Best Practices in Dam and Levee Safety Risk Analysis

Risk Guidelines

July 2015

RECLAMATION
Managing Water in the West

US Army Corps of Engineers
BUILDING STRONG®

Presentation Outline

- Definitions
- Types of Risk
- Risk Measures
  - Annualized Probability of Failure
  - Life Safety
    - Individual
    - Societal/Annualized Life Loss
  - Other Risk Measures
- ALARP
- Risk Assessment
- Risk Management
- Example

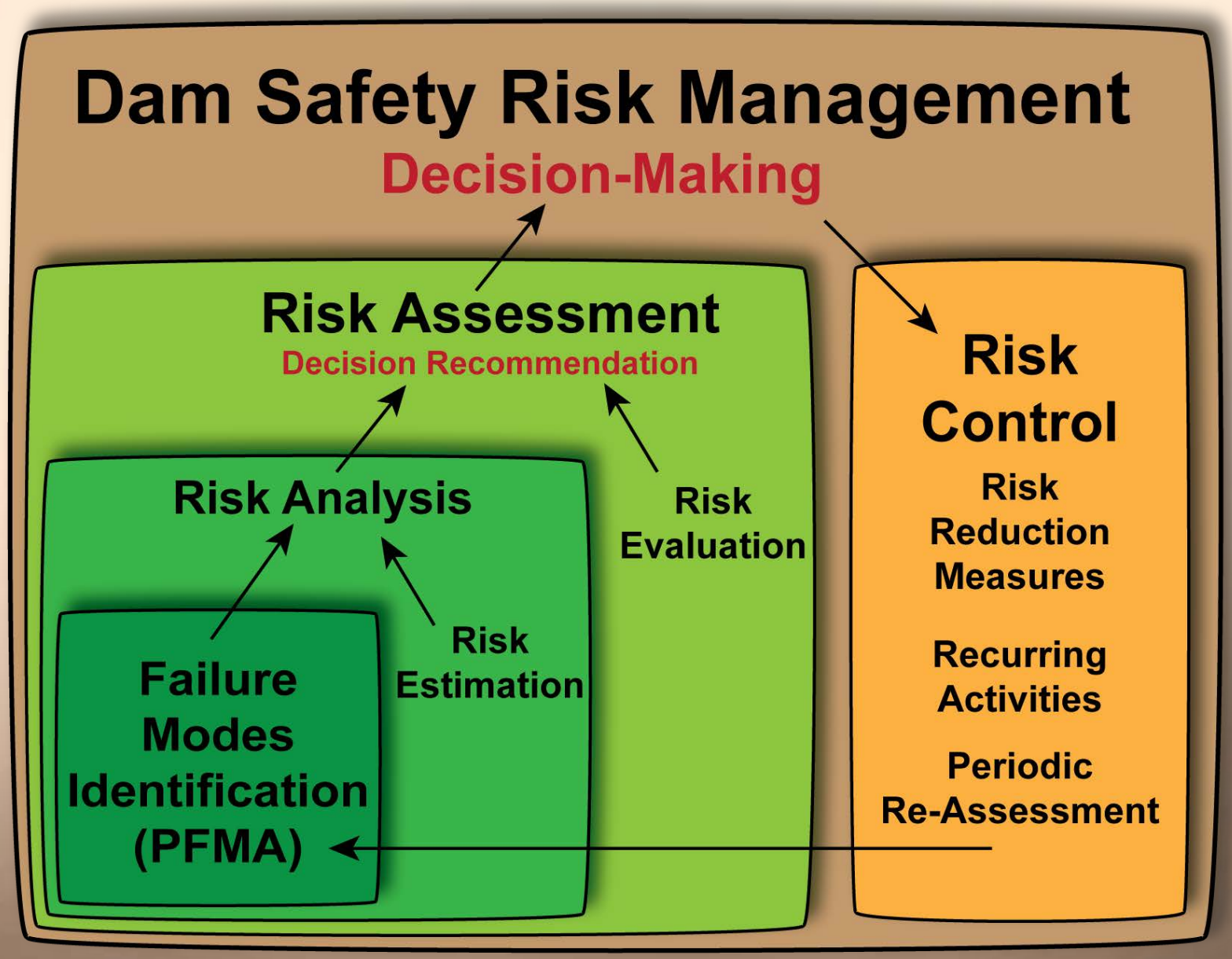
Risk Guidelines

DEFINITIONS

Definitions

- Risk – Risk is frequently defined as a measure of the probability and severity of adverse consequences
  - P(load) x P(failure) $_{\text{given the load}}$ x Consequences $_{\text{given failure}}$
- Risk Analysis – A quantitative calculation or qualitative evaluation of risk
- Risk Assessment – The process of deciding whether risks are tolerable or not and what actions are appropriate
- Risk Management – The process of implementing risk reduction measures and prioritization of risks

