Quantitative Risk Assessment (QRA) – Theory and applications

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NGI

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Geohazards

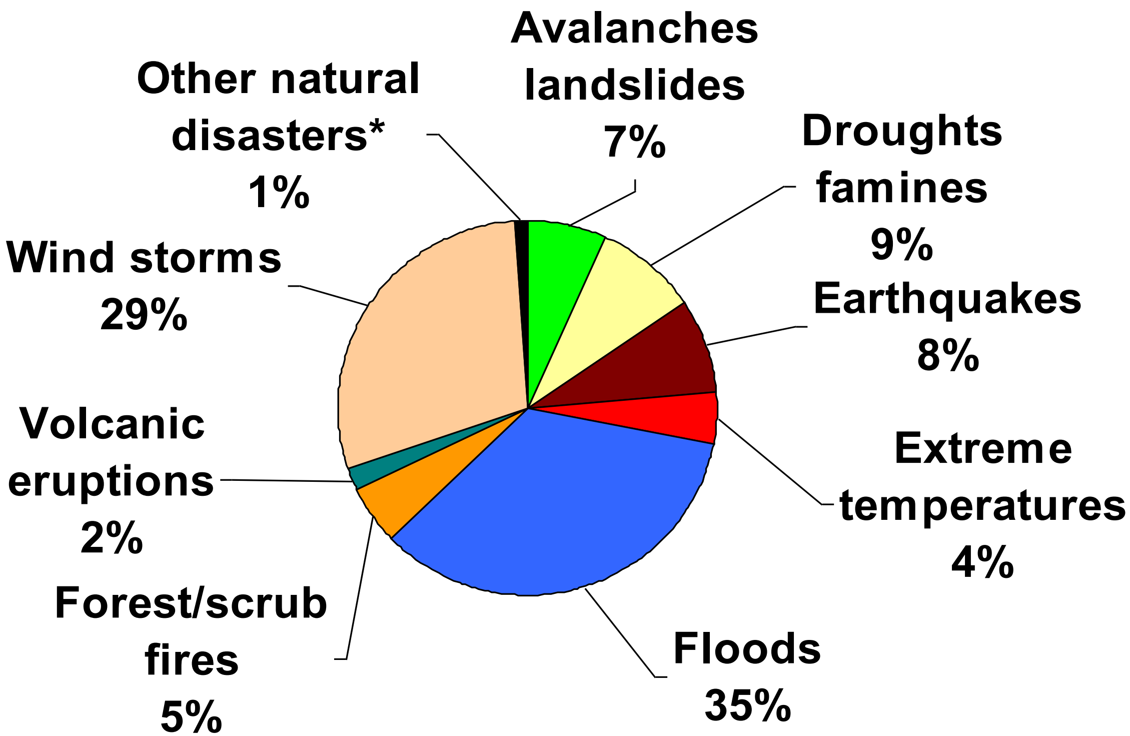
Natural threats

- Flood
- Earthquake
- Tsunami
- Soil- and rockslide
- Snow avalanche
- Wind and storm

Landslides are the natural threat which occur most frequently (compared to other natural threats like flood, earthquake, cyclone and volcano).

Europe is the continent with the next highest fatalities caused by landslides (after America) and with the highest economic consequences.

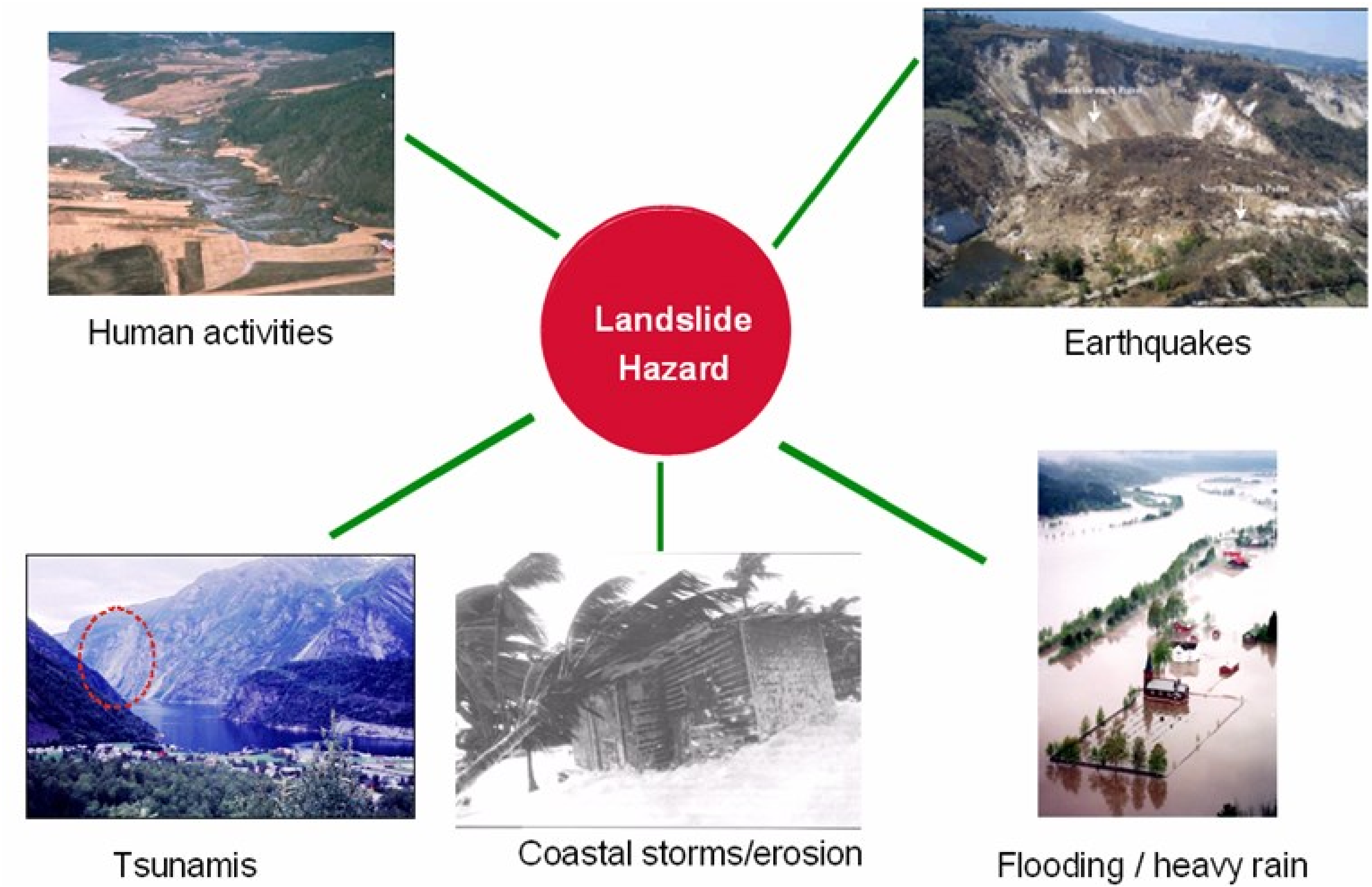
Global incidence of natural disasters (1991-2000)



Much of damage and casualties attributed to earthquakes and floods are caused by the landslides triggered by these events.

Sources: OFDA/CRED international disaster database
& 2001 IFRC World disaster report

Correlation with other types of natural threats



Socio-economic consequences of natural disasters in Europe



		Hazard	Loss of life	Costs
European	45	floods	10,000	105 B€
statistics	1700	landslides	16,000	200 B€
1900-2000	32	earthquakes	239,000	325 B€

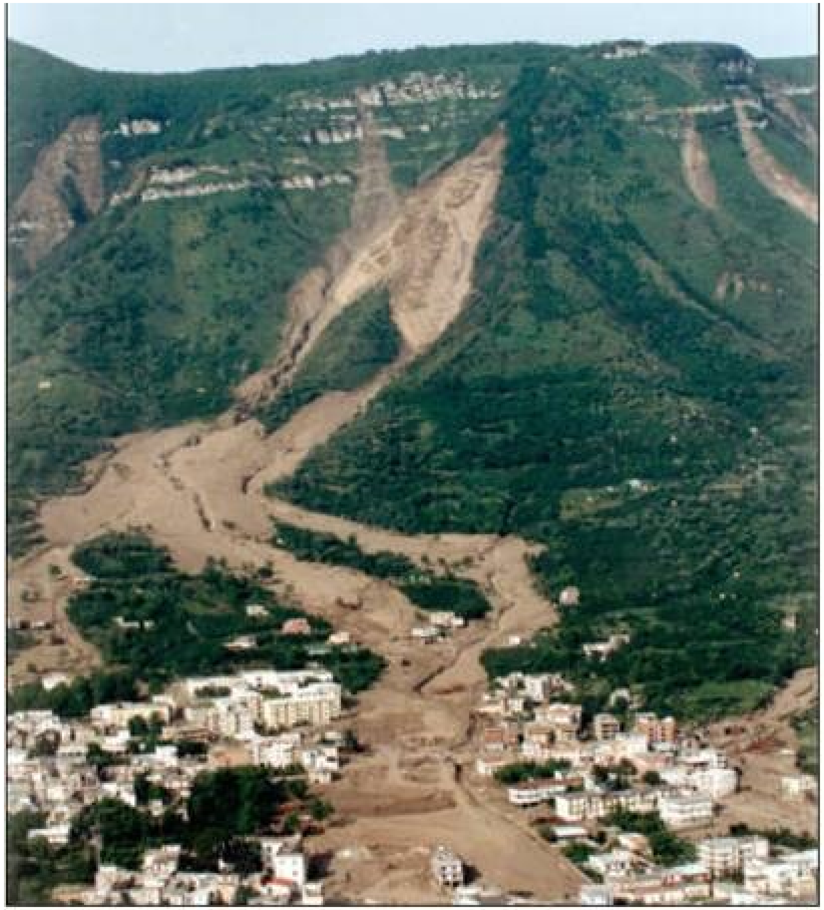
Source: EMDAT/CRED international disaster database

Examples of major landslides

El Salvador – Las Colinas
January 2001
~ 600 casualties

Nicaragua – Casita Volcano slide
October 1998
~2500 casualties

The 5-6 May 1998 mudflows in Sarno ridge area in Campania, Italy



Residents and fatalities of the affected municipalities

Municipality	Residents	Fatalities
Sarno (SA)	31,509	137
Siano (SA)	9,265	5
Bracigliano (SA)	5,105	6
Quindici (AV)	3,023	11
S. Felice a Cancello (CE)	16,771	1
TOTAL	65,673	160

New York City Slide

Landslide problems in Denmark!

The most recent landslide at Møns Klint, which occurred in January 2007. 100 000 m^3 chalk from the cliff section known as St. Taler collapsed into the sea.

Rule of thumb in slope stability evaluation*

* Karstein Lied, NGI

All slopes that look unstable

… will eventually fail.

All slopes that look stable

… will also eventually fail.

DEFINITIONS
(Based on Glossary of TC32 of the ISSMGE)

Danger (Threat): Natural phenomenon that could lead to damage. Described by geometry, mechanical and other characteristics. Can be an existing one, or a potential one, such as a rockfall. Characterisation of threat involves no forecasting.

Hazard: Probability that a particular danger (threat) occurs within a given period of time.

Risk: Measure of the probability and severity of an adverse effect to life, health, property, or the environment.

Risk = Hazard × Potential Worth of Loss

Definition of Risk (from an engineer's viewpoint)

Risk = Hazard x Consequence

$$R = H \cdot V \cdot U$$

H = Hazard (temporal probability of a threat)

V = Vulnerability of element(s) at risk

U = Utility of the consequence to the element(s) at risk

Quantitative Risk Assessment (QRA) of landslides or slope failures

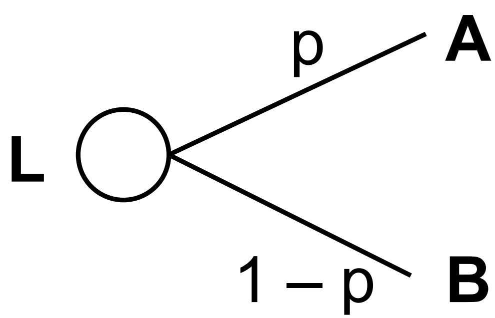
QRA refers to the assessment of threat, hazard, risk and countermeasures in terms of numbers. It addresses the following questions:

- **(1) What can cause harm?** → landslide threat identification
- **(2) How often?** → frequency of failure occurrence (hazard)
- **(3) What can go wrong?** → consequence of failure
- **(4) How bad?** → severity of failure consequence
- **(5) So what?** → acceptability of landslide risk
- **(6) What should be done?** → landslide risk management

QRA is an important element in **Decision Making Under Uncertainty**

Decision Theory

- A calculus for decision-making under uncertainty
- Set of primitive outcomes
- Subjective degrees of belief (probabilities)
- Lotteries: uncertain outcomes



With probability p, outcome **A** occurs.

With probability 1 – p, Outcome **B** occurs.

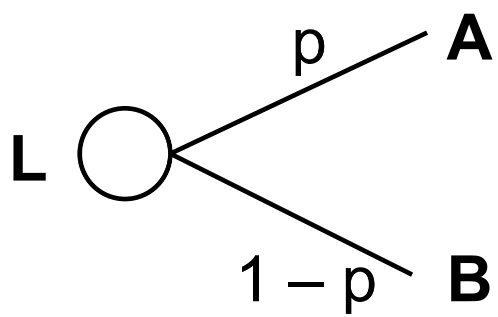
Decision Theory – Utility function

If certain assumptions are satisfied, then there exists U (a real valued function) such that:

- If A > B, then U(A) > U(B)
- If A ≈ B, then U(A) = U(B)

Utility of a lottery = expected utility of the outcomes

$$U(L) = p \times U(A) + (1 - p) \times U(B)$$



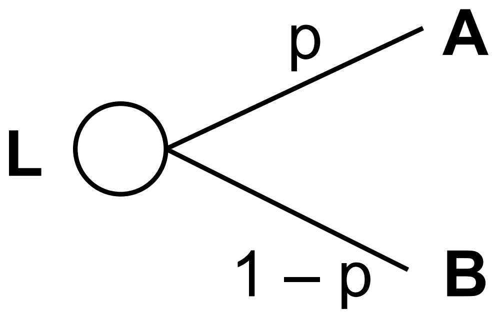
Decision Theory – Utility function

If certain assumptions are satisfied, then there exists U (a real valued function) such that:

- If A > B, then U(A) > U(B)
- If A $\approx$ B, then U(A) = U(B)

Utility of a lottery = expected utility of the outcomes

$$U(L) = p \times U(A) + (1-p) \times U(B)$$



Survey Question 1

Which alternative would you prefer:

A. A sure gain of $240

B. A 25% chance of winning $1000 and a 75% chance of winning nothing

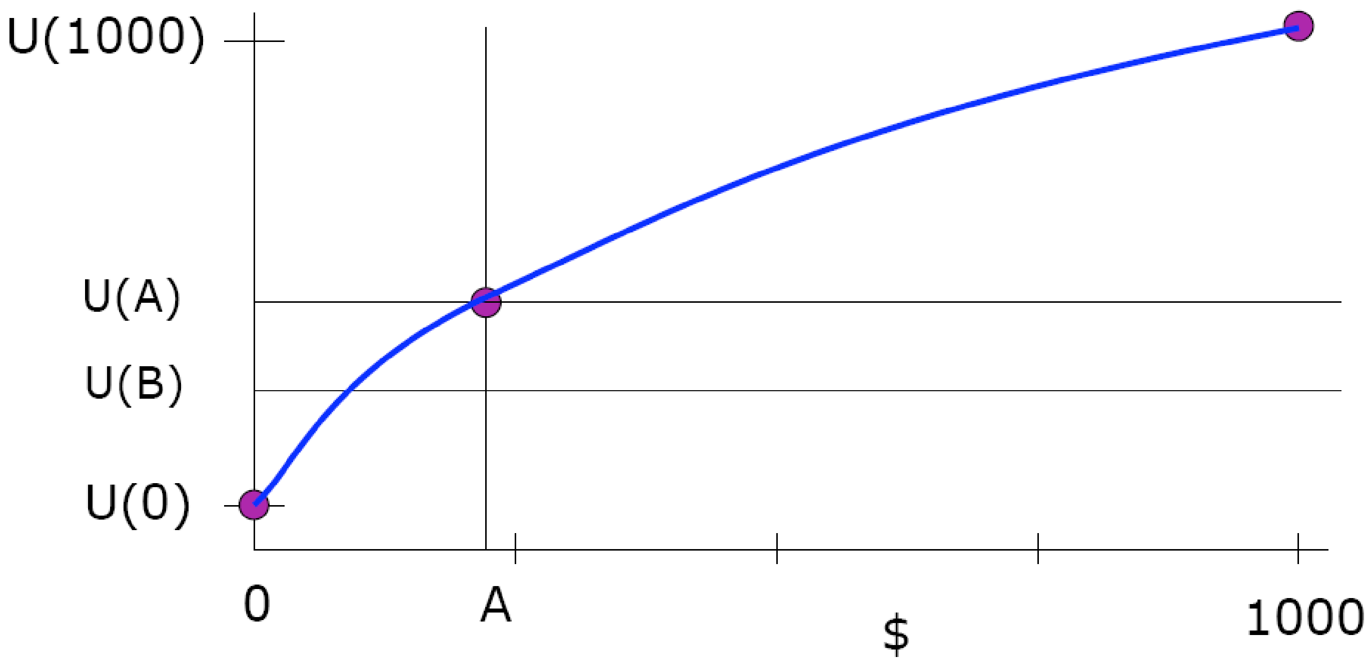
85% prefer option A to option B

- $U(B) = .25\, U(\$1000) + .75\, U(\$0)$
- $U(A) = U(\$240)$
- $U(A) > U(B)$

Utility of Money

- U(B) = .25 U($1000) + .75 U($0)
- U(A) = U($240)
- U(A) > U(B)

