RAC

Engineers & Economists

Utah State University

Workshop on Probabilistic Flood Hazard Assessment – January 2013

Risk-Informed Approach to Flood-Induced Dam and Levee Failures

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United States Nuclear Regulatory Commission
Protecting People and the Environment

U.S. Department of the Interior Bureau of Reclamation

USGS science for a changing world

Who is using risk assessment?

- Reclamation ~ 1995
- Federal Energy Regulatory Commission (FERC) for PFMA ~ 2002
  - Planned introduction of RA (dual path likely) ~ 2015
- Corps of Engineers (USACE) – dams & levees ~ 2007
- USA – Tennessee Valley Authority (TVA) ~ 2011
- Some states
- Many other countries ….

Uses of risk assessment:

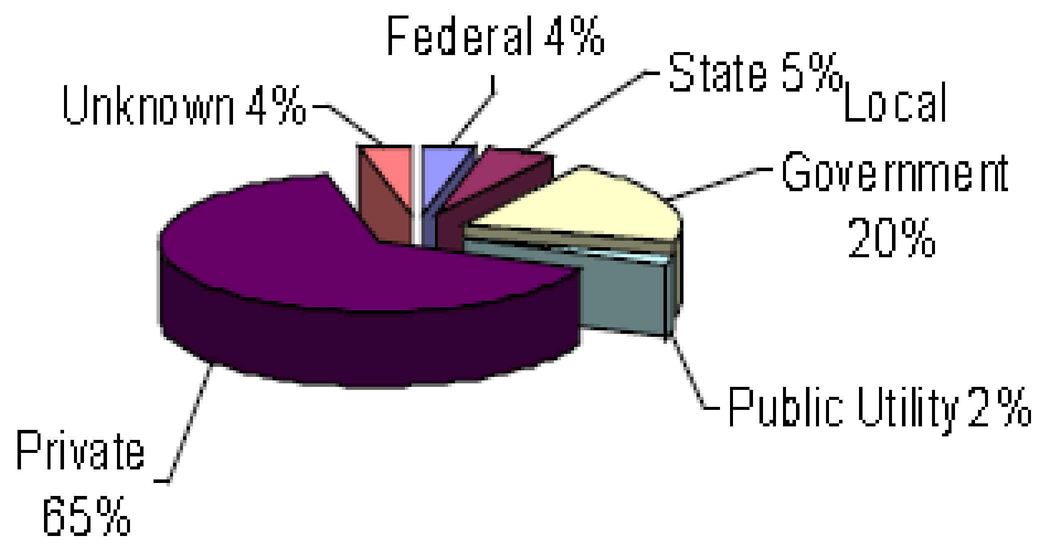
- Risk-informed approach
- Informing decisions about:
  - Understanding existing risks
    - Failure modes, probabilities and consequences
  - the extent and type of risk reduction
    - Structural, non-structural
  - the urgency, priority and phasing of risk-reduction measures
- Informing business processes

Regulation of US dams

Federal dams – self-regulated

Hydropower dams – most regulated by FERC (and the States)

Other dams – most regulated by the States



Trend in regulatory and governance

- Related to incorporation of risk approach into regulation
- From **standards-setting** + **process** to **goal-setting** + **process** e.g. NSW DSC:
  - *Principle C.1: the DSC's approach is practicable **goals-based regulation** and it sets its safety objectives accordingly*
  - *Principle E.3: safety improvements required by the DSC may be **implemented progressively** …*
- Similar trend in **governance** of dam safety by owners that are using risk:
  - Reclamation & USACE: a) defined portfolio risk management **process**, b) emphasize "**making the case**" for safety in contrast to meeting standards, and c) re-evaluation of which standards are "essential"
  - UK dam owner – **rate case, in-house committee**, **"extra-practice" risk reduction** measures not required by "regulator" but to meet safety goals

Outline

- Risk assessment process
- Steps in the process
- Example of results format
- Long dams – levees
- Uncertainty
- Conclusions

Risk Assessment Process: Individual Dams

ICOLD Bulletin 130 terminology

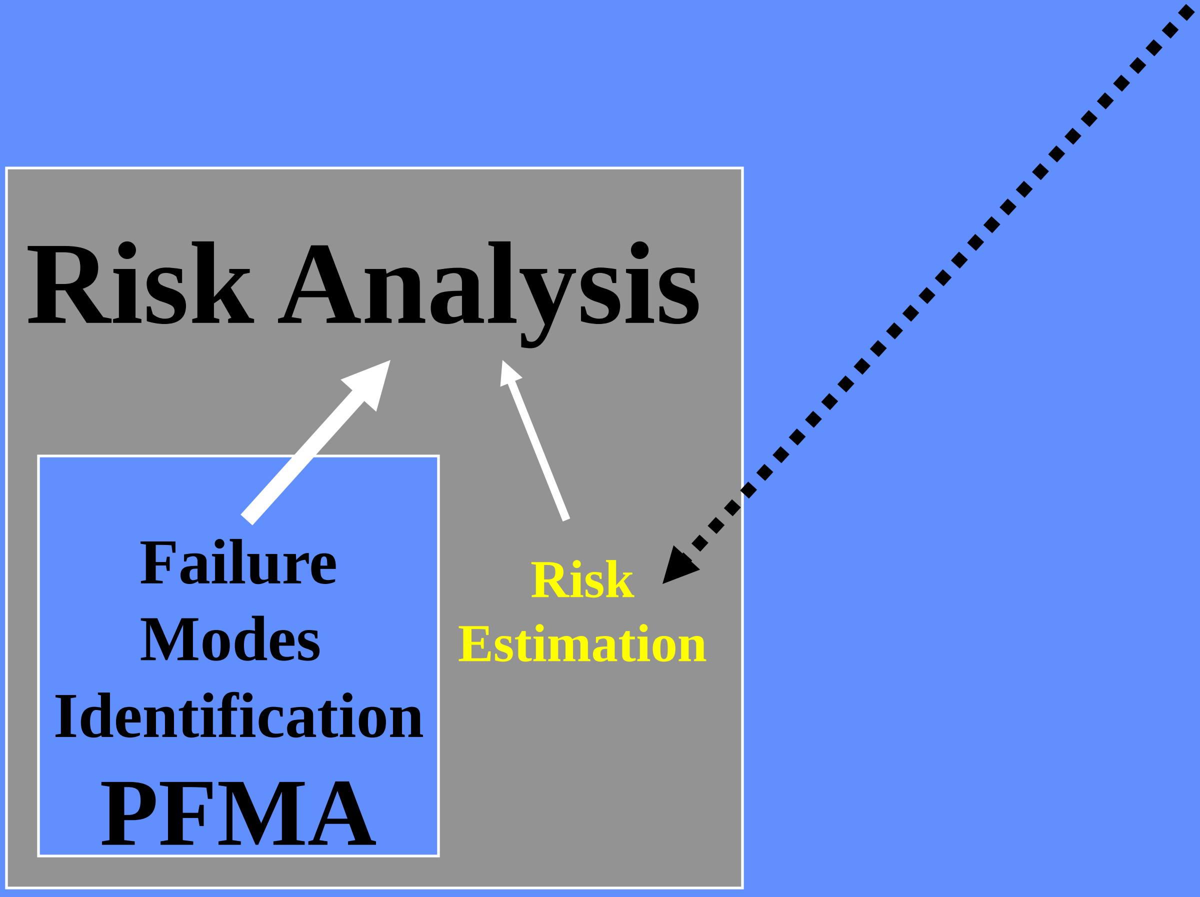
Differs slightly from USACE/OMB terminology

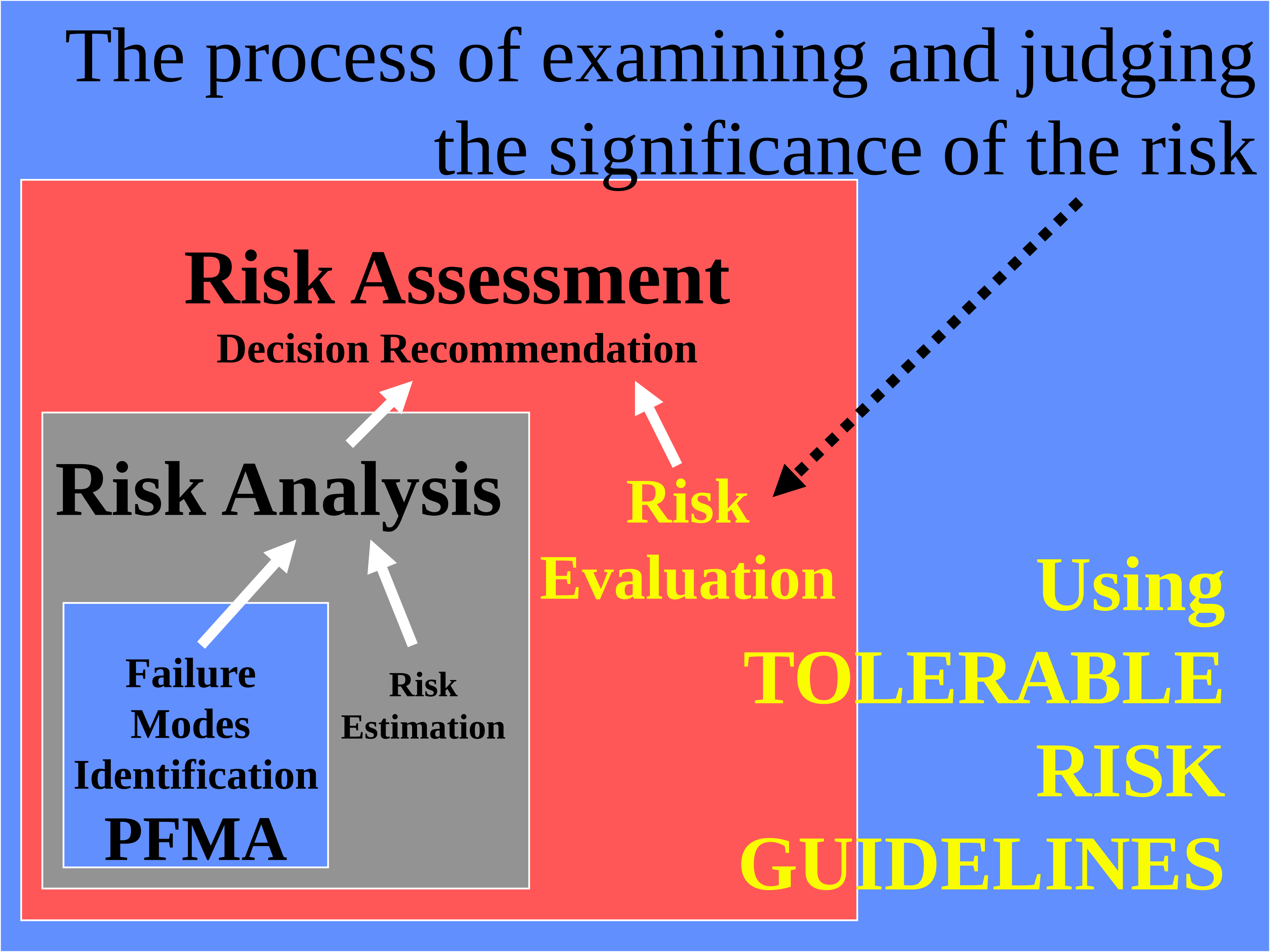
The process of determining a) what can go wrong, why and how, *and b) its consequences*

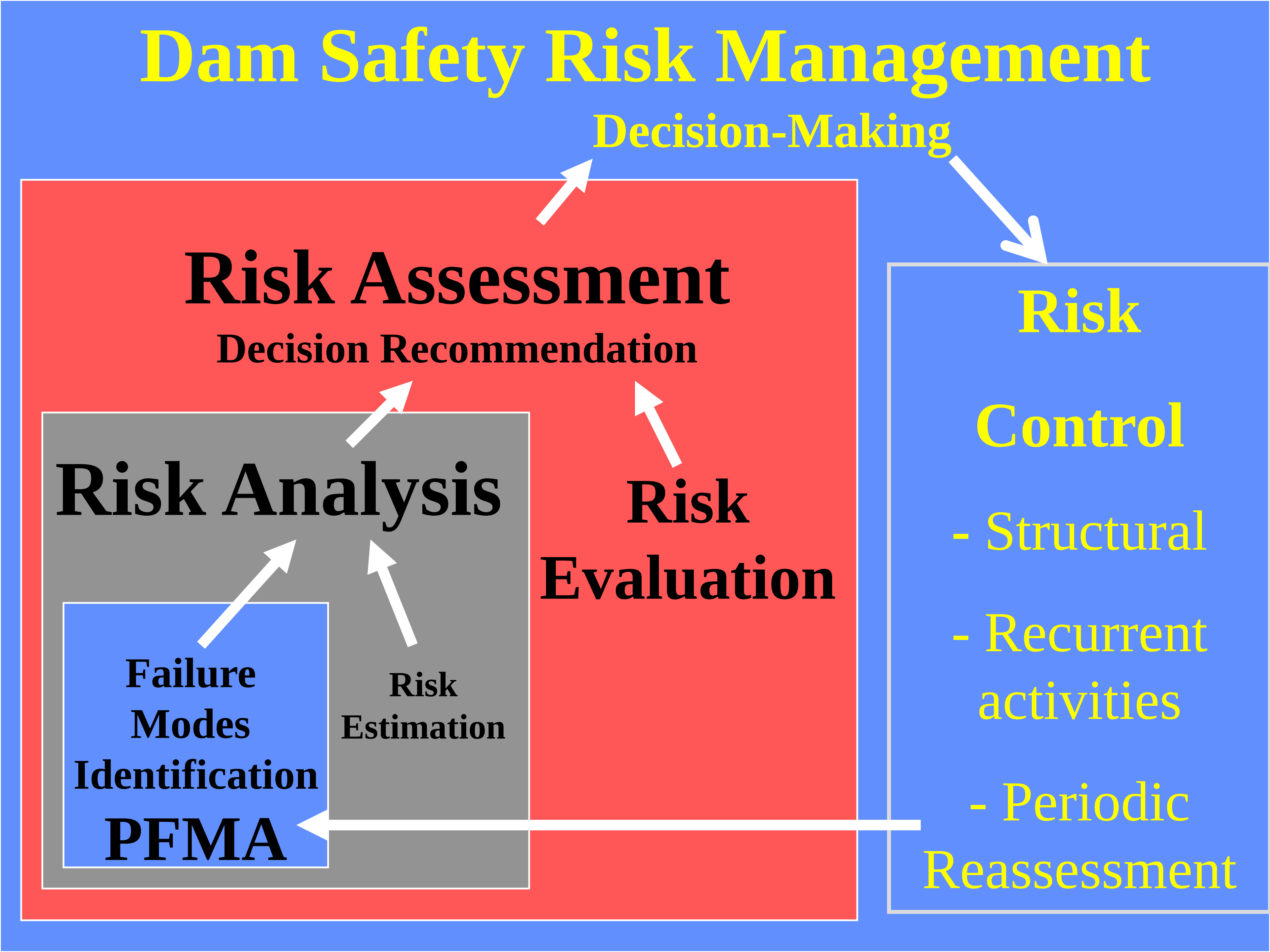
FOUNDATION for RA

Scoping & Risk Identification (PFMA)

The process of quantifying risk: probability (f) and consequences ($, N)




The process of examining and judging the significance of the risk
Risk Assessment
Decision Recommendation
Risk Analysis
Risk Evaluation
Using TOLERABLE RISK GUIDELINES
Failure Modes Identification
PFMA
Risk Estimation


Dam Safety Risk Management
Decision-Making
Risk Assessment
Decision Recommendation
Risk Analysis
Failure Modes Identification
PFMA
Risk Estimation
Risk Evaluation
Risk Control
- Structural
- Recurrent activities
- Periodic Reassessment

Scoping

Scoping and *Risk Identification*

1) **Decisions**
    - **Existing reservoir**
    - **Scope of potential risk management actions**: *Investigations | Surveillance, monitoring and measurement improvements, supervision and management | Interim/immediate risk reduction measures |Long-term risk reduction options | Non-structural risk reduction measures*
2) **Decision context**
    - *Standards and good practice | Stakeholders | safety and Economic Regulators | Owner (governance, insurance, contractual, legal, etc.) | Societal concerns | Environmental | Critical infrastructure and national defence*
3) **Team** composition and roles – **stakeholders**
4) **Decision criteria/guidelines**
    - *Accepted good practice | Tolerability of risk incldg. ALARP | Additional decision bases (owner & stakeholders)*
5) **Level of confidence desired** for decision making
6) ***Define Reservoir System***
7) ***Types of threats and (credible and significant) failure modes***
8) ***Types of consequences***
9) **Define Risk Model Requirements and approach to uncertainty**

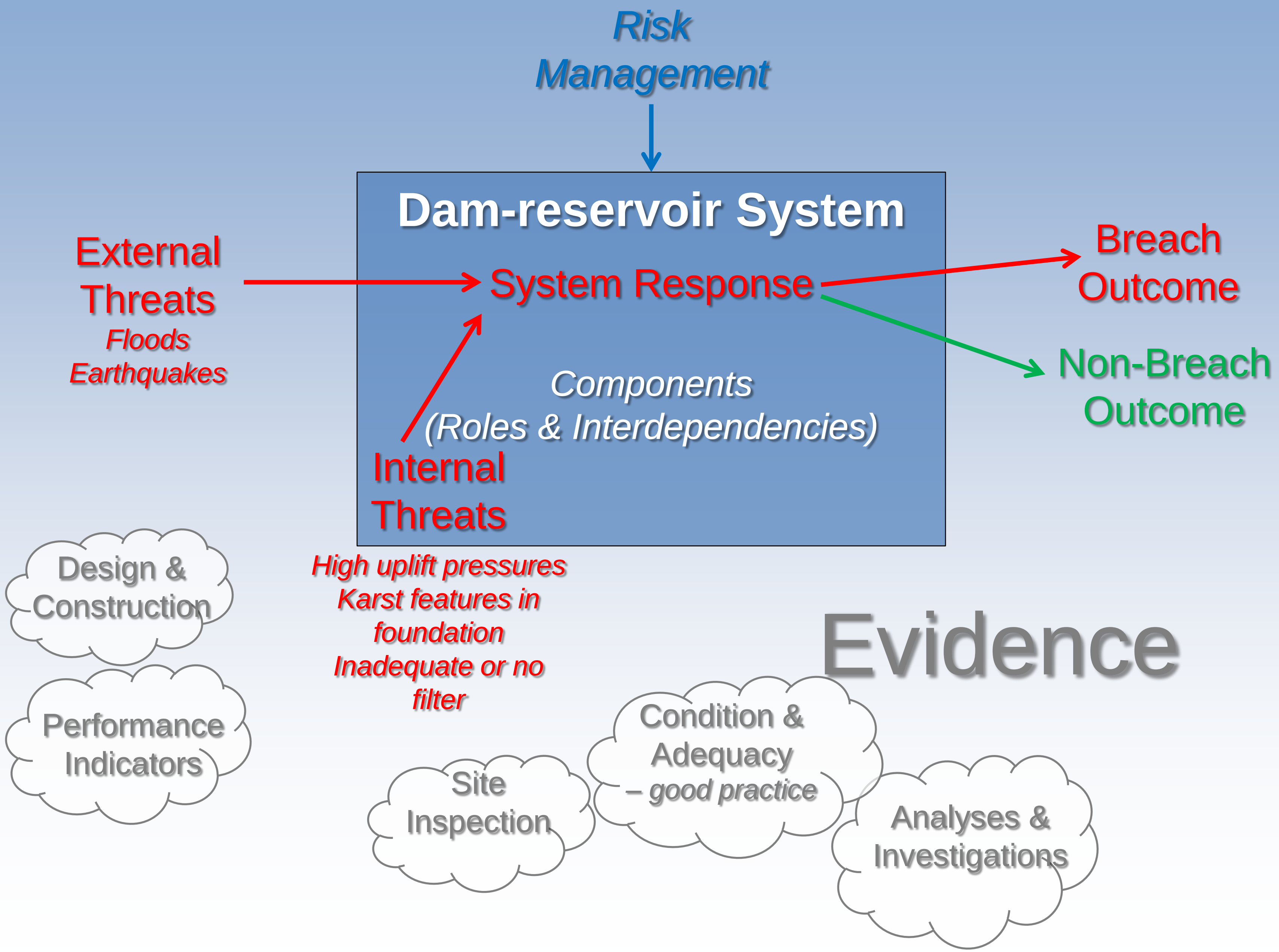
Risk Identification

Hazards – System Response - Consequences

Identification of Potential Failure Modes

- Deductive approach:
  - Systematic **decomposition** of dam into components
  - Identification of the **functional interdependencies** between all components over a **complete range of magnitudes of all types of threats** (initiating events/types of loading)
  - **Resources lists** of threats and potential failure modes
  - Use **outcomes of Engineering Assessment against good practice** BUT think beyond traditional analyses
- Inductive approach
  - Lateral thinking
  - Brain storming
  - Uncommon, unique or odd ball failure mode