Dam Safety Risk Management



U.S. DEPARTMENT OF THE INTERIOR
BUREAU OF RECLAMATION

Federal Guidelines for Dam Safety Risk Management

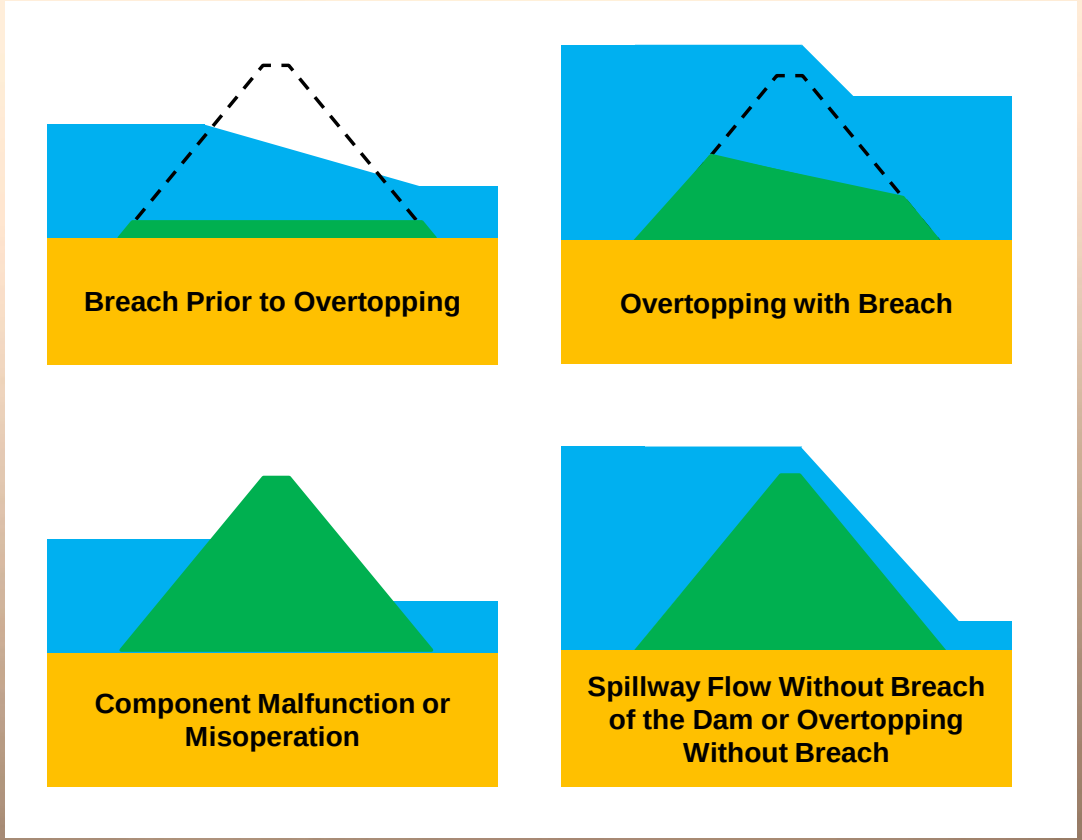
FEMA P-1025/January 2015

FEMA

Risk Guidelines

TYPES OF RISK

Inundation Scenarios



Types of Risk

- Incremental
- Non-Breach
- Residual

*Note: Not all risk types are necessarily estimated or used by each agency

Incremental Risk

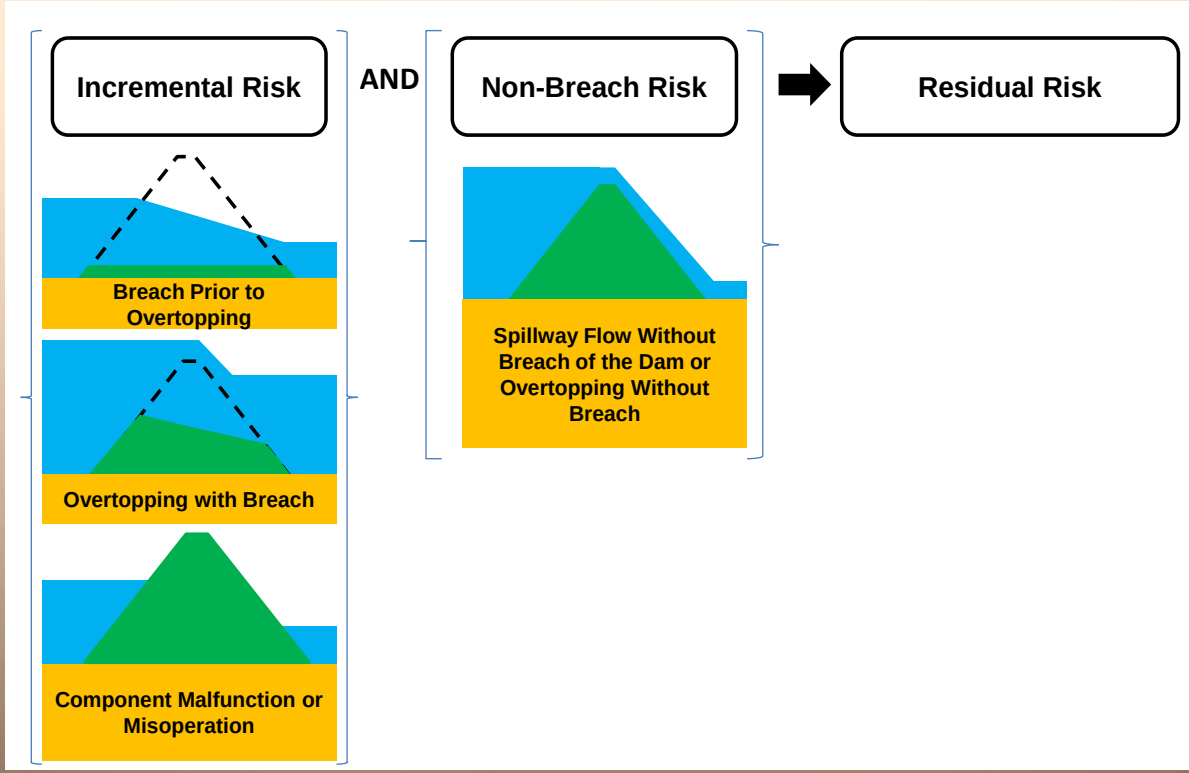
- Risks attributed to the presence of the infrastructure (dam or levee) should the dam or levee fail where the consequences are over and above those that would occur without a dam or levee breach.

Non-Breach Risk

- Risks due to inundation under normal (no fail) dam or levee operations.
  - Large outlet or spillway releases within design capacity that exceed channel capacity
  - Overtopping of dam or levee without breach

Residual Risk

- The risk at any point in time.



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RISK MEASURES

Risk Measures

- Annualized Probability of Failure
- Life Safety
  - Individual
  - Societal
- Economic
- Environmental
- Others

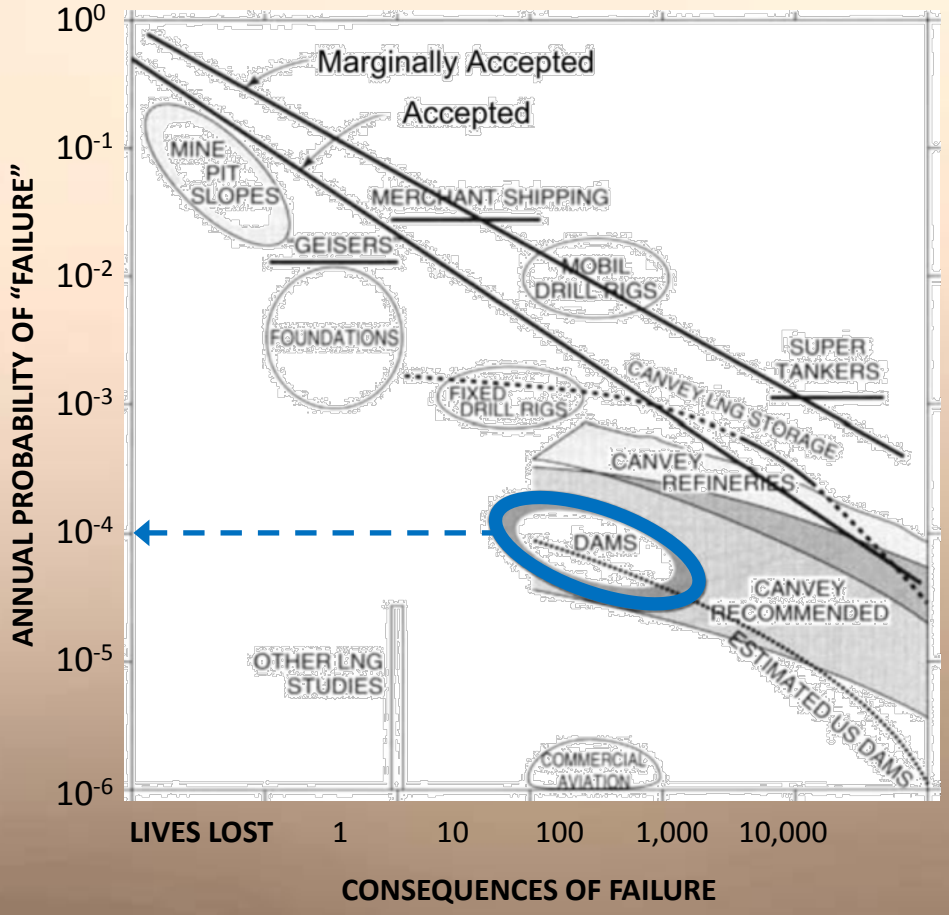
Risk Guidelines

ANNUALIZED PROBABILITY OF FAILURE

Annualized Failure Probability

- Should promote a condition better than existed prior to modern dam safety programs of the late 1970's
- Should result in dam failure being a small portion of the risk people are normally exposed to

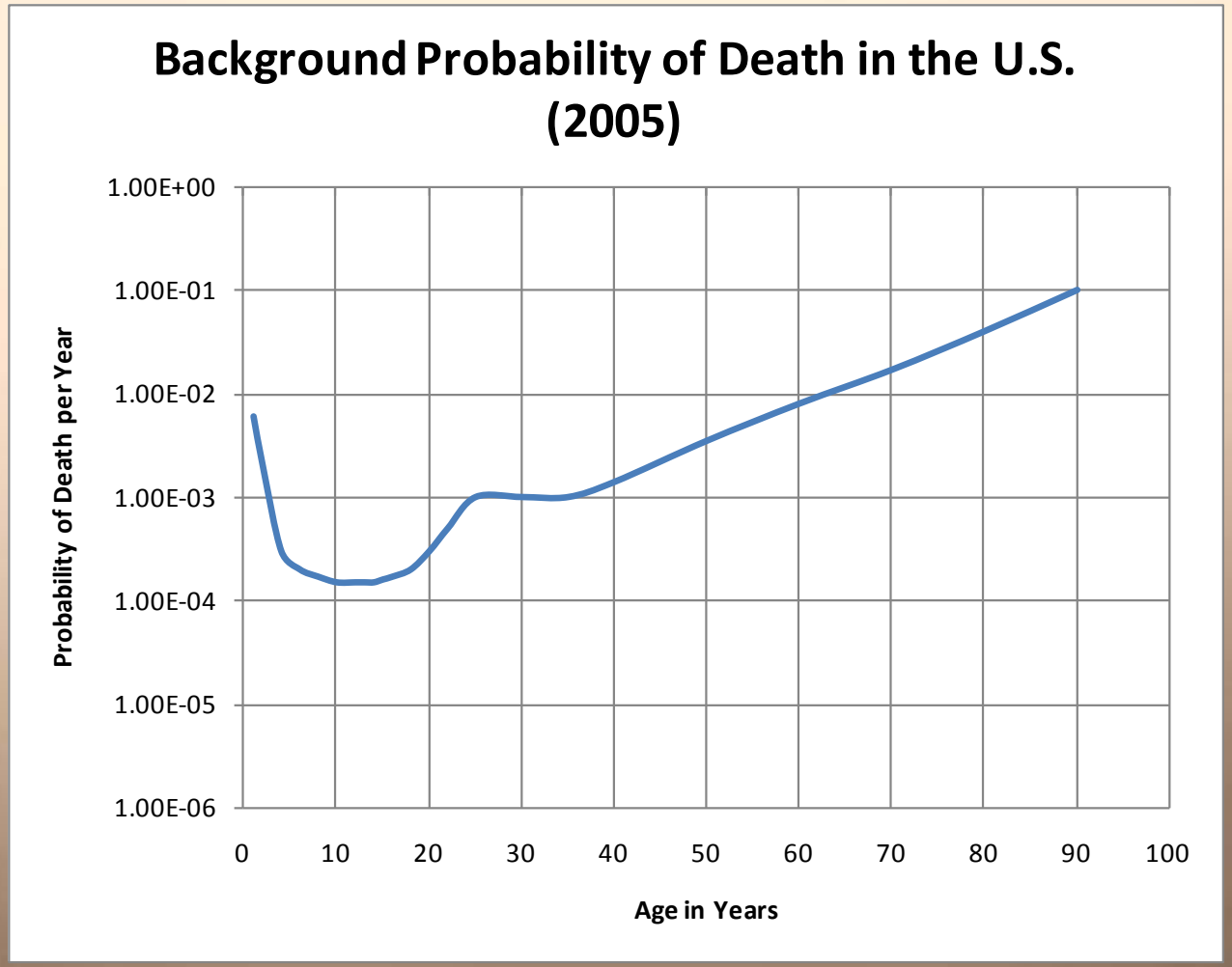
Historical Failure Rates



- APF > 1 in 10,000/year
- Whitman and Baecher (1981)
- Von Thun (1985) 1.4 E-04
- Hatem (1985) 2.6E-04
- M.K. Engineers (1988)
- Foster et al. (1998)
- Douglas et al. (1998)

