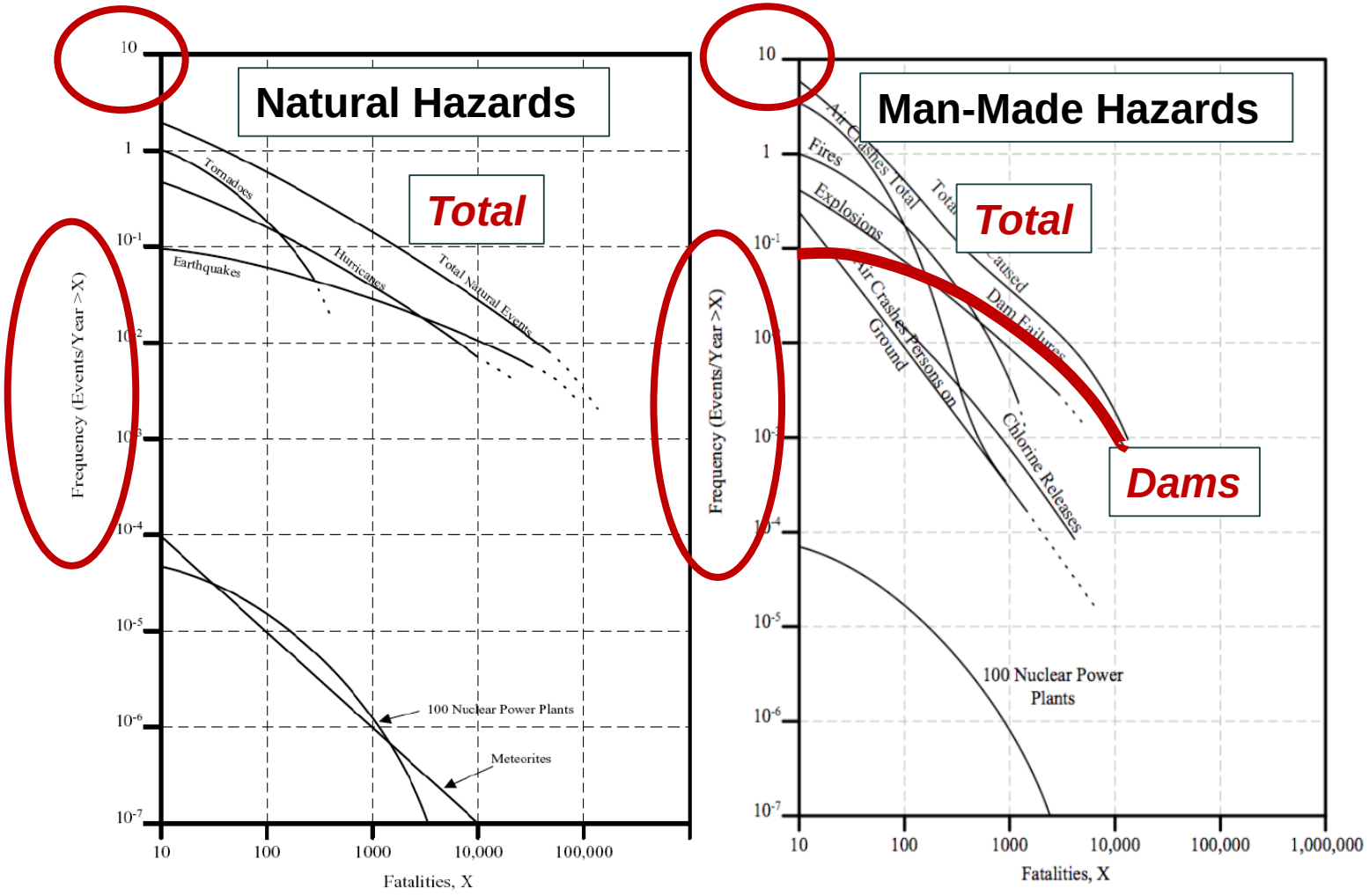
Look at where we have been with respect to public safety.

Assess implications for moving forward.

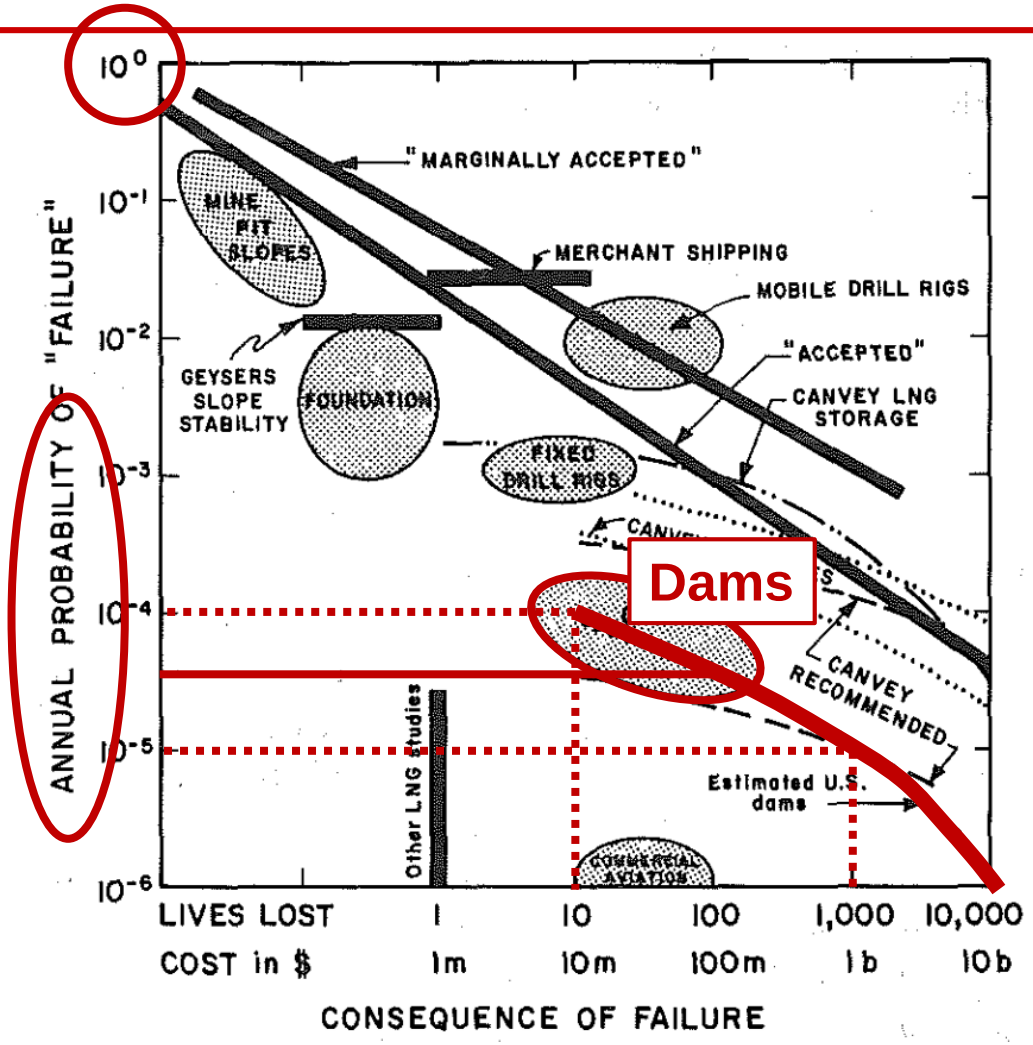
Topics

- Take quick look at the history of empirical F-N relationships for dams.
- Look at the data on fatalities associated with dam failure events.
- Develop empirical, non-parametric F-N relationships from a couple of different perspectives; including an estimate of the uncertainty in the frequency estimates.
- Offer observations

Early U.S. F-N Curves-WASH-1400 (1975)



Whitman (1981)



Fatality Database

- U.S. fatalities only
- Tailings dams are not included (we exclude Buffalo Creek for instance)
- We have primarily relied on the work of others who have compiled information on fatalities that have occurred during dam failures.
- Sources include:
  - Graham (1999)
  - McClelland and Bowles (2002)
  - USBR (2014)
  - National Performance of Dams Program archives
- Used estimates of fatalities associated with failure of the dam and not as a result of flooding that may have occurred during a hydrologic event.

Database Uncertainties

- There are certainly uncertainties in the data.