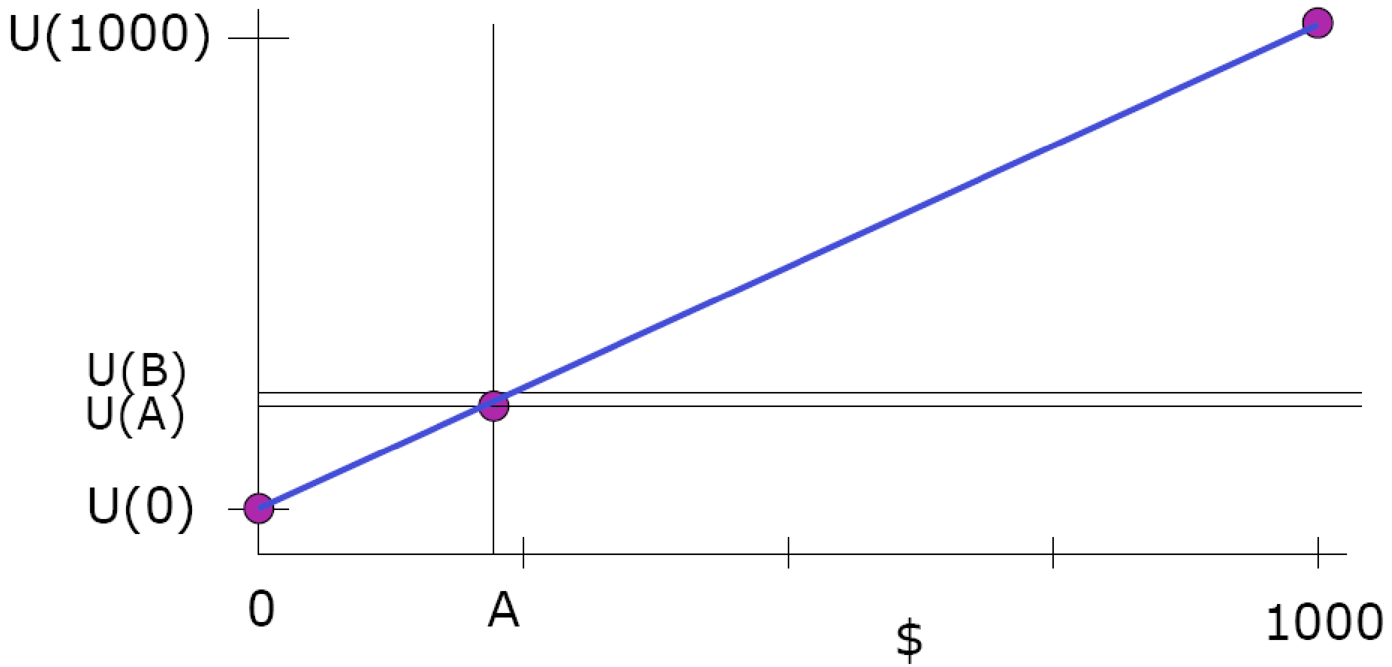
concave utility function
risk averse



Risk neutrality

- U(B) = .25 U($1000) + .75 U($0) = U($250)
- U(A) = U($240)

linear utility function
risk neutral



Survey Question 2

Which alternative would you prefer:

- C. A sure loss of $750
- D. A 75% chance of losing $1000 and a 25% chance of losing nothing