Failure modes identification



Dam-reservoir system

Hardware

- Reservoir
- Hillsides
- Dam(s)
- Abutments
- Foundations
- Appurtenances
- Equipment
- Instrumentation
- Communications
- Other features relevant to safe operation

Dam-reservoir System

Components
(Roles & Interdependencies)

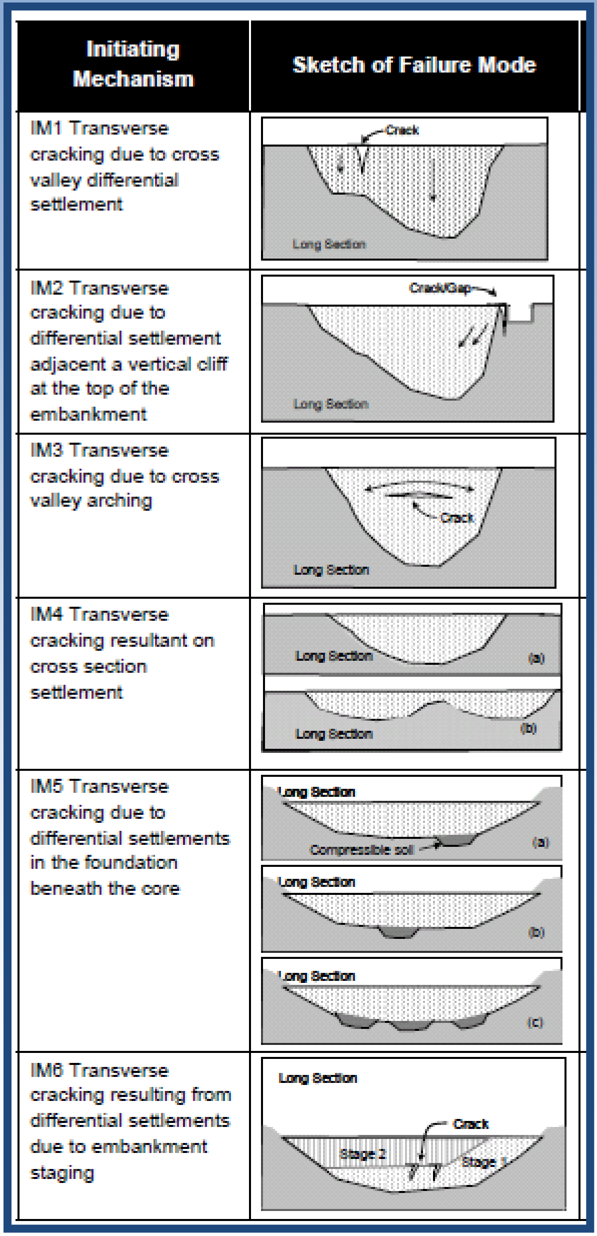
Liveware - Human factors

- Operations & maintenance
- Monitoring & surveillance
- Supervision & inspection
- Management – on & off site

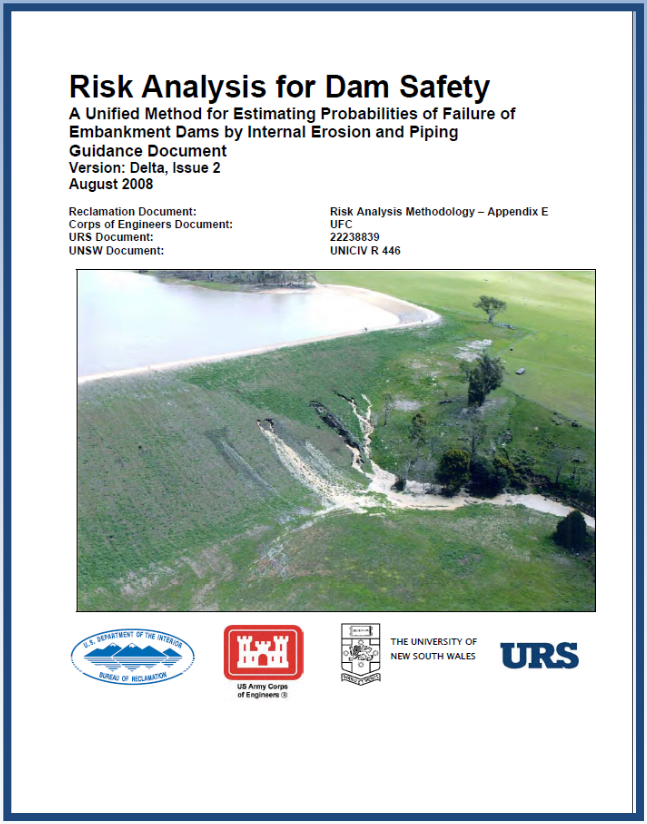
Software - manuals, logic, procedures & software

- Operations & maintenance
- Monitoring & surveillance
- Inspection
- Automated or remote control of operations
- Inflow flood forecasts
- Management systems
- Decision protocols

"Resource lists"



Initiating Mechanism	Sketch of Failure Mode
IM1 Transverse cracking due to cross valley differential settlement	Crack; Long Section
IM2 Transverse cracking due to differential settlement adjacent a vertical cliff at the top of the embankment	Crack/Gap; Long Section
IM3 Transverse cracking due to cross valley arching	Crack; Long Section
IM4 Transverse cracking resultant on cross section settlement	Long Section (a); Long Section (b)
IM5 Transverse cracking due to differential settlements in the foundation beneath the core	Long Section; Compressible soil (a); Long Section (b); Long Section (c)
IM6 Transverse cracking resulting from differential settlements due to embankment staging	Long Section; Crack; Stage 2; Stage 1



Risk Analysis for Dam Safety

A Unified Method for Estimating Probabilities of Failure of Embankment Dams by Internal Erosion and Piping

Guidance Document

Version: Delta, Issue 2

August 2008

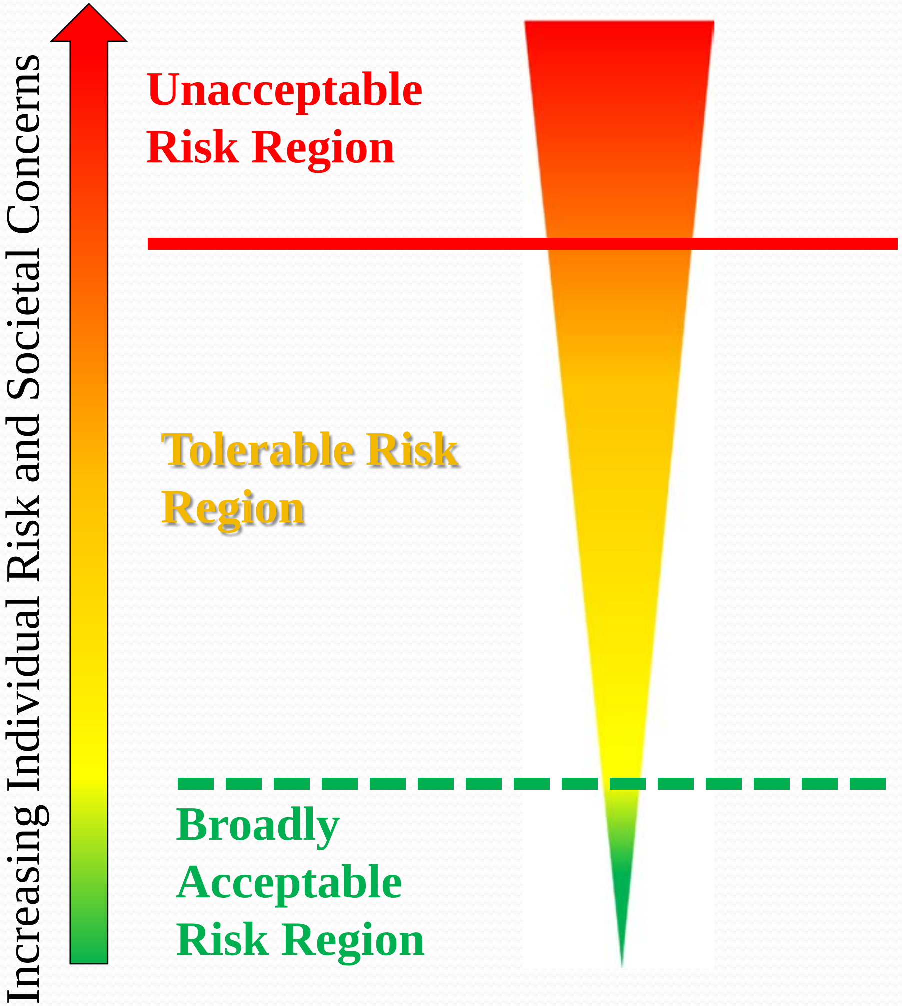
Reclamation Document:	Risk Analysis Methodology – Appendix E
Corps of Engineers Document:	UFC
URS Document:	22238839
UNSW Document:	UNICIV R 446

Risk Evaluation

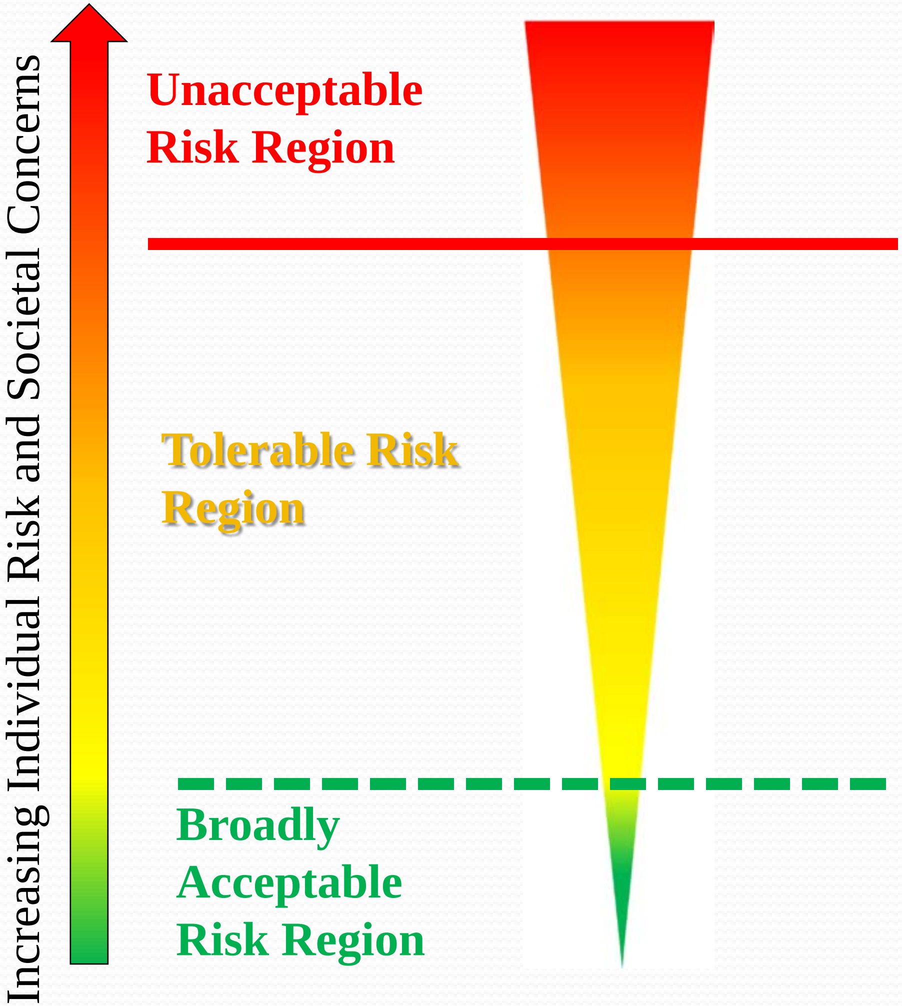
Tolerability of Risk – Tolerable Risk Guidelines

Tolerability of Risk Framework

(HSE 2001)

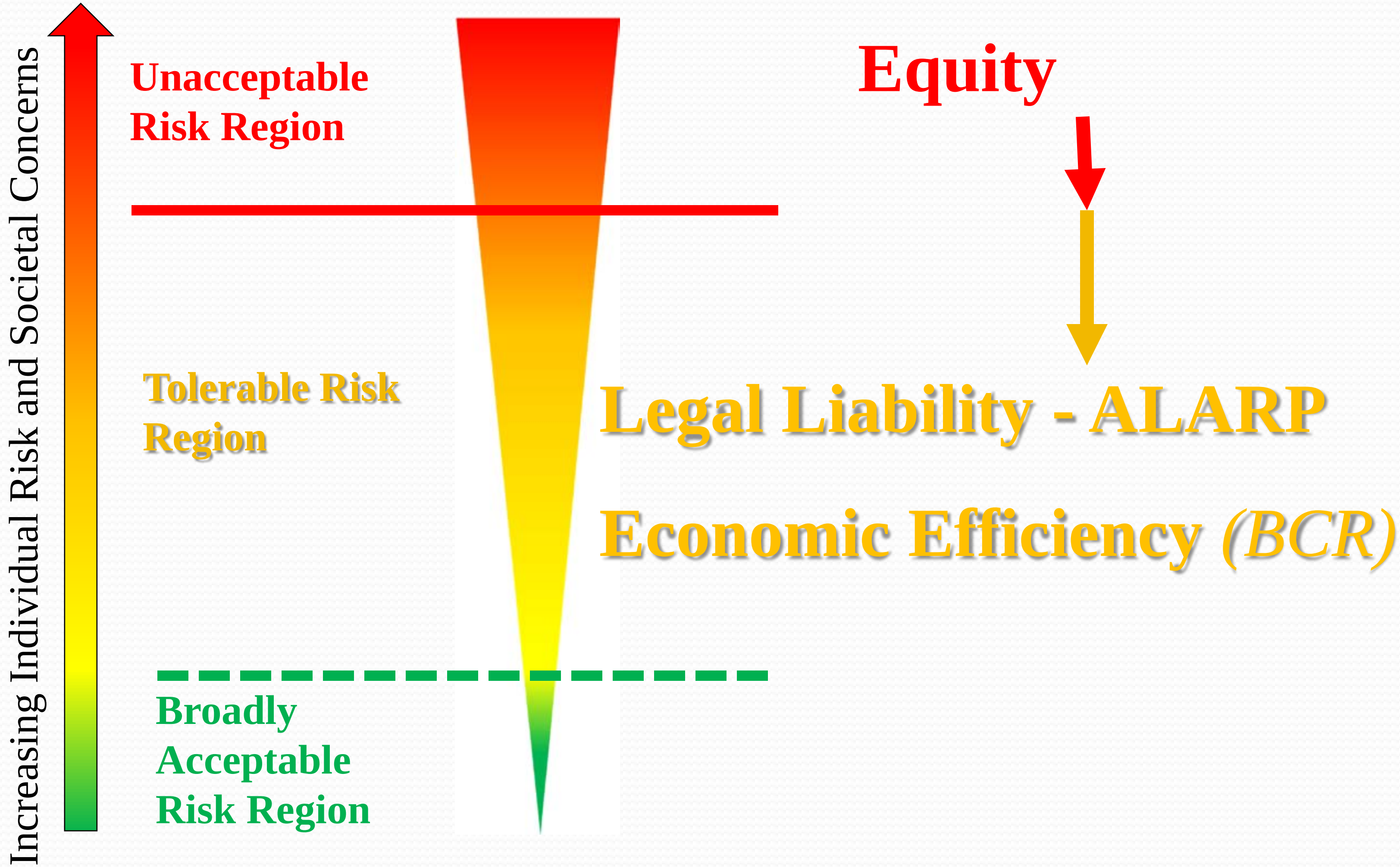


Risk

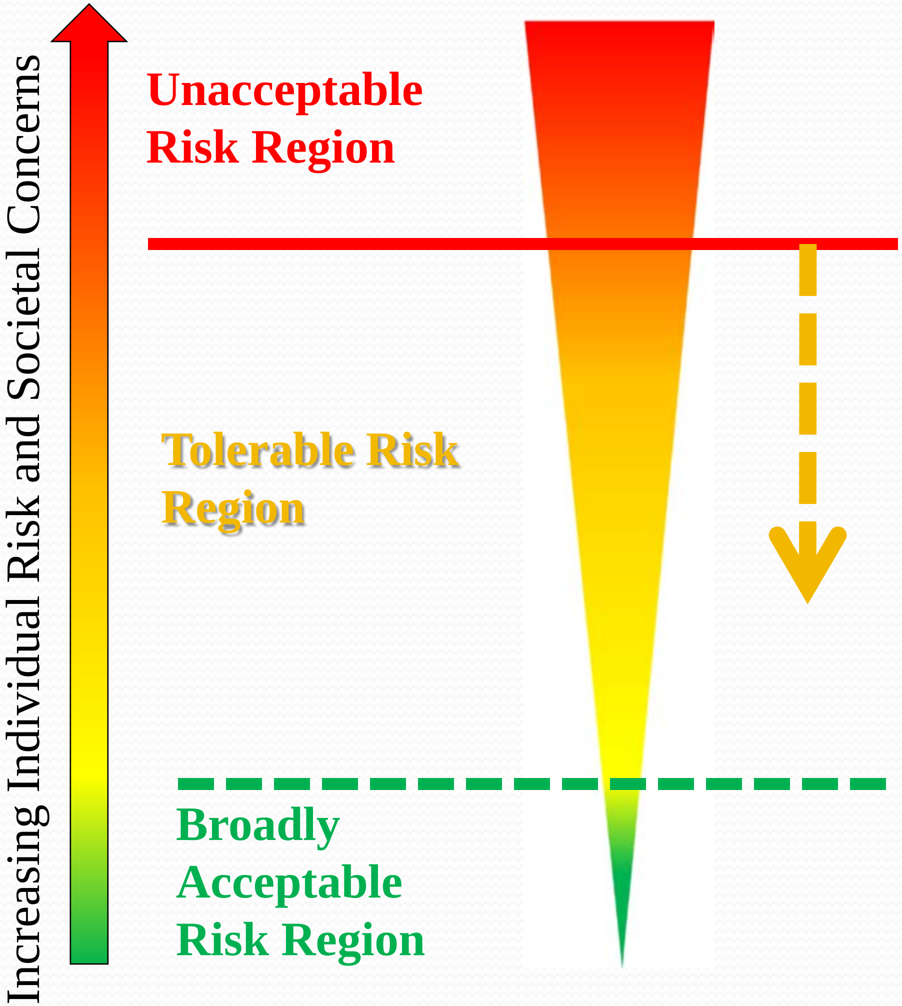


- *The* ***probability*** *of undesirable* ***consequences***
- *Probability of an* ***uncontrolled release*** *of the contents of a reservoir*
- *Probability of consequences to* ***life, health, property, or the environment*** *of dam failure (NPP effects)*