- Sources of uncertainty include:
  - Data completeness – do we have all of the events that have resulted in fatalities,
  - Number of fatalities
  - Number of fatalities associated with the performance of the dam

Fatality Data Summary

Parameter/Summary	Value(s)
Period of Record	1850 – 2016
Number of Years of Record	167
Number of Dam Failures Resulting in Fatalities	63[a]
Long-Term Frequency of Occurrence of Dam Failures Events per Year in which there were Fatalities[b]	0.38
Fraction of Dam Failures Resulting in Fatalities	0.04
Range on the Number of Fatalities that Occurred as a Result of a Dam Failure	1 – 2,209[c]
Total Number of Fatalities Over the Period of Record (A range is shown based on the variation in the estimates of the number of fatalities that occurred)	3,432 - 3,736
Long-Term Annual Average Number of Fatalities Over the Period of Record[d]	20.6 - 22.4
Long-Term Annual Average Number of Fatalities for the Period of Record, Exclusive of the 1889 South Fork Dam Failure[d]	7.3 - 9.1

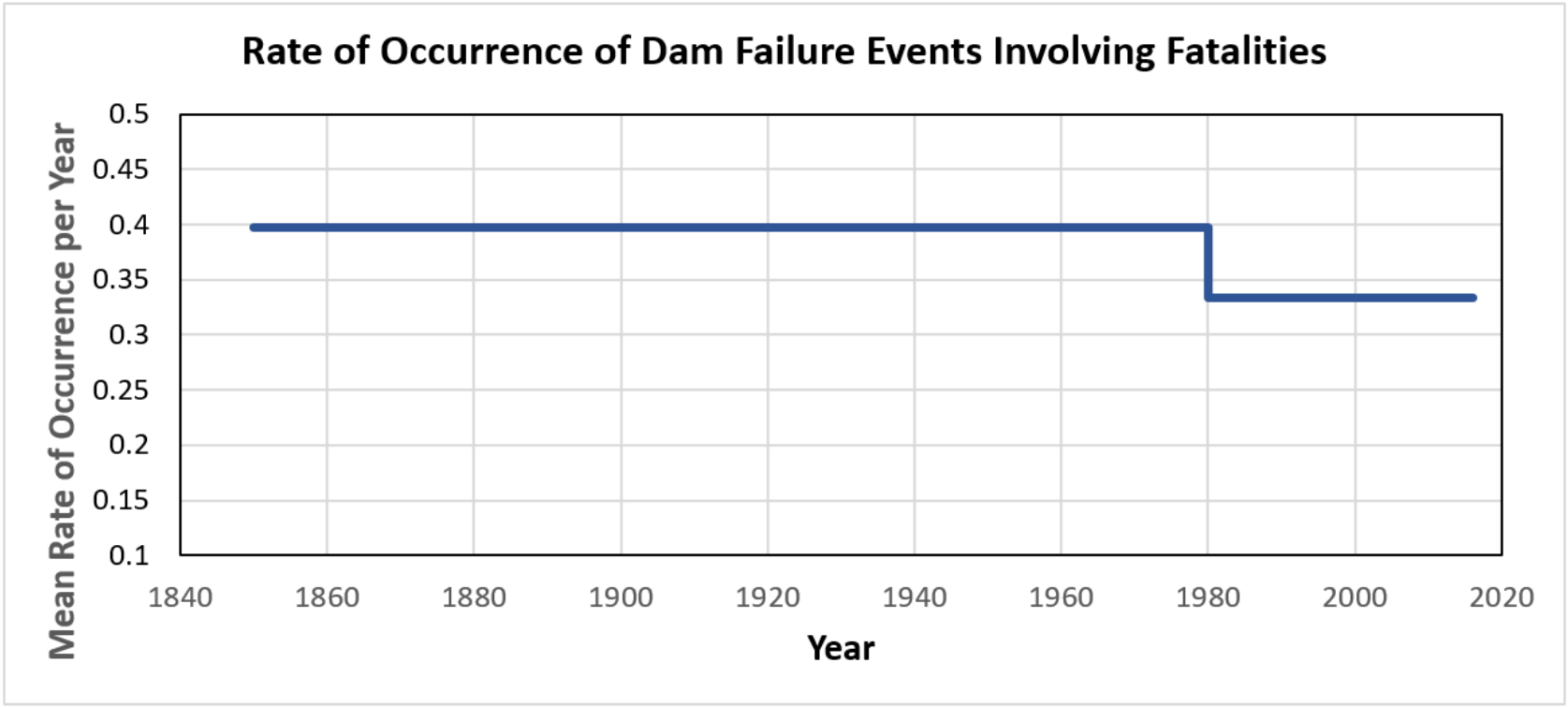
[a] The Staffordville Reservoir failure in 1877 is not included in this value. Documentation of this failure indicates fatalities did occur, however, there is no information on how many (Jorgenson 1920).

[b] This is simply the number of events divided by the number of years in the record.

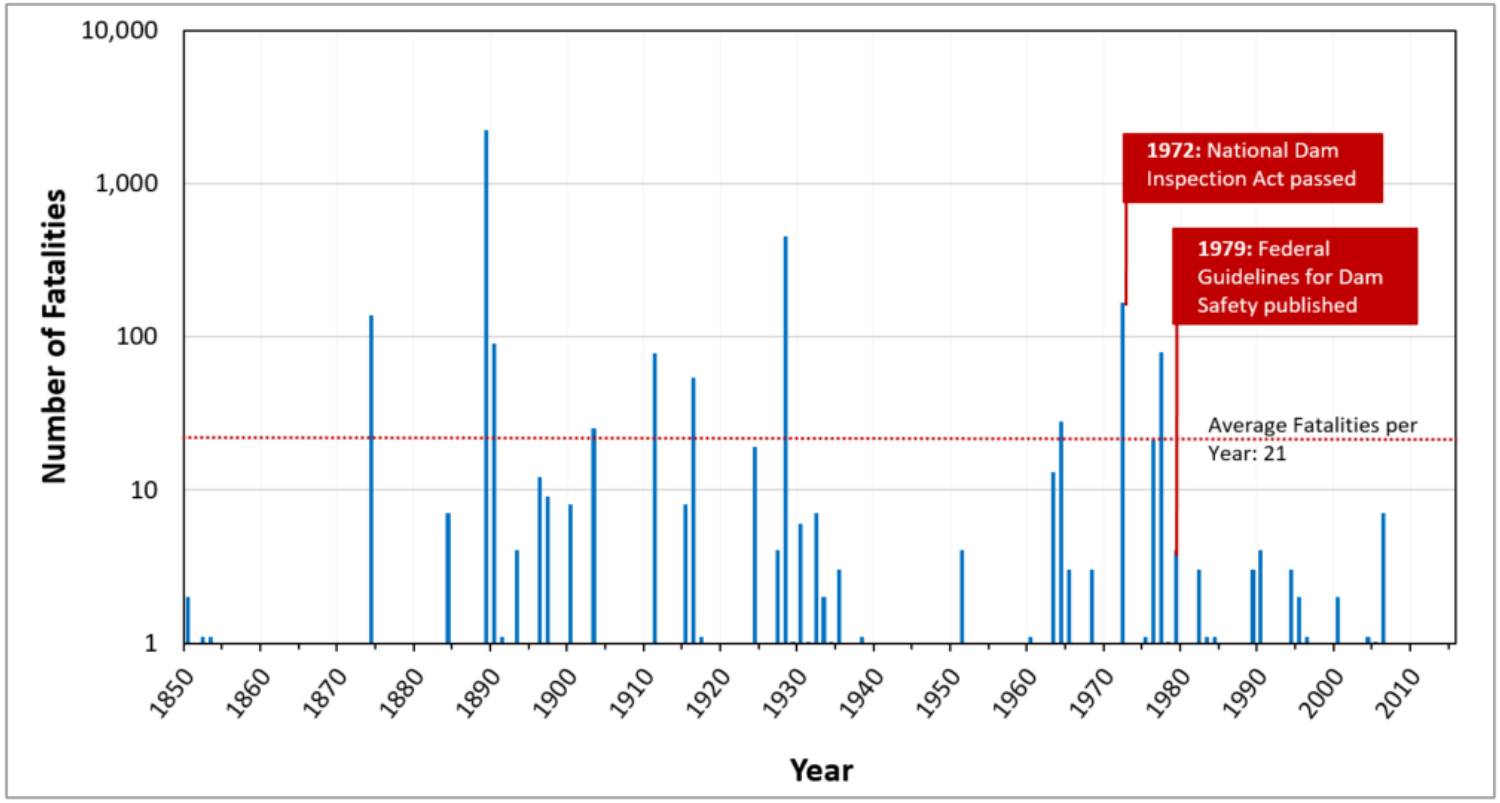
[c] This is the range on the number of fatalities that have occurred, given one or more fatalities occurred.

[d] Calculated as the total number of fatalities divided by the number of years of record. The range of values reflects the differences in the estimated number of fatalities in the historic record.

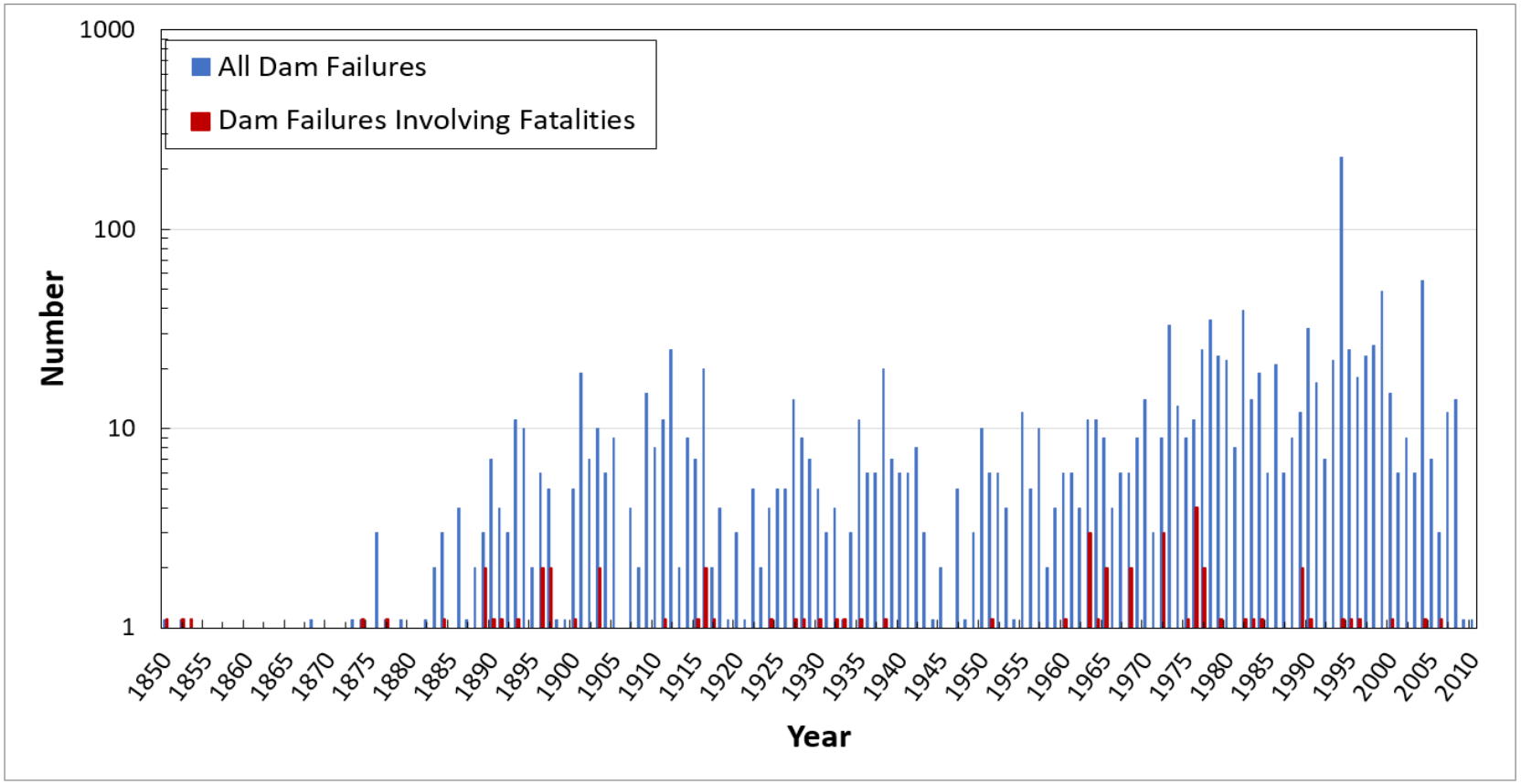
Rate of Occurrence of Dam Failures Involving Fatalities