Background Risk

Chance of death for people living in an inundation zone is typically small



From CDC

Annualized Failure Probability

- *"Reclamation terms this measure of risk Annualized Failure Probability, and uses a guideline of 1 in 10,000 per year for the accumulation of failure likelihoods from all potential failure modes that would result in life-threatening unintentional release of the reservoir. When the mean estimate is above this threshold level there is generally increasing justification to take action to reduce or better understand the risks. Below this threshold level there is generally decreasing justification to reduce or better understand the risks."*

Risk Guidelines

LIFE SAFETY RISKS

Individual Risk

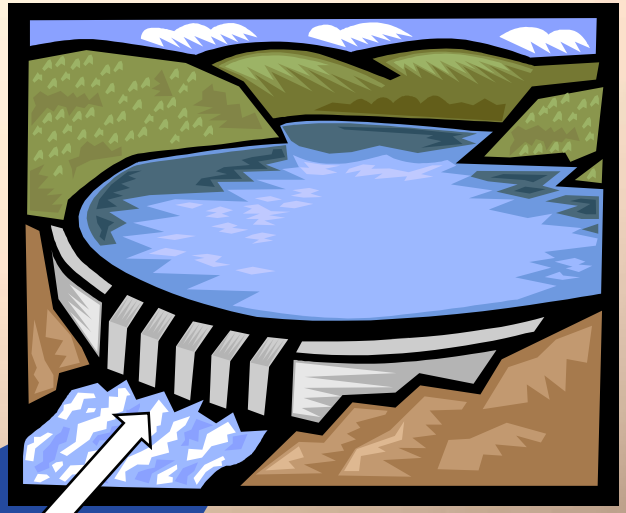
Individual risk is the probability of harm to individuals and the things they value. This risk is associated with the most exposed individual. Individual risk is the sum of the risks from all failure modes associated with the hazards that affect that person.

Guidelines are established to provide a level of protection even if the consequences are not high.

Individual Risk

Under the conservative assumption that the individual is always present (100% exposed)
Ignoring evacuation and survival

Individual Living Downstream



Σ

Individual Risk = Sum of the probabilities of failure for each failure mode and each loading increment that affect this individual

Individual Risk

- Health and Safety Executive (UK)
  - *"For members of the public who have a risk imposed on them 'in the wider interest of society' this* [individual risk of death] *limit is judged to be an order of magnitude lower* [than for workers] – *at 1 in 10,000 per annum."*

Individual Risk

- ANCOLD
  - *"For existing dams, an individual risk to the person or group, which is most at risk, that is higher than 10^{-4} per annum is unacceptable, except in exceptional circumstances.*

Individual Risk

- NSW DSC
  - *"For existing dams, the DSC's limit of tolerability is 1 in 10,000 per annum, which is the same as that of ANCOLD and of the Health and Safety Executive, United Kingdom (HSE)."*

Individual Risk

- CDA
  - *"The individual risk should be considered in terms of the 'maximally exposed individual' that is permanently resident downstream of the dam. Typically the maximally exposed individual is exposed to the hazard significantly more than 50% of the time. The maximum level of individual risk should generally be less than 10^{-4}/year."*

Individual Risk

- USACE
  - *"For existing dams, the individual risk to the identifiable person or group by location, that is most at risk, should be less than a limit value of 1 in 10,000 per year, except in exceptional circumstances."*

Risk Guidelines

SOCIETAL RISK/ANNUALIZED LIFE LOSS

Societal Risk/Annualized Life Loss

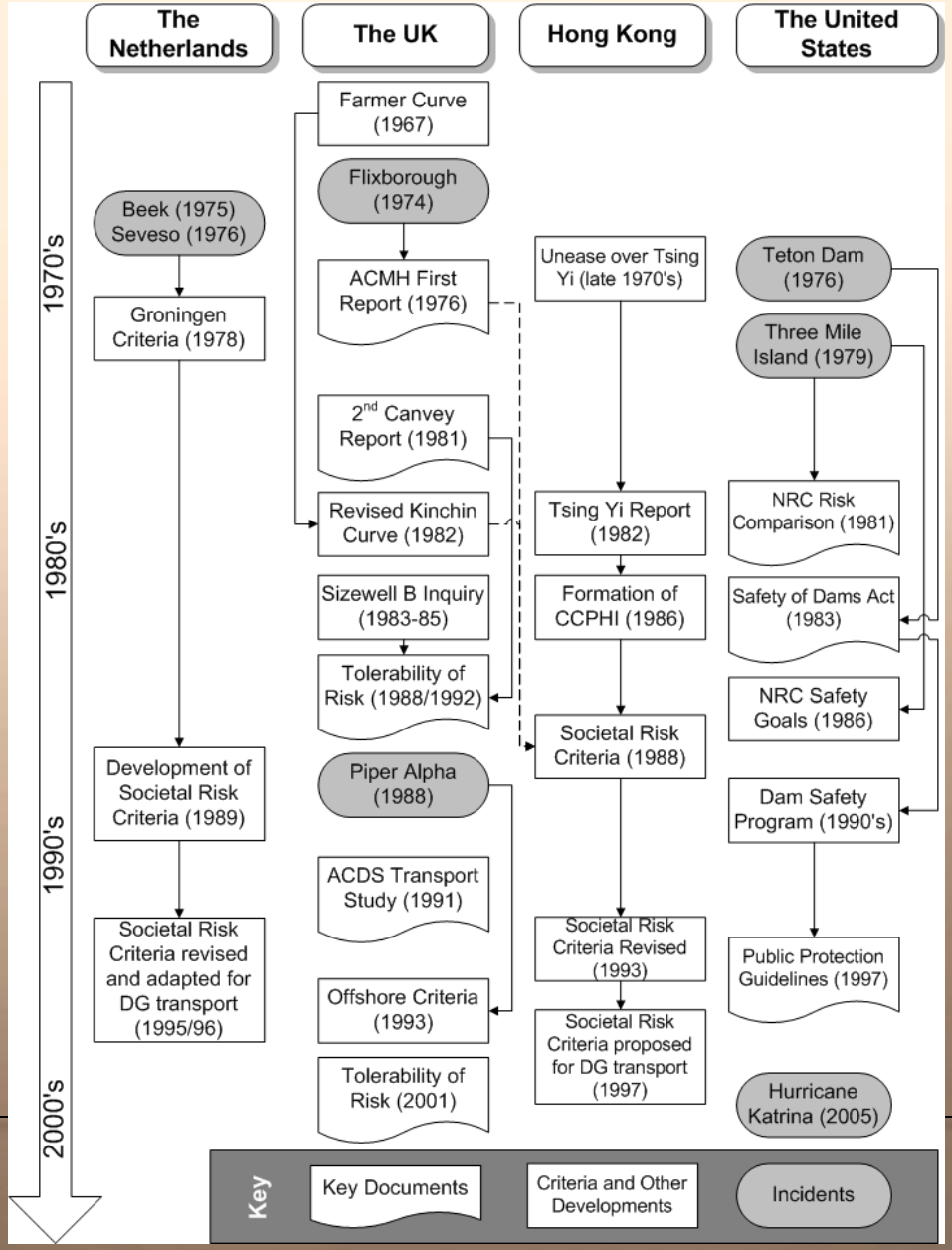
Societal risks are the probability and severity of adverse consequences from hazards that impact on society as a whole and create a socio-political response because multiple fatalities occur in one event. Society is increasingly averse to hazards as the scale of the consequences increase.

If high consequence events happen at a rate higher than society is willing to tolerate, legislative action usually follows (as was the case for the 1979 Dam Safety Legislation following numerous dam failures including Teton Dam).