General basis for reducing risk

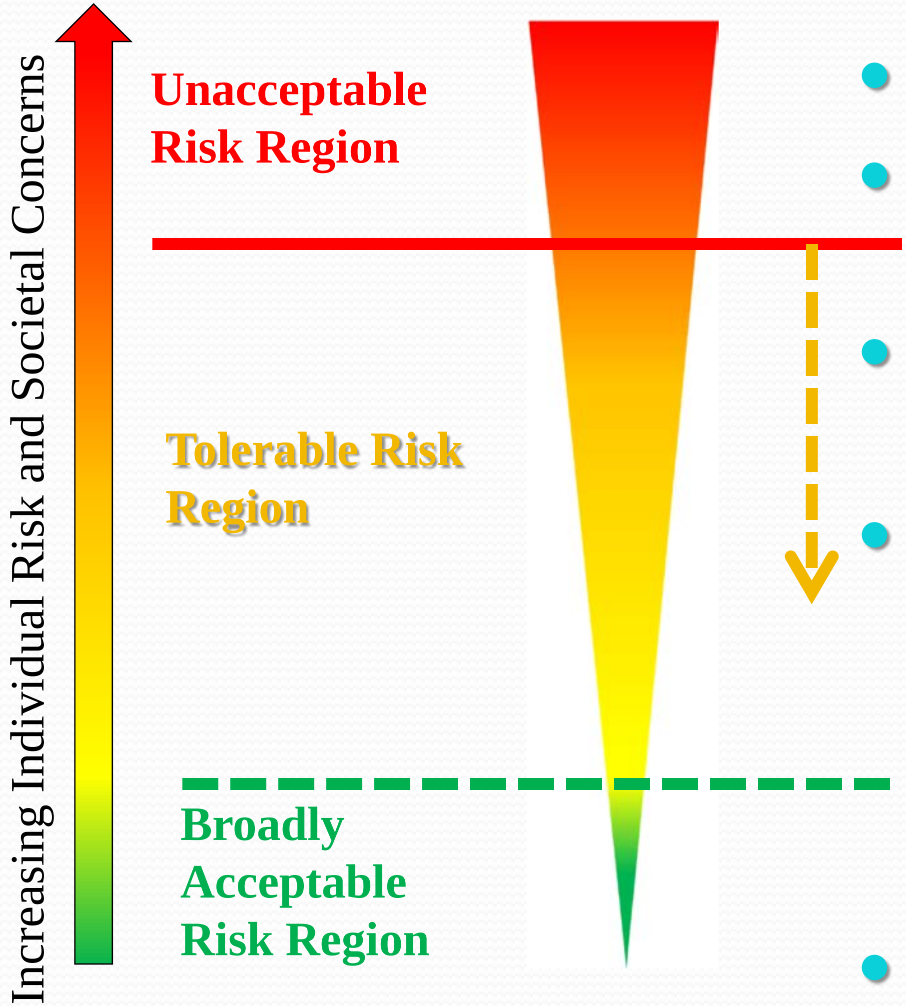


TOLERABLE RISK REGION



- People are prepared to accept risk in the Tolerable Region to secure benefits (1) provided that:
  - Not so low as to be broadly acceptable (2)
  - Confident risks are being properly assessed and managed (3)
  - Residual risks are periodically reviewed and, if appropriate, are further reduced to ensure that they remain as low as reasonably practicable (ALARP) (4)
- Tolerable risk not defined simply by a line
- Determined by on-going management not just design considerations

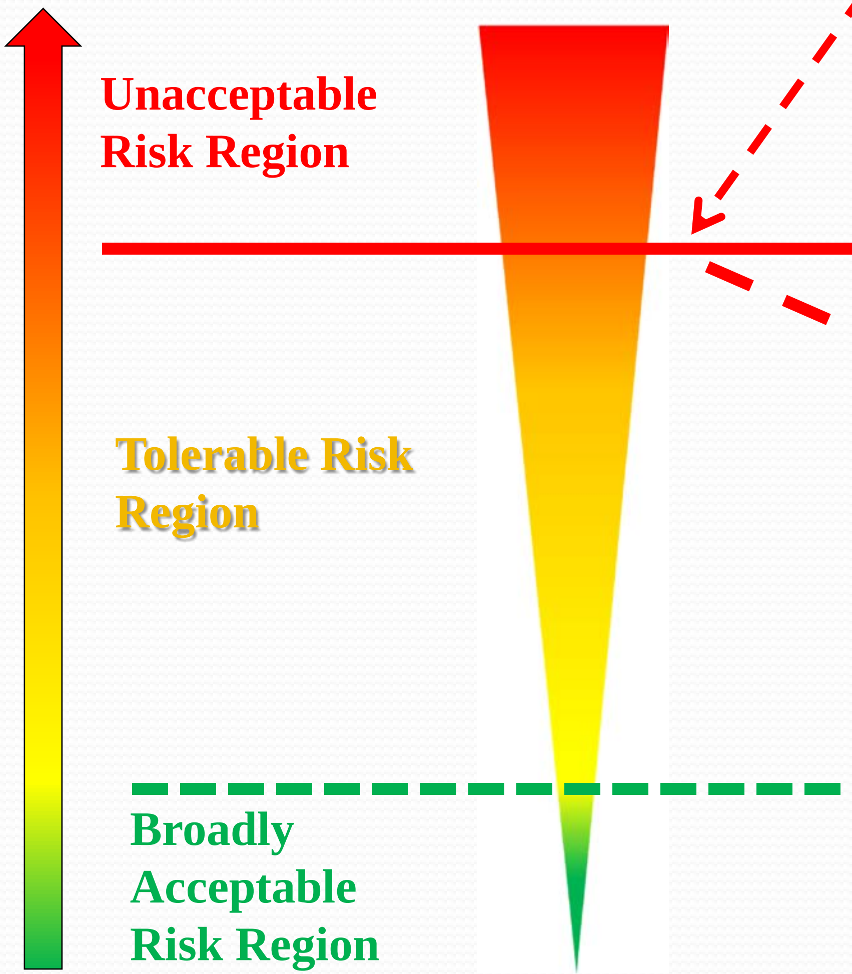
ALARP

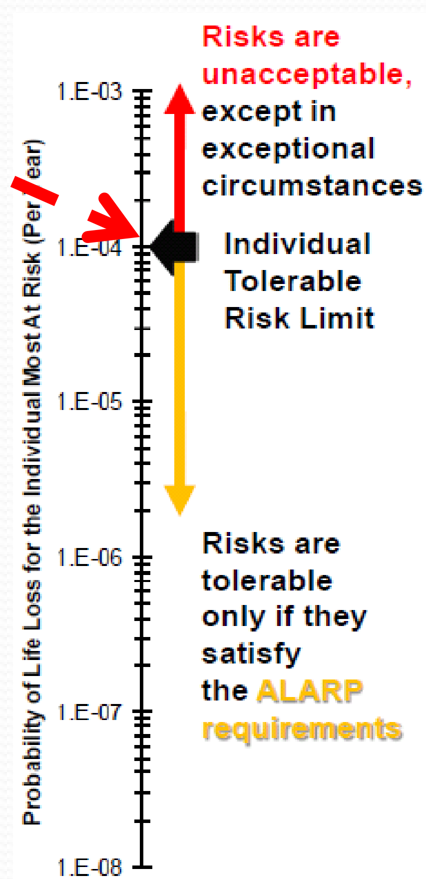


- Optioneering: *"One accepts options, not risks" Fischhoff et al. (1981)*
- Affordability not considered
- Consider risk transfers
  - E.g. d/s to u/s for dam raise
- Accepted good practice **RISK INFORMED**
- Disproportionality of incremental cost to incremental risk reduction benefit *(BCR goal < 1.0, e.g. 0.1 – 0.33, Ford Pinto class action ~ 1.0)*
- Ultimately matter of judgment
- Considers societal concerns

USACE Individual Risk (IR) Limit = 1 in 10,000 /yr

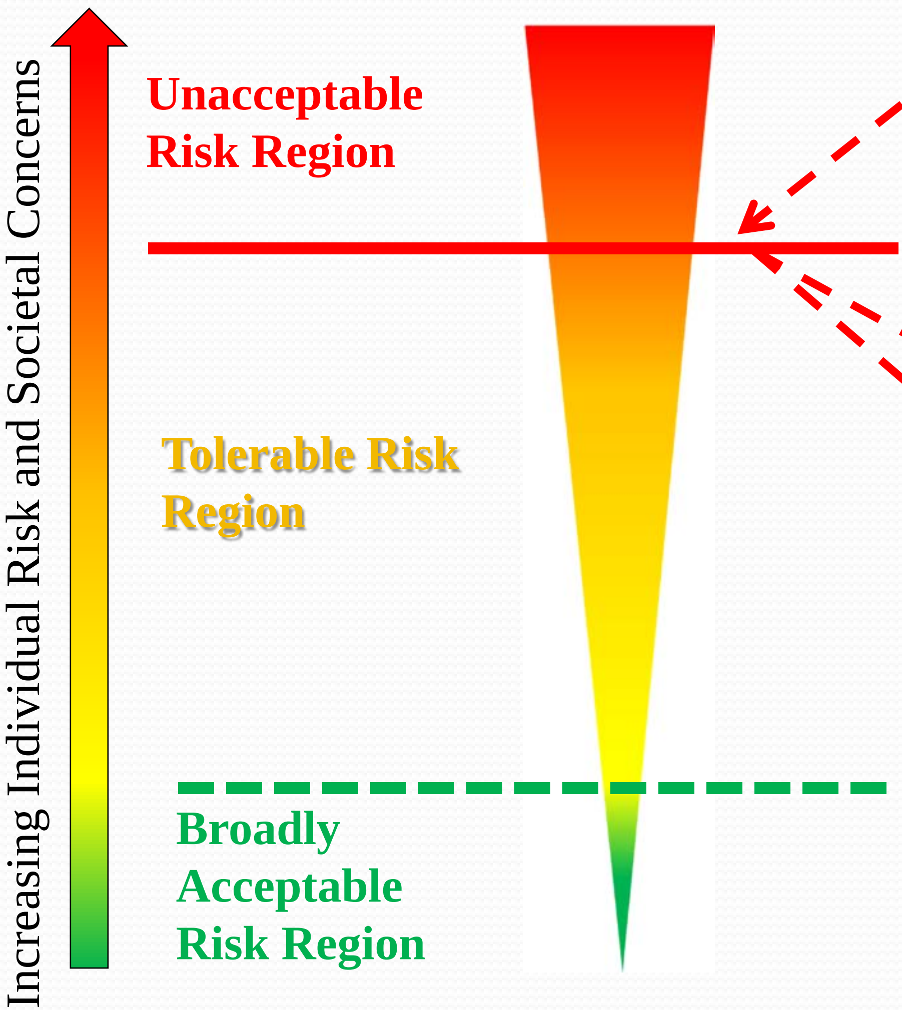
- Probability of life loss for the most exposed individual
  - IR = APF*Prob (Exposure|Failure) *Prob(Life Loss|Exposure&Failure)

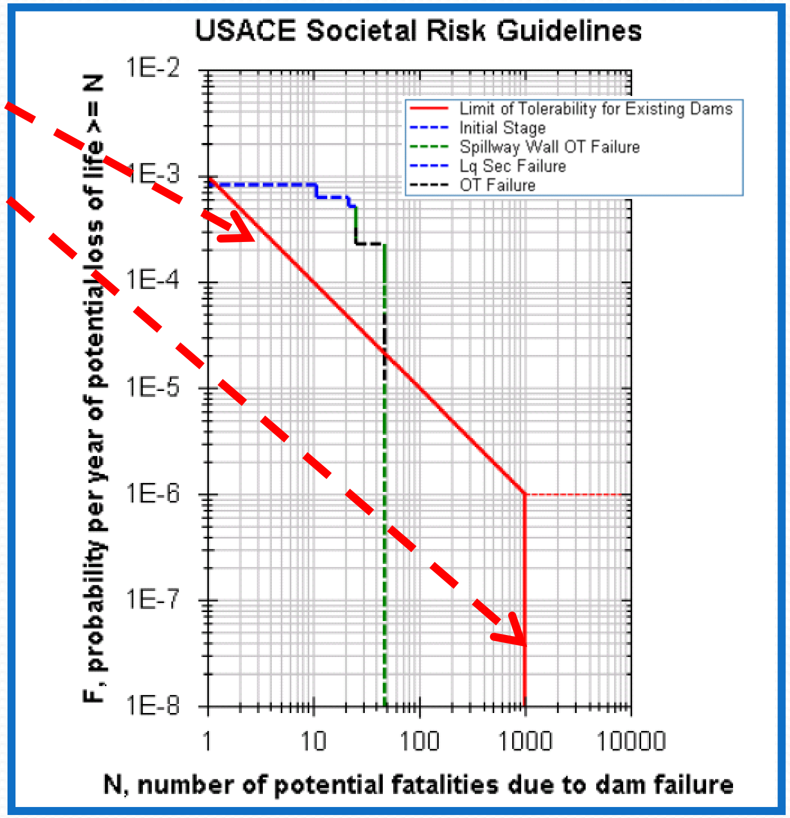




USACE Societal Risk Limit

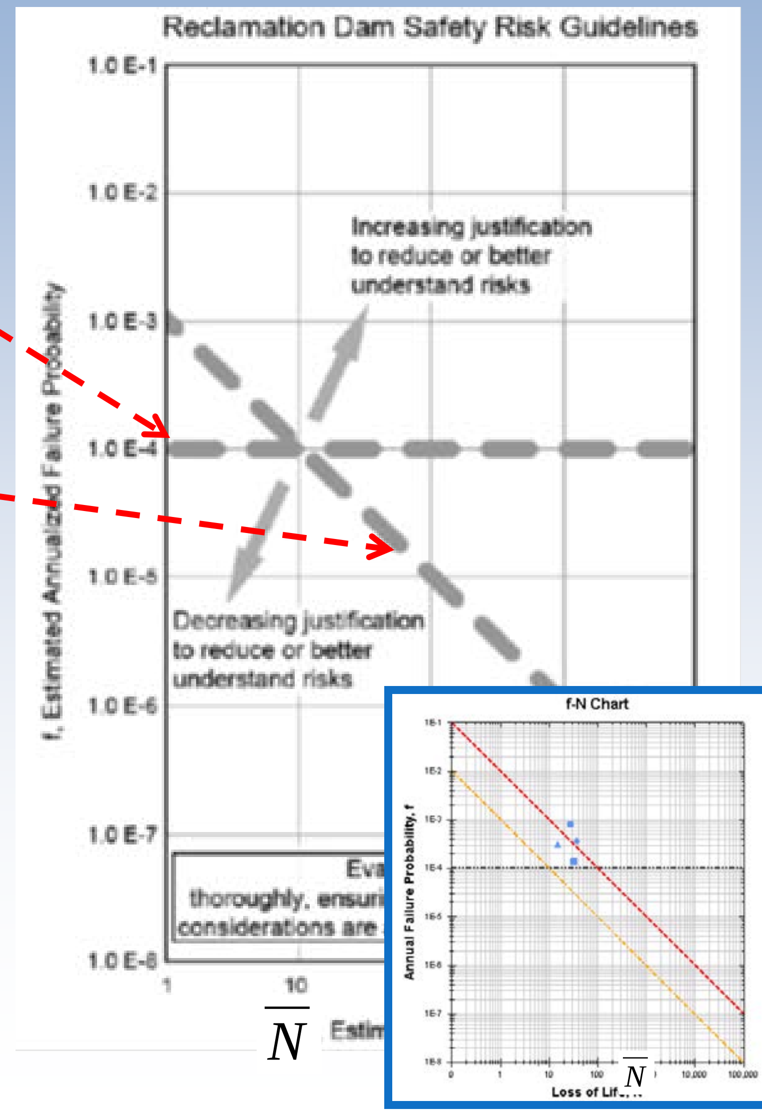
- A probability distribution (F-N chart) of the number of fatalities in the entire Population at Risk



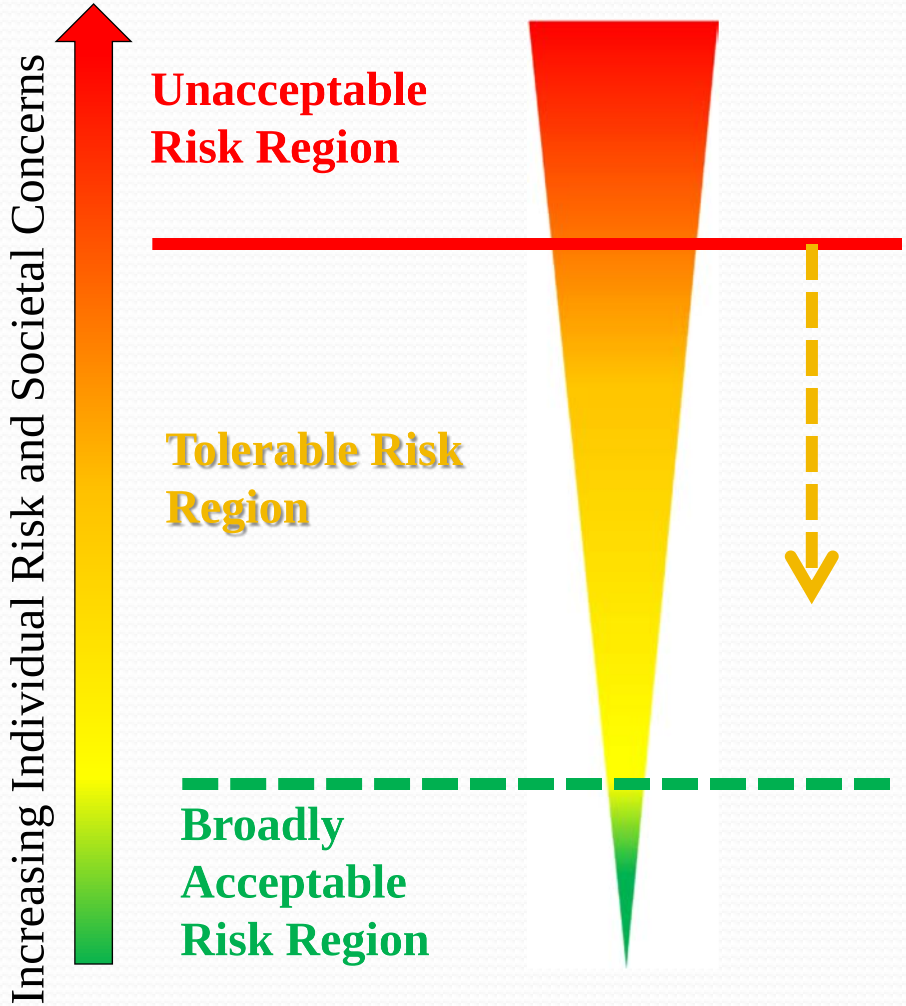


Reclamation (2011) dam safety risk guidelines chart

- Different to an F-N chart
- Annual Probability of failure (APF) guideline is horizontal line at 1 in 10 000/year
  - Originally based on Reclamation portfolio failure rates
  - Now referred to as a substitute for an individual risk guideline
- Annualized Life Loss (ALL) guideline is sloping line at 0.001 lives/year
- Reference lines not limits
  - generally target about an order below sloping line
- $\overline{N}$ value on horizontal axis is a weighted average or expected value of life loss computed as ALL/APF.
  - Averaging is over all initiating events or loading types, all intervals of loading magnitude, all failure modes and all exposure combinations.
  - Life loss estimates for each combination are weighted by the likelihood that each combination will occur.