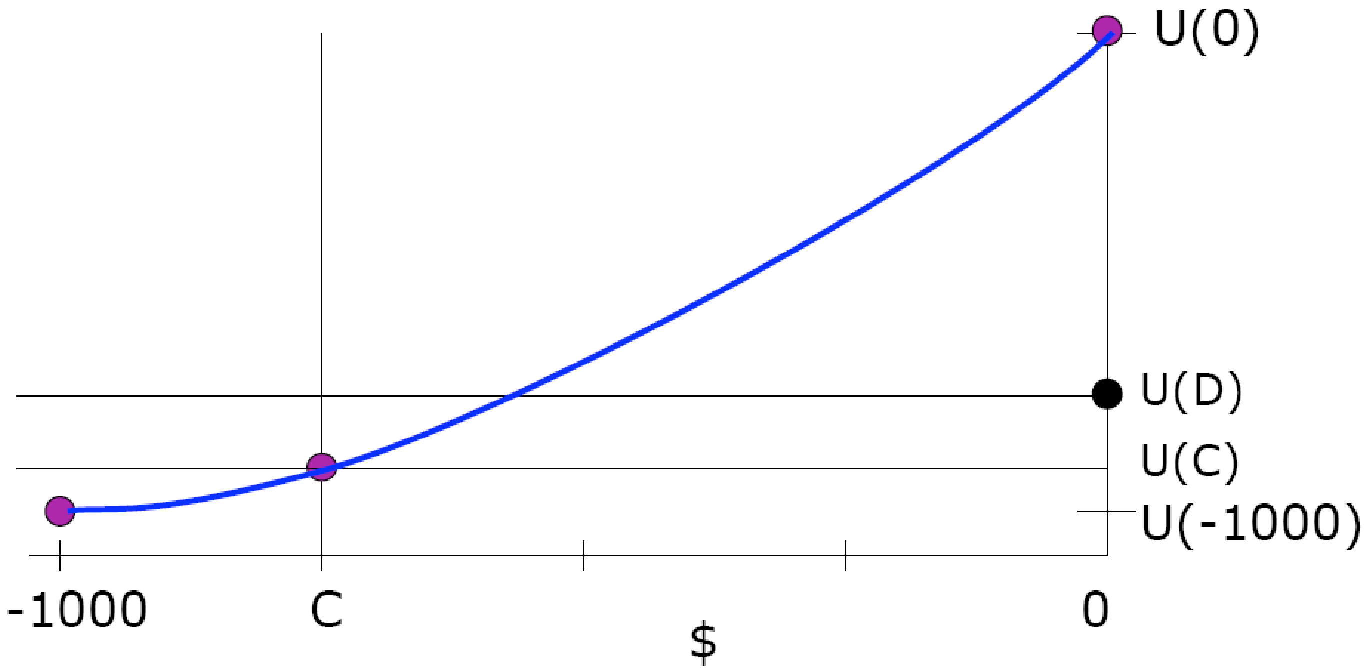
91% prefer option D to option C

- $U(D) = .75\ U(-\$1000) + .25\ U(\$0)$
- $U(C) = U(-\$750)$
- $U(D) > U(C)$

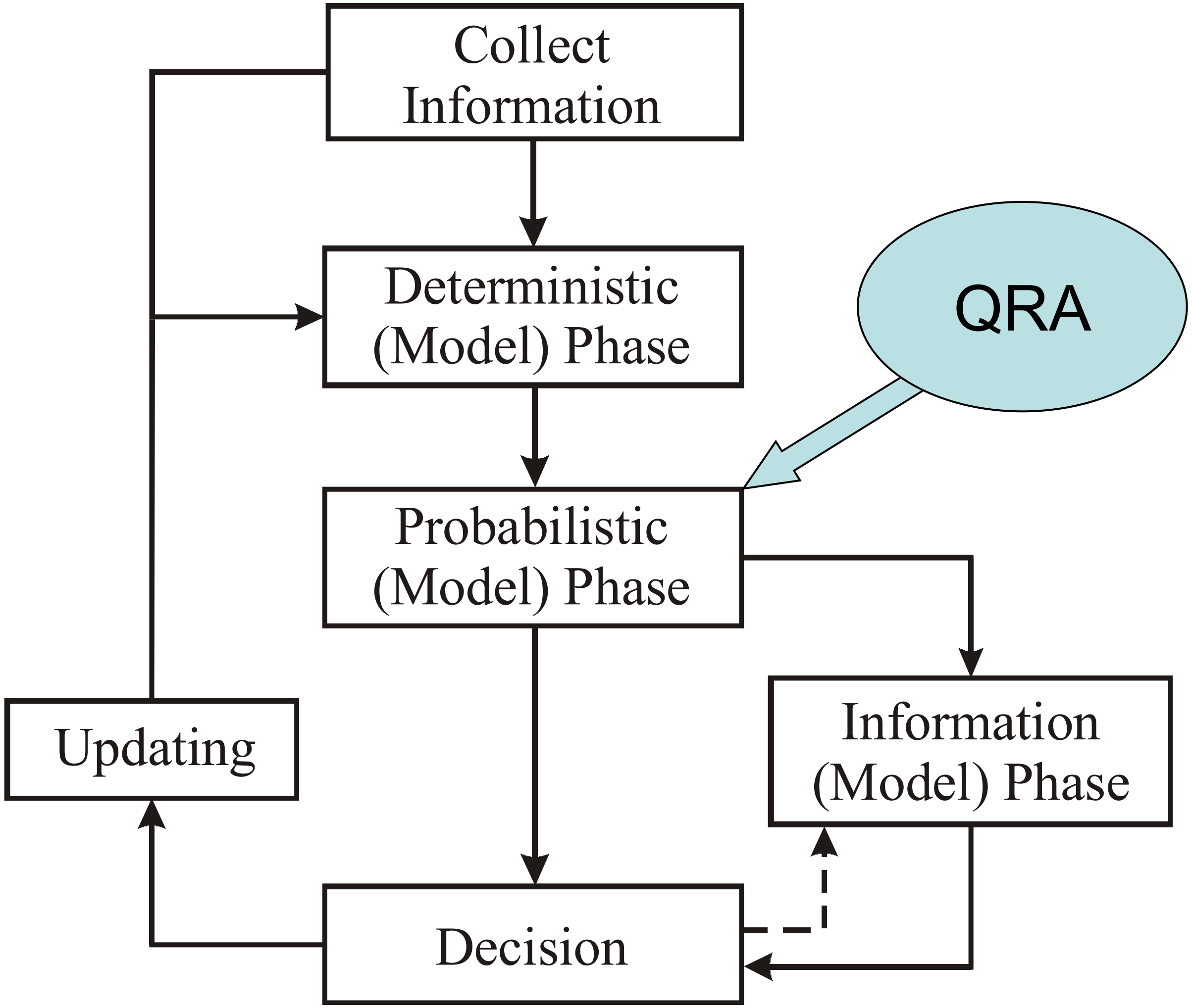
Risk seeking in losses

- $U(D) = .75\ U(-\$1000) + .25\ U(\$0)$
- $U(C) = U(-\$750)$
- $U(D) > U(C)$

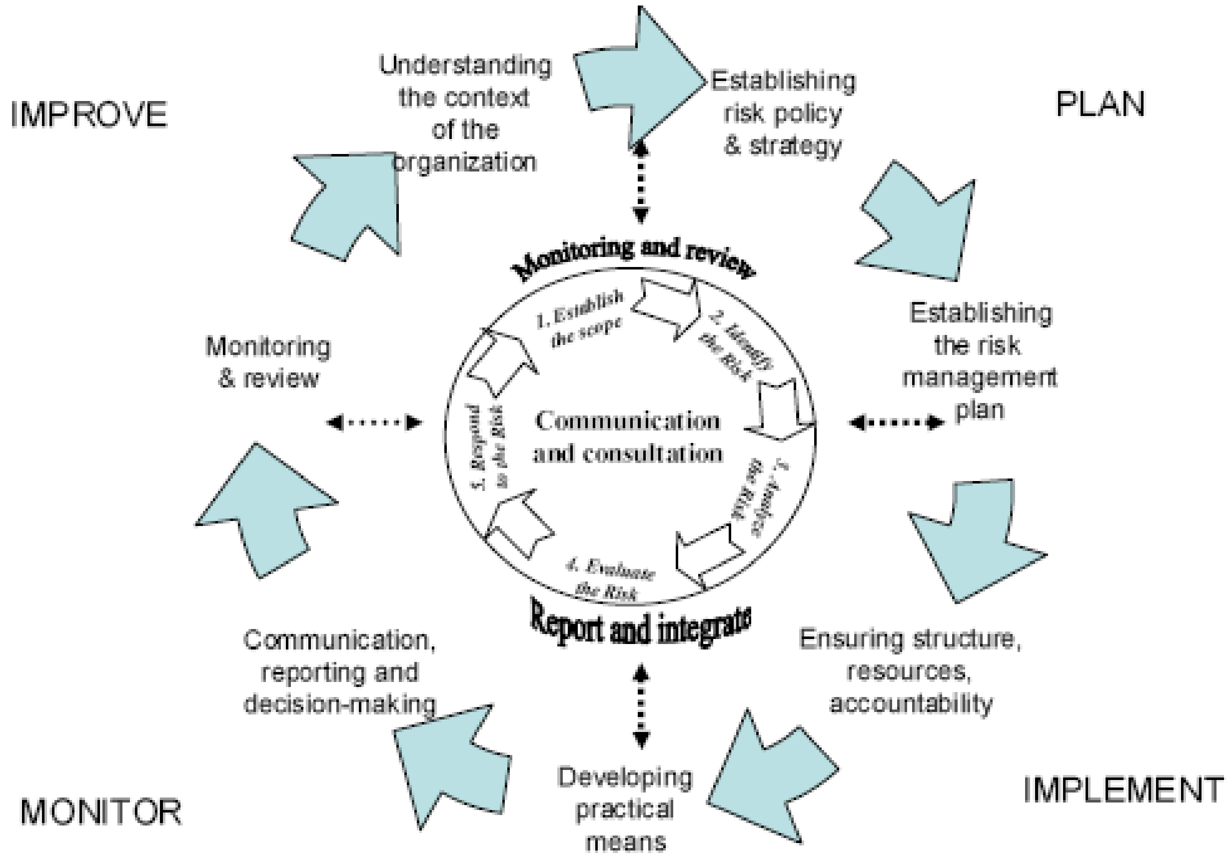
convex utility function
risk seeking



Decision Making Under Uncertainty



Risk management process is easy …



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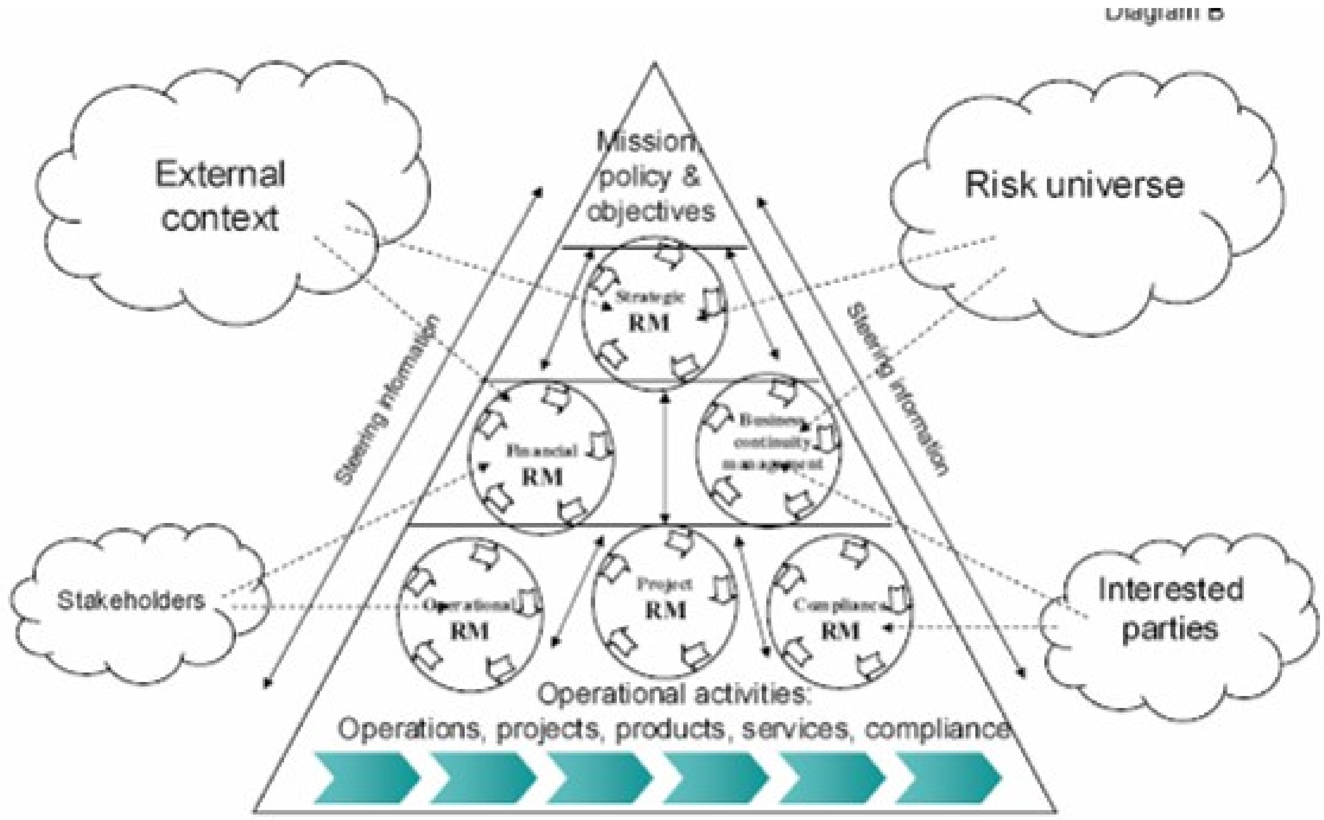
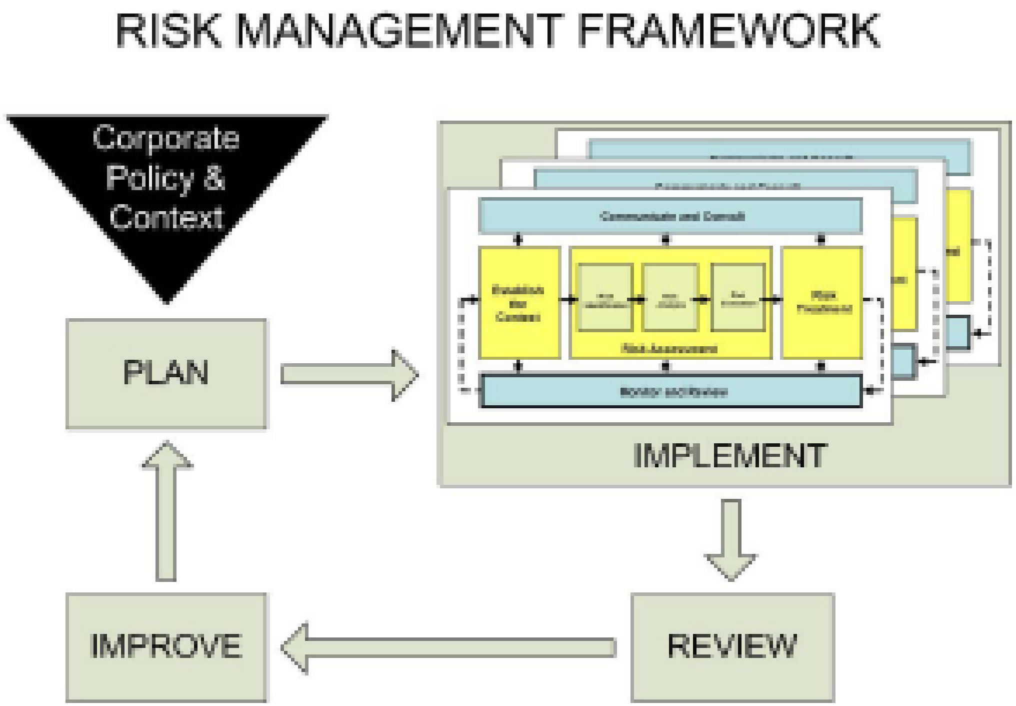
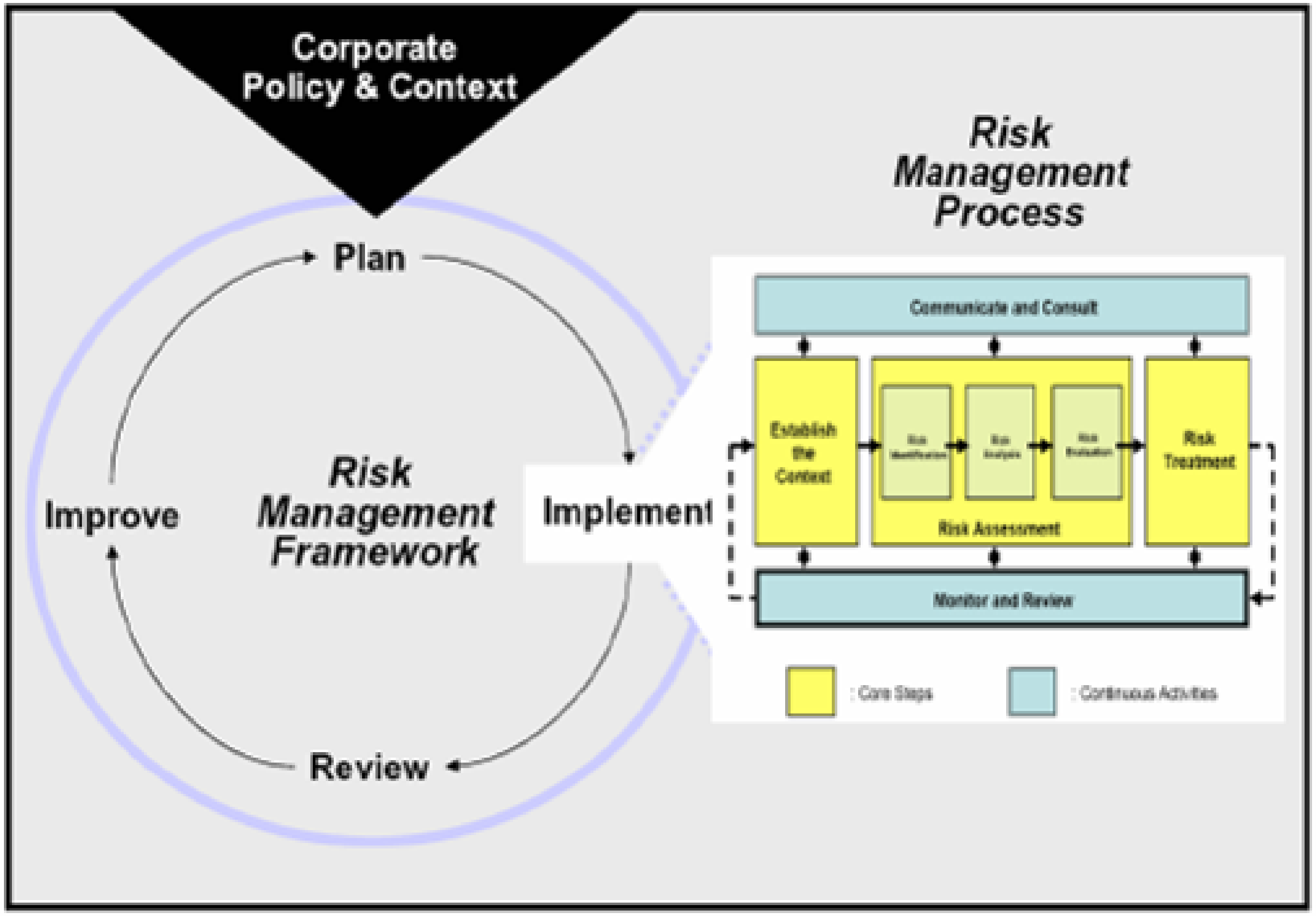


Risk management processes in various functions and levels of an organization addressing a variety of risks

Risk management process is easy …



Risk management process is easy …



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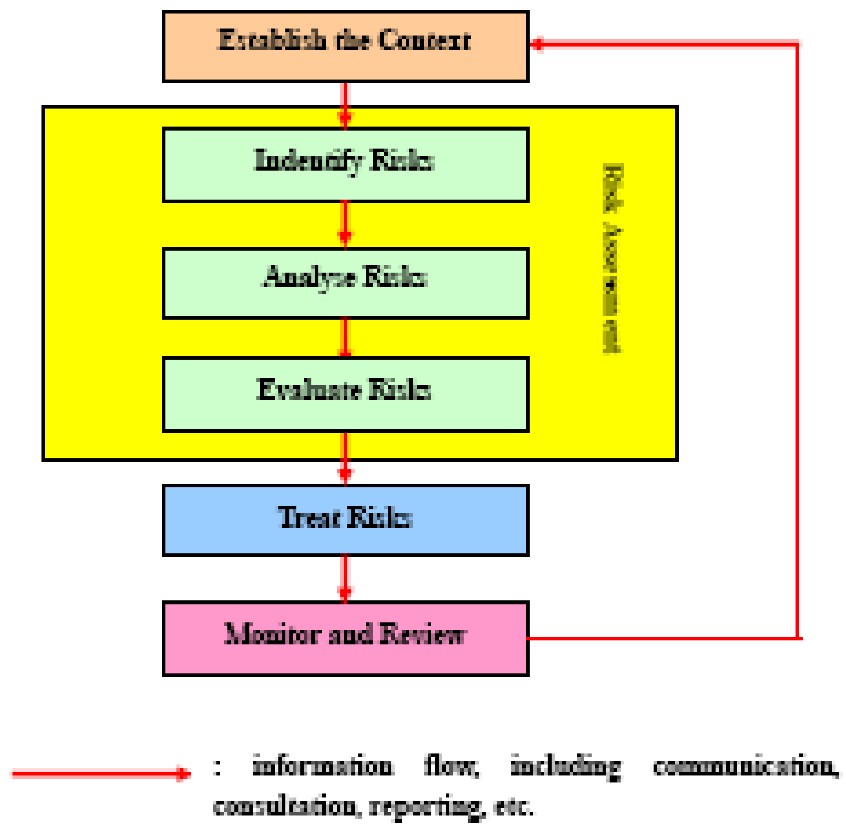
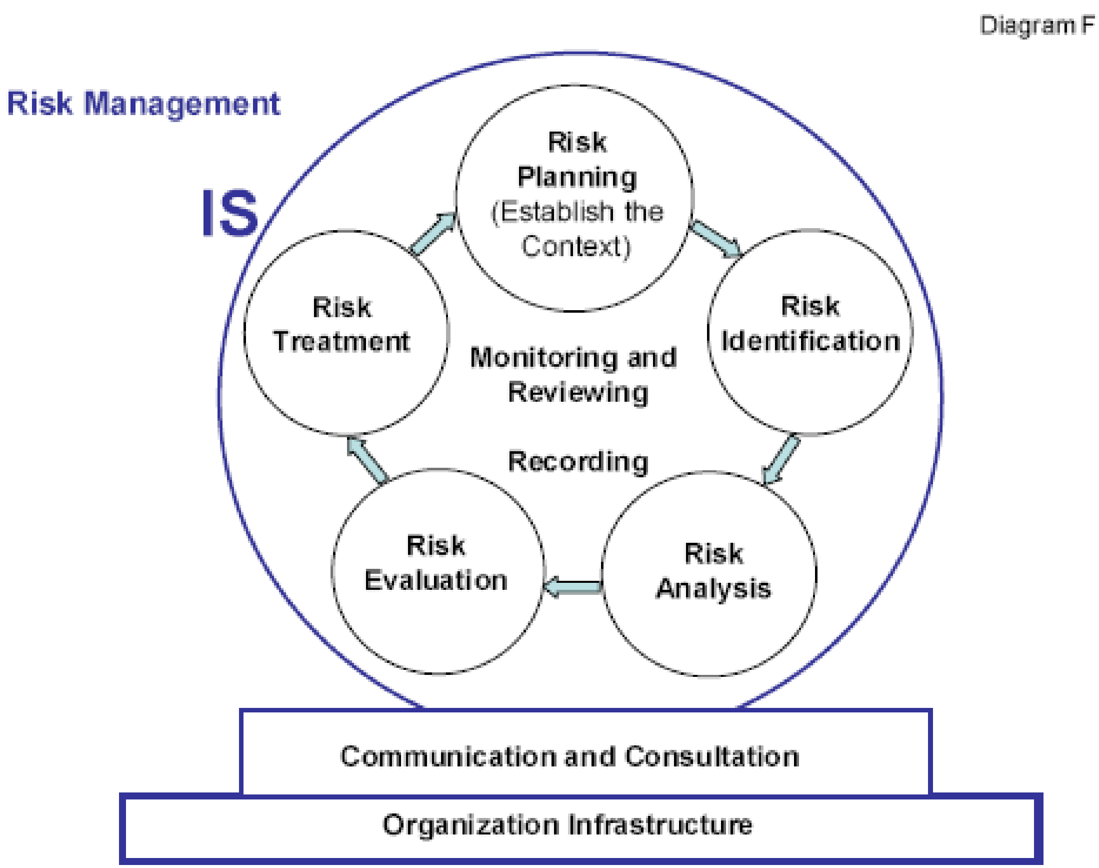
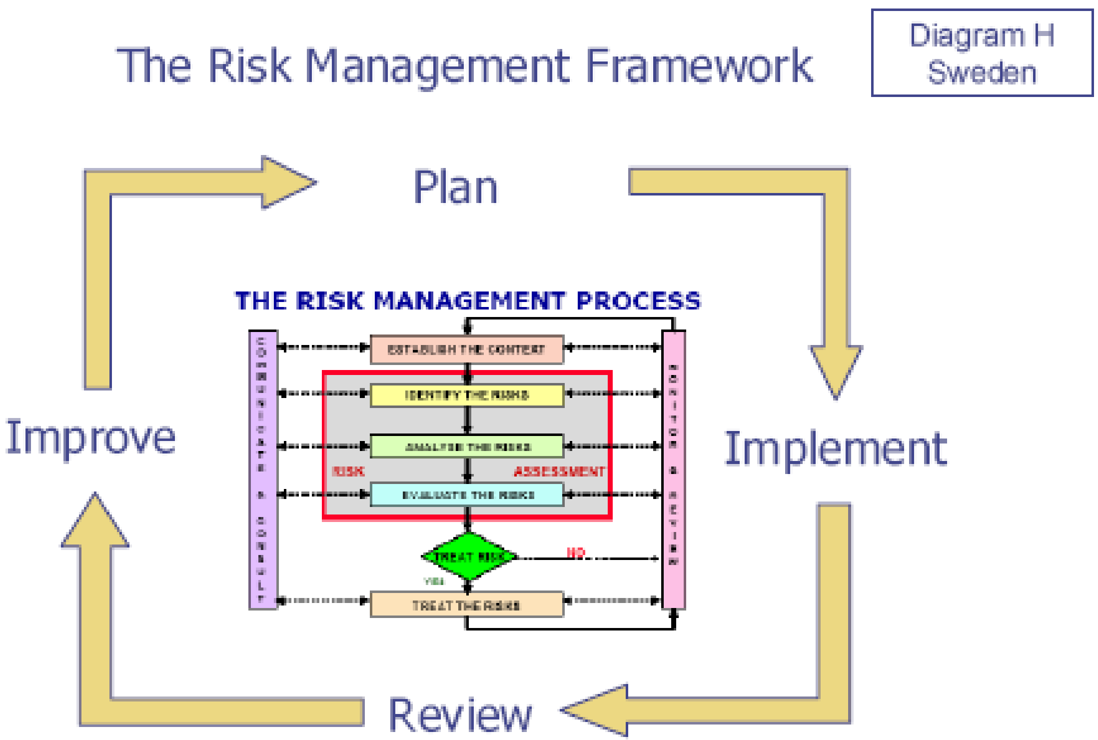