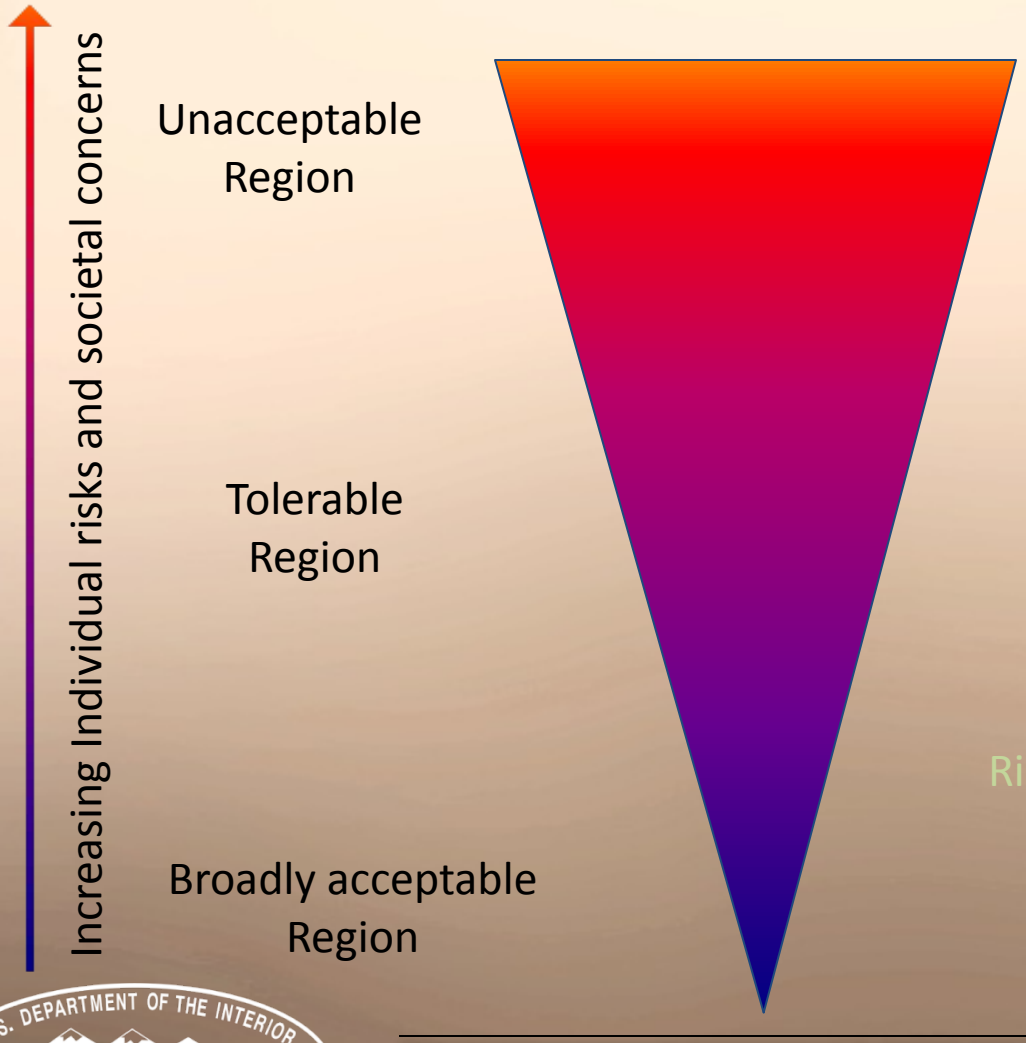
Societal Risk/Annualized Life Loss (continued)

- Attributes of hazards that give rise to societal concerns (ANCOLD):
  - Severity not controllable
  - Catastrophic
  - Results difficult to control
  - Certain to be fatal
  - Risks and benefits inequitable
  - Threatens future generations
  - Not easily reduced
  - Involuntary
  - Affects them personally
  - Risk getting worse

Milestones in Societal Risk Guideline Development



UK HSE Tolerable Risk Framework

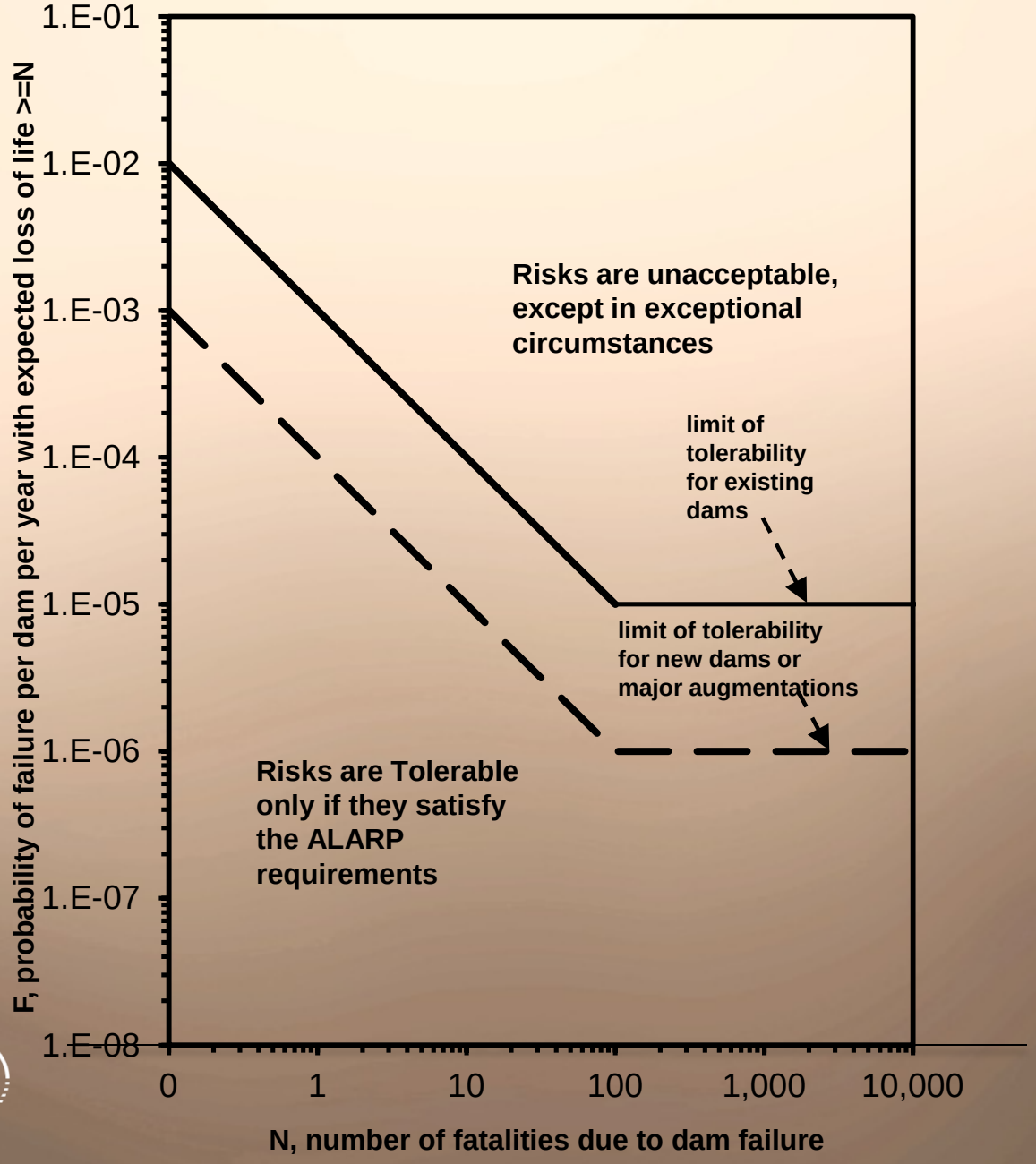


Risks Cannot be justified except in extraordinary circumstances

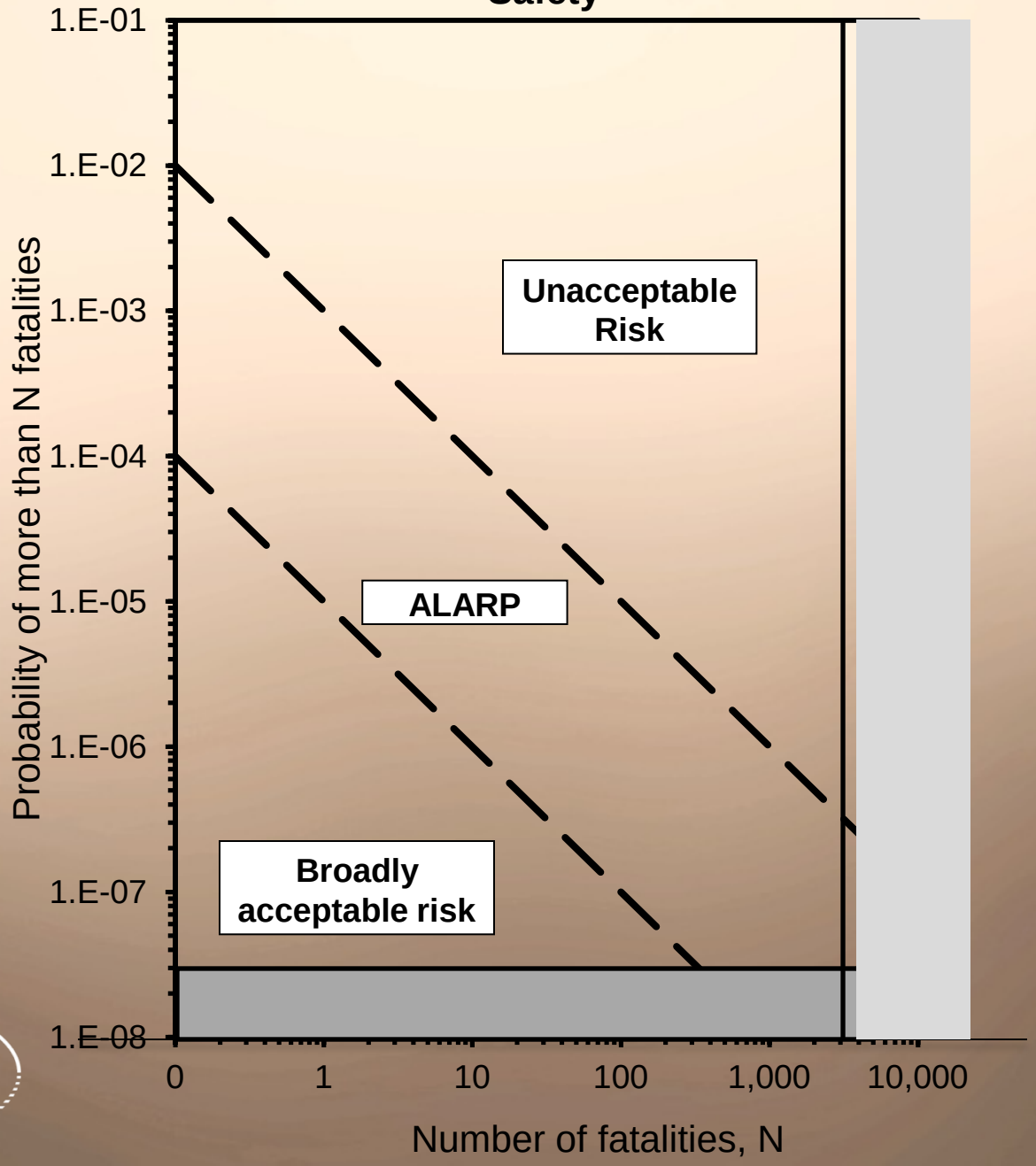
People and society are prepared to accept risk in order to secure benefits - Risks must be controlled - ALARP Control measures must be introduced