USACE Adequately Safe Dam: DSAC V



1) Meets all essential USACE *engineering* guidelines,
2) With no unconfirmed dam safety issues, AND
3) With tolerable residual risk (including ALARP)

RISK INFORMED

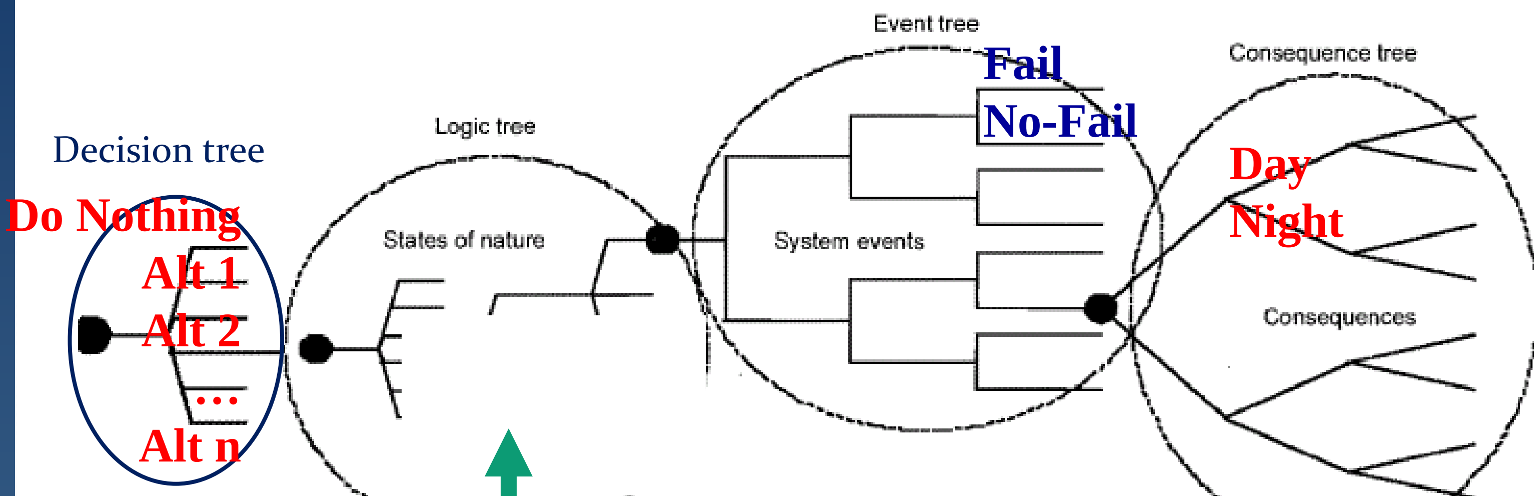
Risk Analysis Model

With Uncertainty

DAMRAE

Benefit: Can separate (knowledge) uncertainty about Existing Condition (States of Nature) from other uncertainties (loading SRP, consequences)

Decision Tree – Logic Tree – Event Tree – Consequences Tree



Decision Alternatives – States of Nature – System Performance Loading & System Response – Consequences & Exposure

E.g. - Flaw exists or does not exist
- Extent of liquefiable zone

Benjamin and Cornell 1970

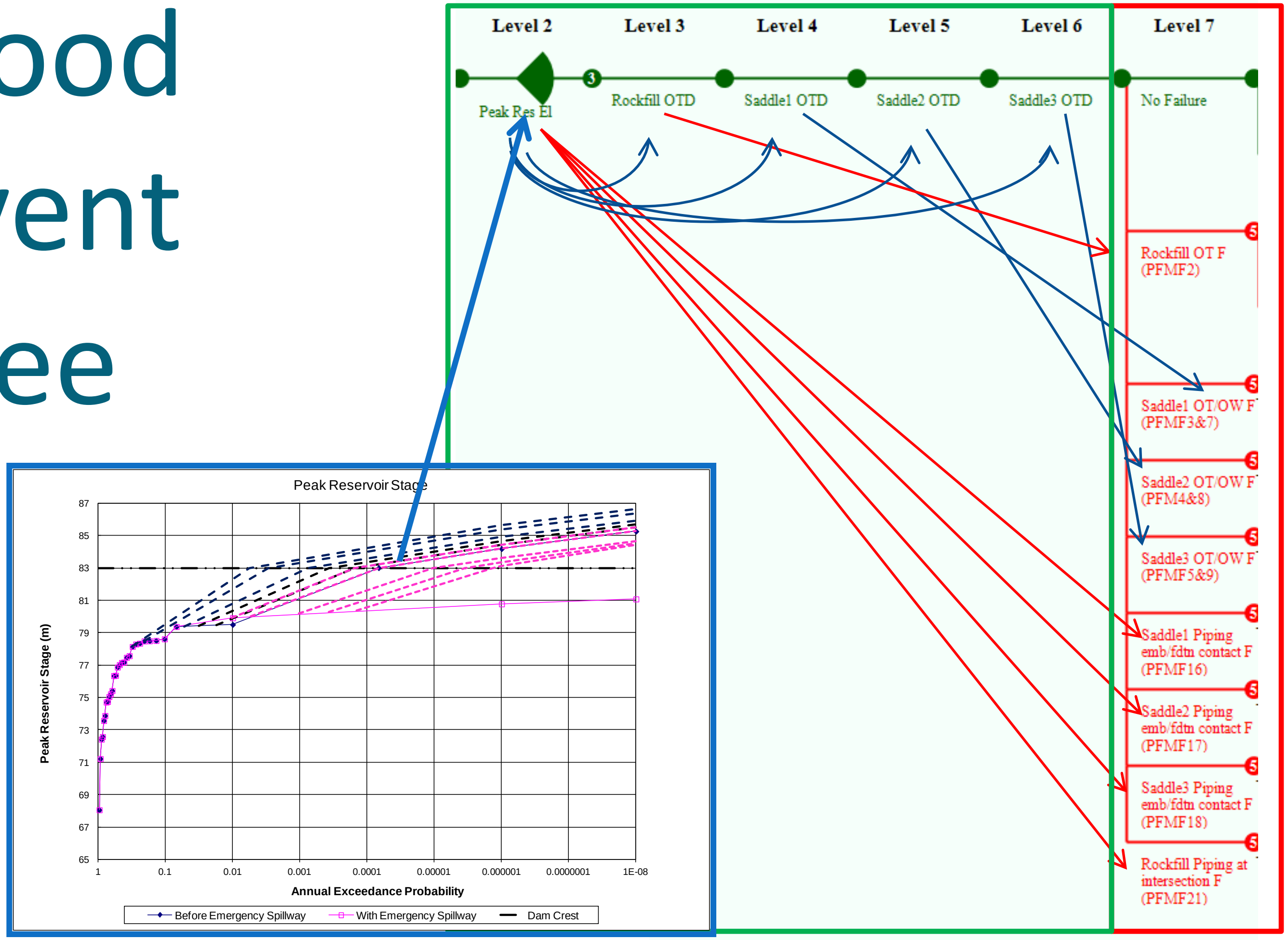
- Introduction
- DAMRAE Background
- Uncertainty version DAMRAE-U
  - ✓ Decision Tree – Logic Tree – Event Tree
  - ✓ Simulation Types
  - ✓ Example RA
- Summary

Utah State University

Application of Event Trees

- Separate trees for each type of initiating event:
  - e.g. Floods & Earthquakes
  - **Independent** & additive ($f_{Total} = f_{Flood} + f_{Earthquake}$)
  - Joint occurences
- Branches at chance nodes can represent
  - **System responses** of the dam system to loading sequences
  - **Human actions and interventions** - timeliness and effectiveness
  - **Emergency response** and factors affecting survival in flooding
  - **Continuously operating or standby systems** – e.g. spillway gates

Flood Event Tree

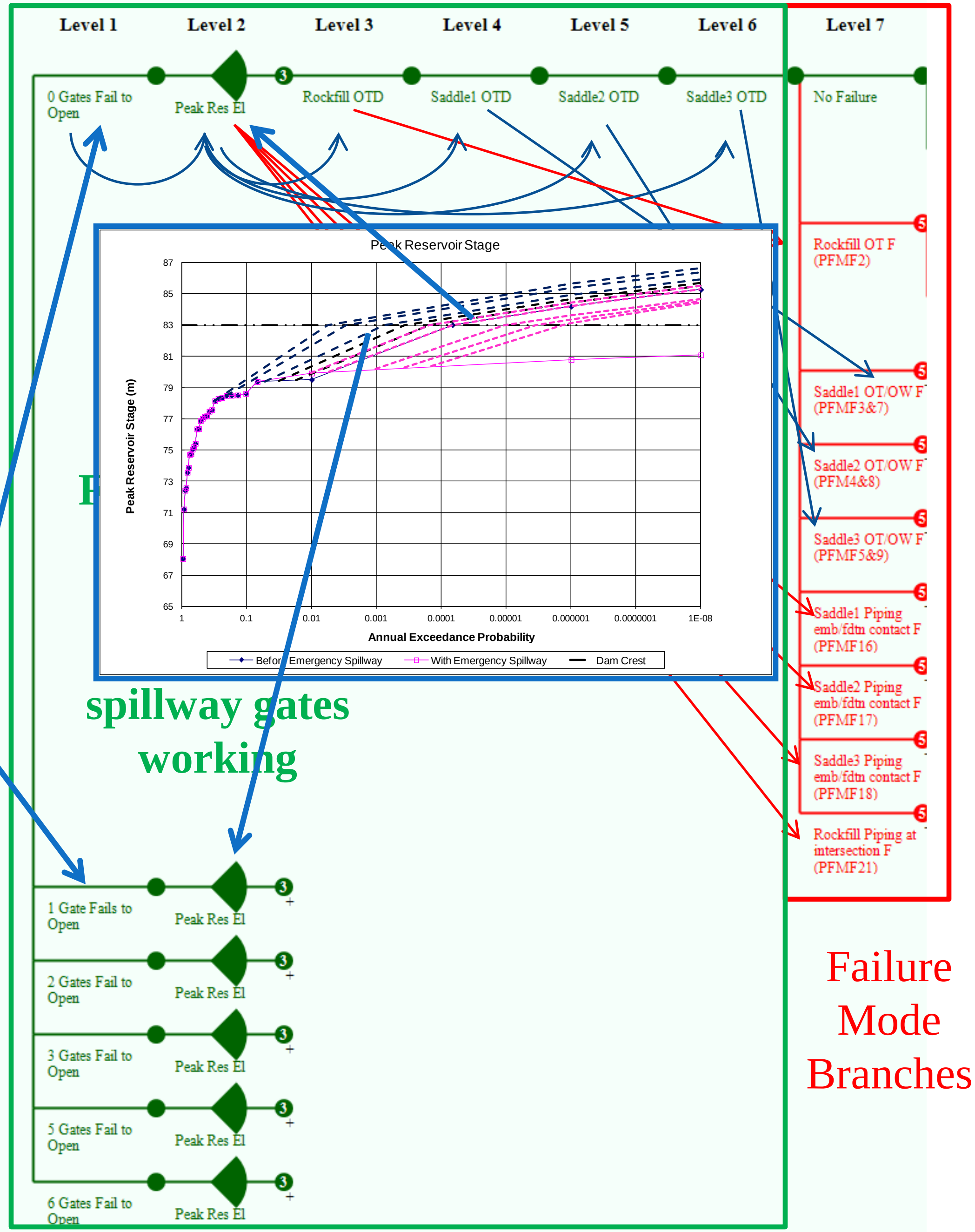


Flood Loading Branches

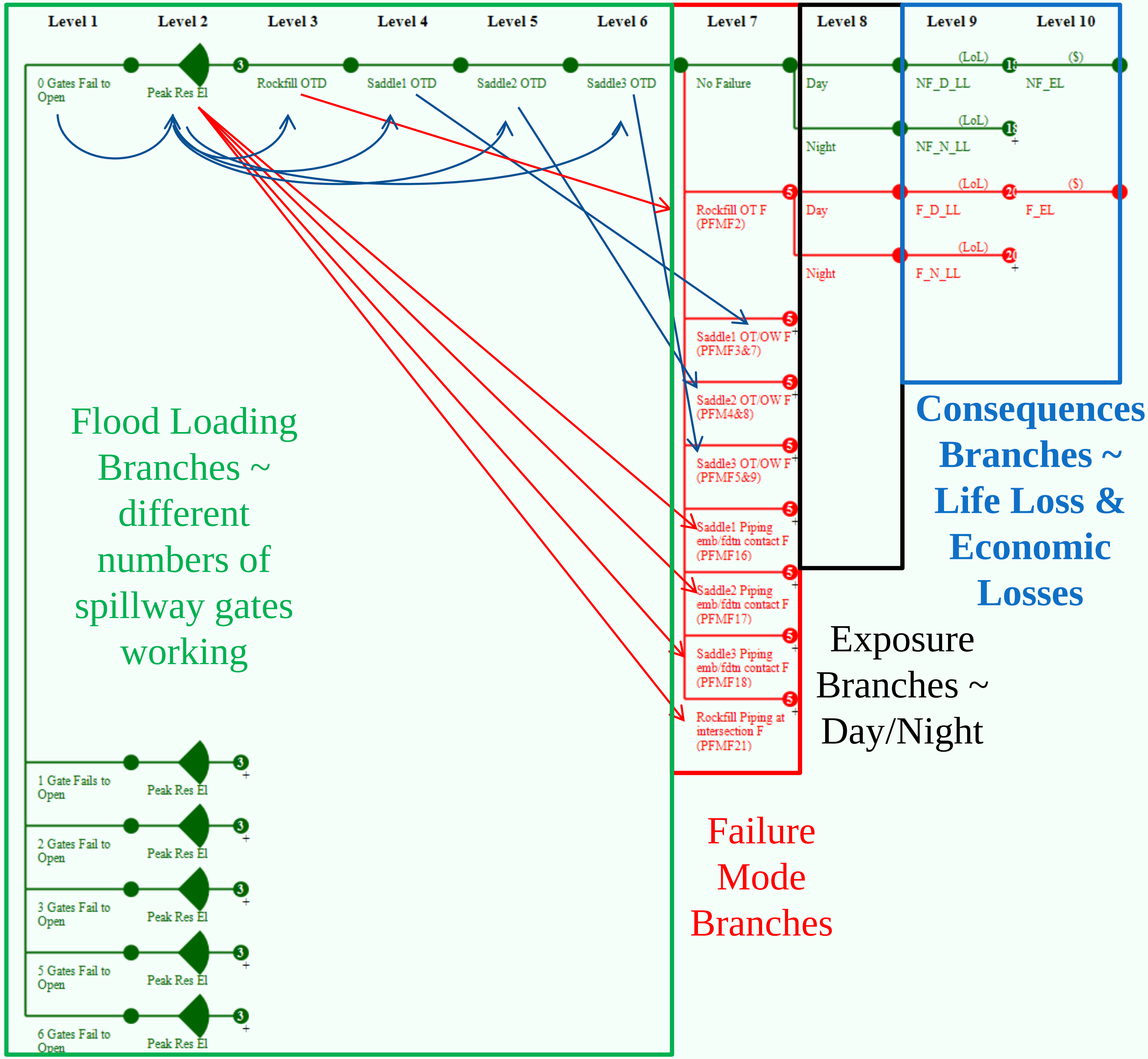
Failure Mode Branches

Flood Event Tree

Main Dam Spillway	
Number of Gates Failing to Open at a Time (r)	Total Probability of Failure to Open of r Gates at a Time
0	0.932
1	0.056
2	0.001
3	0.000
5	0.010



Flood Event Tree



Flood Hazard Requirements

Implications of risk approach for specifying flood hazards:

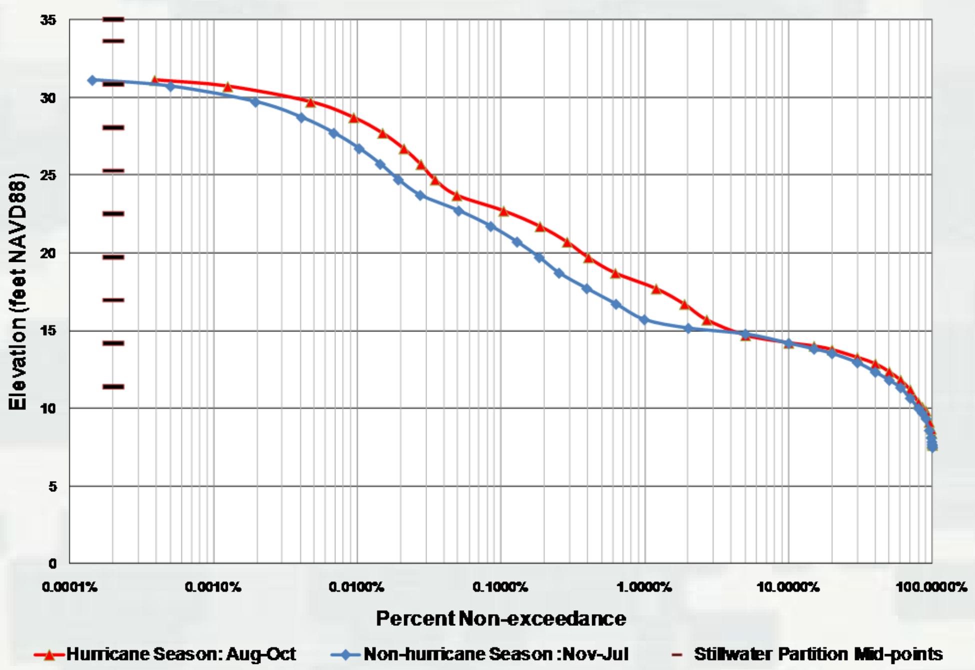
- **Entire probability distribution of reservoir inflow floods** up to and exceeding PMF
- **Joint probability distribution of reservoir inflow floods and downstream floods** needed where downstream consequences are affected by flows originating downstream of the reservoir that is being evaluated.
  - **Higher dimensional joint probability distributions** needed in cases where multiple reservoirs exist in the same catchment such that spatial and temporal correlations.
  - **Continuous simulation may be needed for large basins with multiple reservoirs** where there can be a range of combinations of storage levels or for reservoirs or lakes that have limited discharge capacity relative to inflow flood volumes, especially where these lakes are subject to significant wind effects.