Risk management process is easy …

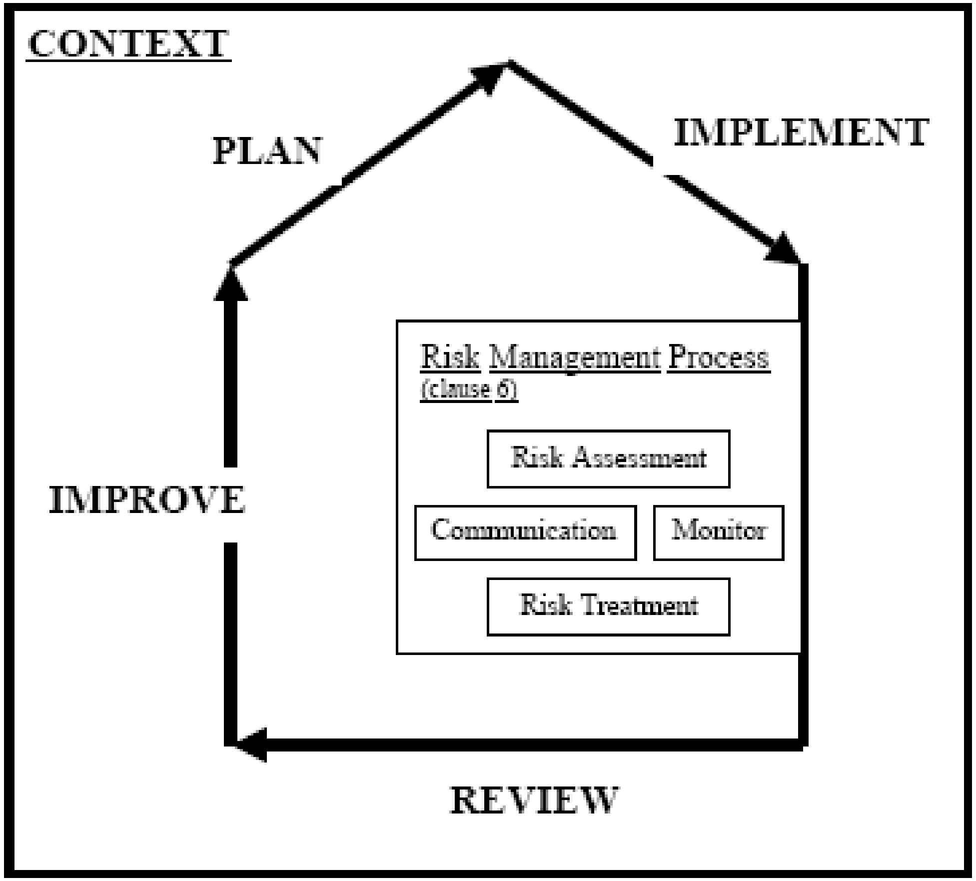


Risk management process is easy …

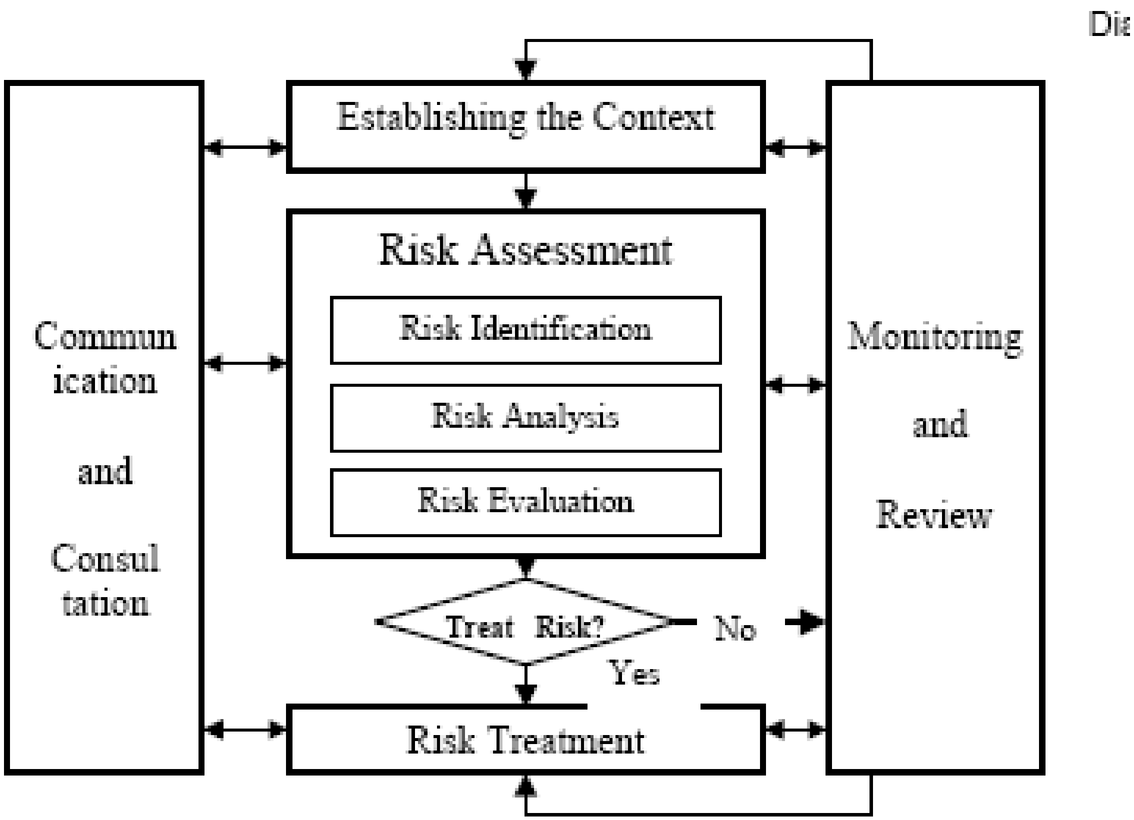


Risk management process is easy …

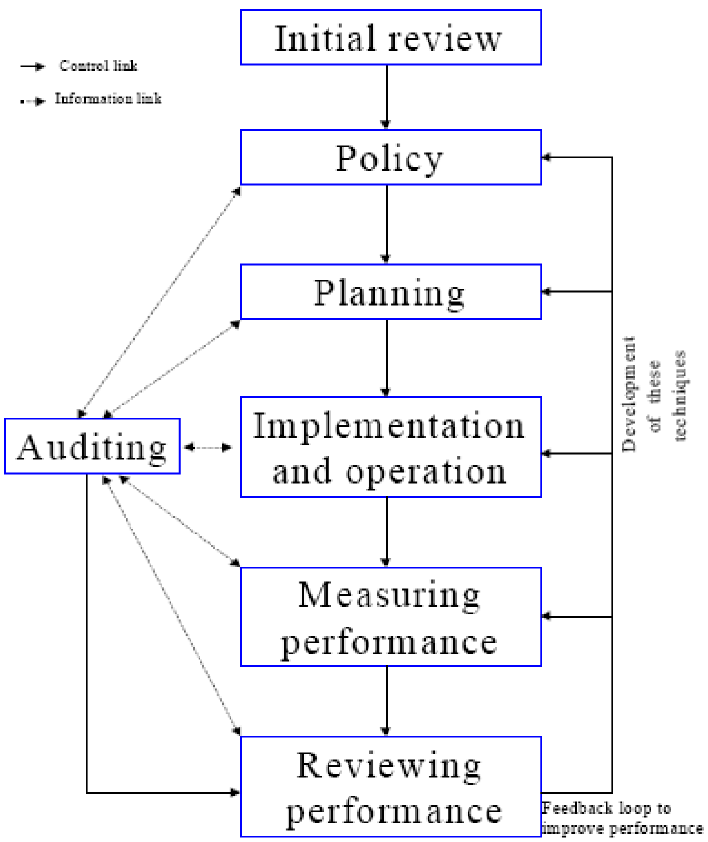
Figure 1 Framework for Organization-Wide Risk Management