Risk regarded as insignificant, further effort to reduce risk not required unless easily achieved

Revised ANCOLD Societal Risk Reference Guideline

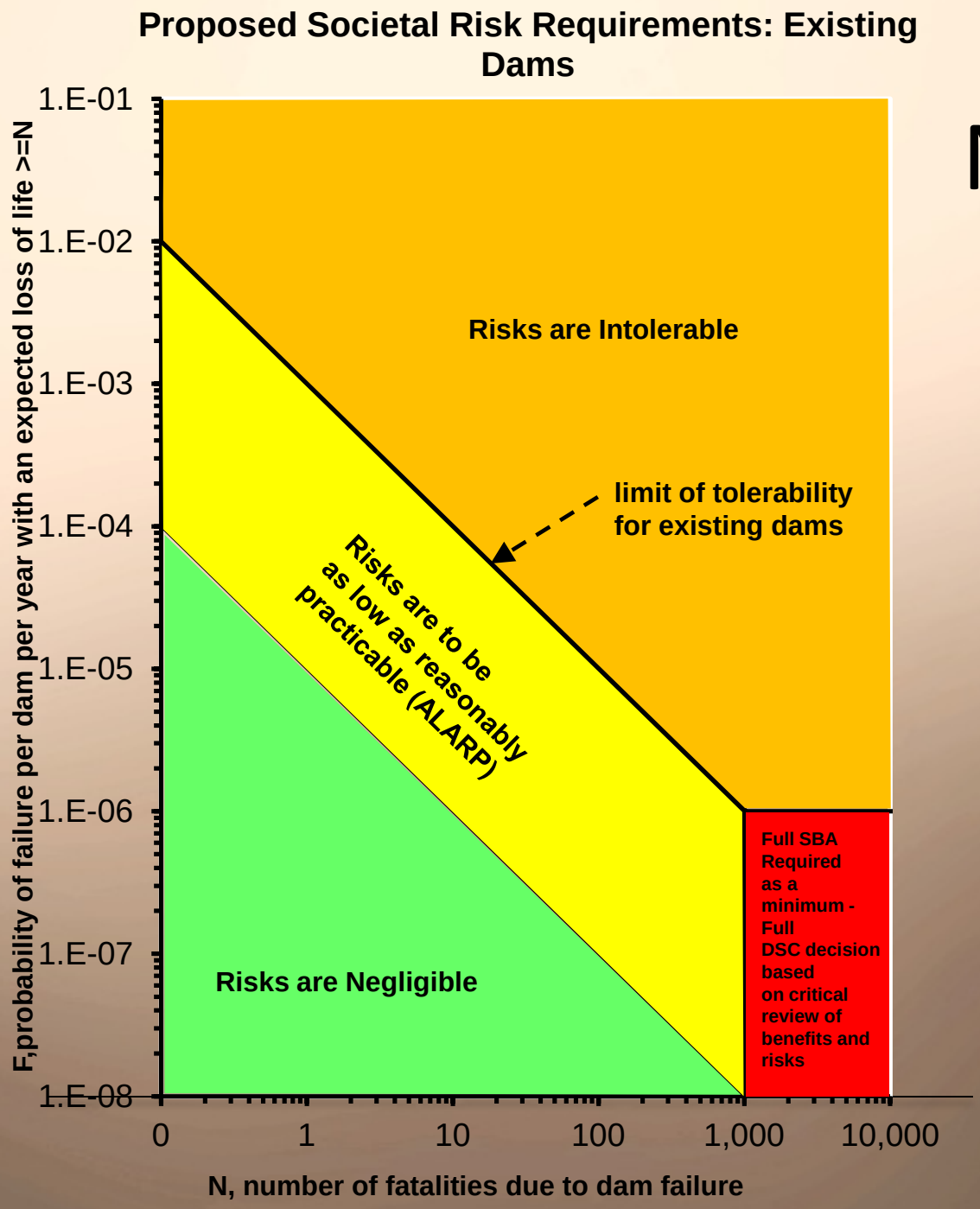


Suggested Societal Risk Levels for Dam Safety



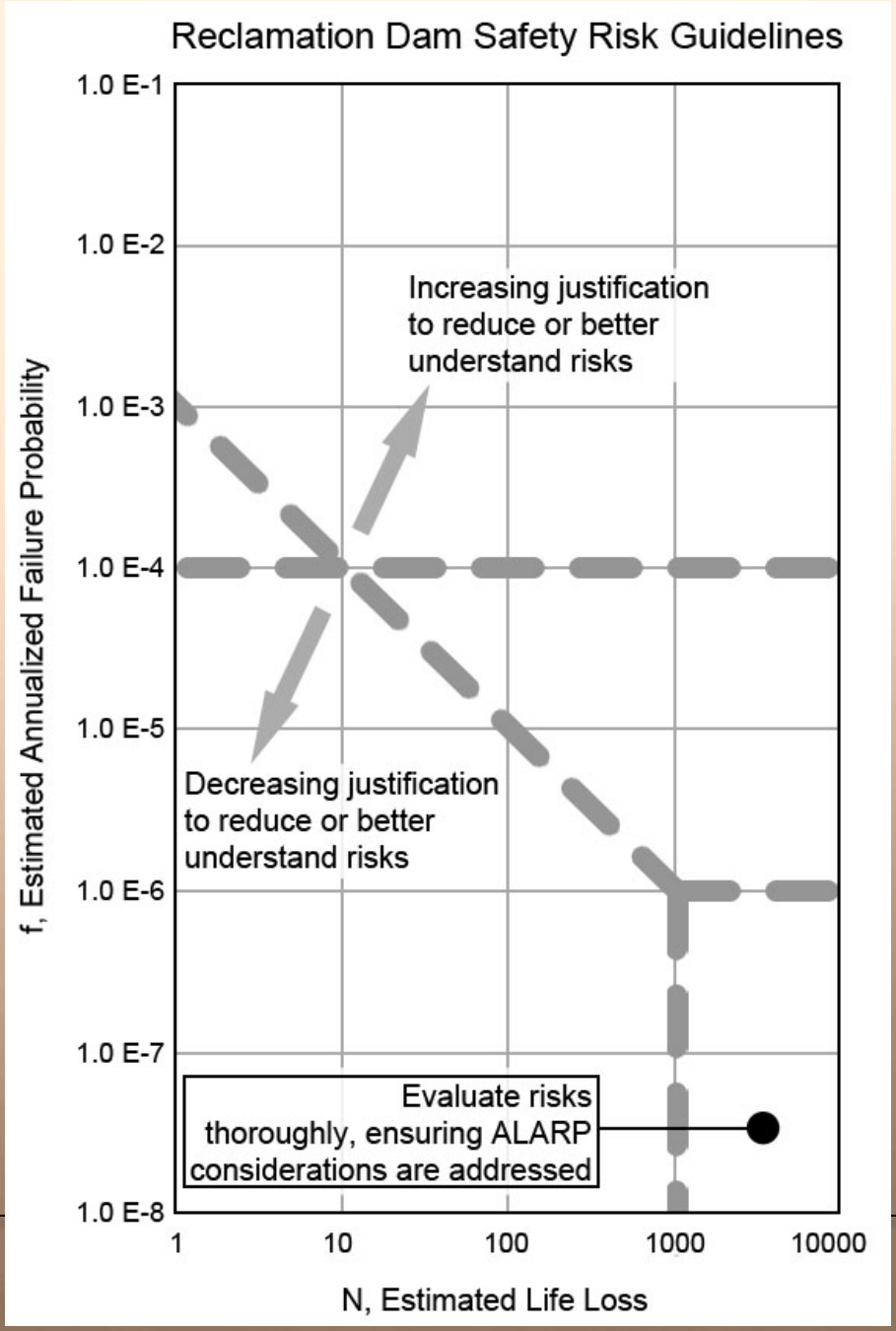
CDA

Guidelines are an order of magnitude lower for new dams and major augmentations

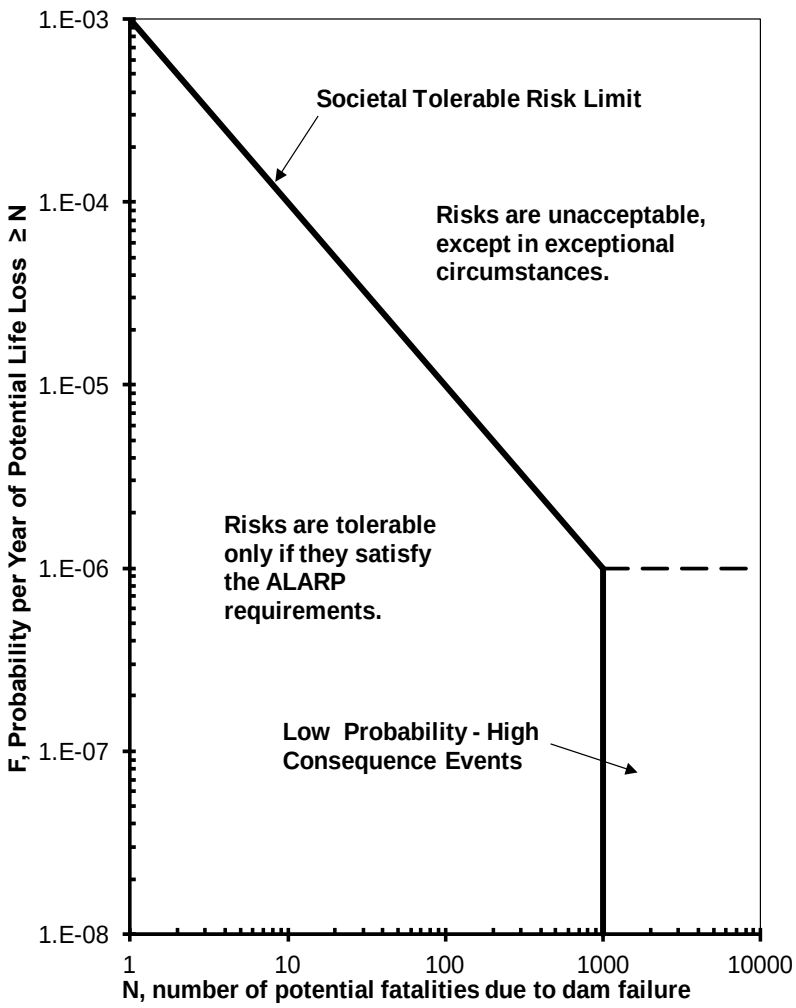


NSW DSC

USBR


Reclamation Dam Safety Risk Guidelines
f, Estimated Annualized Failure Probability
1.0 E-1
1.0 E-2
1.0 E-3
1.0 E-4
1.0 E-5
1.0 E-6
1.0 E-7
1.0 E-8
1
10
100
1000
10000
N, Estimated Life Loss
Increasing justification to reduce or better understand risks
Decreasing justification to reduce or better understand risks
Evaluate risks thoroughly, ensuring ALARP considerations are addressed

USACE


1.E-03
1.E-04
1.E-05
1.E-06
1.E-07
1.E-08
F, Probability per Year of Potential Life Loss ≥ N
Societal Tolerable Risk Limit
Risks are unacceptable, except in exceptional circumstances.
Risks are tolerable only if they satisfy the ALARP requirements.
Low Probability - High Consequence Events
1
10
100
1000
10000
N, number of potential fatalities due to dam failure

(b)

Commonalities / Differences

- Commonalities
  - Annualized Failure Probability
  - Sloping Societal Risk/Annualized Life Loss Threshold
- Differences
  - Flavor of Terminology (e.g. “Increasing Justification” vs. “Unacceptable”)
  - F-N or f-N
  - High Consequence / Low Probability Events

Risk Guidelines

OTHER RISK MEASURES

Other Risk Measures

- Economic
  - Direct
  - Indirect
- Environmental
- Historical/Cultural
- Others

Risk Guidelines

ALARP PRINCIPLE

ALARP

- As Low as Reasonably Practicable
- What can be reasonably done without spending an inordinate amount of time, money, and/or resources relative to the risk reduction benefits, and deciding if that is good enough?

ALARP

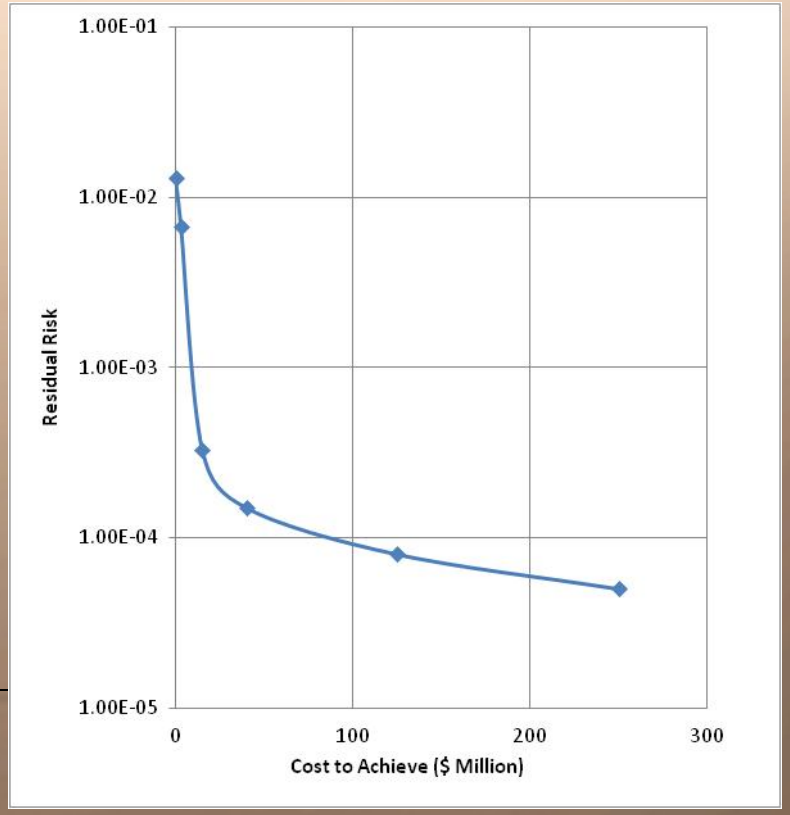