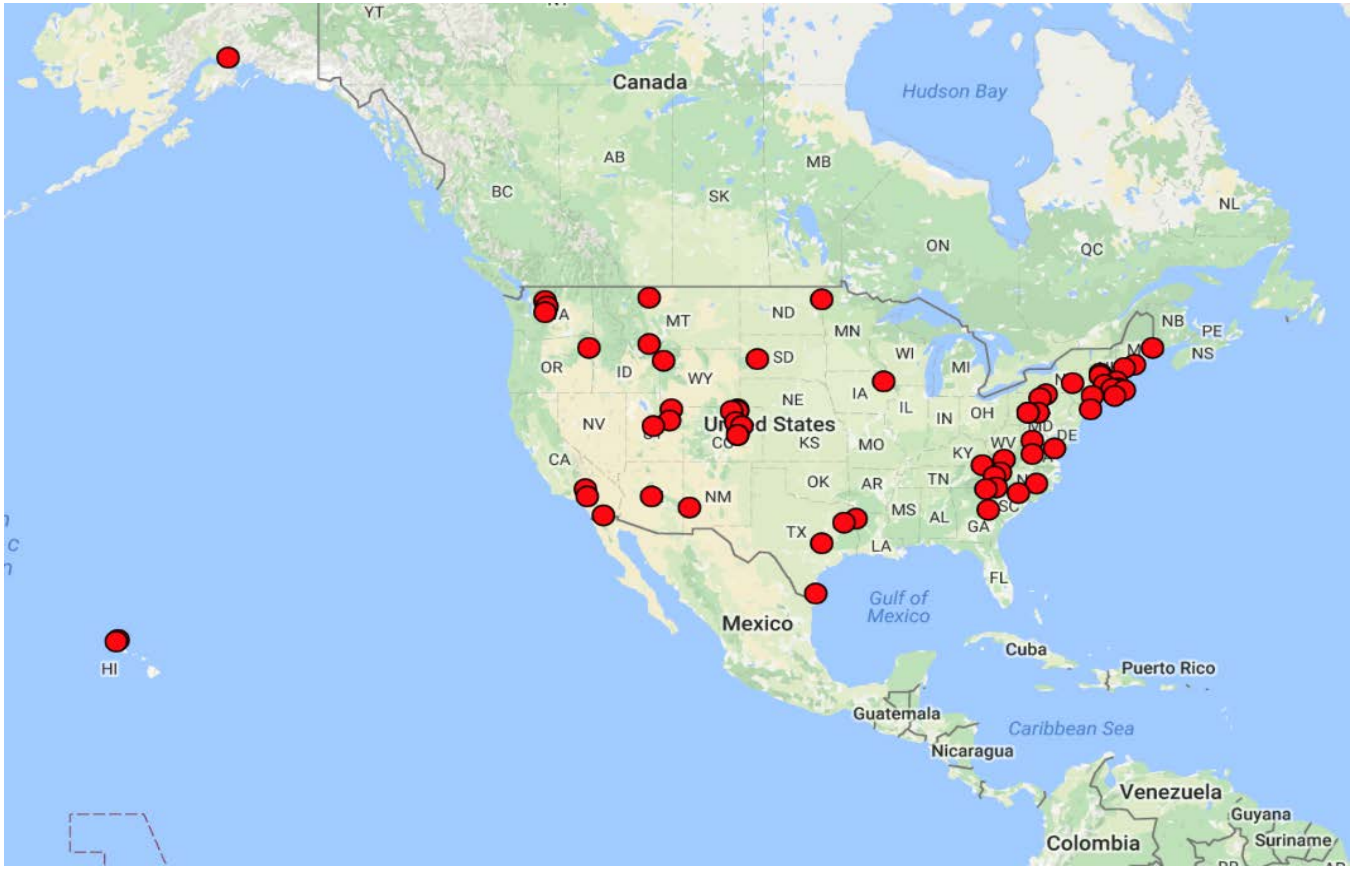
Timeline of Fatalities



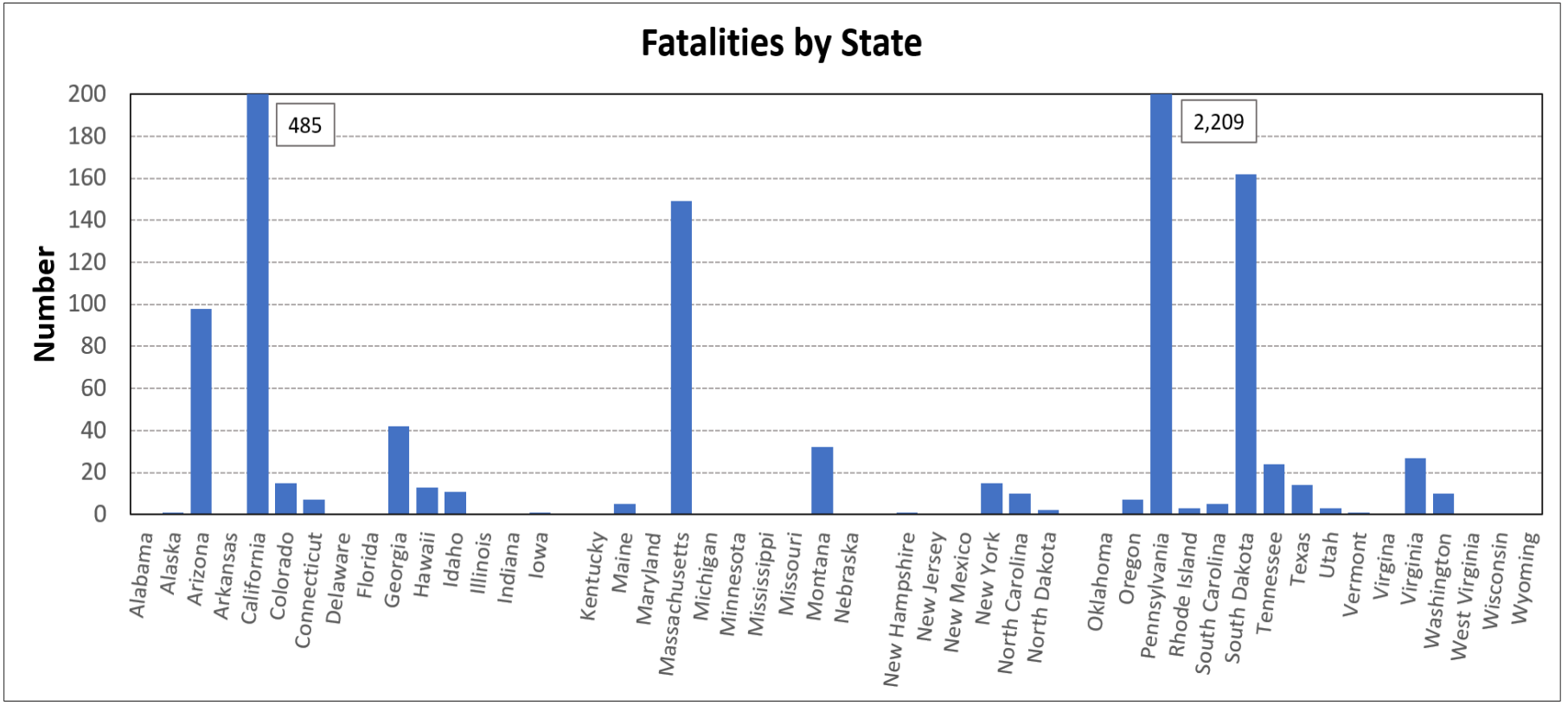
Timeline of Dam Failures & Fatalities



Geographic Distribution



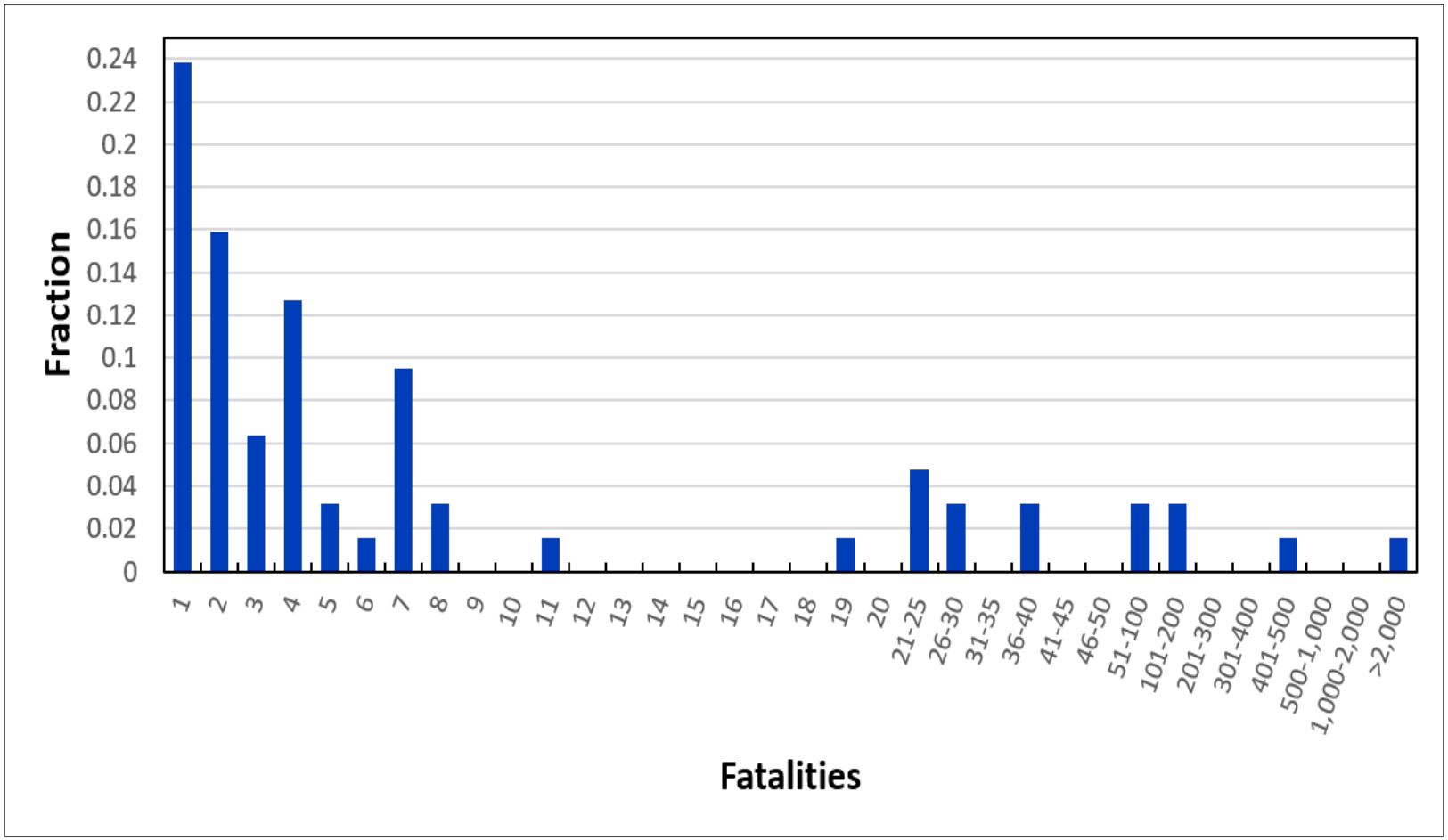
Number of Fatalities by State



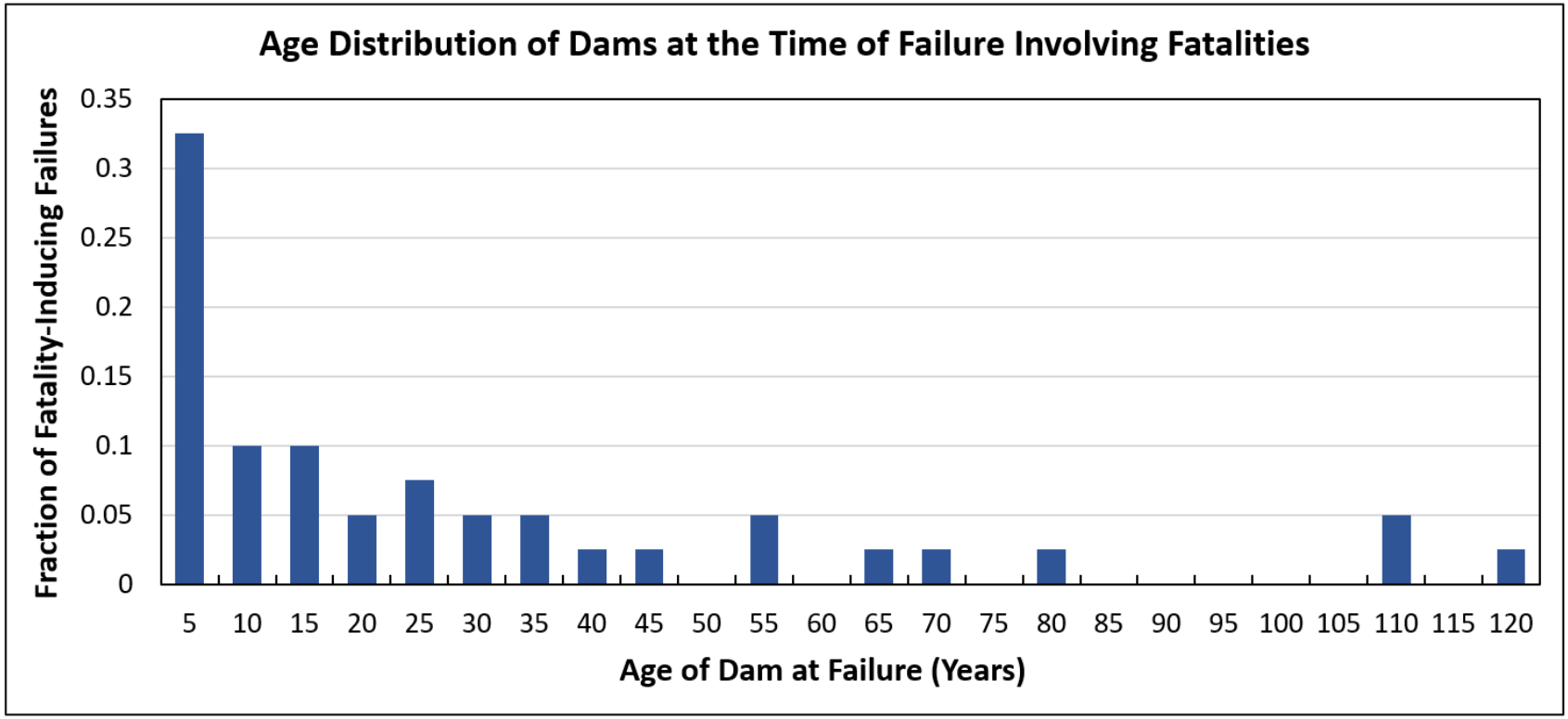
Distribution of Fatalities per Dam Event

- The figure on the following page shows the distribution on the number of fatalities that have occurred.
- Interestingly, the distribution on dam fatalities is somewhat bi-modal. Most dam failure events are associated with 10 or fewer fatalities. A large fraction (40%) have involved 1 or 2 deaths.
- At the other extreme, there are events that have resulted in 20 or more.
- One of the unique aspects of the risks associated with dams is the potential for a large number of fatalities. Not many man-made activities pose a threat large enough to cause 100s or 1,000s of fatalities in a single event.