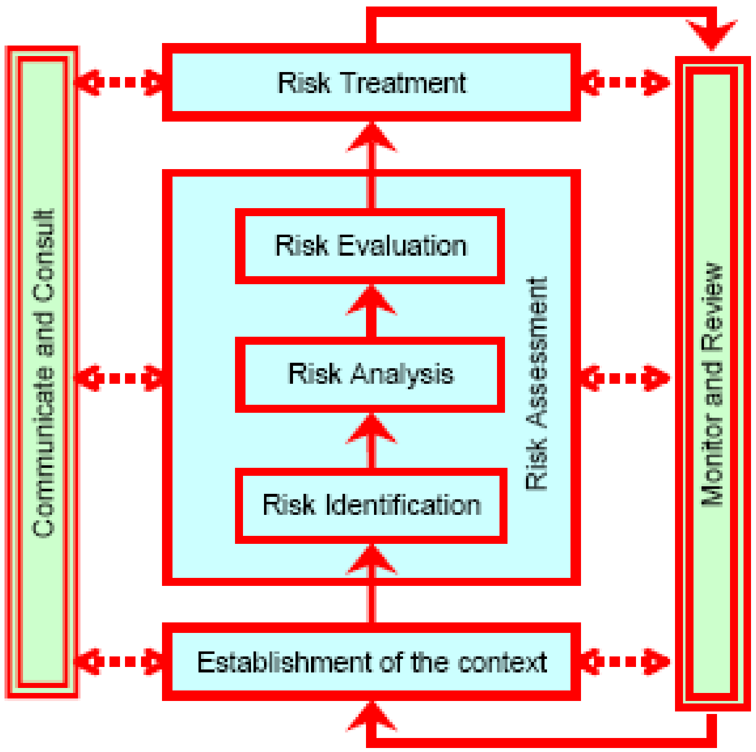
Risk management process is easy …



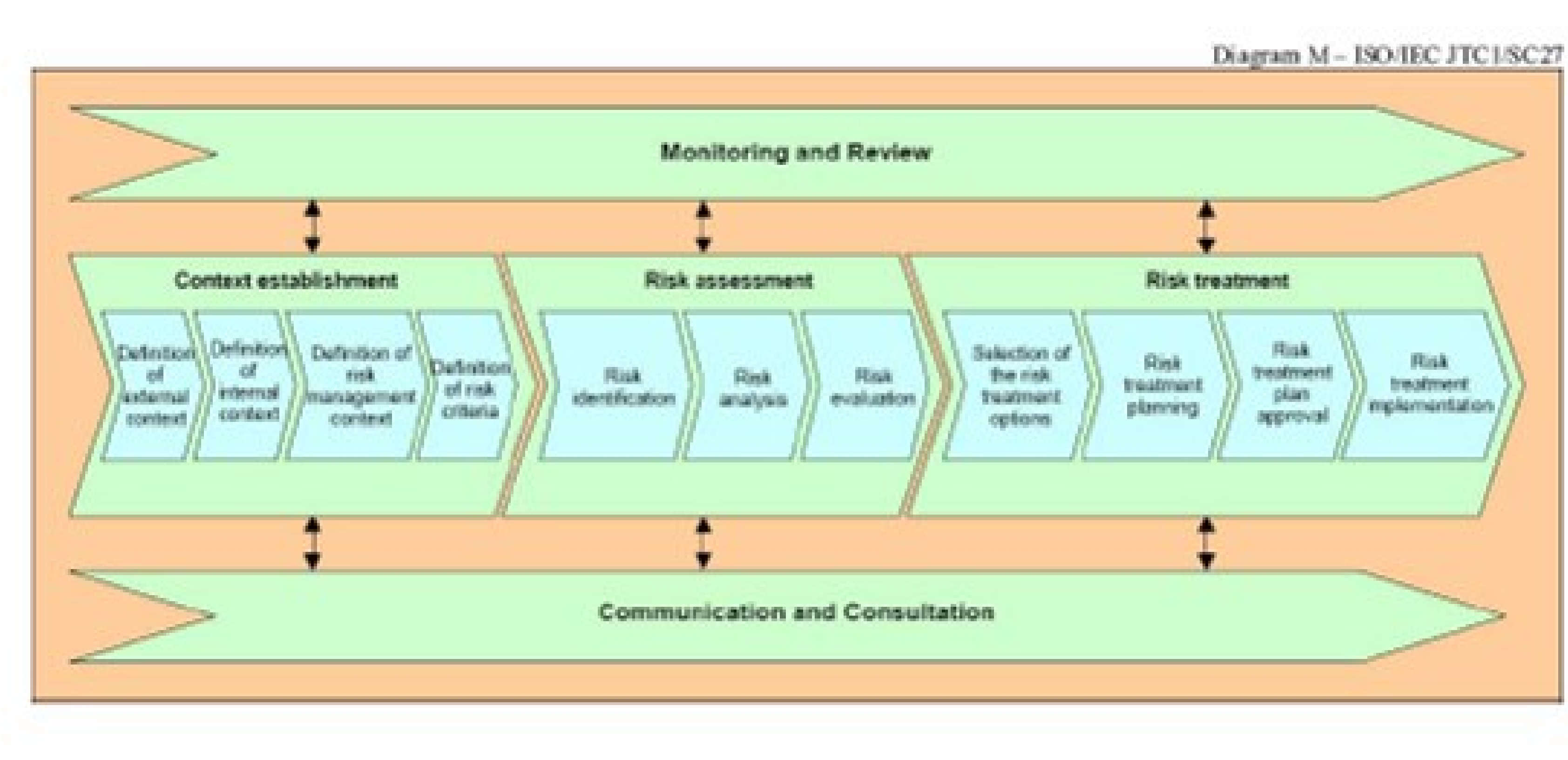
Risk management process is easy …



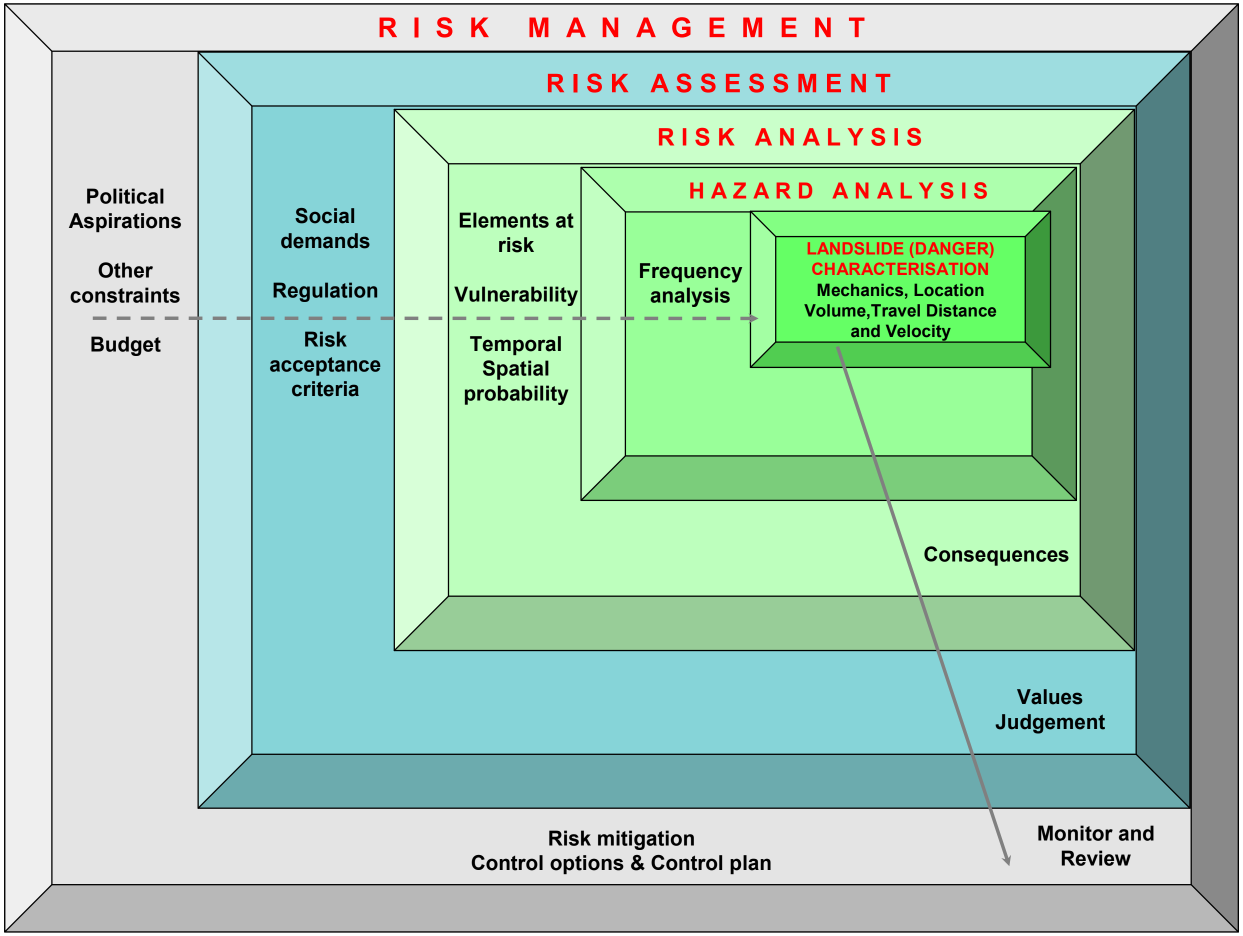
Risk management process is easy …



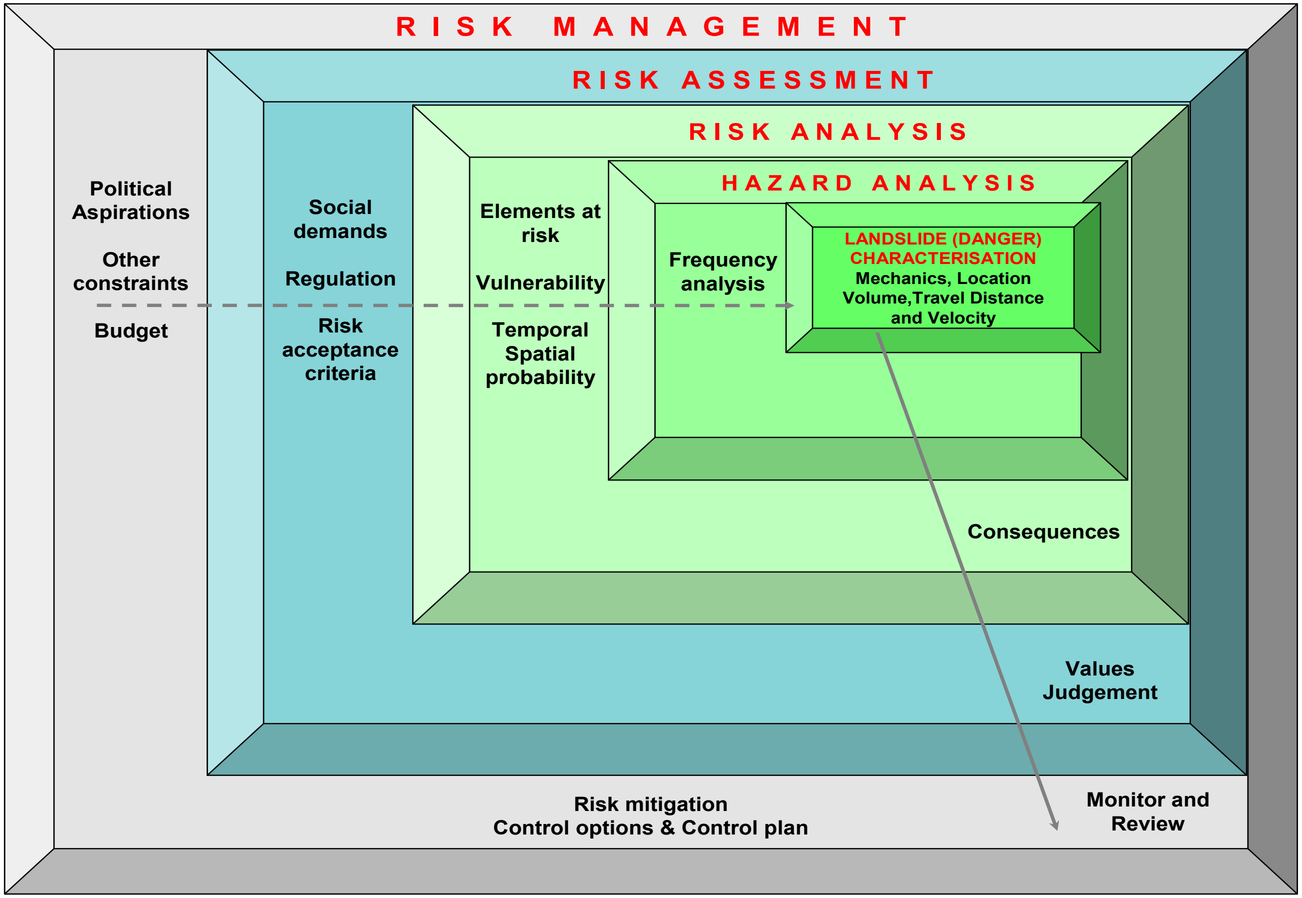
Risk management process is easy …



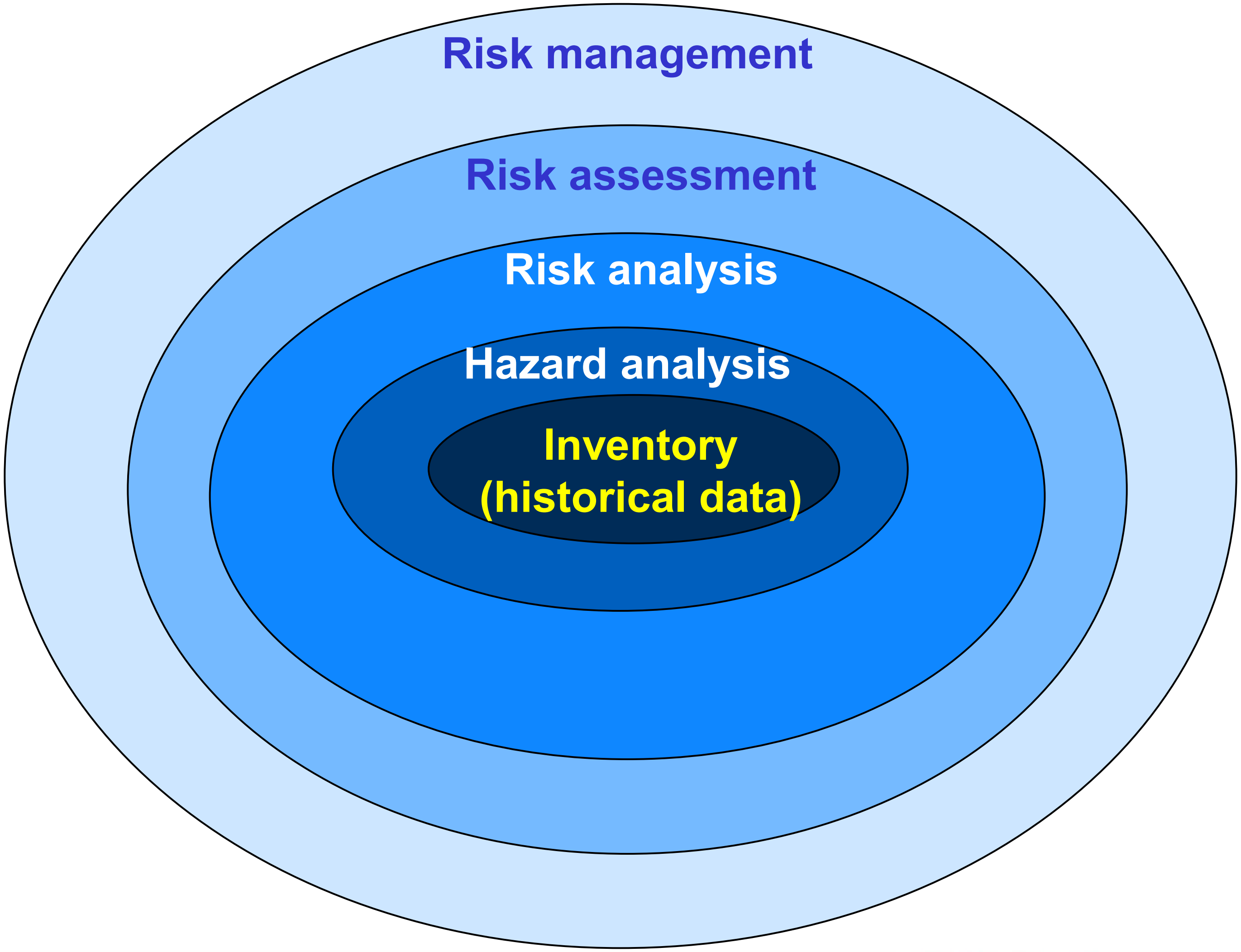
Risk management process is easy …



Landslide risk management framework (JTC1 experts)



Landslide risk management framework (NGI)



Computation of Hazard

- Heuristic methods
- Statistical methods
- Probabilistic methods
  - Reliability analyses
  - Monte Carlo Simulations

Example of heuristic/statistical approach

New York State Rockfall Hazard Rating Procedure

Relative Hazard = GF x SF x HEF

GF = Geologic Factor
= Sum of Seven Subjectively Assessed Indicators:

Fractures, Bedding Planes, Block Size, Rock Friction, Water/Ice, Rock Fall History, Backslope

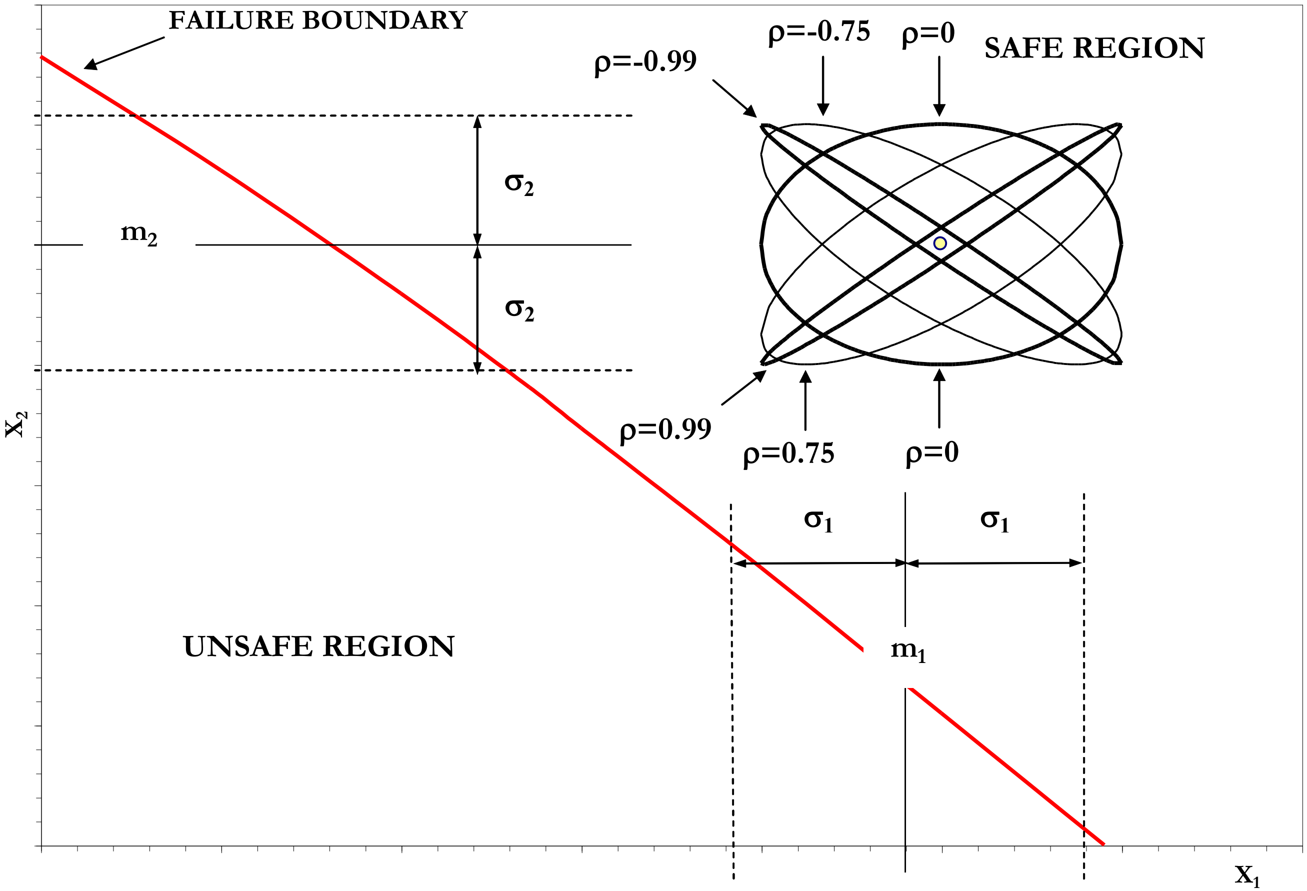
SF = Section Factor

Ditch and Slope Geometry (Largely Deterministic)

HEF = Human Exposure Factor

Probability of Being Hit by Falling Rock or Hitting Rock Lying on Road (Objective or Subjective Probabilistic Assessment)

Probabilistic methods: Reliability Analysis



β = Reliability Index

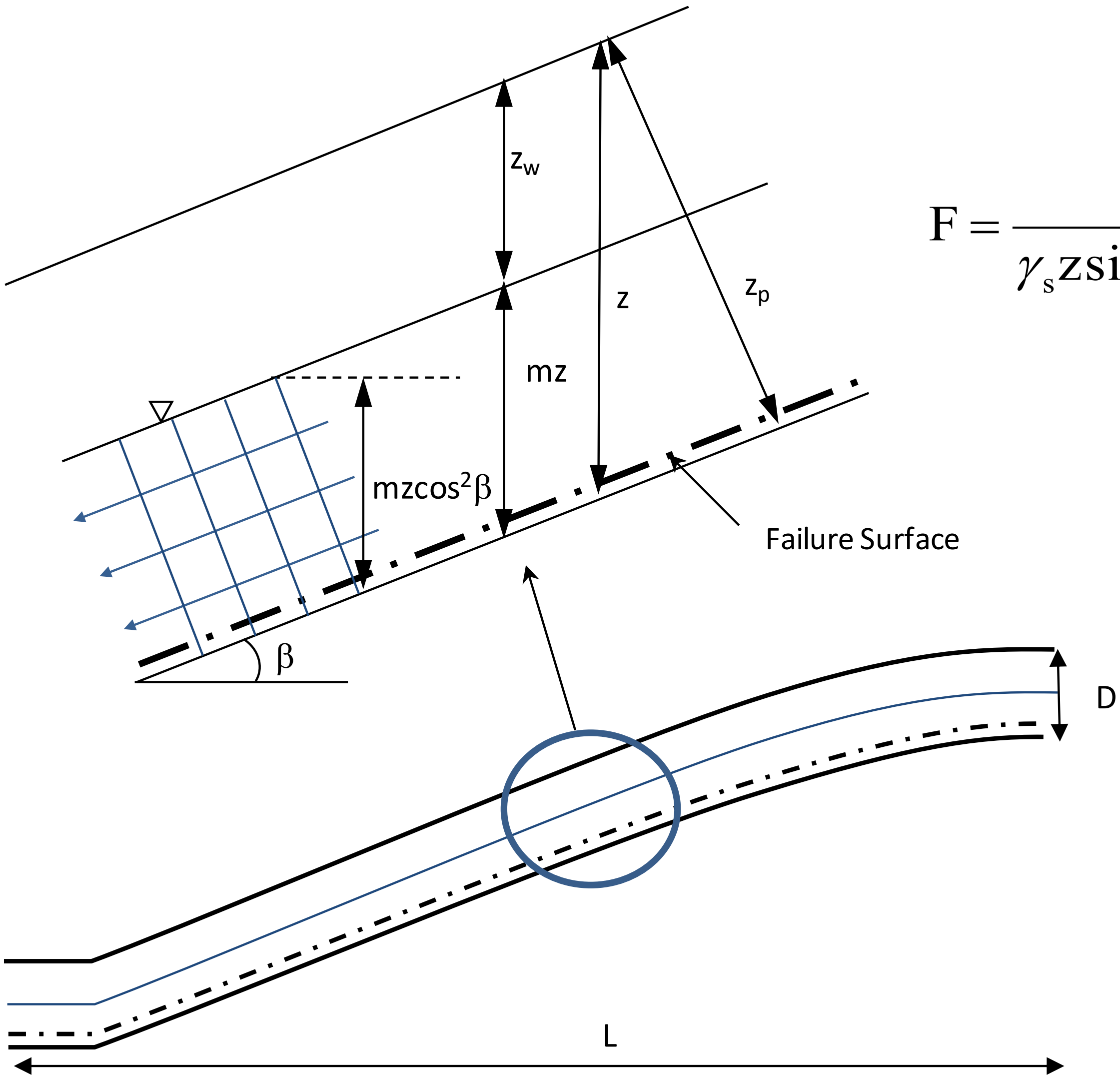
Single variable:

$$\beta = \frac{E[X] - X^*}{\sigma[X]}$$

Multiple variables:

$$\beta = \min_{\underline{X} \in \Omega} \sqrt{\left(\underline{X} - E[\underline{X}]\right)^T \underline{\Sigma}_X^{-1} \left(\underline{X} - E[\underline{X}]\right)}$$

Slope Stability



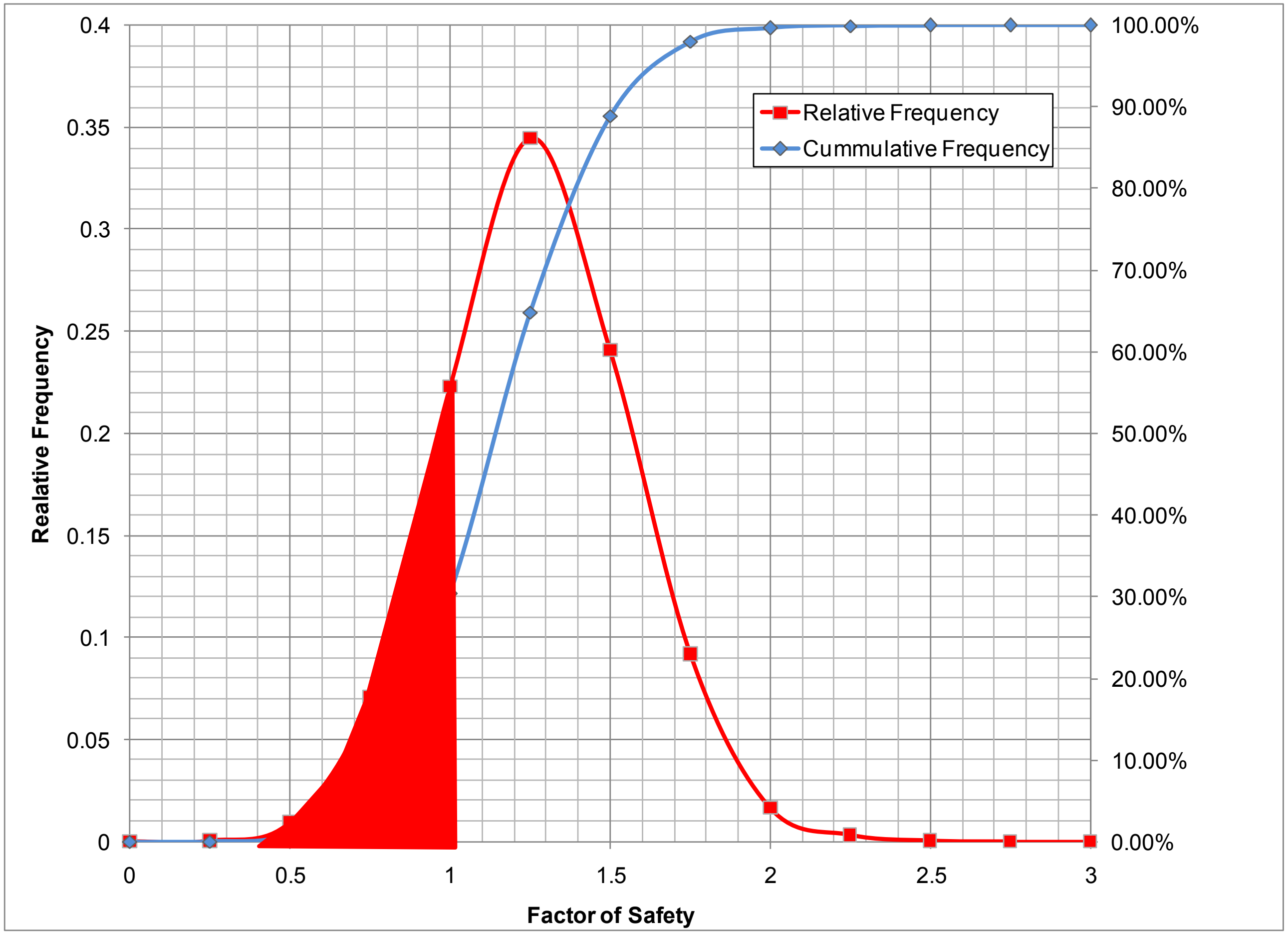
$$F = \frac{c'}{\gamma_s z \sin\beta \cos\beta} + \left(1 - m\frac{\gamma_w}{\gamma_s}\right)\left(\frac{\tan\phi'}{\tan\beta}\right)$$