- To make a judgment on whether risks are ALARP, the following should be taken into account (adapted from NSW DSC, 2006):
  - The level of risk in relation to the established risk guidelines;
  - The disproportion between the sacrifice (money, time, trouble and effort) in implementing the risk reduction measures and the subsequent risk reduction achieved;
  - The cost-effectiveness of the risk reduction measures;
  - Any relevant recognized good practice; and
  - Societal concerns as revealed by consultation with the community and other stakeholders.
- The general intent of ALARP is to evaluate whether risks should be reduced, and if so, how far.
- A balance between equity and efficiency is implied by using the principle

Efficiency and Equity Disproportionality

- Efficiency
  - The need for society to distribute and use available resources to achieve the greatest benefit.
- Equity
  - The right of individuals and society to be protected, and the right that the interests of all are treated with fairness.
- Disproportionality
  - Disproportionality measures the ratio of the annualized costs to implement a risk reduction measure versus the annualized risk cost without the risk reduction measure. Disproportionality is used as a method to evaluate ALARP.

ALARP

- A rigorous evaluation of disproportionality can be performed (as described above)
- Or a more qualitative assessment can be considered whereby “break points” related to diminishing returns are identified



Risk Guidelines

RISK ASSESSMENT

Principles

- Remedial actions should do no harm.
- The goal of remedial actions is to reduce risk.
- Some remedial actions may have unintended consequences. In order to implement some remedial actions, construction risks may be excessive during certain phases of the work.
- A remedial action to address a specific potential failure mode can increase the probability of another potential failure mode.
- Decisions should be risk-informed, not risk-based.

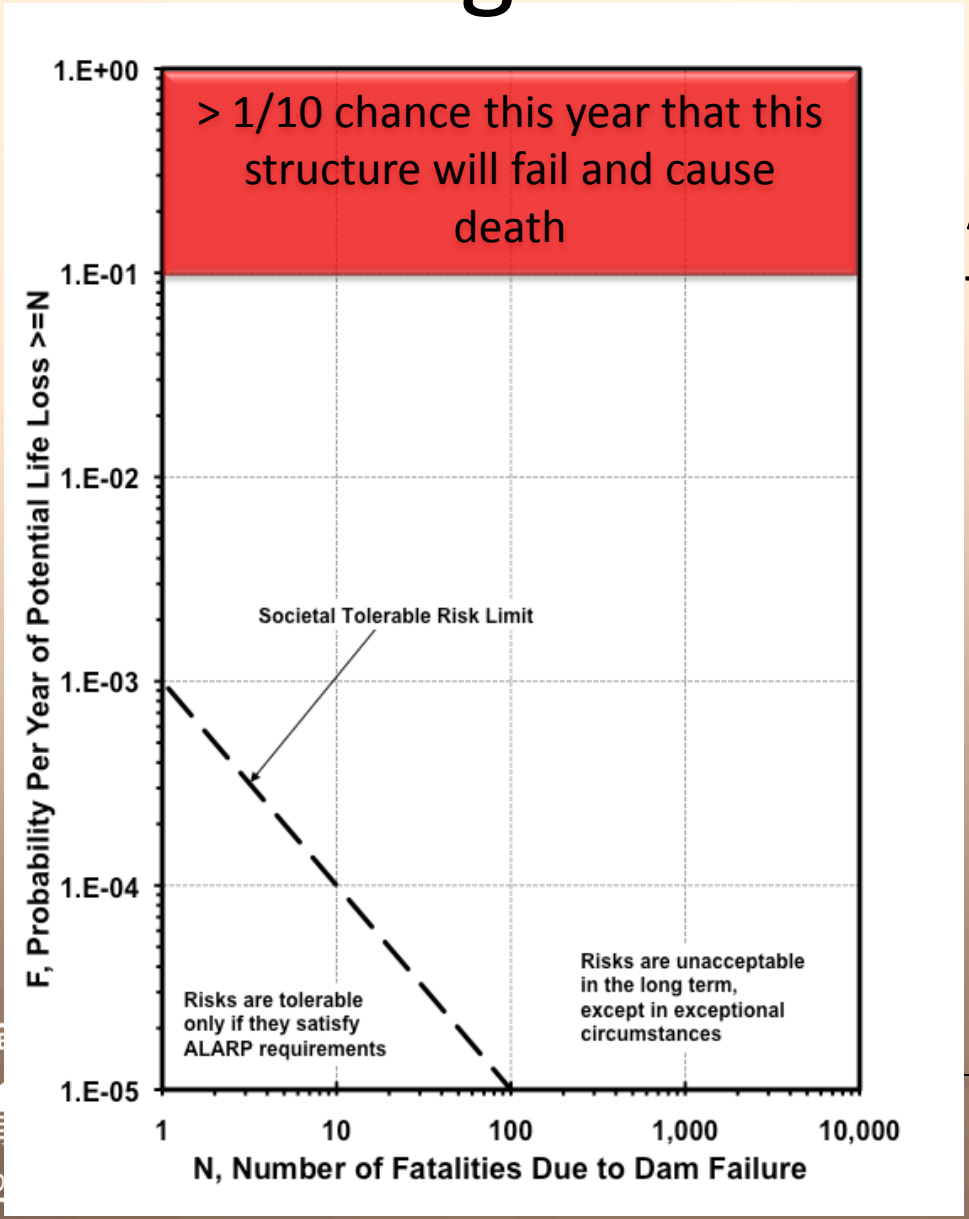
Principles (con't)