Distribution on the Number of Fatalities



Age Distribution



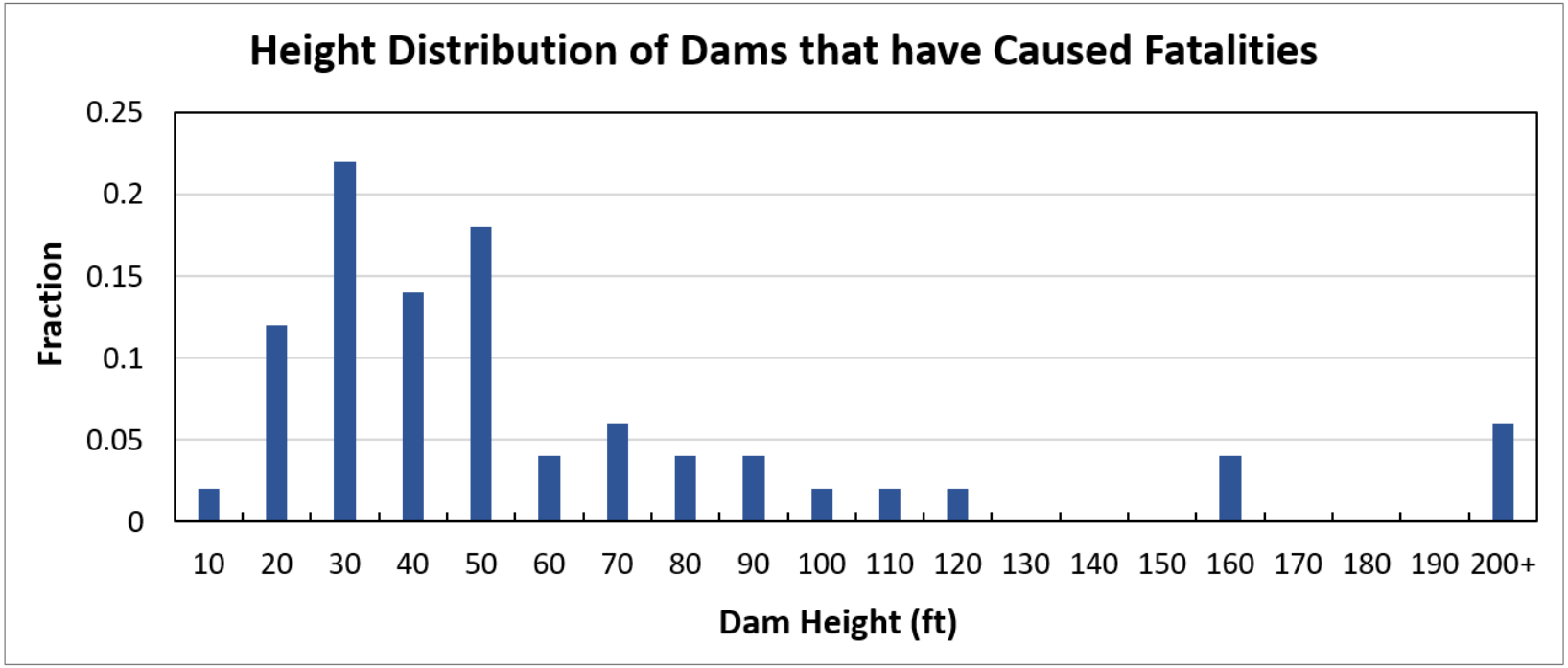
Dam Height and Fatalities

- Many of the dam failures that have involved fatalities have been ‘small’ dams; 50 feet in height or less.

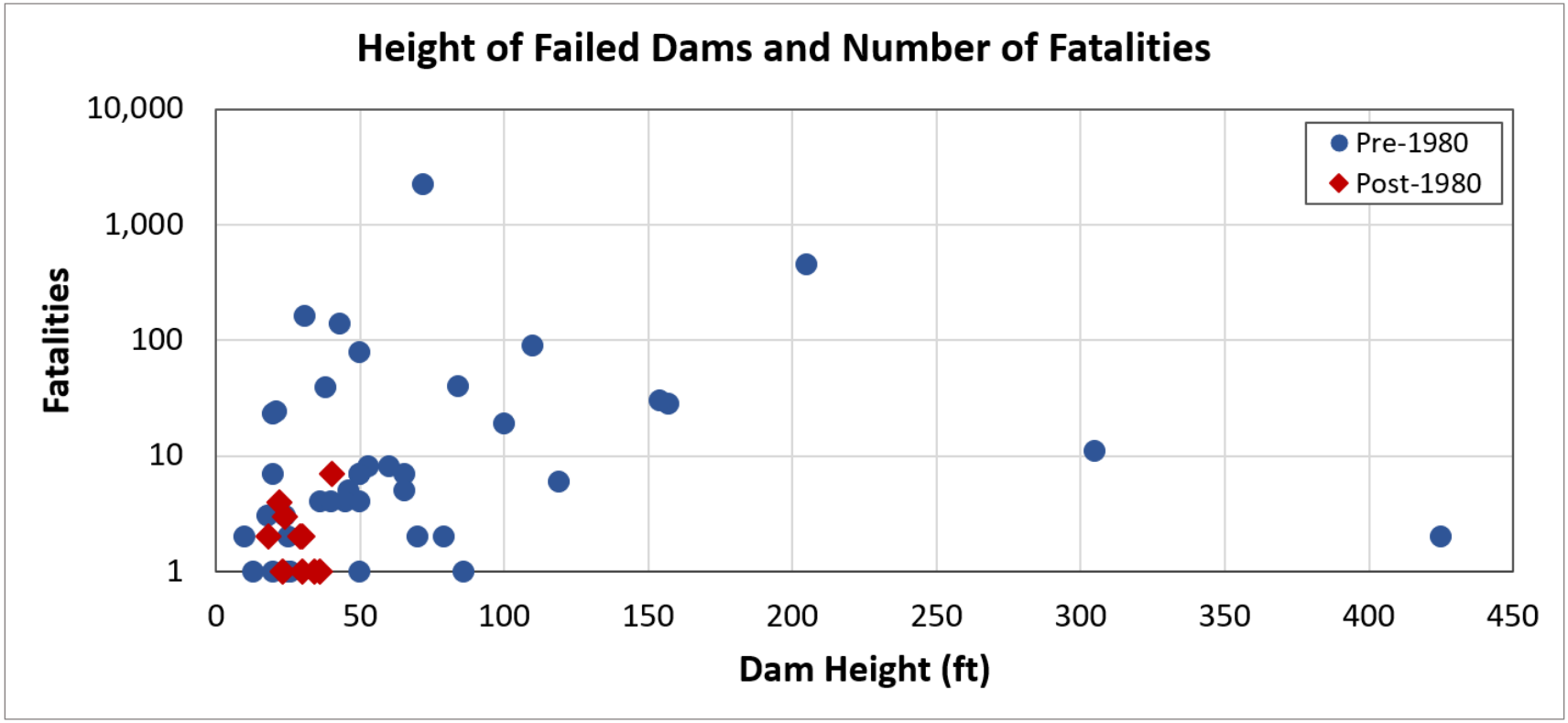
- Interestingly, since 1980 the dam failures that have involved fatalities have been relatively small structures (less than 40 feet in height).

- Dam failure events since 1980 have resulted in less than 10 fatalities, whereas older events have resulted in much larger fatalities.