Variable	Mean	St. Dev
c'	15	5
ϕ'	30	5
z	25	0
γw	1	0
γs	2.75	0
m	0.4	0.1
β	35	2.5

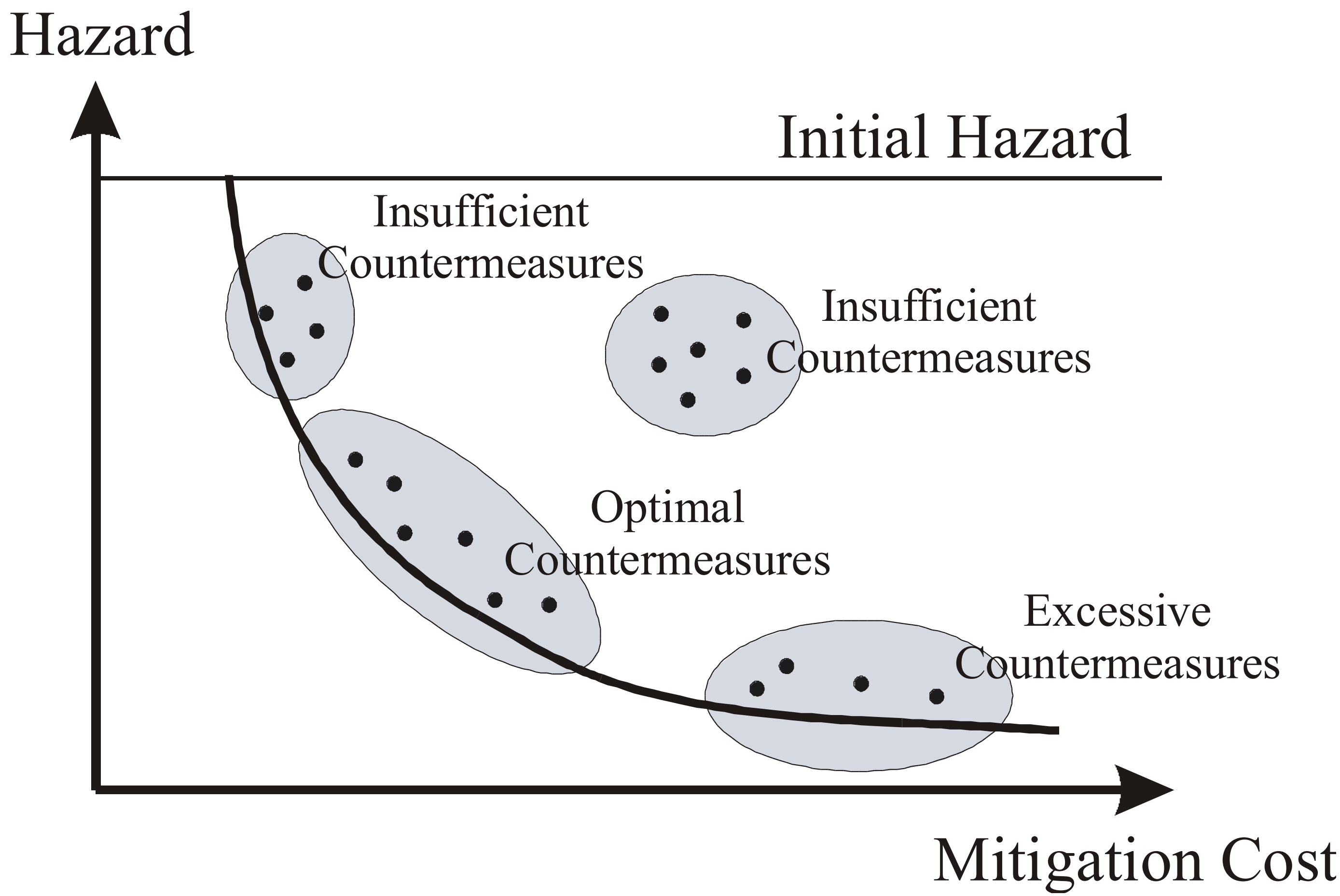
P[F<1] = P[T]=0.30

Computation of Hazard

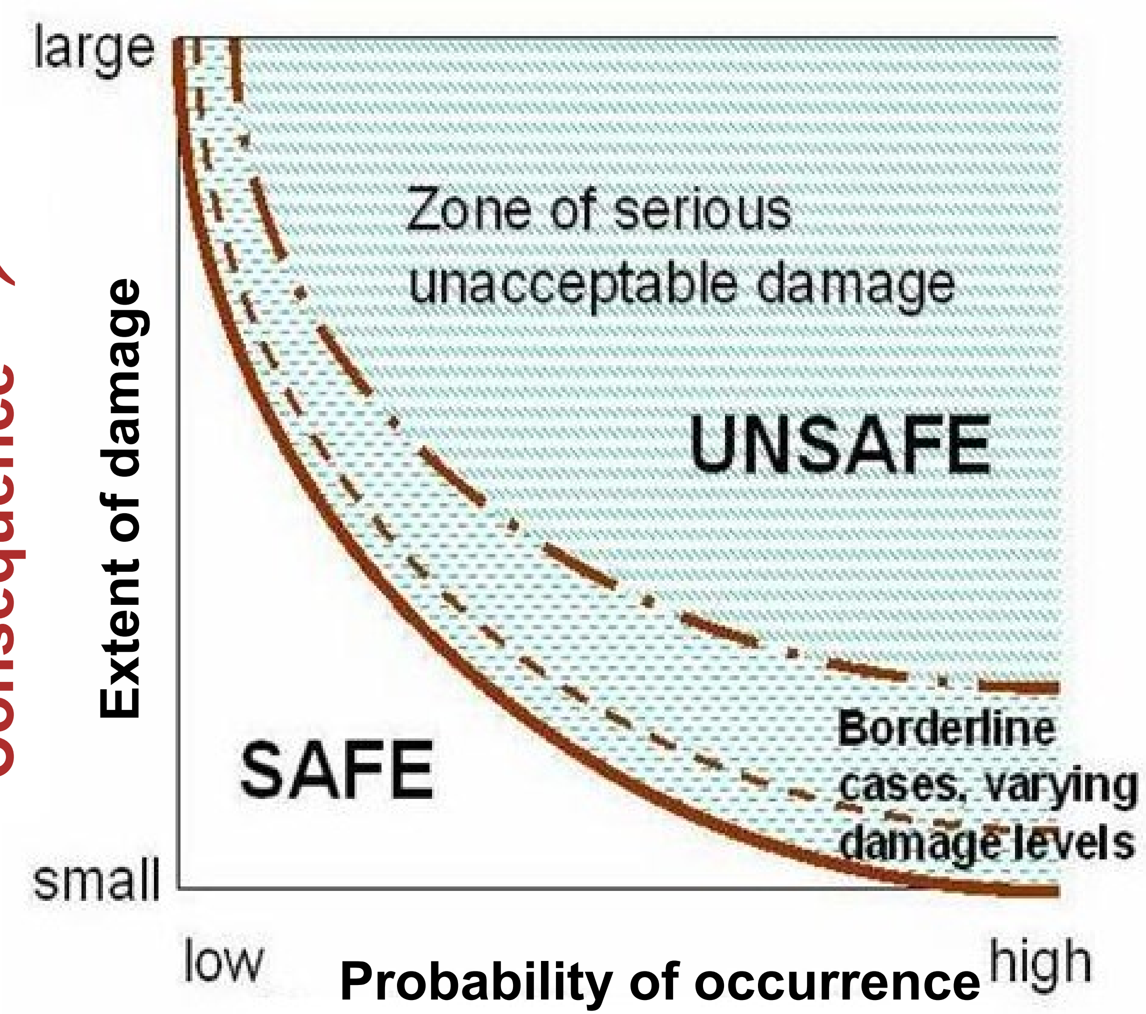
Hazard = P[Threat] = P[Factor of safety < 1] = 0.30



Relation Between Marginal Cost and Hazard Reduction

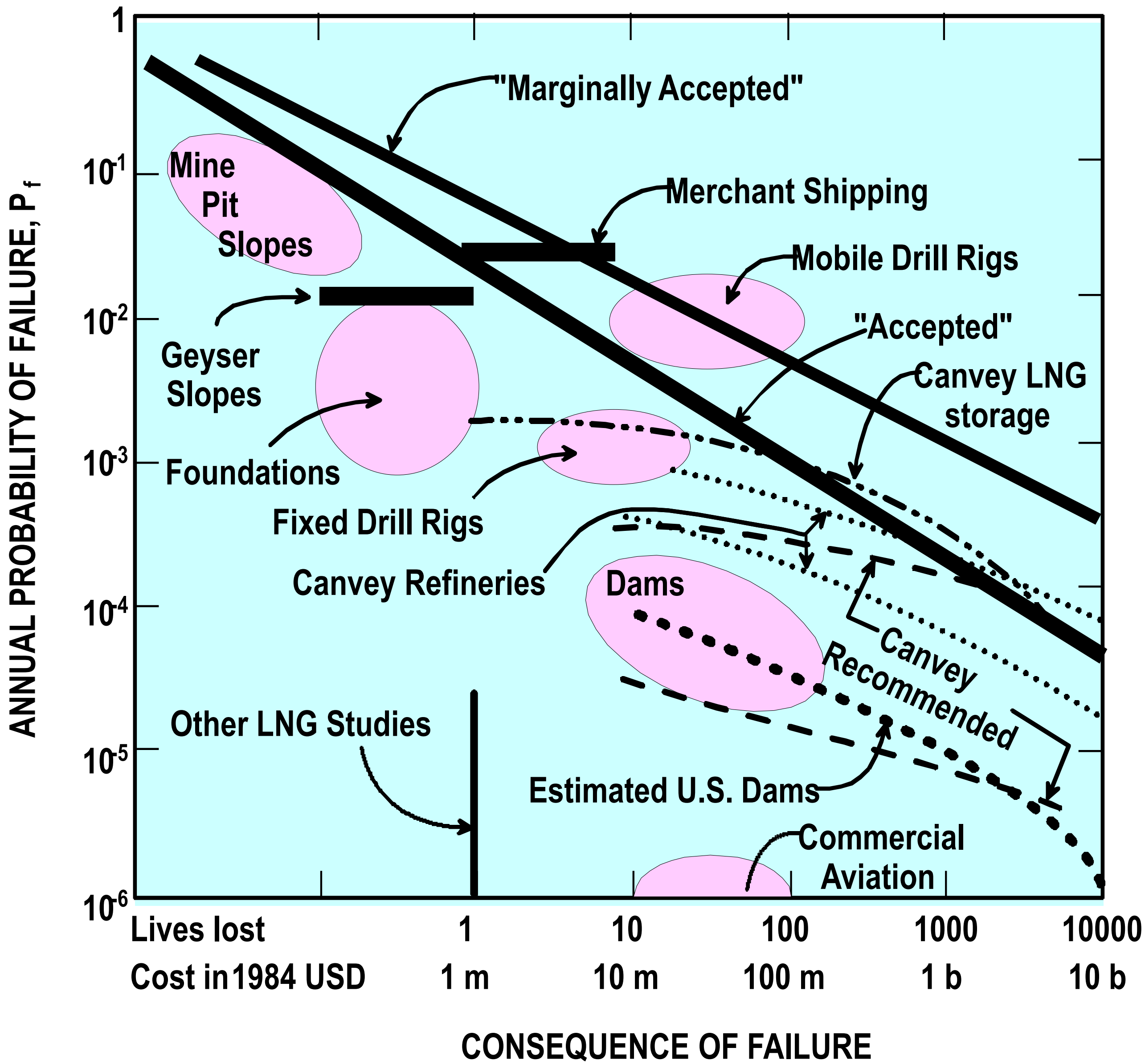


How much risk is acceptable?



Consequence →

Hazard →


ANNUAL PROBABILITY OF FAILURE, P_f
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
"Marginally Accepted"
Mine Pit Slopes
Merchant Shipping
Mobile Drill Rigs
"Accepted"
Geyser Slopes
Canvey LNG storage
Foundations
Fixed Drill Rigs
Canvey Refineries
Dams
Canvey Recommended
Other LNG Studies
Estimated U.S. Dams
Commercial Aviation
Lives lost
1
10
100
1000
10000
Cost in 1984 USD
1 m
10 m
100 m
1 b
10 b
CONSEQUENCE OF FAILURE

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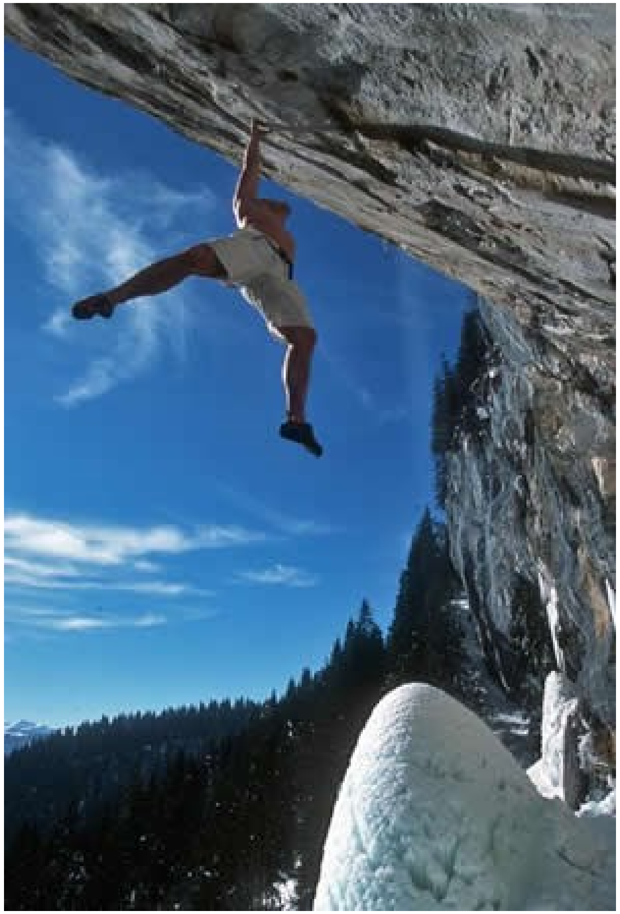
How much risk are we willing to accept?

Depends on whether the situation is voluntary or imposed.