- Decisions should be based on consideration of the results of a risk analysis as a key input, but other factors, such as the uncertainty and confidence in the risk estimates, should also be considered.
- Decisions should not be based solely on where risk estimates plot on an f-N or F-N chart.
- The decisions made should consider the risk estimates, including the uncertainty and confidence in the risk estimates, the likely outcomes if dam safety actions are completed, and other factors important to an agency's mission.

Decisions

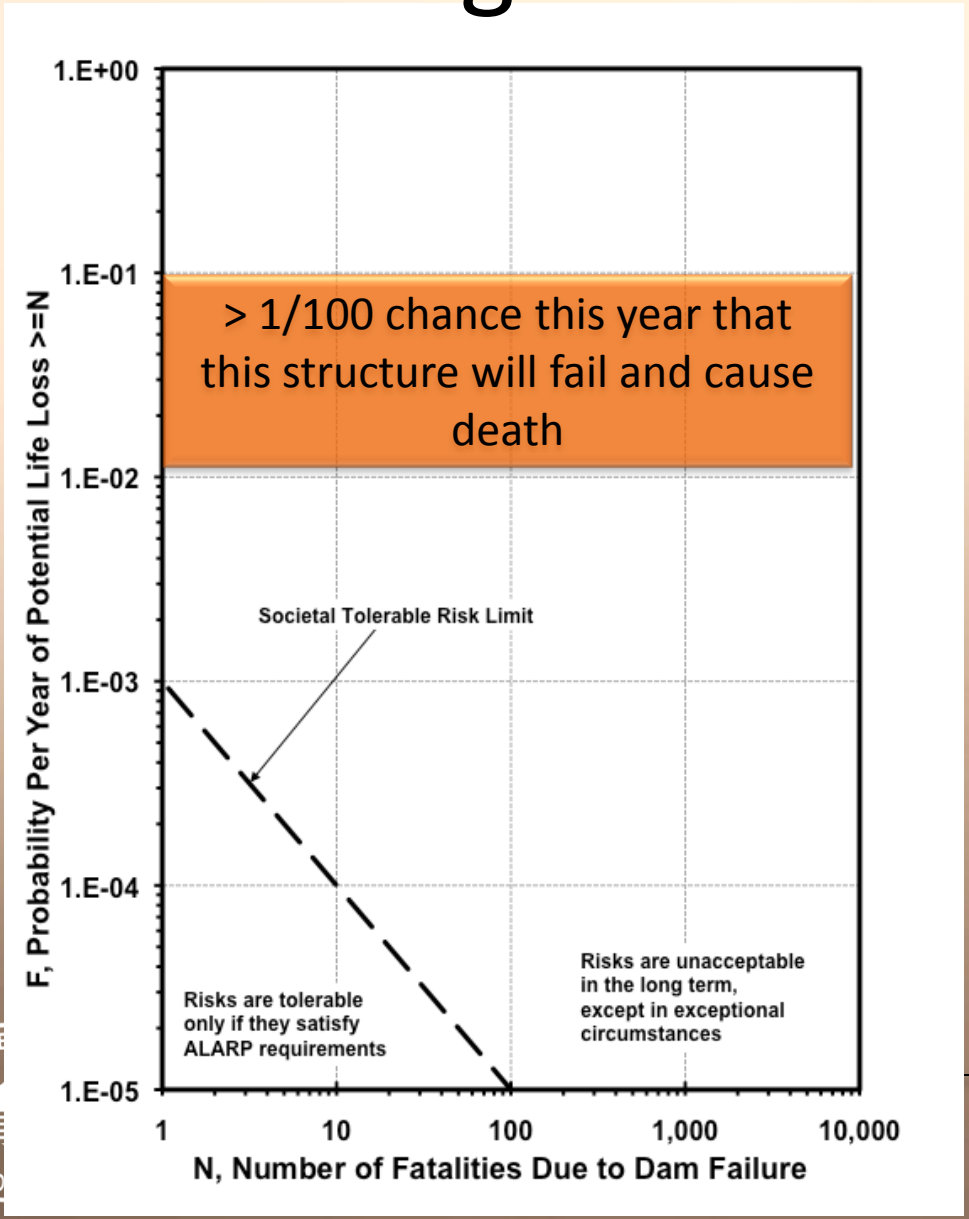
- Four Basic Pieces of Information
  - Risk Estimate
  - Estimated Range of Uncertainty (and Confidence)
  - Case to Support Risk Estimate
  - Recommended Course of Action
- Strategy
  - Use the risk estimate in relation to the risk guidelines and the safety case to support rational consistent decisions

Translating Failure Probabilities



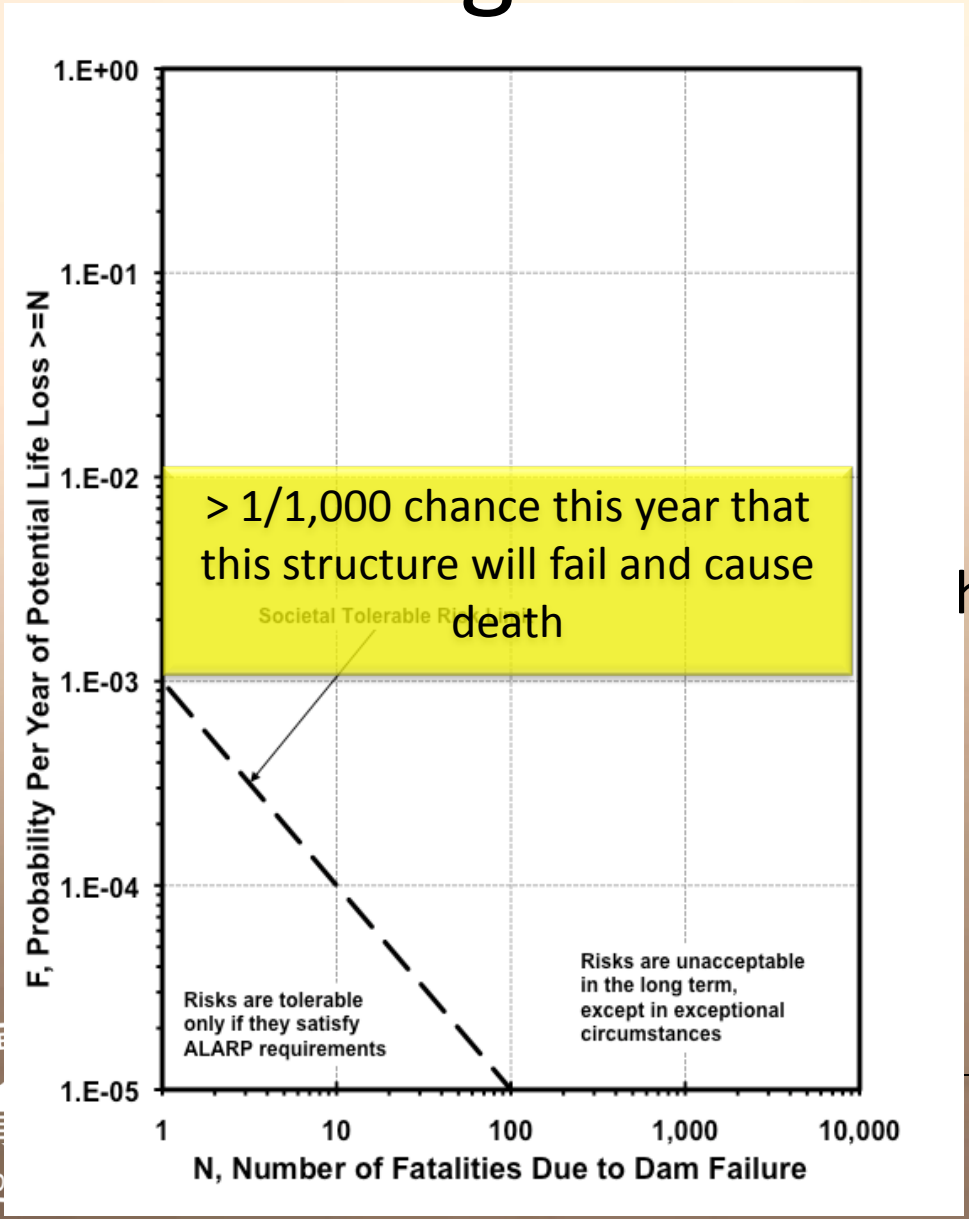
Very Strong Statement! Allowing for uncertainty, failure is virtually certain **THIS YEAR** unless intervention is taken immediately.