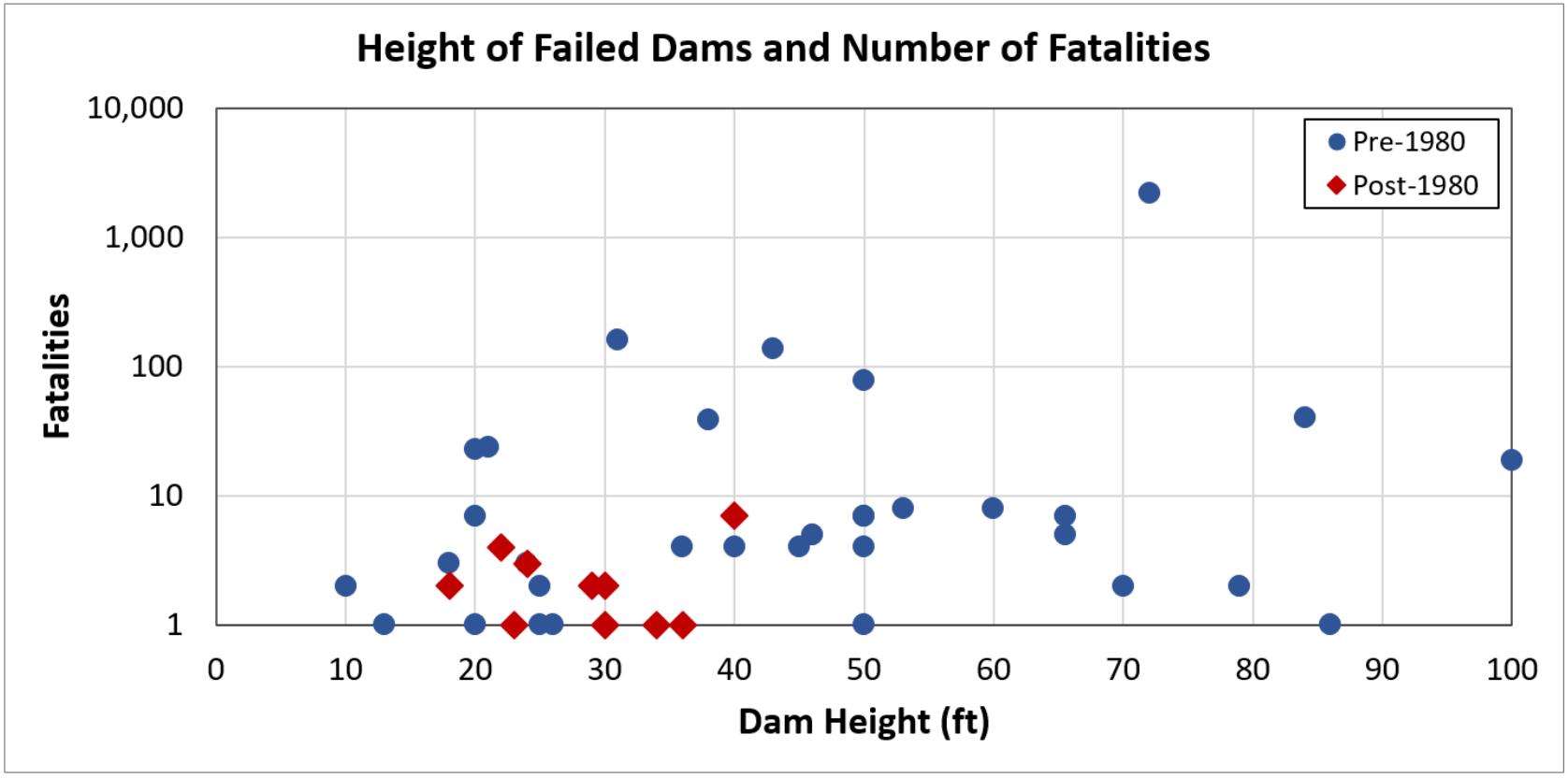
Height Distribution of Dams



Dam Height and Fatalities



Dam Height and Fatalities



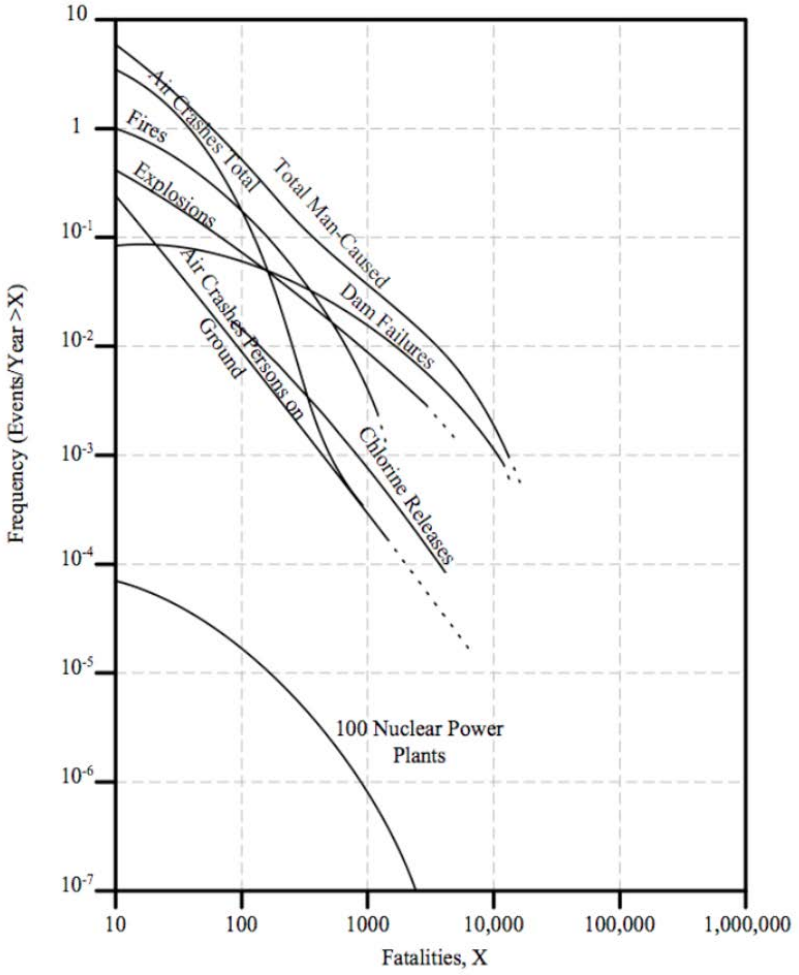
NPDP

F-N Analysis Methodology

- We want to estimate the ***frequency*** (mean rate) of occurrence/ exceedance (***f***/***F***) of fatalities associated with dam failure events.
- Units will be Number of Occurrences per Year or per Dam-Year (e.g., 0.1, 1, 10, ….)
- We are not estimating the ***probability*** of occurrence or exceedance!
- We will look at this from a couple of perspectives:
  - Portfolio Level, and
  - Facility Level

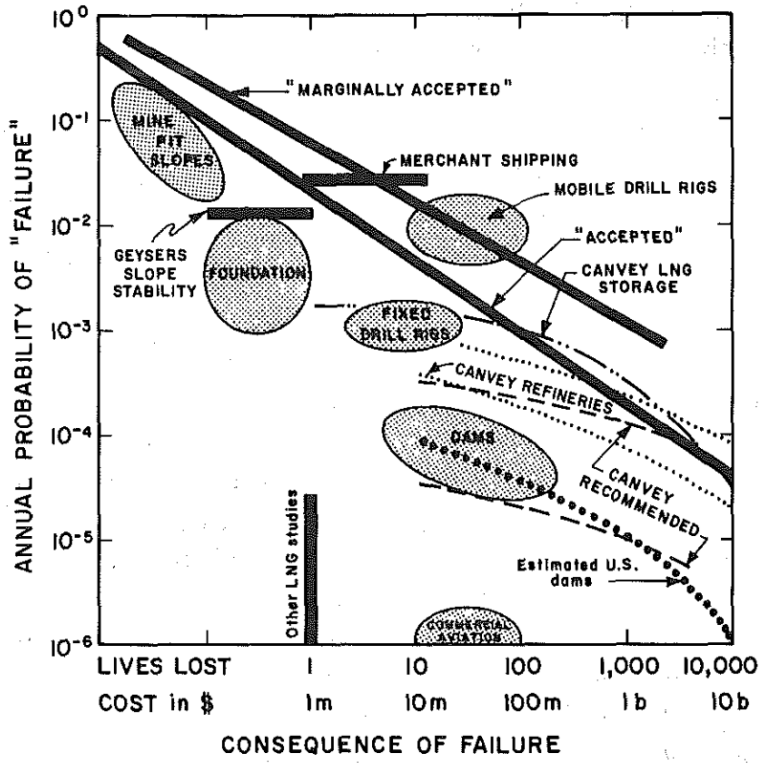
F-N Analysis Methodology (cont.)

- Portfolio Level – Allows comparison of different events/activities; natural hazards (earthquakes, floods, etc.), and man-made accidents (commercial air travel, industrial accidents, maritime accidents, etc.) .



F-N Analysis Methodology (cont.)

- Facility Level – Accounts for the number of facilities in a portfolio, and the exposure of populations to the hazard. The units in this case are the frequency of occurrence or exceedance per year of facility operation.



F-N Analysis Methodology (cont.)

Portfolio Level Analysis

$f(n)$ = Frequency (mean rate) per Year $= \frac{i_n}{T_R} \frac{(No.\ of\ Occurrences)}{(No.\ of\ Trials)}$

i = Number of occurrences of an event; n=100 fatalities for example

T_R = period of record

F-N Analysis Methodology (cont.)

Facility Level Analysis

$f(n)$ = Frequency (mean rate) per Year of Operation $= \frac{i_n}{T_{YO}}$

i = Number of occurrences of the event; n=100 fatalities for example

T_{YO} = Years of operation of facilities in the portfolio; accounts for the number of facilities, their years of operation and the exposure of communities to the hazard

F-N Analysis Methodology (cont.)

Frequency of Exceedance (*F*)

$$F(N \geq n) = \Sigma f(n)$$

Estimating *F/ f* Based on Actual Threat Level

- To estimate ***f*** (and ***F***) at each fatality level, we should take into account:
  - The number of occurrences of a given number of fatalities (n), and
  - The number of dams that actually expose large enough populations to produce those fatalities.

- Stated differently, of the 15k+ High Hazard dams in the country:
  - How many can produce 1 or more fatalities? – In principle, all of them.
  - How many could produce 1,000 or more fatalities? – Certainly not all of them; Exactly how many, we don't know.

F-N Analysis Methodology (cont.)

Facility/Threat Level Analysis

$f(n)$ = Frequency (mean rate) per Year of Operation $= \frac{i_{n=100}}{T_{YO,100}}$

i = Number of occurrences of the event; n=100 fatalities for example

$T_{YO,100}$ = Years of operation of facilities in the portfolio; accounts for the number of facilities, their years of operation and the facilities that can lead to to 100 fatalities.

Missing Data

- We do not have information on the threat dams pose to downstream populations (aka, population-at-risk) for all dams in the U.S.

- Without this information, we can at least assess the degree to which it makes a difference to the estimate of the Facility Level ***F***-N result.

Number of Fatalities	High
0	0
1-9	0.25
10-99	0.35
100-999	0.30
1,000+	0.10

Accounting for Uncertainty

- A significant source of uncertainty is the limited period of record and the number of fatality events.
- The limited period-of-record leads to uncertainty in the estimate of ***f*** and ***F***
- Use a bootstrap simulation approach (Efron, 1979) to estimate the uncertainty (confidence intervals) in the estimate of the frequency of the number of fatalities.