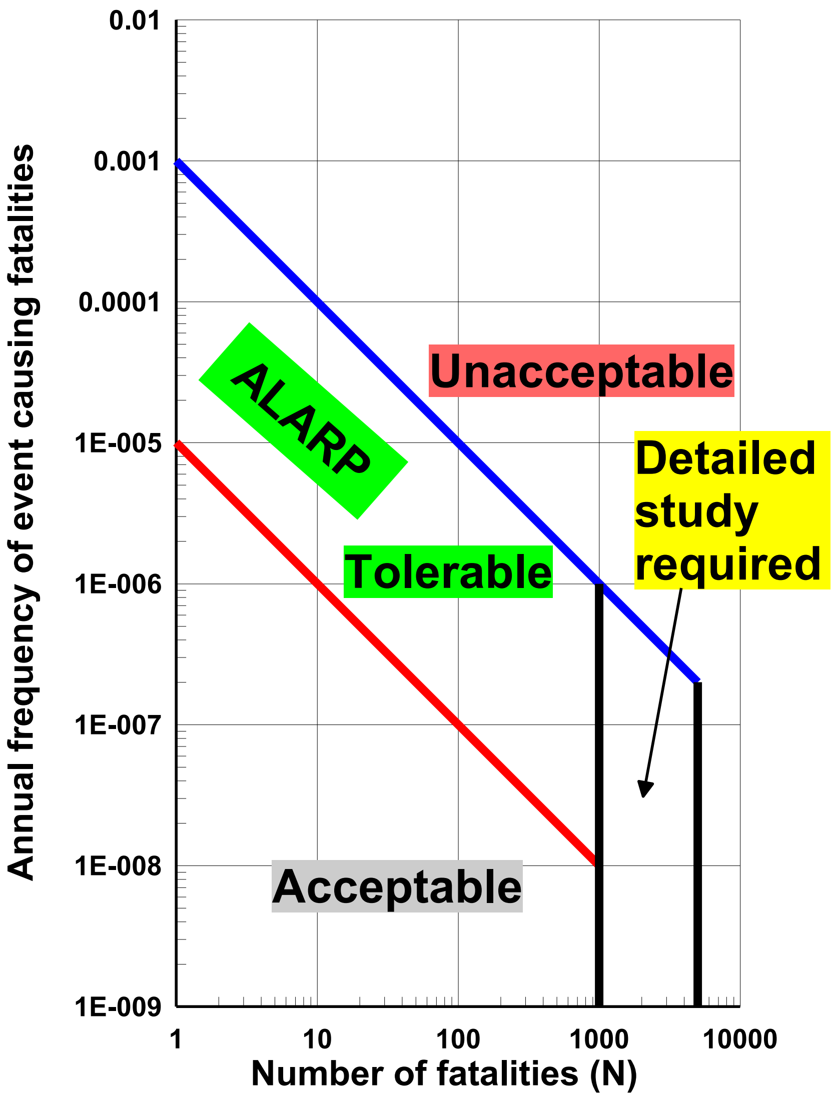


Acceptable / Tolerable Risk

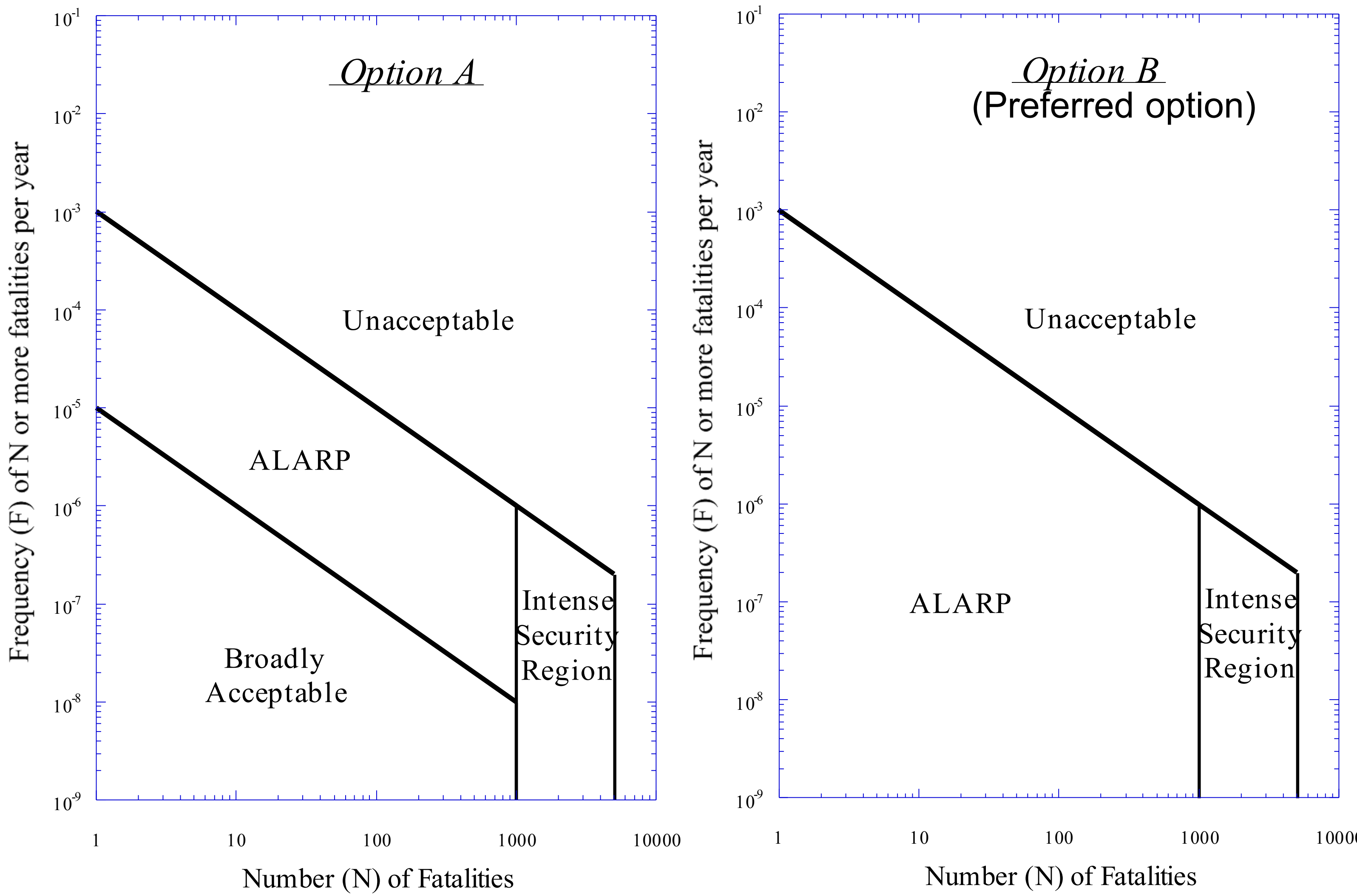
Criteria of Hong Kong Geotechnical Engineering Office

Societal: F - N Charts (Ho et al., 2000)

ALARP =
As Low As Reasonably Practical

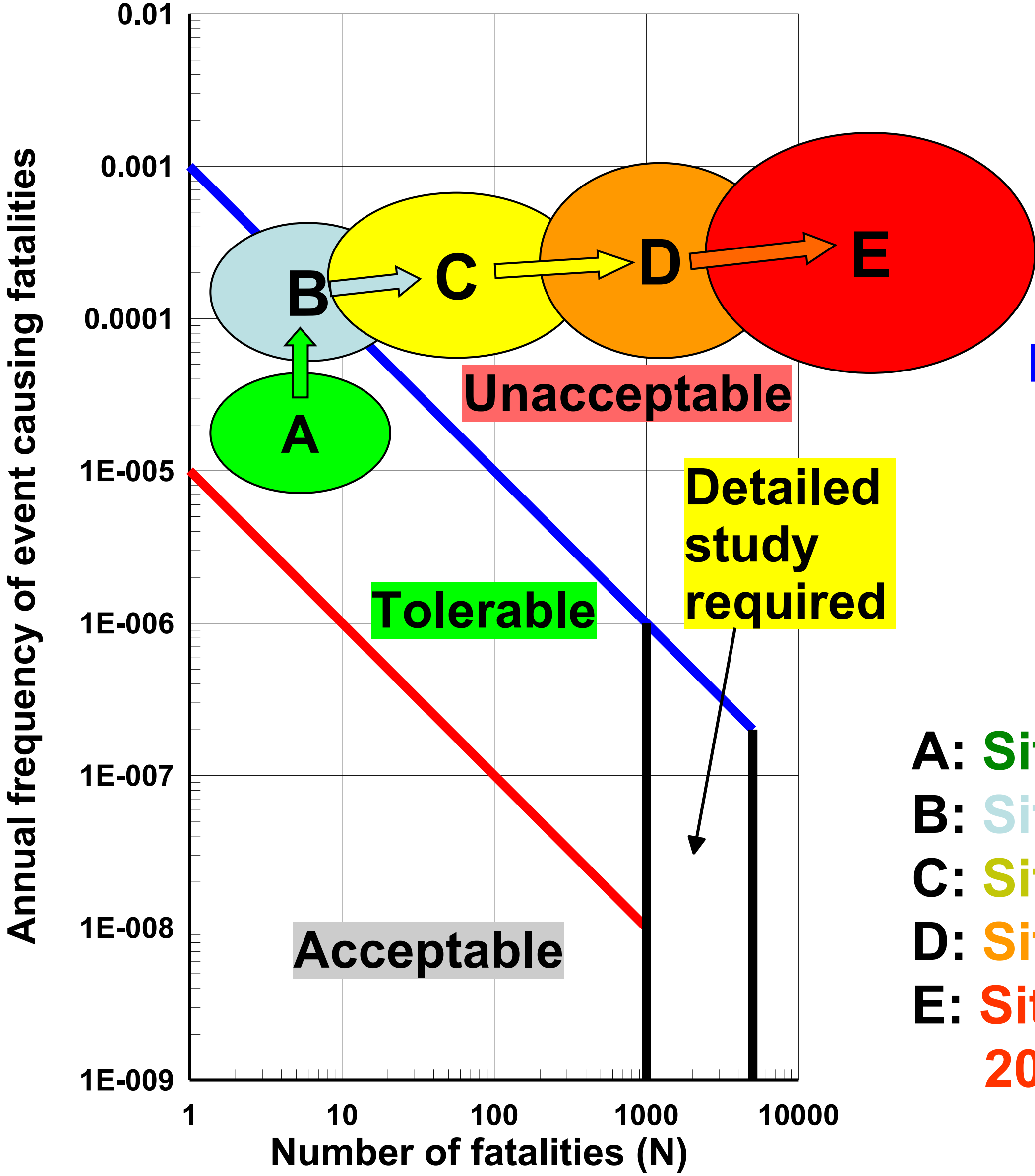


Consideration of Life Losses



Tsunami risk mitigation strategy in Thailand

Thailand – Aftermath of 26 December 2004 tsunami



Example:

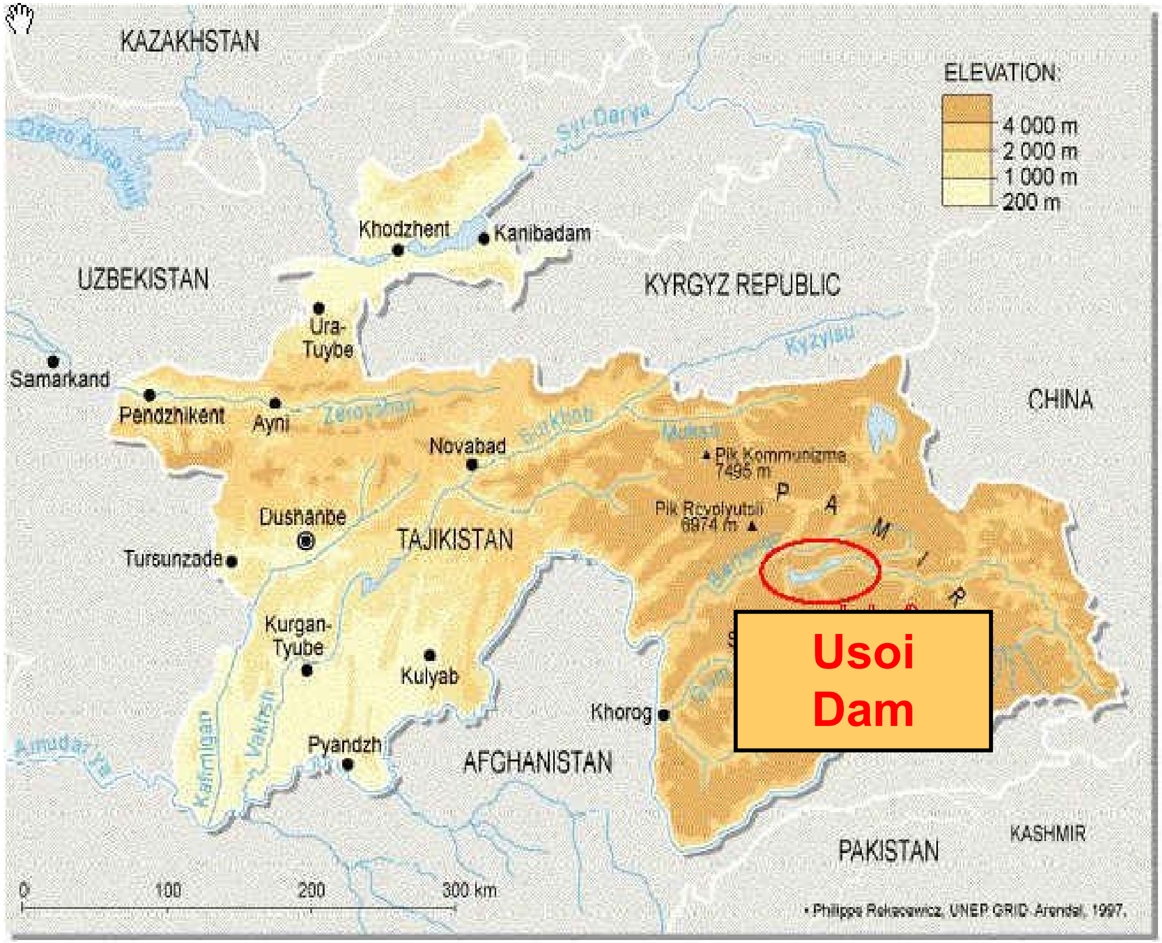
Evolution of tsunami risk in Thailand with time

A: Situation today
B: Situation in 50-100 years
C: Situation in 100-200 years
D: Situation in 200-300 years
E: Situation before 26 Dec. 2004 and after ~300 years

Example:
Usoi Dam on Lake Sarez in Tajikistan

Usoi Dam is a 600m high landslide dam.

It is the largest dam in the world!



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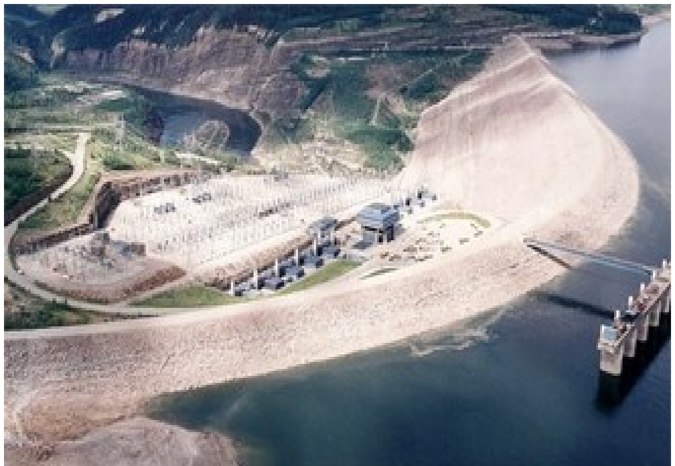
Usoi dam and Lake Sarez

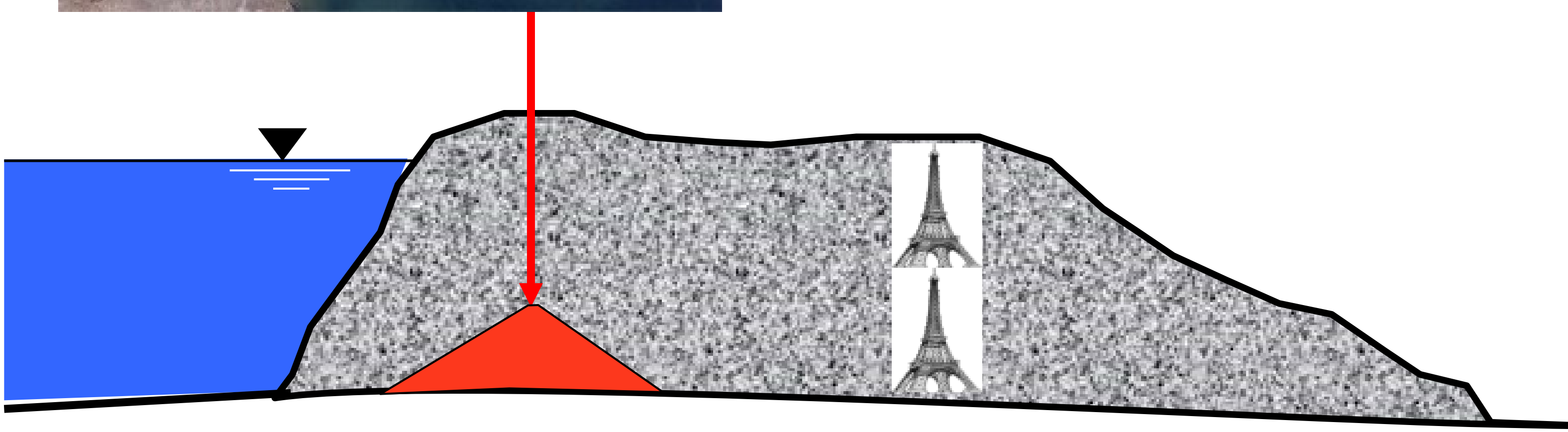
Usoi dam

How big is Usoi dam?



Bennett dam, 183 m
One of the largest dams in North America

- Eifel tower in Paris



Horizontal scale of Usoi Dam is compressed

Lake Sarez

Length, ~ 60 km
Maximum depth: 500 m
Maximum width: 3.3 km
Average width: 1.3 km
Volume: ~ 17 km^3
Elevation 3260 – 3265 m

The threat and consequences

- The 600 m high Usoi dam is the largest dam in the world.
- Lake Sarez behind the dam currently holds 17 cubic-kilometers of water.
- If the dam were to fail, the resulting flood would be a catastrophe of inconceivable dimensions!
- Flood waters would flow down the Bartang valley to the Panj River valley and end up in the Aral Sea.