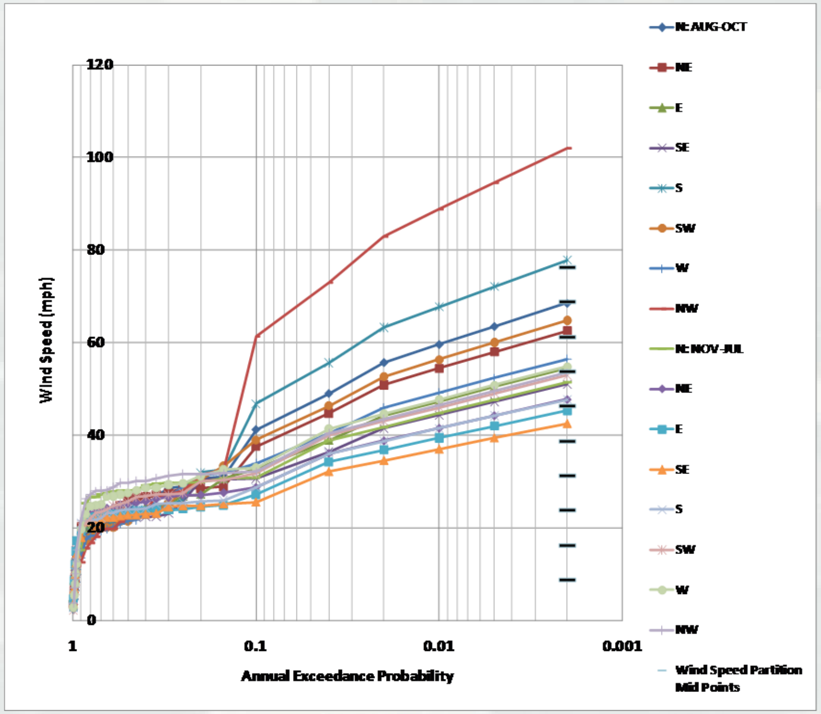
Loading Variables for Failure Modes

Primary Loading Variables

1) Stillwater elevation (E)

2) Peak annual wind speed (S_n) *normal to the dike*

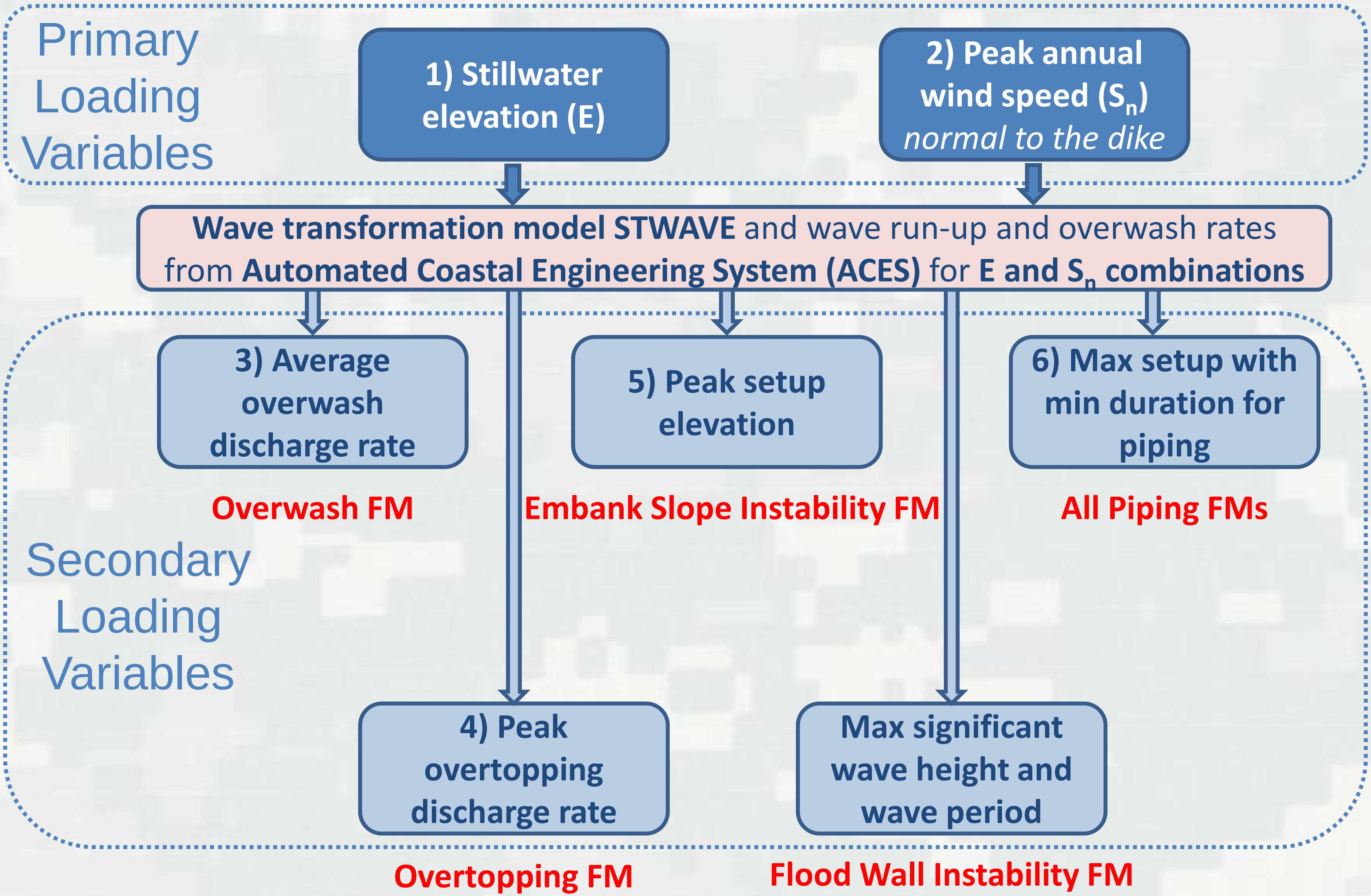




Stillwater Stage-duration for 2 wind seasons

Peak Annual Wind Speed for 2 seasons & 8 directions

Loading Variables for Failure Modes

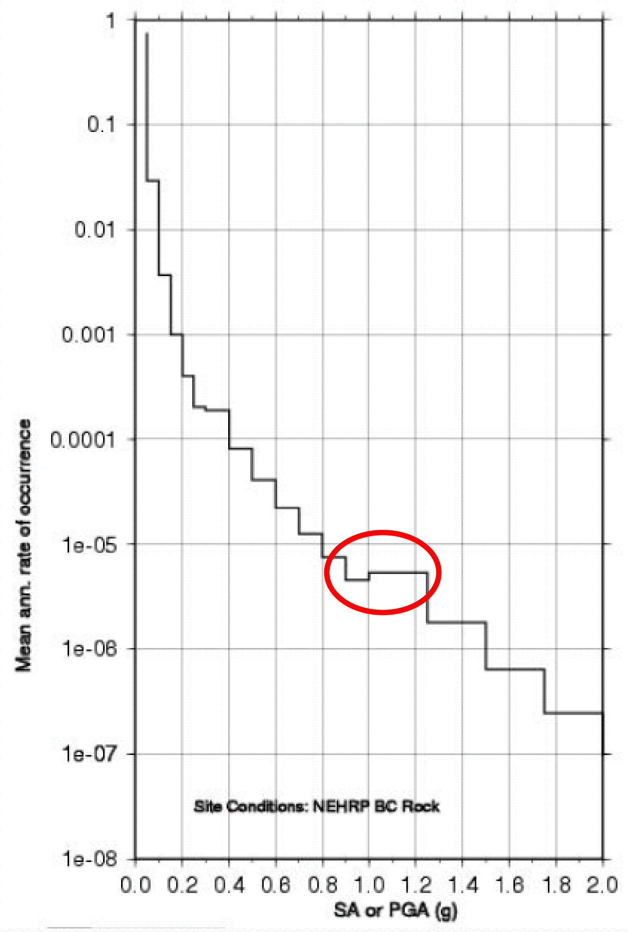


Earthquake Hazard

Coincident Reservoir Loading

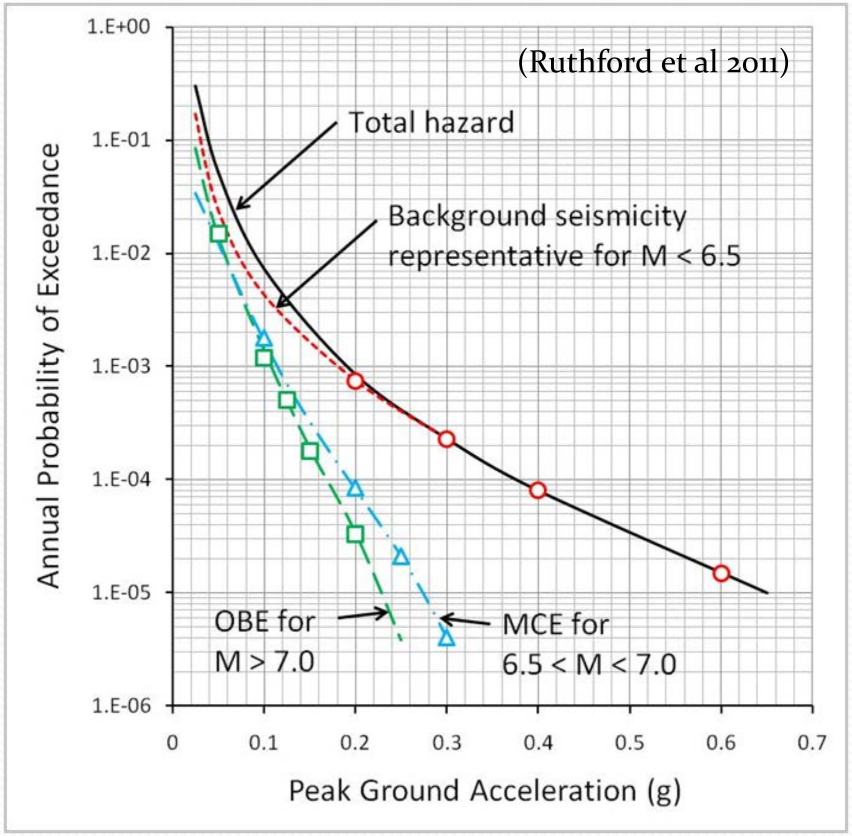
Earthquake Loading

- Peak ground acceleration (PGA) vs. annual exceedance probability (AEP) based on a site-specific hazard, or
- USGS Ground Motion Parameter Calculator for latitude and longitude:
  - http://earthquake.usgs.gov/research/hazmaps/design/
- Generally, Hard Rock option used in central and eastern US and Firm Rock option in western US.



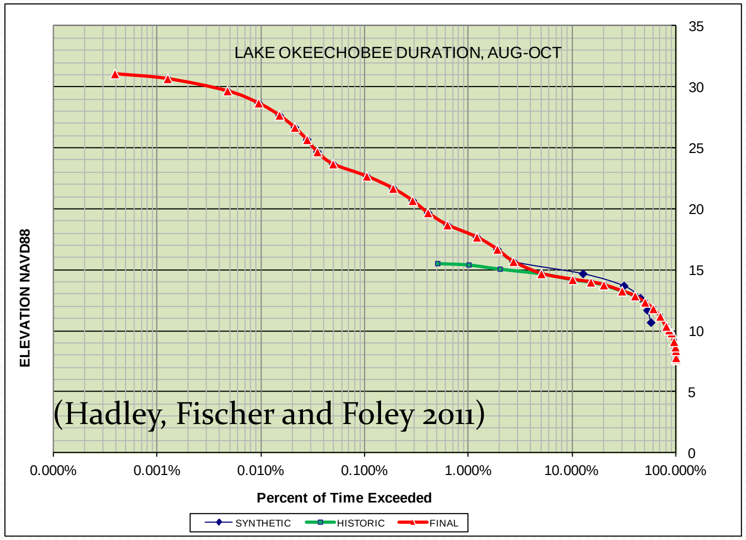
Earthquake Loading

- Most likely magnitude (mode or Mhat) can be used for risk assessment *unless performance is magnitude dependent such as for liquefaction.*
- A deaggregated relationship for statistical mean and modal sources using USGS Banded Deaggregation tool:
  - http://eqint.cr.usgs.gov/deaggband/2002/index.php

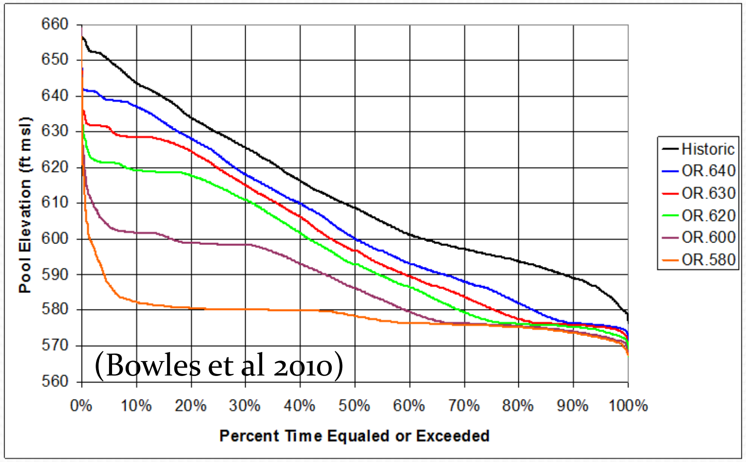


Coincident Pool for Earthquake Loading

- Stage-duration based on current operating rules for existing dam
  - Extended to rare floods
- Modify if changes in operating rules are to be evaluated as a risk reduction measure
- Use seasonal stage-duration relationships if significant differences in consequences with season



(Hadley, Fischer and Foley 2011)



(Bowles et al 2010)

System response probabilities

Fragilities

Estimating system response probabilities

1) Observed frequencies
   - Mass-produced mechanical and electrical components
     - May need to adjust for operating and environmental differences
   - Historic data on internal erosion failures and incidents (E.g. UNSW, USACE Internal Erosion Toolbox)
     - Adjustment of historical frequencies for site-specific factors using Bayes' theorem and judgment
2) Reliability analysis
   - Deriving a distribution of interest from distributions on other variables (e.g., Taylor series expansion or Monte Carlo simulation)
     - Distribution of Factor of Safety from distributions of strength parameters

Estimating system response probabilities

3) Subjective probability
    - Expert elicitation
    - Must be evidence based
4) Fault Trees
    - E.g. spillway gate reliability

Consequences

Focus on life loss

Life-Loss Consequences

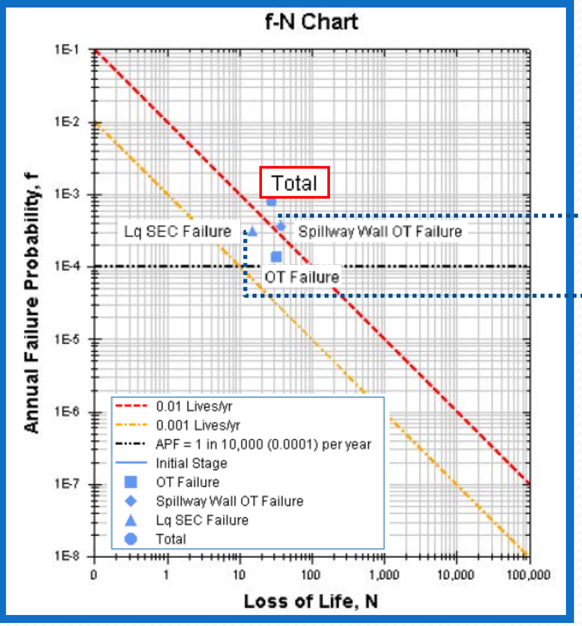
1) Semi-Empirical
   - ***USBR (Graham 1999)***
     - Flood severity, Flood severity understanding and Warning time
     - Evacuation not separately considered
2) Spatially-Distributed Dynamic Simulation
   - ***HEC FIA*** *(Simplified LIFESim)*
     - No traffic modeling and no consideration of velocity effects
   - ***LIFESim*** *– USU for USACE*
     - External flood simulation →Fate of buildings (shelters) →Warning and evacuation (traffic modeling)→Loss of life/survival
     - Uses readily available GIS data (HAZUS)
     - Provides estimates with uncertainty
   - ***LSM*** *- BC Hydro*
     - Tracks individuals