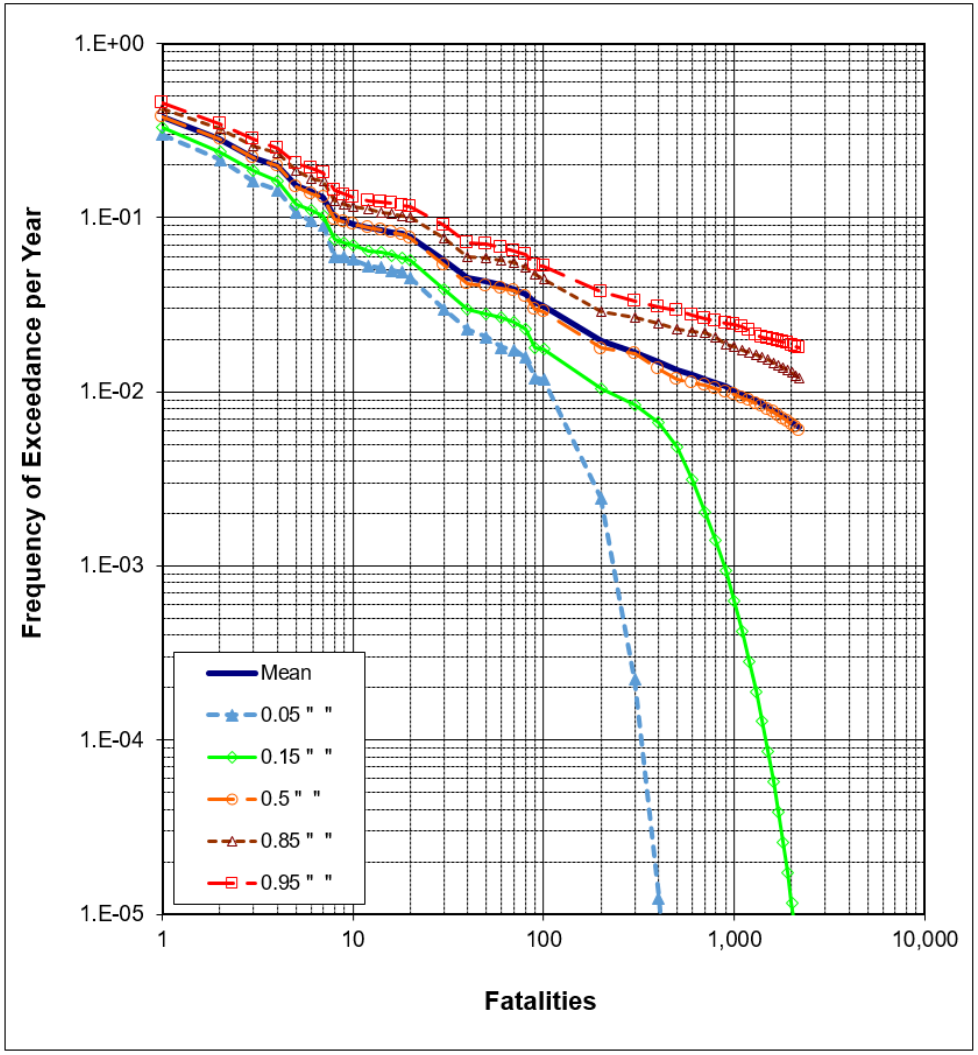
Analysis Cases and Results

- Case 1 - Portfolio Level Analysis

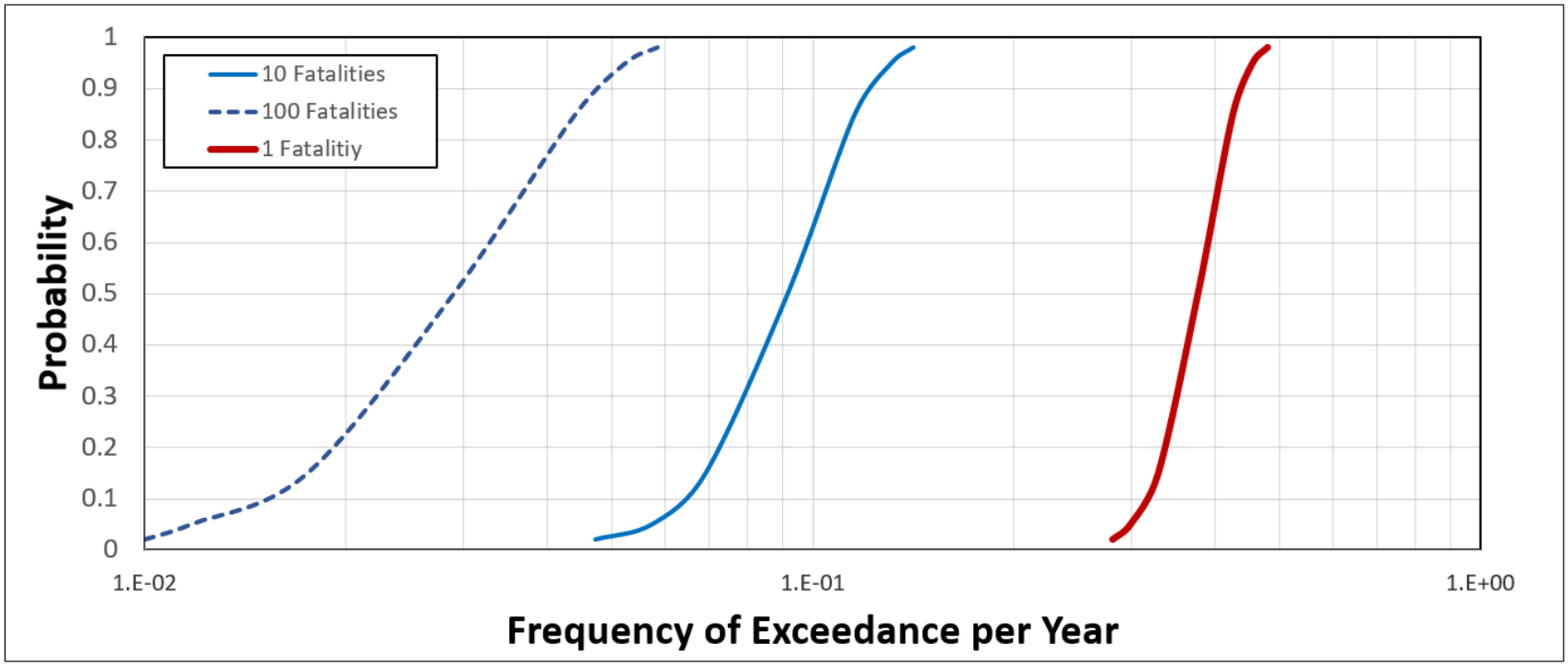
- Case 2 – Facility Level Analysis - High Hazard Dams
  (This case accounts for the dam years of operation of High Hazard dams, without taking into account the threat level)