Translating Failure Probabilities



Strong Statement. If the structure is a flood risk management facility, this means it is providing zero benefits for the 1% event, and may in fact be increasing consequences for that event – difficult to make the case for risk tradeoffs (severe reservoir restriction)

Translating Failure Probabilities



Likelihood of failure is more than 10 times higher than the average dam in the U.S. This includes all of the high, significant and low hazard structures built by everyone.

Risk Guidelines

RISK MANAGEMENT

Risk Management

- Risk management encompasses activities related to making risk-informed decisions, prioritizing evaluations of risk, prioritizing risk reduction activities, and making program decisions associated with managing an inventory of facilities.
- The primary goal of risk management is to implement actions to either: accept, further monitor or evaluate, control, or reduce risk, while considering the cost and benefits of any actions taken.

Prioritization of Actions

- Reclamation
  - Dam Safety Priority Rating (DSPR)
- USACE
  - Dam Safety Action Classification (DSAC)
  - Levee Safety Action Classification (LSAC)

Principles

- The objective of an organization should be to reduce dam safety risk as effectively and as efficiently as possible.
- Each organization should have a transparent process for establishing priorities and the urgency of completing dam safety actions.
- Incorporate flexibility in prioritizing work within a portfolio, allowing for adjustments in planned work as new, high priority issues are identified.
- Use a dedicated, established group to review and prioritize proposed dam safety actions within a portfolio or when establishing urgency for action at a specific dam.
- Independent review is critical to the credibility of this process.
- The urgency of completing dam safety actions should be commensurate with risk.

Risk Guidelines

EXAMPLE

Example f-N vs. F-N

- Dam with three risk-driver potential failure modes
  - PFM 1 has 2 potential failure scenarios, one w/high consequences and one with low consequences
  - PFM 2 has essentially constant consequences with increasing loading
  - PFM 3 has increasing consequences with increasing loading
- Plot f-N pairs related to potential failure modes
- Plot F-N cumulative risk curve
- Although these are different, it is instructive to plot both on the same graph

Failure End Branch	Annualized Failure Probability	Incremental Life Loss	Annualized Life Loss
Potential Failure Mode 1			
1	2.2E-04	34	7.48E-03
2	1.1E-05	225	2.48E-03
3	7.5E-05	34	2.55E-03
4	3.2E-06	225	7.20E-04
Total	3.09E-04	43	1.32E-02
Potential Failure Mode 2			
1	3.3E-05	125	4.13E-03
2	6.7E-06	125	8.38E-04
3	1.2E-06	125	1.50E-04
Total	4.09E-05	125	5.11E-03
Potential Failure Mode 3			
1	3.6E-05	15	5.40E-04
2	1.1E-05	34	3.74E-04
3	7.3E-06	57	4.16E-04
4	4.5E-06	82	3.69E-04
5	1.3E-06	114	1.48E-04
Total	6.01E-05	31	1.85E-03
Summation			
Grand Total	4.10E-04	49	2.02E-02

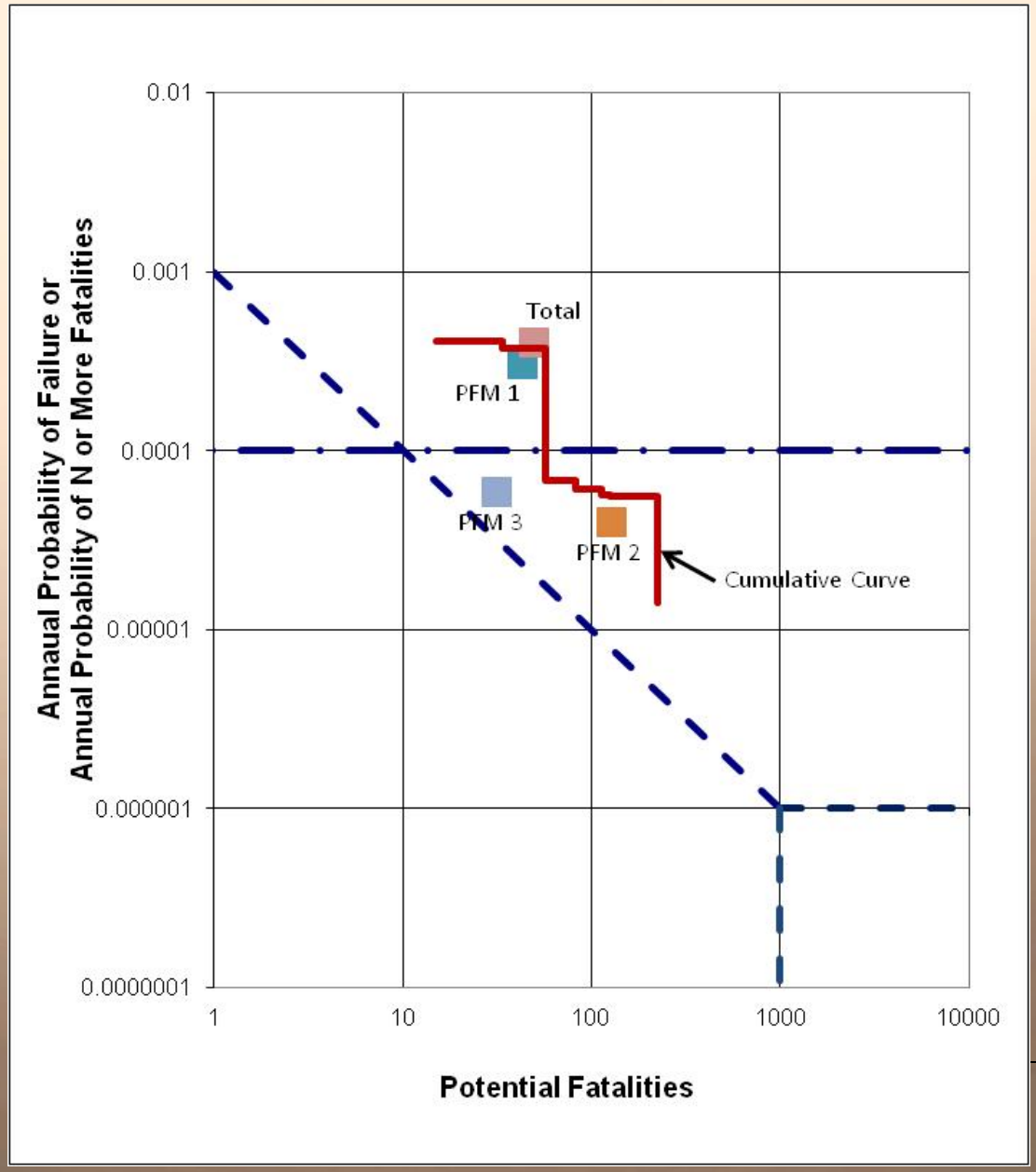
Weighted Value

Cumulative Risk Curve

- Rearrange end branches in order of descending consequences (regardless of failure mode)
- Sum annualized failure probabilities incrementally for each consequence level
- Plot starts at highest consequence level, steps up to next incremental AFP, then steps left to next highest consequence level, etc.

Potential Failure Mode	End Branch	Consequences	Annualized Failure Probability	Cumulative Failure Probability
1	4	225	3.2E-06	1.42E-05
1	2	225	1.1E-05	
2	3	125	1.2E-06	5.51E-05
2	2	125	6.7E-06	
2	1	125	3.3E-05	
3	5	114	1.3E-06	5.64E-05
3	4	82	4.5E-06	6.09E-05
3	3	57	7.3E-06	6.82E-05
3	2	34	1.1E-05	3.74E-04
1	3	34	7.5E-05	
1	1	34	2.2E-04	
3	1	15	3.6E-05	4.10E-04

Example Plot



f-N Plot

- All three potential failure modes exceed Societal Risk/Annualized Life Loss Guidelines individually
- PFM 1 also exceeds annualized failure probability/individual risk guideline
- Total risk exceeds both guidelines
- PFM 1 contributes most of the risk

F-N Plot

- There are some failure scenarios with as many as 225 lives lost and some with as little as 15
- The probability of various consequences levels is illustrated
- All failure scenarios exceed risk guidelines individually and some may exceed individual risk guidelines

F-N vs. f-N plot

- Both plots convey similar information
- Reclamation has opted for the f-N plot exclusively since it is failure mode focused and experience suggests it is easier for decision makers to understand
- USACE uses both