Calculate the risk

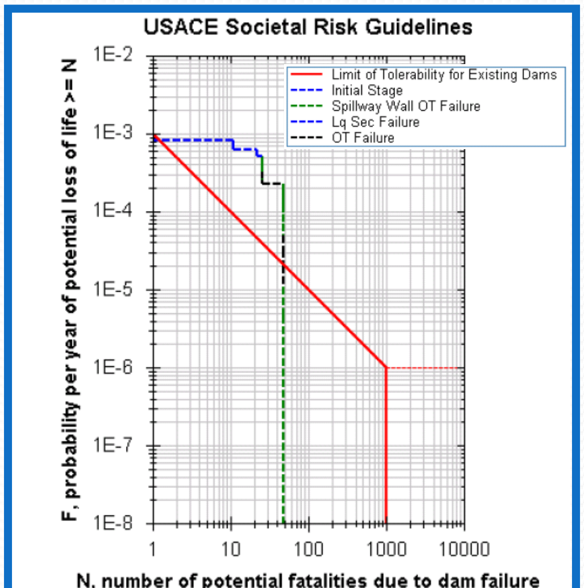
Risk Analysis Calculations

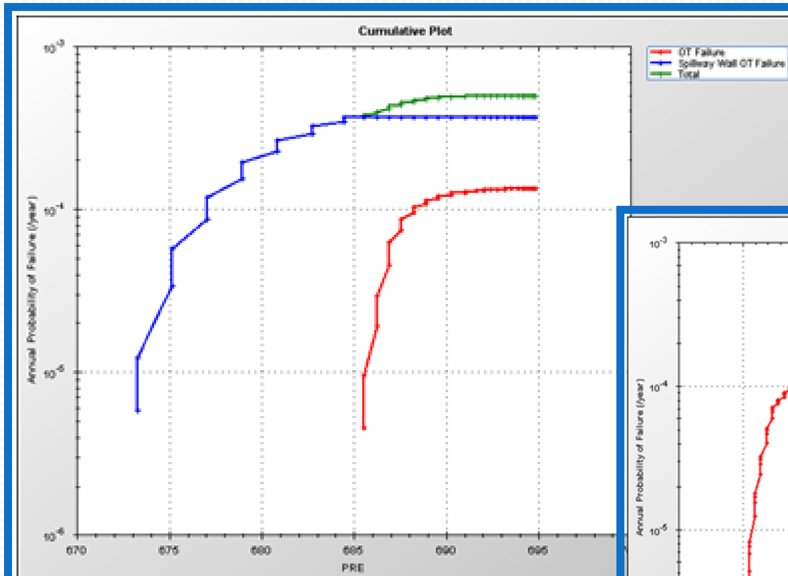
- Precision Tree
  - Not ideal for dam safety applications
  - @Risk for uncertainty analysis
- Spreadsheets
  - Inflexible, inefficient and fragile
- DAMRAE (USACE, TVA, RAC)
  - RAC/USU for USACE
  - More efficient than Precision Tree and Spreadsheets
  - Free to federal agencies
  - Commercial licenses and training for consultants starting in 2013
  - DAMRAE-U with uncertainty analysis under development

Existing Dam Results

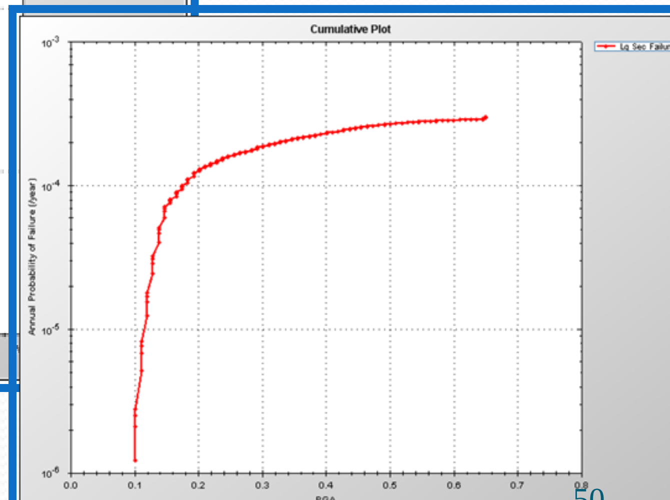


Run	Tolerable Risk Limit Guidelines Evaluation Summary		Failure Mode	Probability of Failure (APF)				Annualized Life Loss (ALL)		Annualized Economic Consequences	
							Percent of Total		Percent of Total		Percent of Total
				(/year)		(year)	(-)	(lives/year)	(-)	($/year)	(-)
BASE RUN:											
Existing Dam											
	Probability of Failure (APF)	No	OT Failure	1.33E-04	1 in	7,519	17%	4.43E-03	20%	1,172	17%
			Spillway Wall OT Failure	3.67E-04	1 in	2,725	46%	1.36E-02	60%	3,231	46%
	Individual Risk	No	Lq Sec Failure	2.99E-04	1 in	3,344	37%	4.68E-03	21%	2,634	37%
	Societal Risk	No									
	Annualized Life Loss (ALL)	No									
				7.99E-04	1 in	1,252	100%	2.27.E-02	100%	7,037	100%

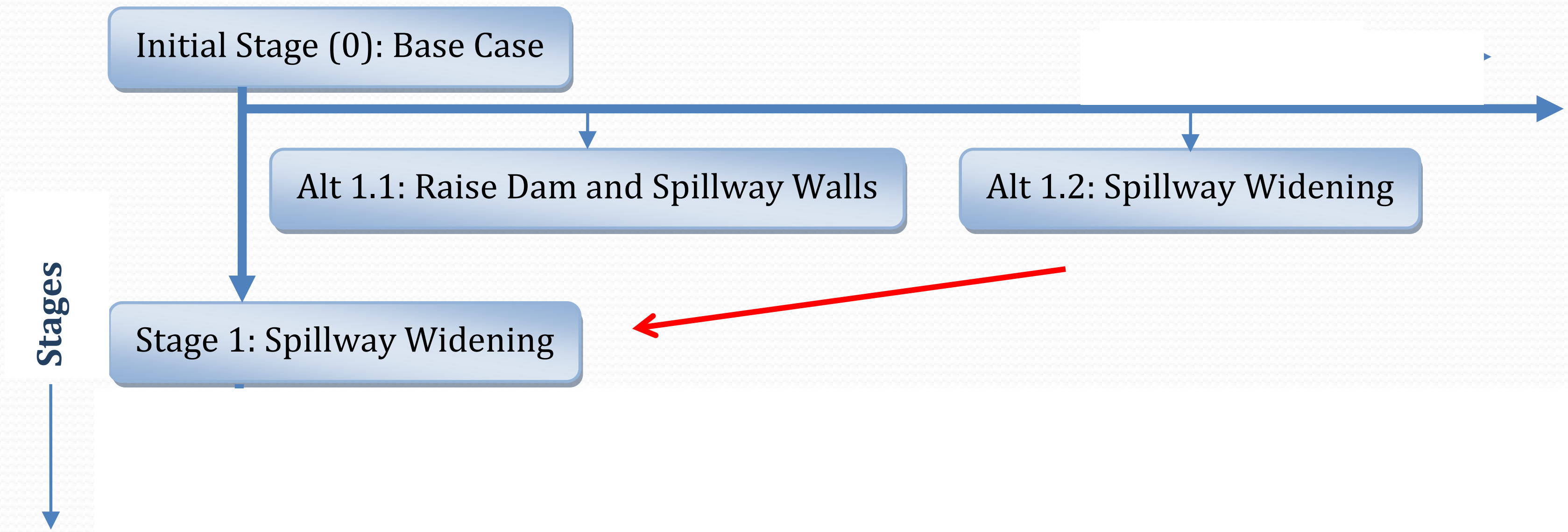




Summary Engineeirng Assessment	
Flood	NP
Earthquake	NP
Normal Operating	P



Risk-reduction – structural

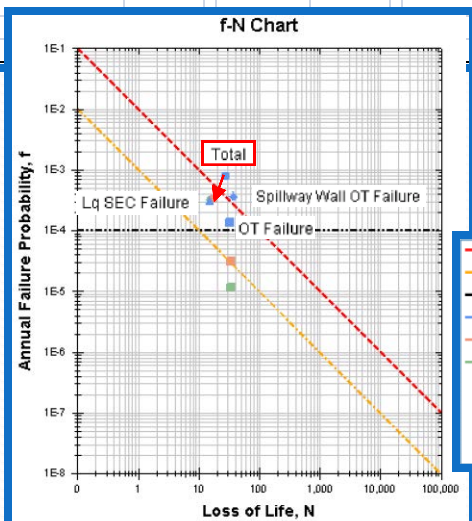


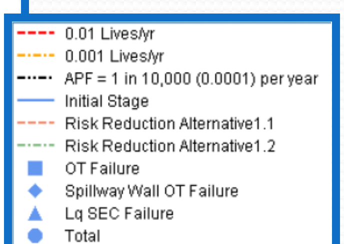
Alt 1.2 (Stage 1): Spillway Widening

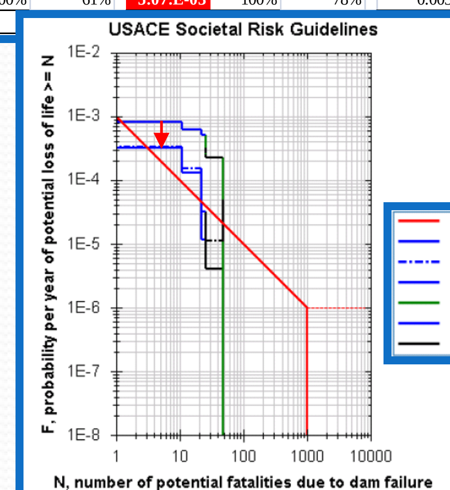
Run	Cost as Annualized Cost ($M/year)	USACE Tolerable Risk Guidelines Evaluation Summary: Part 1) Limit Guidelines		USACE Tolerable Risk Guidelines Evaluation Summary: Part 2) ALARP Justification for Risk Reduction		Failure Mode	Probability of Failure (APF) (/year)		(year)	Percent of Total (-)	Percent Reduction (-)	Annualized Life Loss (ALL) (lives/year)	Percent of Total (-)	Percent Reduction (-)	Annualized Economic Consequences ($M/year)	Percent of Total (-)	Percent Reduction (-)
BASE RUN:																	
Existing Dam																	
		Probability of Failure (APF)	No			OT Failure	1.33E-04	1 in	7,519	17%		4.43E-03	20%		0.001	17%	
		Individual Risk	No			Spillway Wall OT Failure	3.67E-04	1 in	2,725	46%		1.36E-02	60%		0.003	46%	
		Societal Risk	No			Lq Sec Failure	2.99E-04	1 in	3,344	37%		4.68E-03	21%		0.003	37%	
		Annualized Life Loss (ALL)	No														
							7.99E-04	1 in	1,252	100%		2.27.E-02	100%		0	100%	
RISK REDUCTION RUN:																	
Stage 1 - Spillway widening																	
	1.827	Probability of Failure (APF)	No	Benefit/ Cost Ratio	0.002	OT Failure	1.14E-05	1 in	87,719	4%	91%	3.88E-04	8%	91%	0.000	4%	91%
		Individual Risk	No			Spillway Wall OT Failure	0.00E+00	1 in	-	0%	100%	0.00E+00	0%	100%	-	0%	100%
		Societal Risk	No	Dispropor-tionality Ratio (R)	16.66	Lq Sec Failure	2.99E-04	1 in	3,344	96%	0%	4.68E-03	92%	0%	0.003	96%	0%
		Annualized Life Loss (ALL)	No														
							3.10E-04	1 in	3,222	100%	61%	5.07.E-03	100%	78%	0.003	100%	61%

Percent Reduction calculated from previous stage i.e. Stage 0: Existing Dam

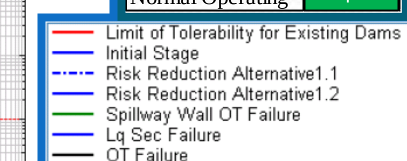
Plots contain: 1) Existing Dam; 2) Alt 1.1: Raise Dam and Spillway Walls; and 3) Alt 1.2 (Stage 1): Spillway Widening



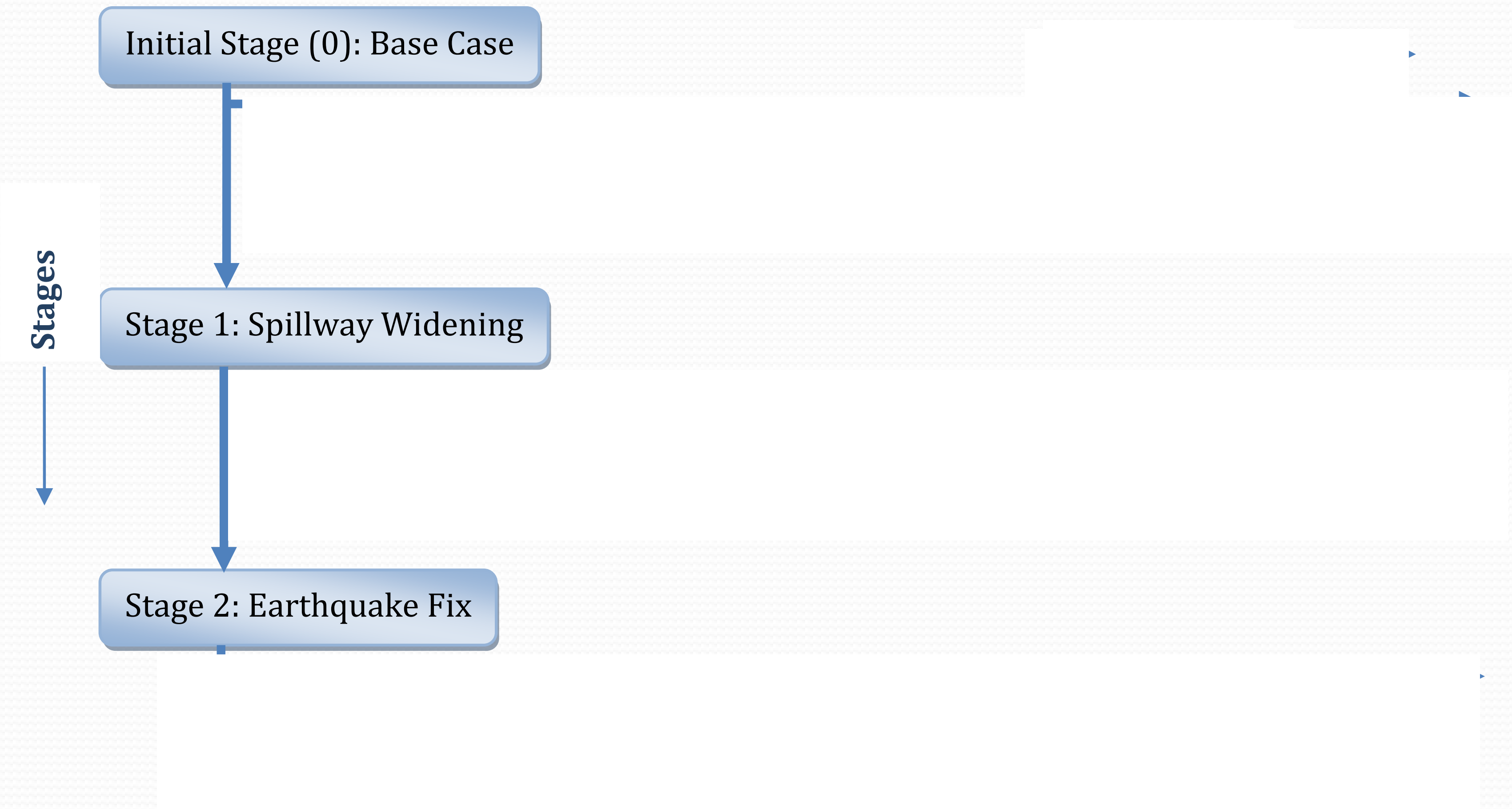




Summary Engineeirng Assessment	
Flood	P
Earthquake	NP
Normal Operating	P



Risk-reduction – structural



Stage 2: Earthquake Fix

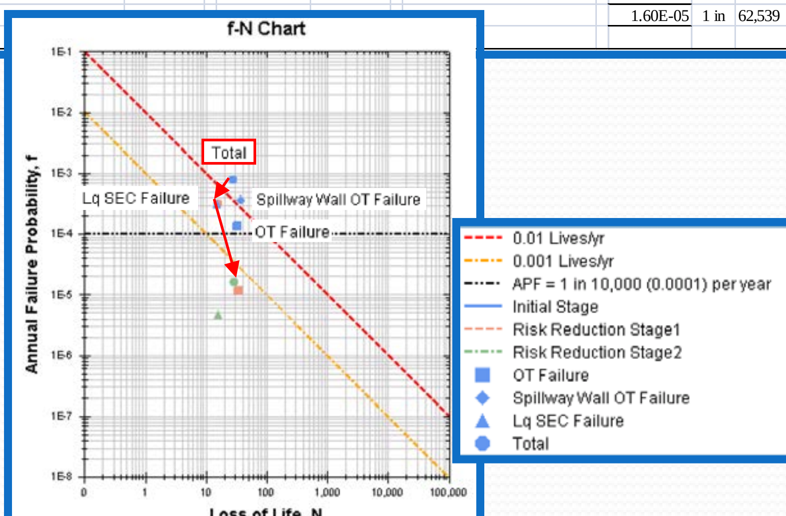
Run	Cost as Annualized Cost ($M/year)	USACE Tolerable Risk Guidelines Evaluation Summary: Part 1) Limit Guidelines		USACE Tolerable Risk Guidelines Evaluation Summary: Part 2) ALARP Justification for Risk Reduction		Failure Mode	Probability of Failure (APF) (/year)		(year)	Percent of Total (-)	Percent Reduction (-)	Annualized Life Loss (ALL) (lives/year)	Percent of Total (-)	Percent Reduction (-)	Annualized Economic Consequences ($M/year)	Percent of Total (-)	Percent Reduction (-)
RISK REDUCTION RUN:																	
Stage 1 - Spillway widening																	
	1.827	Probability of Failure (APF)	No	Benefit/ Cost Ratio		OT Failure	1.14E-05	1 in	87,719	4%	91%	3.88E-04	8%	91%	0.000	4%	91%
						Spillway Wall OT Failure	0.00E+00	1 in	-	0%	100%	0.00E+00	0%	100%	-	0%	100%
		Individual Risk	No		0.002	Lq Sec Failure	2.99E-04	1 in	3,344	96%	0%	4.68E-03	92%	0%	0.003	96%	0%
		Societal Risk	No	Disproportionality Ratio (R)	16.66												
		Annualized Life Loss (ALL)	No														
							3.10E-04	1 in	3,222	100%	61%	5.07.E-03	100%	78%	0.003	100%	61%

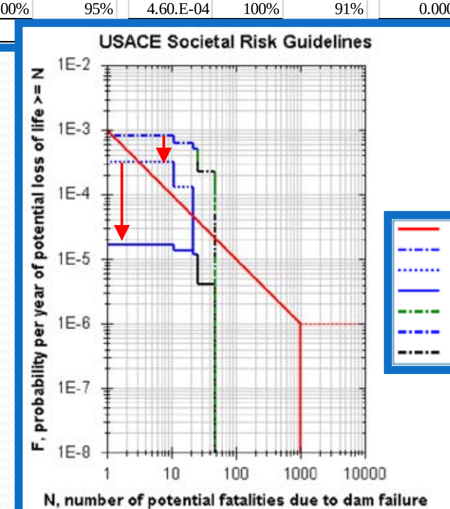
Percent Reduction calculated from previous stage i.e. Stage 0: Existing Dam