- Case 3 – Facility/Threat Level - High Hazard Dams Accounting for Threat Level

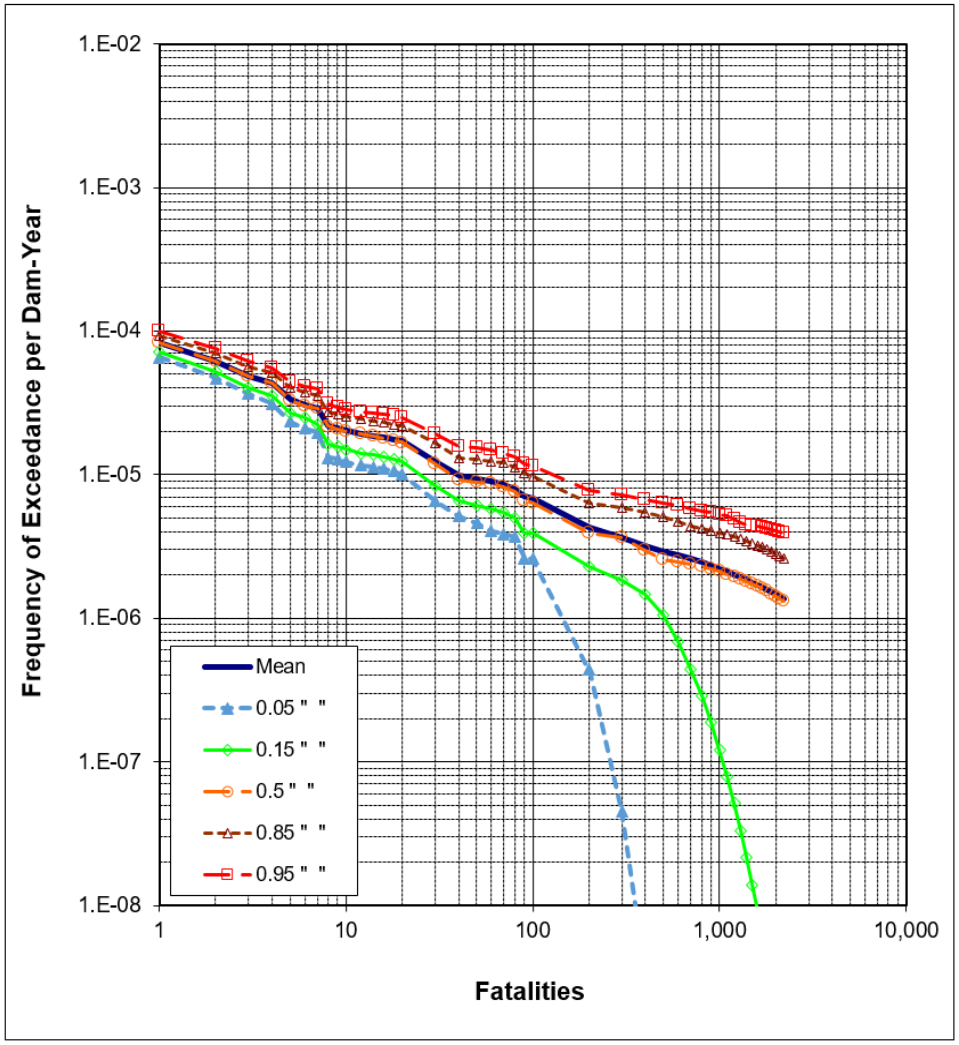
Portfolio Analysis Results



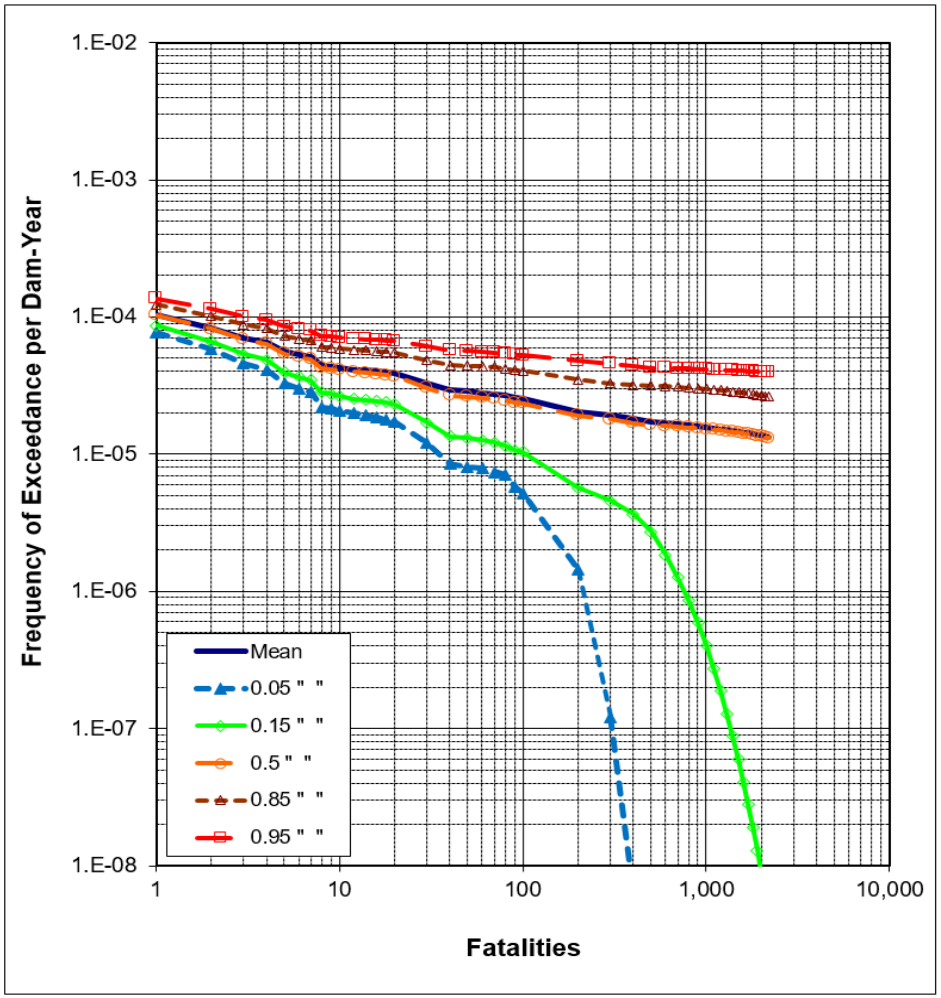
View of the Uncertainty



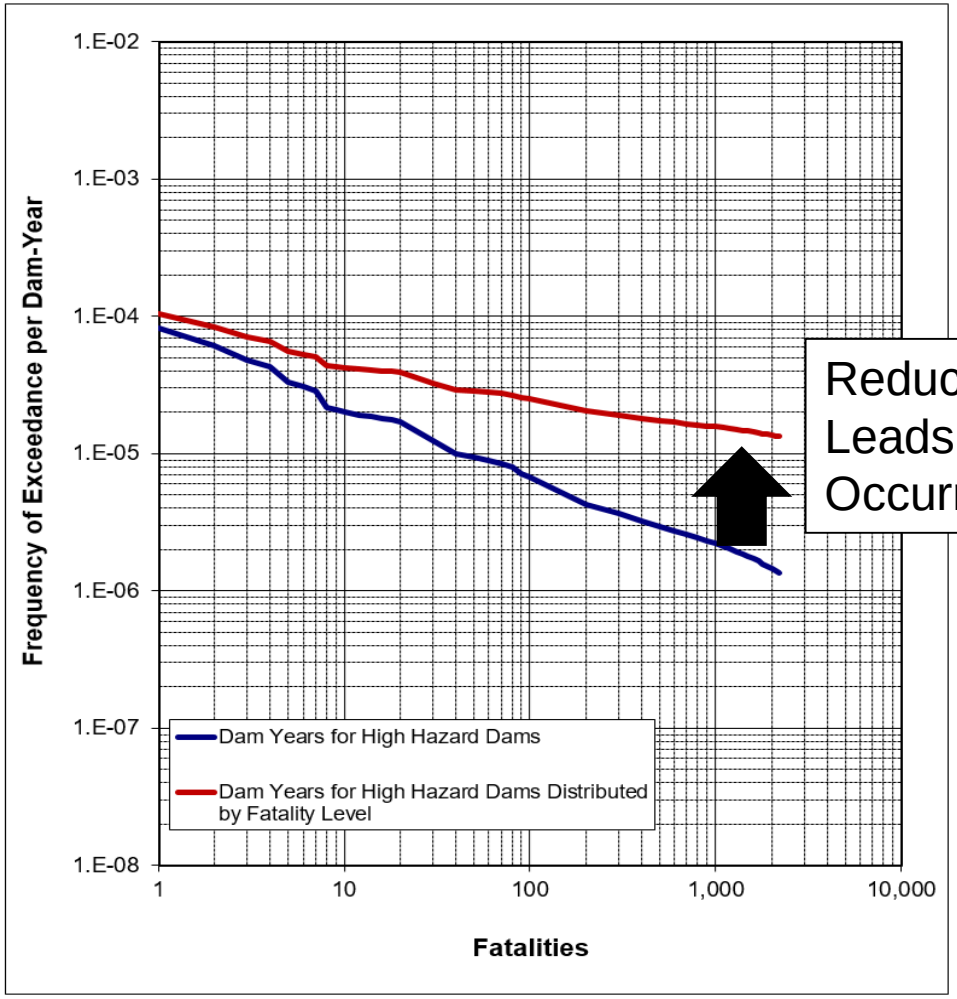
Case 2 – Facility Level Results



Case 3 – Facility/Threat Level Results



Comparison Case 2 / Case 3



Reduced Number of Trails Leads a Higher Rate of Occurrence.

Observations

- Historically, about 4% of dam failure events have involved fatalities.
- The occurrence of dam failure events that have resulted in fatalities, occurs, on average, once every 3-4 years – not particularly rare.
- There is some indication this rate is lower since 1980; A benefit of dam safety (serendipity)?

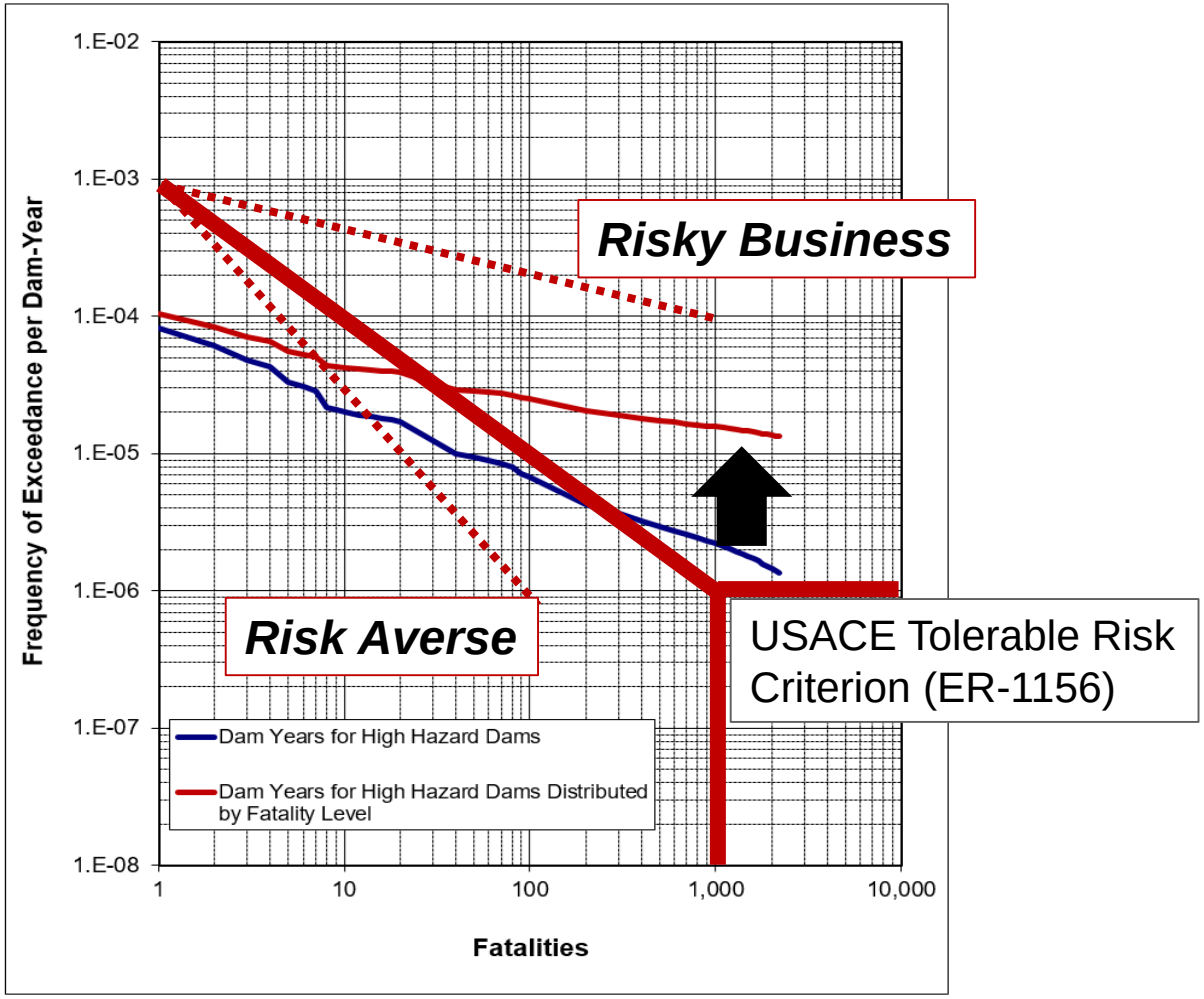
Observations (cont.)

- Understanding the historic ***F***-N relationship, societal risk, requires a bit better understanding of the exposure of populations to the hazards of dam failures.

- The following slide shows the tolerable risk criterion in use by the U.S. Army Corps of Engineers. The slope of the line is -1, which indicates a risk 'neutral' approach to risk management, which is common. The figure also shows the Facility Level ***F***-N results.

- The slope of the Facility Level ***F***-N results suggest a much flatter slope, indicating the management of dams in the U.S. has been very risky, at least historically. Just how risky is unclear, since we do not have the data to measure the frequency of events involving large fatalities.

Observations (cont.)



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