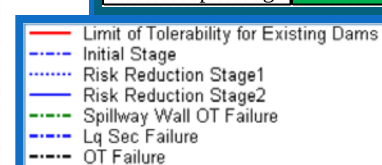
Run	Cost as Annualized Cost ($M/year)	USACE Tolerable Risk Guidelines Evaluation Summary: Part 1) Limit Guidelines		USACE Tolerable Risk Guidelines Evaluation Summary: Part 2) ALARP Justification for Risk Reduction		Failure Mode	Probability of Failure (APF) (/year)		(year)	Percent of Total (-)	Percent Reduction (-)	Annualized Life Loss (ALL) (lives/year)	Percent of Total (-)	Percent Reduction (-)	Annualized Economic Consequences ($M/year)	Percent of Total (-)	Percent Reduction (-)
RISK REDUCTION RUN:																	
Stage 2 - Earthquake Fix																	
	4.6	Probability of Failure (APF)	Yes-ALARP?	Benefit/ Cost Ratio		OT Failure	1.14E-05	1 in	87,719	71%	0%	3.88E-04	84%	0%	0.000	72%	0%
						Spillway Wall OT Failure	0.00E+00	1 in	-	0%		0.00E+00	0%		-	0%	
		Individual Risk	Yes-ALARP?		0.001	Lq Sec Failure	4.59E-06	1 in	217,865	29%	98%	7.17E-05	16%	98%	0.000	28%	98%
		Societal Risk	Yes-ALARP?	Disproportionality Ratio (R)	159.74												
		Annualized Life Loss (ALL)	Yes-ALARP?														
							1.60E-05	1 in	62,539	100%	95%	4.60.E-04	100%	91%	0.000	100%	95%

Percent Reduction calculated from previous stage i.e. Stage 1 (Alt 1.2): Spillway Widening

Plots contain: 1) Stage 0: Existing Dam; 2) Stage 1 (Alt 1.2): Spillway Widening; and 3) Stage 2: Earthquake Fix







Summary Engineeirng Assessment	
Flood	P
Earthquake	P
Normal Operating	P

Make the case for a decision

Recommend and make the case for a decision

- A Logical Set of Arguments…
  - Recommending additional safety-related action is justified, or no additional safety-related action is justified.
- The case is convincing when owners or regulators sense that the following are coherent:
  - the dam's existing condition and ability to withstand future loading,
  - the risk estimates,
  - and the recommended actions.
- Numbers are not the sole basis for decision-making
- Address the sensitivity (uncertainty) … to key parameters … and recommended actions

Nate Snorteland – USSD 2010

Long Dams - Levees

Length Effects

Length Effects are different to shifts in geotechnical conditions

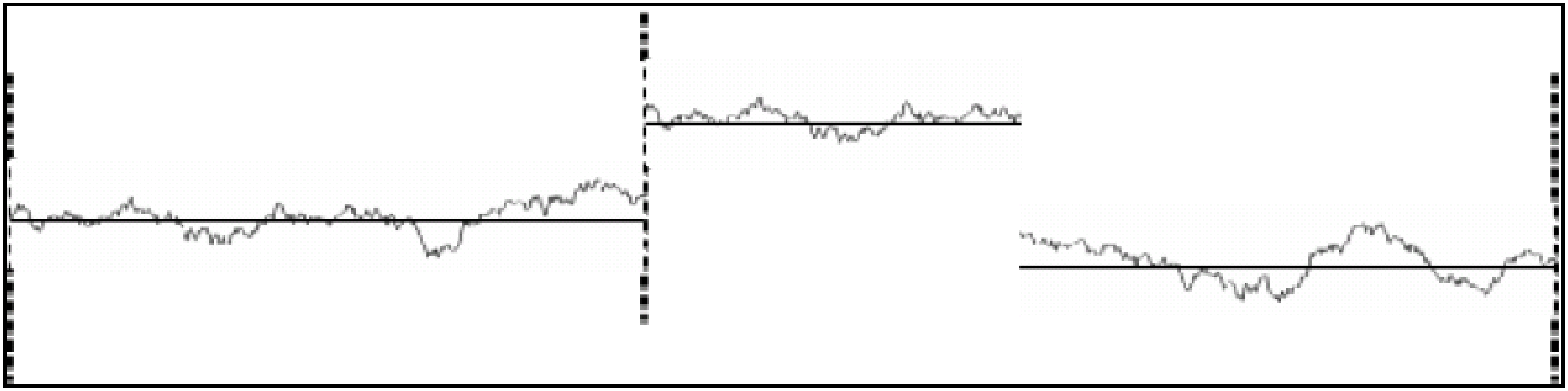
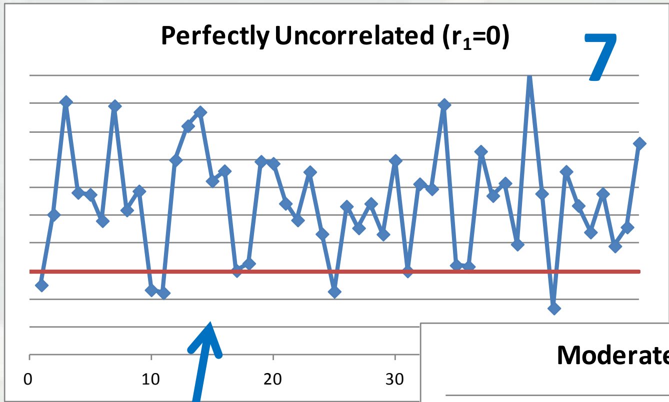
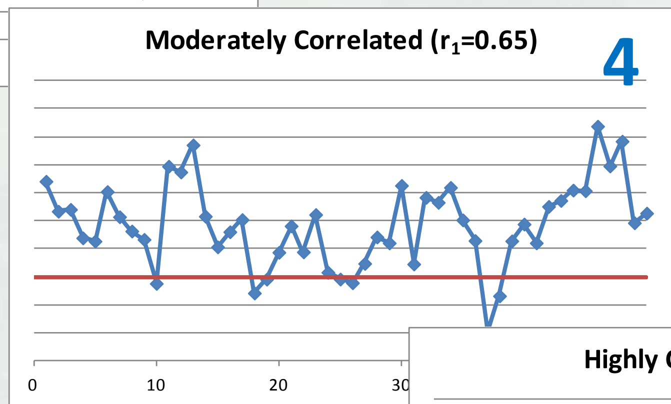


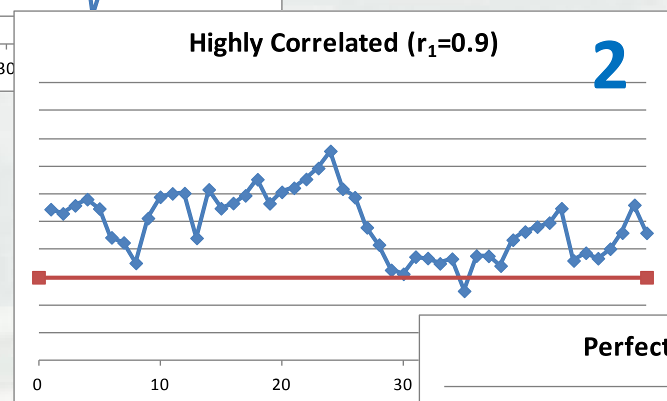
Figure 2. Schematic diagram showing the variability of some engineering property in space (e.g., soil strength, surge elevation, etc.). The spatial variability is divided into sections assessed to be homogeneous, and means are estimated for each.

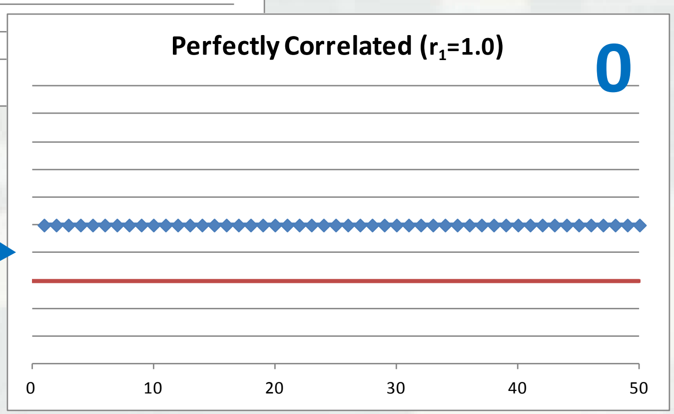
- the issue of **length effects** is related to the **degree of spatial correlation** in these properties rather than that the soils are classified to be the same or to have similar properties.
- **"correlation"** here refers to an **expected tendency for the failure of more than one adjacent CSR** to occur during the **same loading event combination** and within the **same geotechnical conditions**.

Length Effects







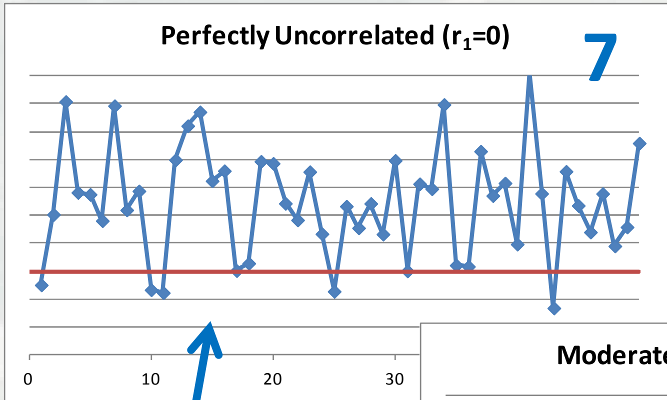


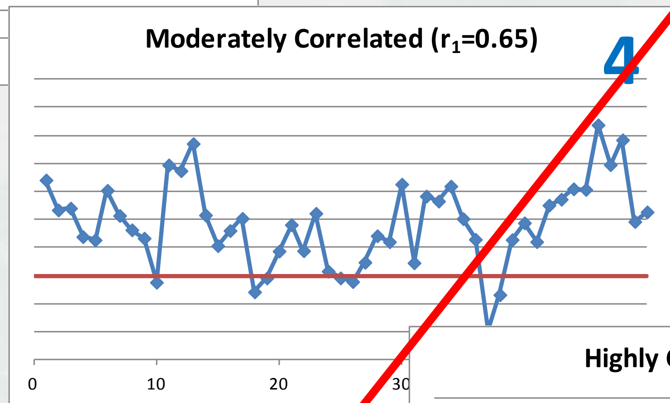
Probability of failure for n CSRs assuming **independent** failure modes (DeMorgan):

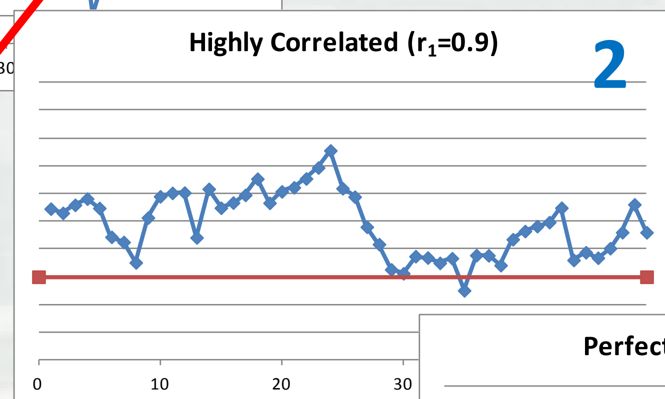
$$P(\text{System failure}) = 1 - \prod_{k=1,n} (1-p_k)$$
$$= 1 - (1-p_1)*(1-p_2)* \ldots *(1-p_n)$$

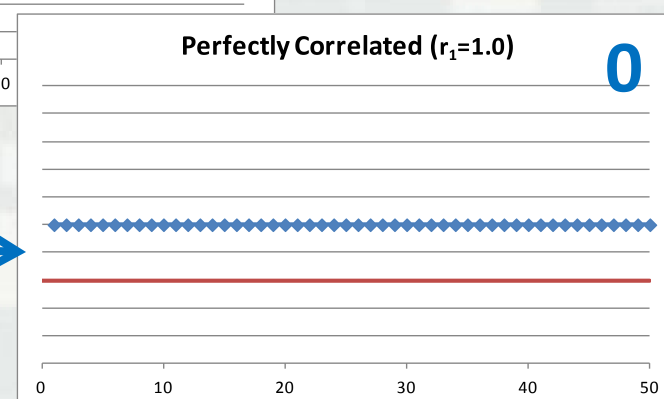
assuming **dependent** failure modes:

$$P(\text{System failure}) = Max_{k=1,n}(p_k)$$









All failure modes considered independent at the CSR level (1,600 feet) except piping through foundation

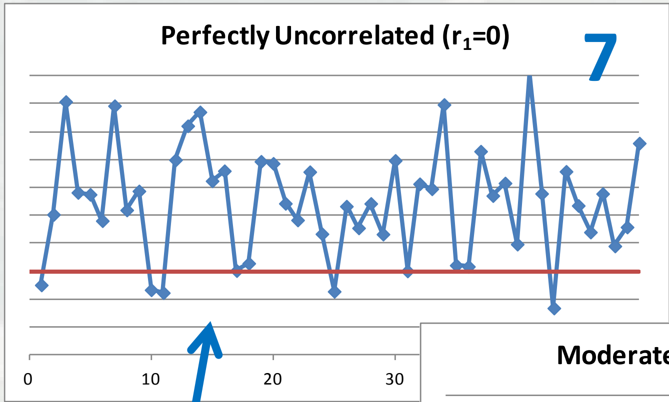
Probability of failure for n CSRs assuming **independent** failure modes (DeMorgan):

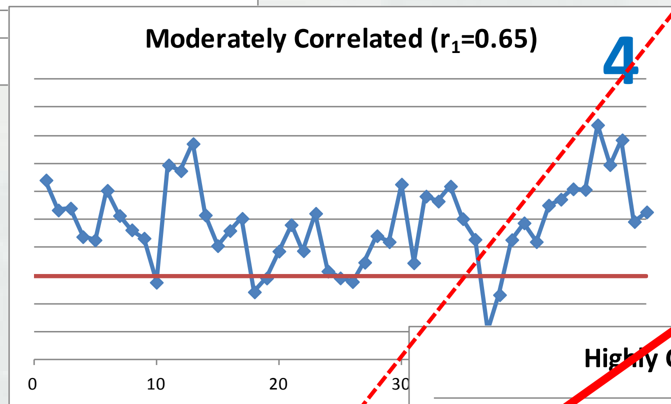
$$P(\text{System failure}) = 1 - \prod_{k=1,n} (1-p_k)$$

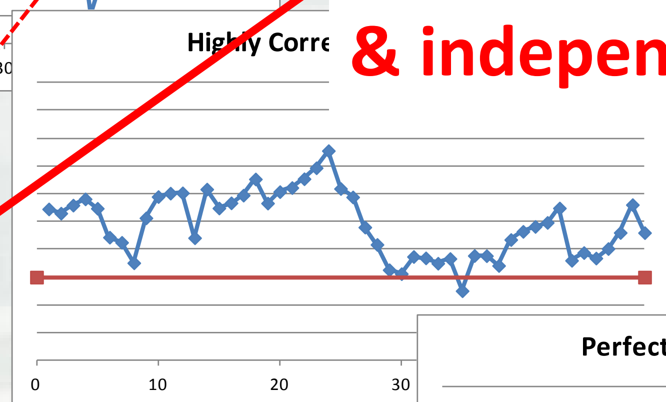
$$= 1 - (1-p_1)*(1-p_2)* \ldots *(1-p_n)$$

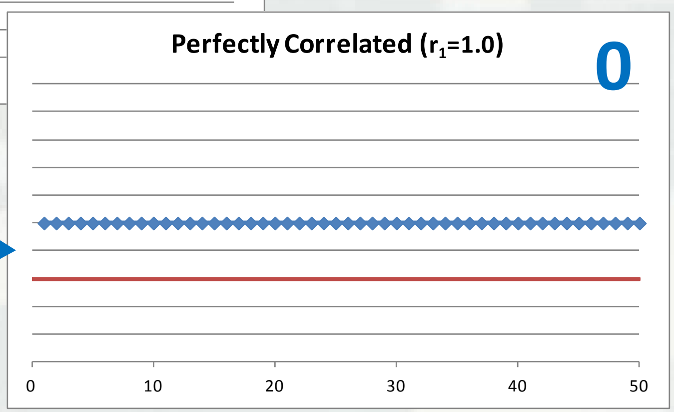
assuming **dependent** failure modes:

$$P(\text{System failure}) = \text{Max}_{k=1,n}(p_k)$$









All failure modes considered independent at the CSR level (1,600 feet) except piping through foundation – used average of dependent & independent cases

Probability of failure for n CSRs assuming <u>**independent**</u> failure modes (DeMorgan):

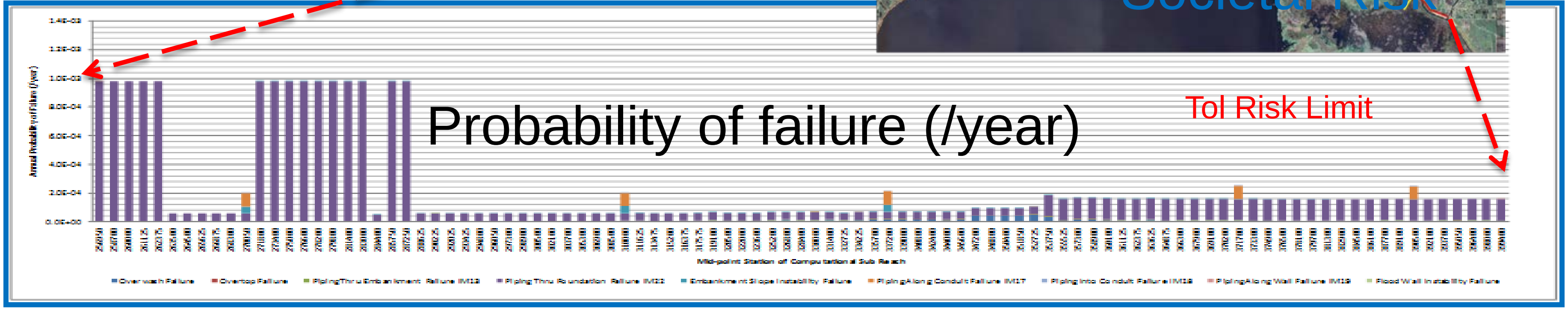
$$P(\text{System failure}) = 1 - \prod_{k=1,n} (1-p_k)$$

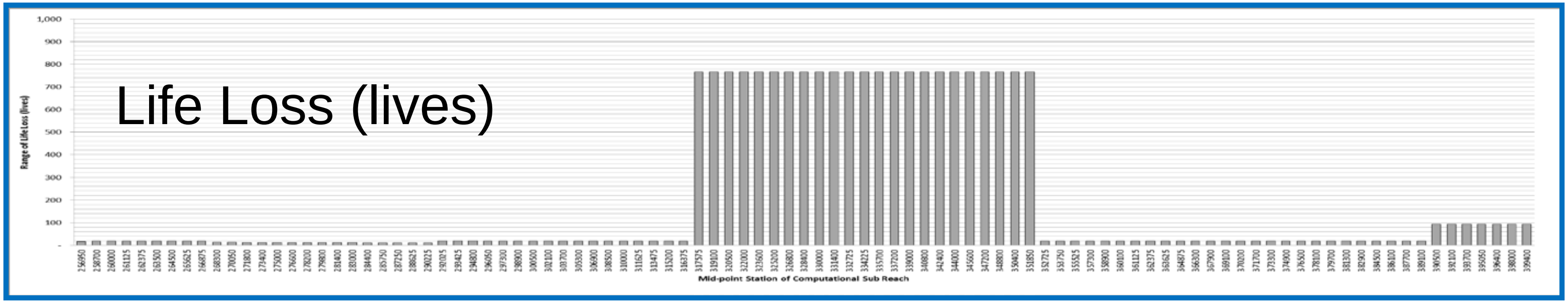
$$= 1 - (1-p_1)*(1-p_2)* \ldots *(1-p_n)$$

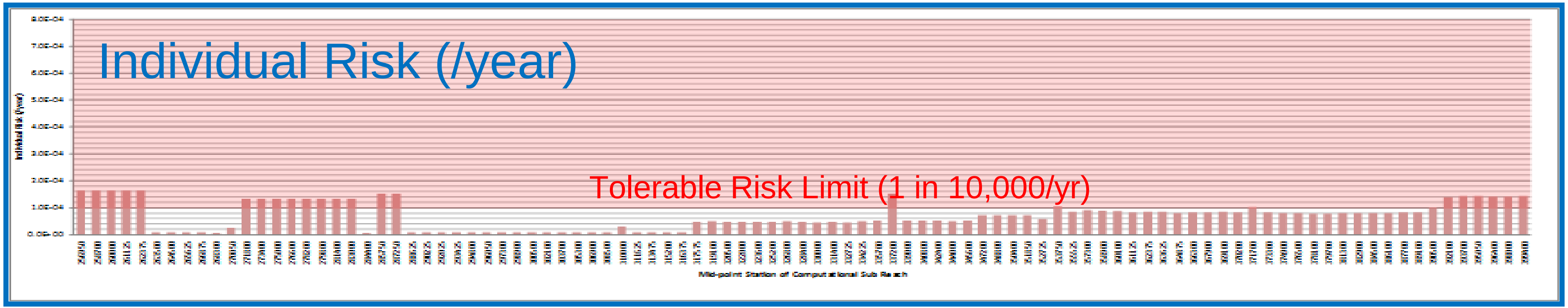
assuming <u>**dependent**</u> failure modes:

$$P(\text{System failure}) = \text{Max}_{k=1,n}(p_k)$$

Risk Management: Examples of Long Dam/ Levee System Risk Profiles







Uncertainty

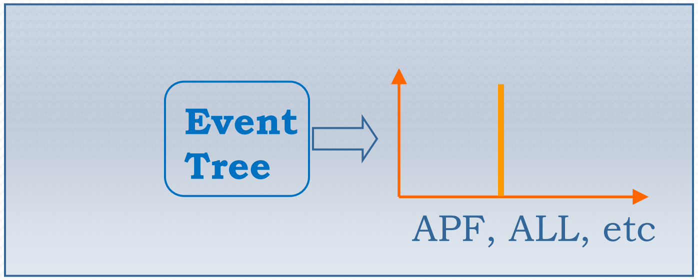
RAC Engineers & Economists

Simulation Types

DAMRAE-U

➢ *Deterministic Mode*

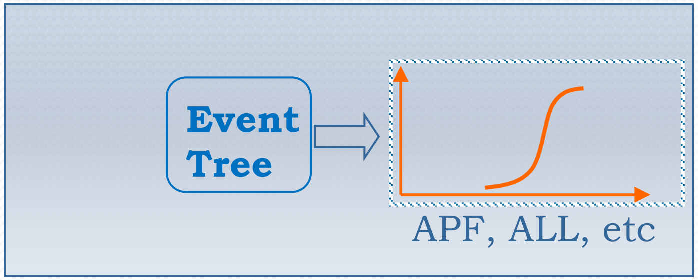
- *INPUTS: Natural variabilities in loading, SRPs & consequences*
- *INPUTS: No (knowledge) uncertainties*
- *RESULTS: Only natural variabilities*



➢ *Uncertainty Mode*

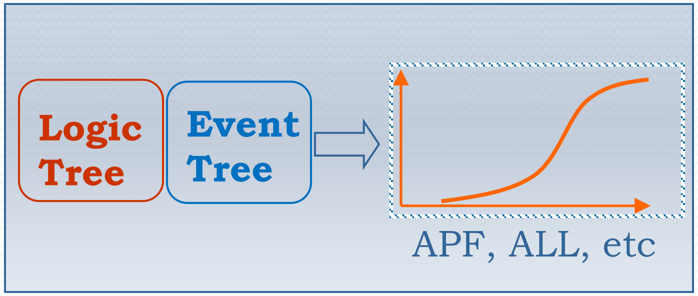
➢ *Event Tree (ET) Simulation (Type-0)*

- *INPUTS: Natural variabilities in loading, SRPs & consequences*
- *INPUTS: ET uncertainties*
- *RESULTS: Lumps uncertainties & natural variabilities*



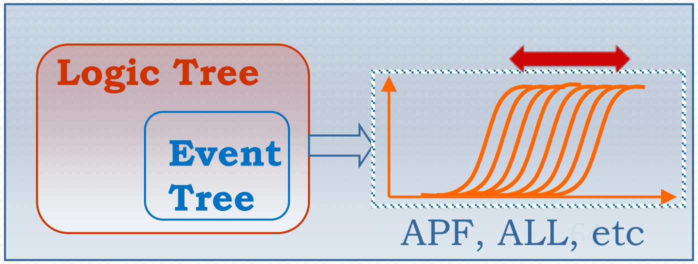
➢ *Logic Tree (LT)-Event Tree Type-I Simulation*

- *INPUTS: Separates uncertainties into LT (Existing condition) and ET variables*
- *RESULTS: Lumps LT & ET uncertainties and natural variabilities*



➢ *Logic Tree-Event Tree Type-II Simulation*

- *INPUTS: Separates uncertainties into LT and ET variables*
- *RESULTS: Separates LT (Existing condition) uncertainties into separate curves of ET uncertainty and natural variabilities*



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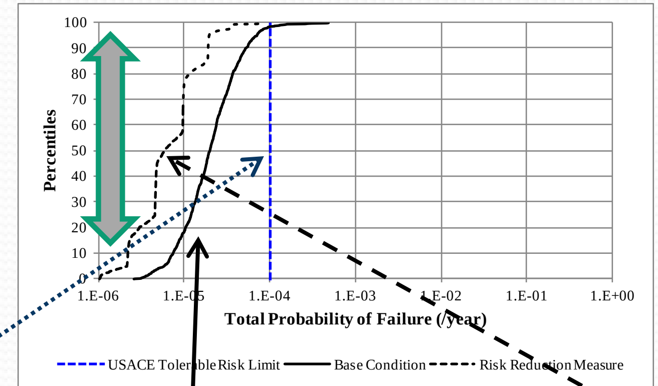
Results: Annual Probability of Failure (APF)

- **Introduction**
- **DAMRAE Background**
- **Uncertainty version DAMRAE-U**
  - ✓ **Simulation Types**
  - ✓ **Example RA - Results**
- Summary

Type I simulation



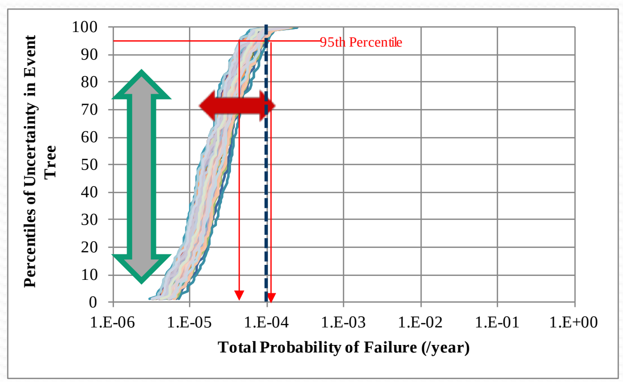
Variability and Knowledge uncertainty in Event Tree

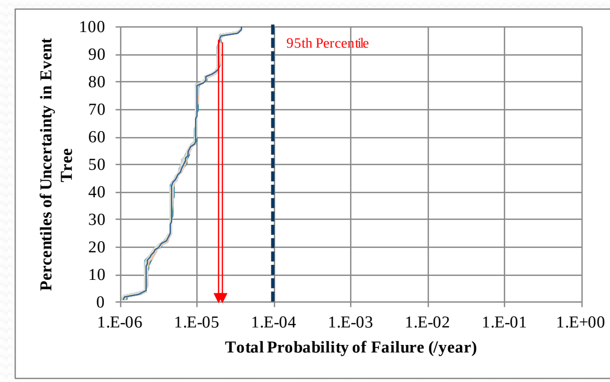
Tolerable Risk Limit 1 in 10,000 /year

Base Condition

Piping Risk Reduction Measure

Type II simulation





Existing condition uncertainty (*piping elevation threshold*) *in Logic Tree*

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Results: Annualized life loss estimates (ALL)

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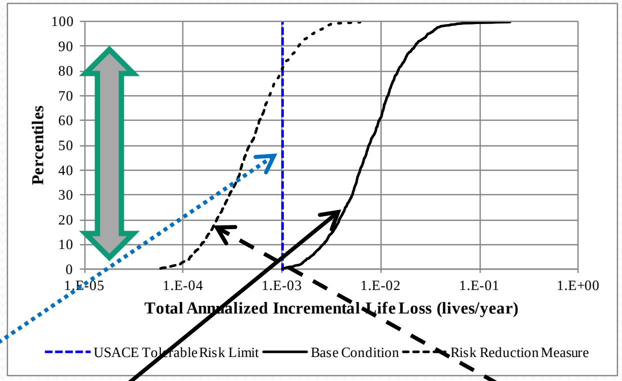
- Introduction
- DAMRAE Background
- Uncertainty version DAMRAE-U
  - ✓ Simulation Types
  - ✓ Example RA - Results
- Summary

Type I simulation



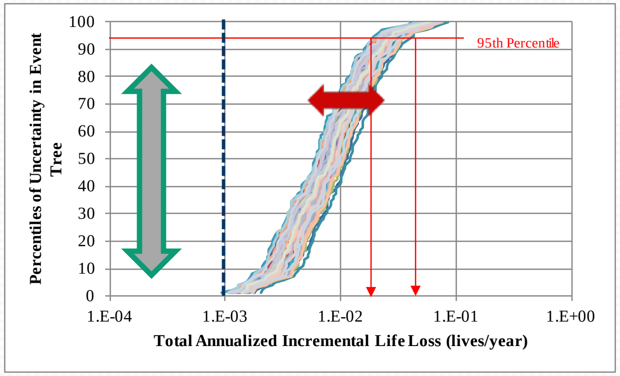
Variability and Knowledge uncertainty in Event Tree

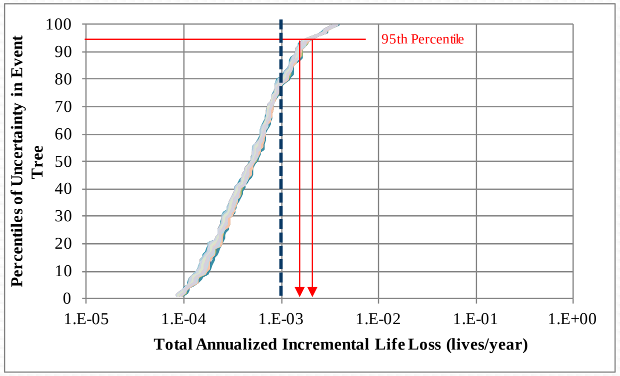
Tolerable Risk Limit
0.001 lives/year

Base Condition

Piping Risk Reduction Measure

Type II simulation





Existing condition uncertainty (*piping elevation threshold*) *in Logic Tree*

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Results: f-Ñ Charts (APF, f vs Average Life Loss, Ñ)

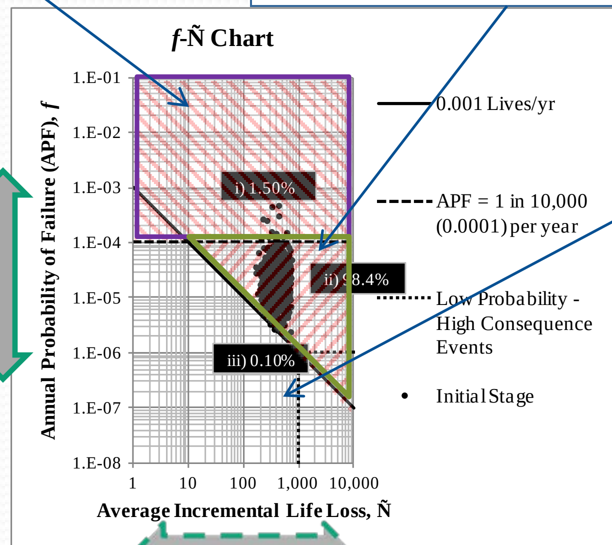
- Introduction
- DAMRAE Background
- Uncertainty version DAMRAE-U
  - ✓ Simulation Types
  - ✓ Example RA - Results
- Summary

Region i) APF≥1 in 10,000
Does not meets APF TRG

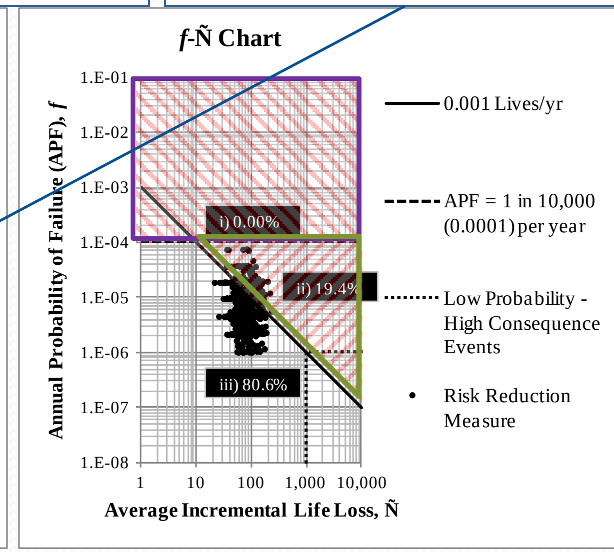
Region ii) APF<1 in 10,000
and ALL≥0.001
Meets APF but not ALL TRG

Region iii) APF<1 in 10,000
and ALL<0.001
Meets APF & ALL TRG

Type I simulation



Base Condition



Piping Risk Reduction Measure

Variability and Knowledge uncertainty in Event Tree

Type II simulation

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Results: F-N Charts (AEP, F vs Life Loss, N)

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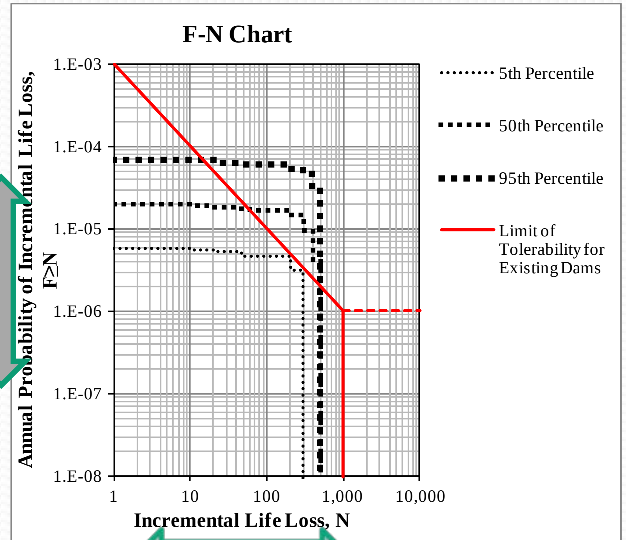
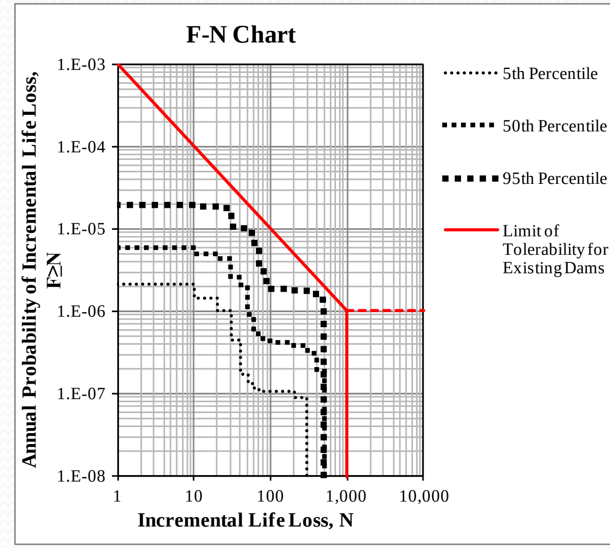
Engineers & Economists

- Introduction
- DAMRAE Background
- Uncertainty version DAMRAE-U
  - ✓ Simulation Types
  - ✓ Example RA - Results
- Summary

Type I simulation



Base Condition



Piping Risk Reduction Measure

Variability and Knowledge uncertainty in Event Tree

Type II simulation

Utah State University

Conclusions

Information for assessing external hazards at NPPs

- Flood hazard characterization
  - at all upstream dams and intervening areas below last dam and NPP
- Dam performance
  - full range of hazards including reliability of discharge facilities (e.g. spillway gates, effects of debris and ice, etc.)
- Dam breach modeling for all failure modes
- Flood routing and inundation modeling
  - for full range of no-breach and breach floods
- Performance of "perimeter" flooding protection (IA)
  - e.g. levees, closures, etc.
- Characterization of flooding risk at NPP (IA)
  - all flooding paths
  - All relevant flooding attributes and effects
    - peak elevations, time for EM, residual reservoir storage, power generation after dam failure, time for emergency measures)

Some areas for improvement

- More systematic use of **Failure Modes Identification**
- Better **risk assessment scoping** and **risk model formulation**
- Length effects
- PFHA
- System response probability estimation
- Reliability of discharge facilities (spillway gates)
- **Software** designed for dam safety RA – e.g. DAMRAE
- Better consideration of **uncertainties**
- Effect on **Non-breach/Non-failure risk**
- "**Making the case**" to decision makers – deliberative process
- *Better **integration** with owner's business including*

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http://uwrl.usu.edu/people/faculty/bowles.html