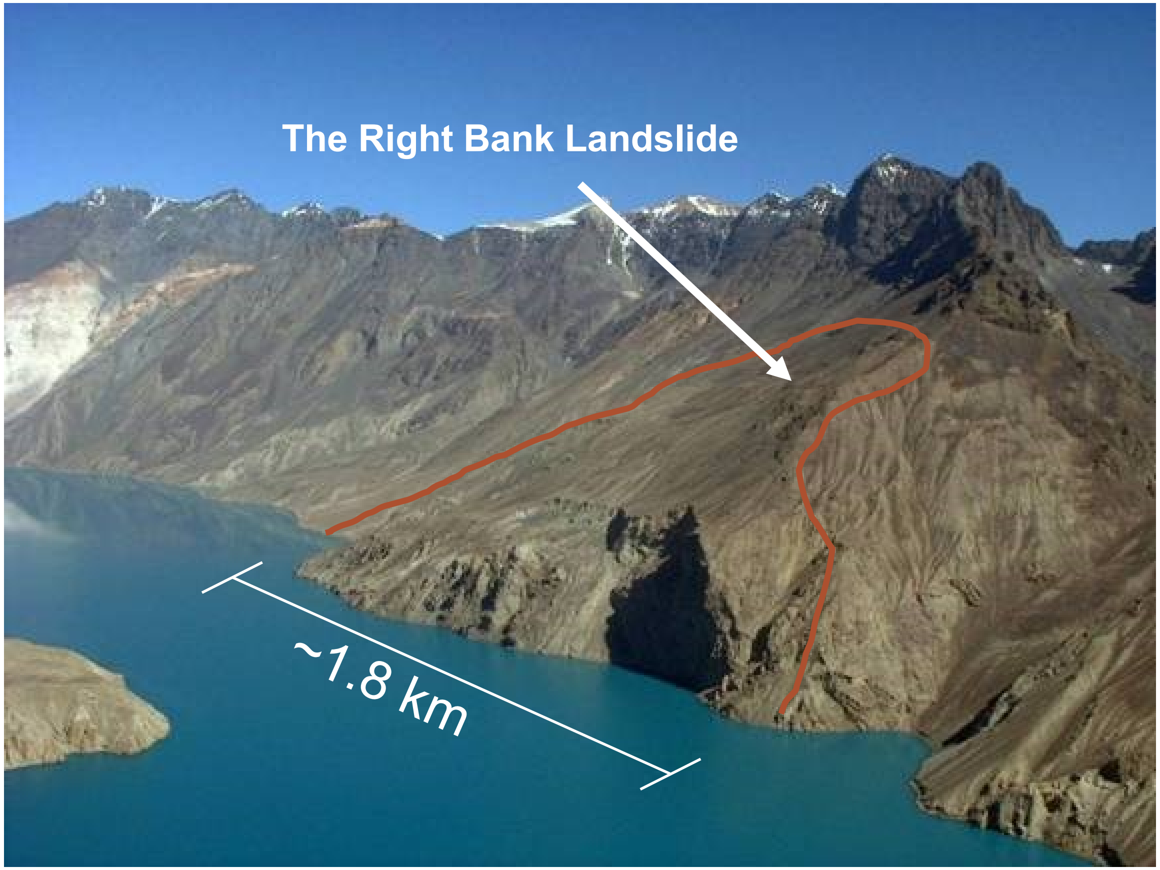
Valleys downstream

Bartang valley

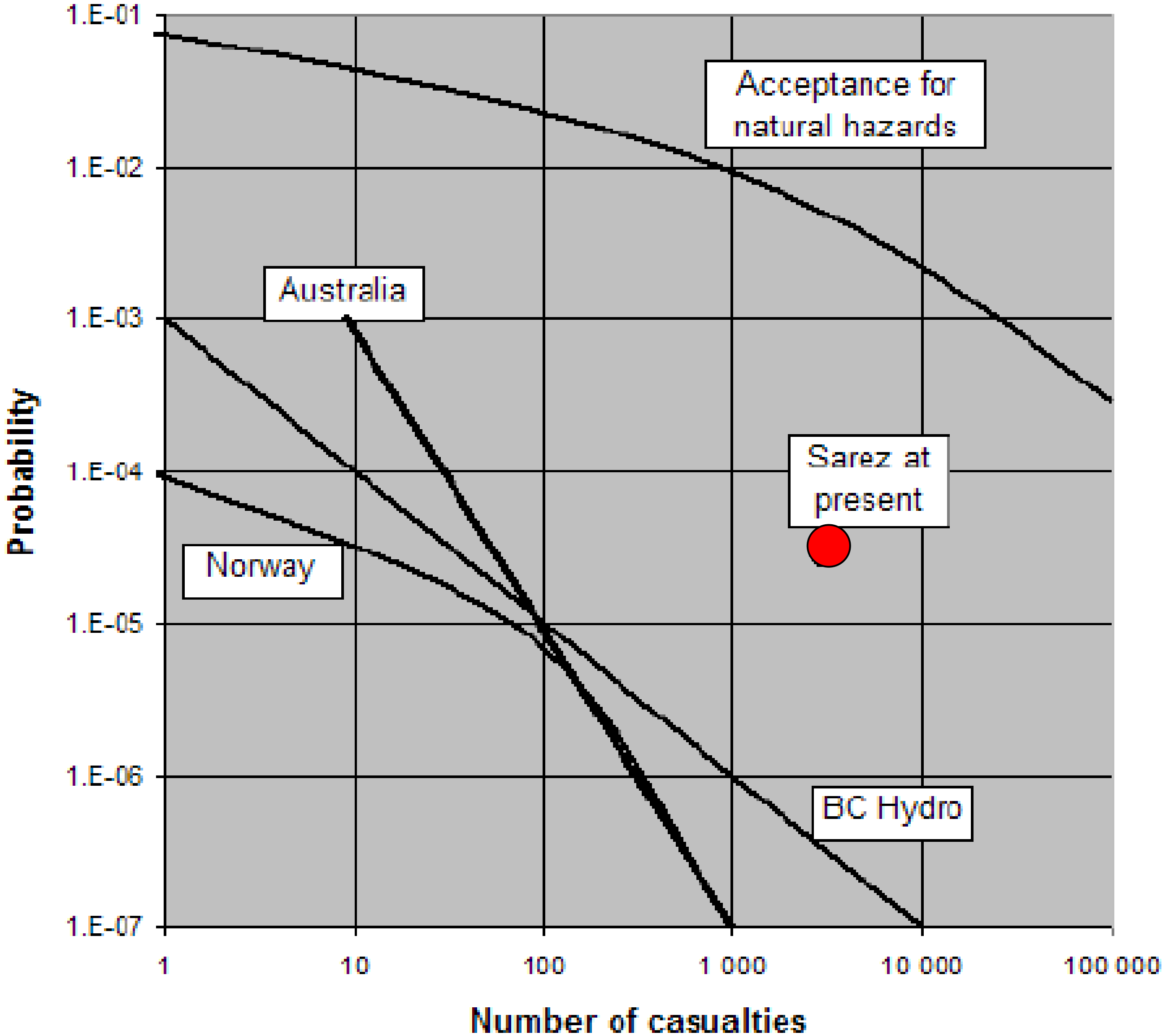
Panj valley between Tajikistan and Afghanistan

Disaster scenarios at Lake Sarez

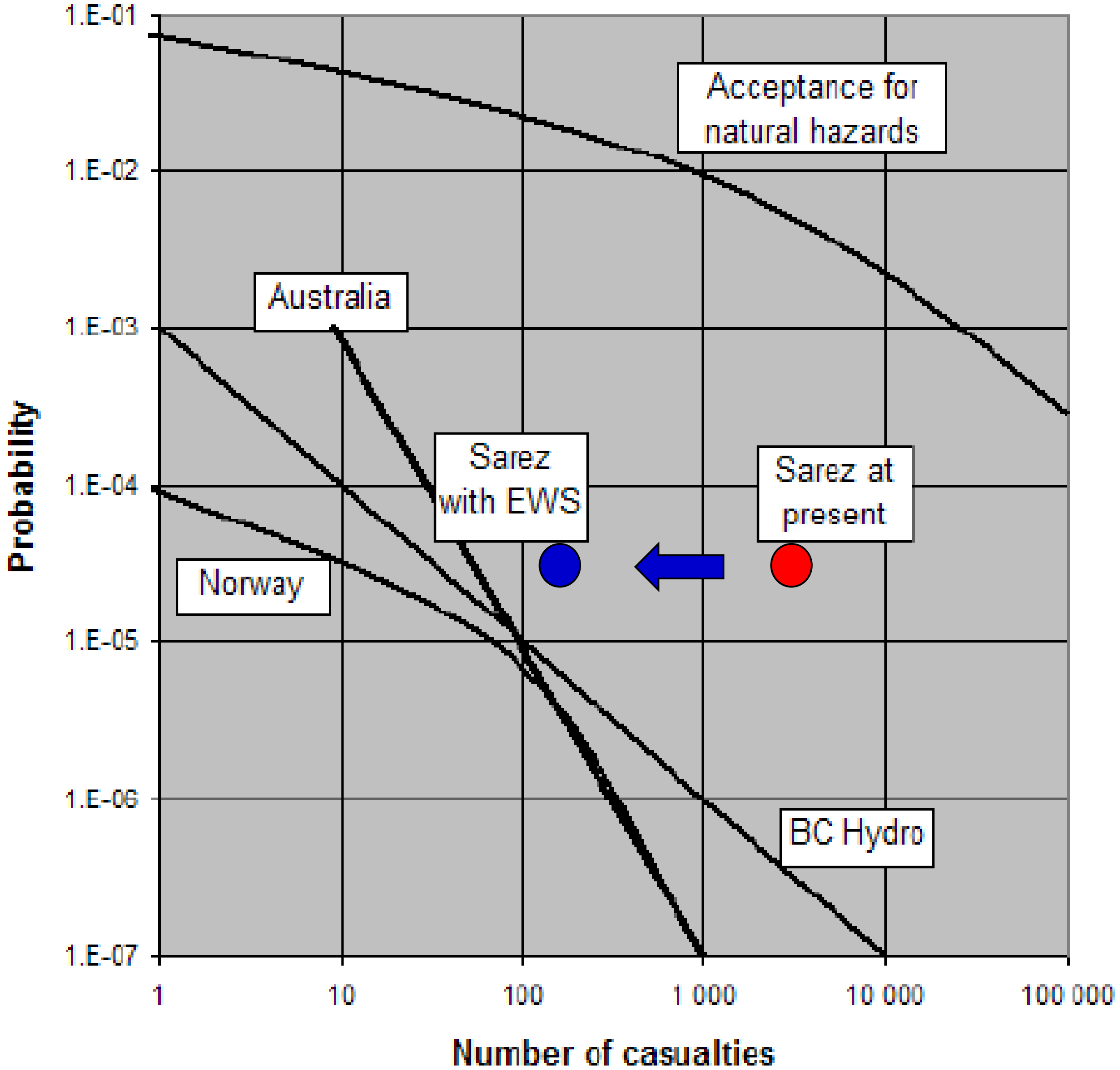
Right bank active landslide



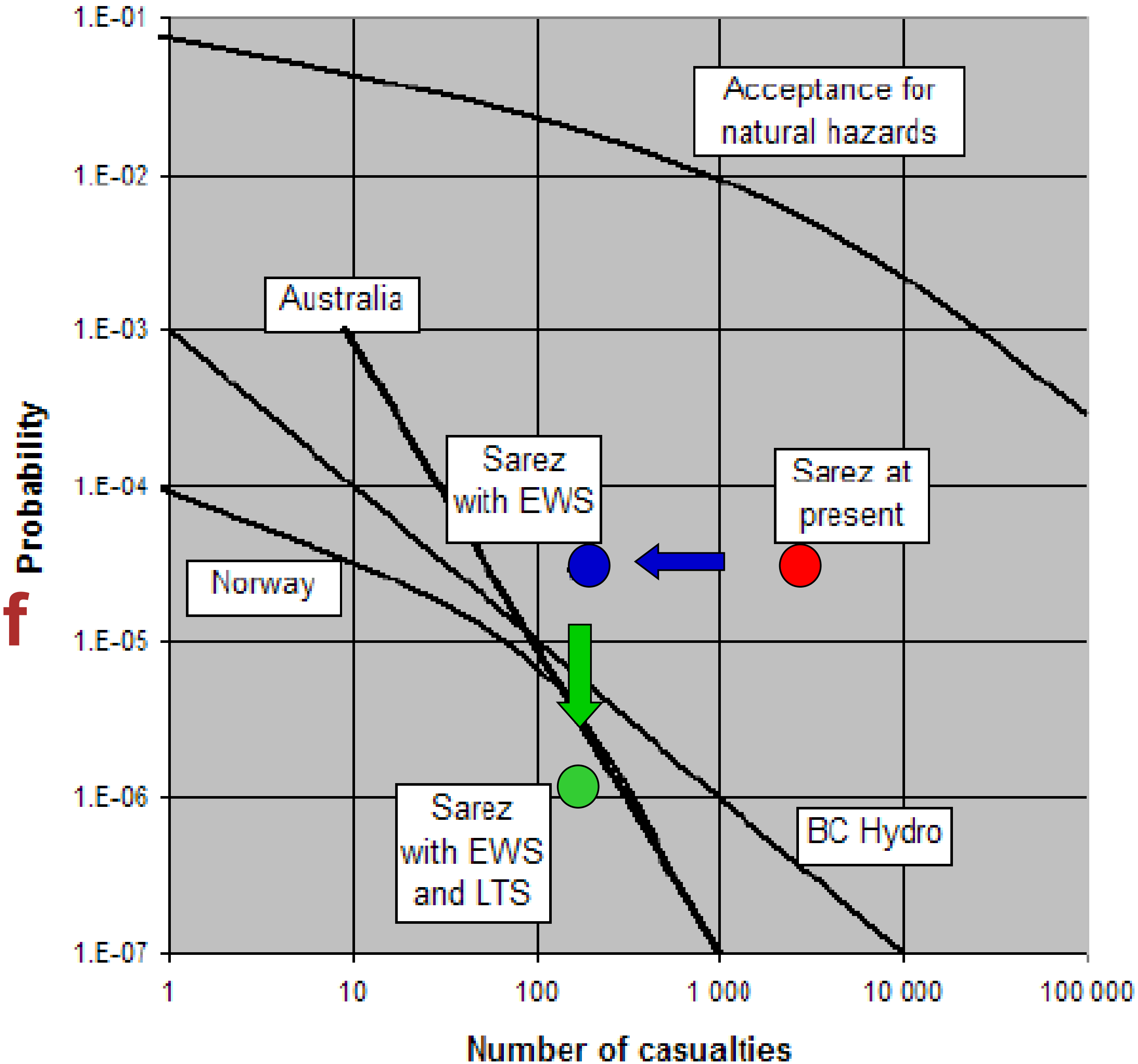
No mitigation measures



Mitigation with early warning system (EWS)



Mitigation with EWS and lowering of reservoir



Example: "Slope Safety" programme in Hong Kong

“Slope Safety” programme in Hong Kong

Quotes from http://hkss.cedd.gov.hk/hkss/eng/studies/qra/

The use of **QRA** technique in evaluating and managing landslide risk is gradually becoming recognized by the geotechnical practitioners in Hong Kong.

Using the technique of **QRA**, it was shown that the overall landslide risk arising from old substandard man-made slopes in Hong Kong had been reduced to less than 50% of the 1977 level by 2000, through the Government's Landslip Preventive Measures (LPM) Programme.

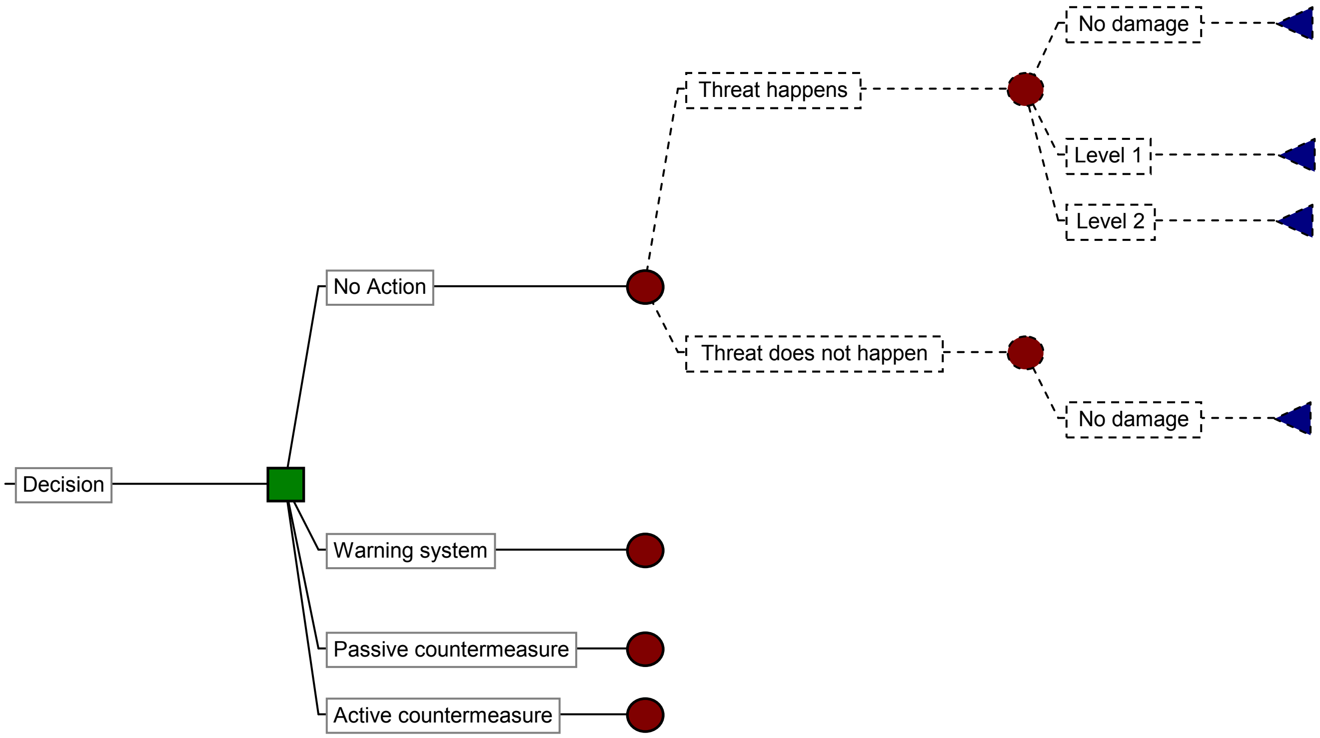
Decision Tree Tool

Advantages:

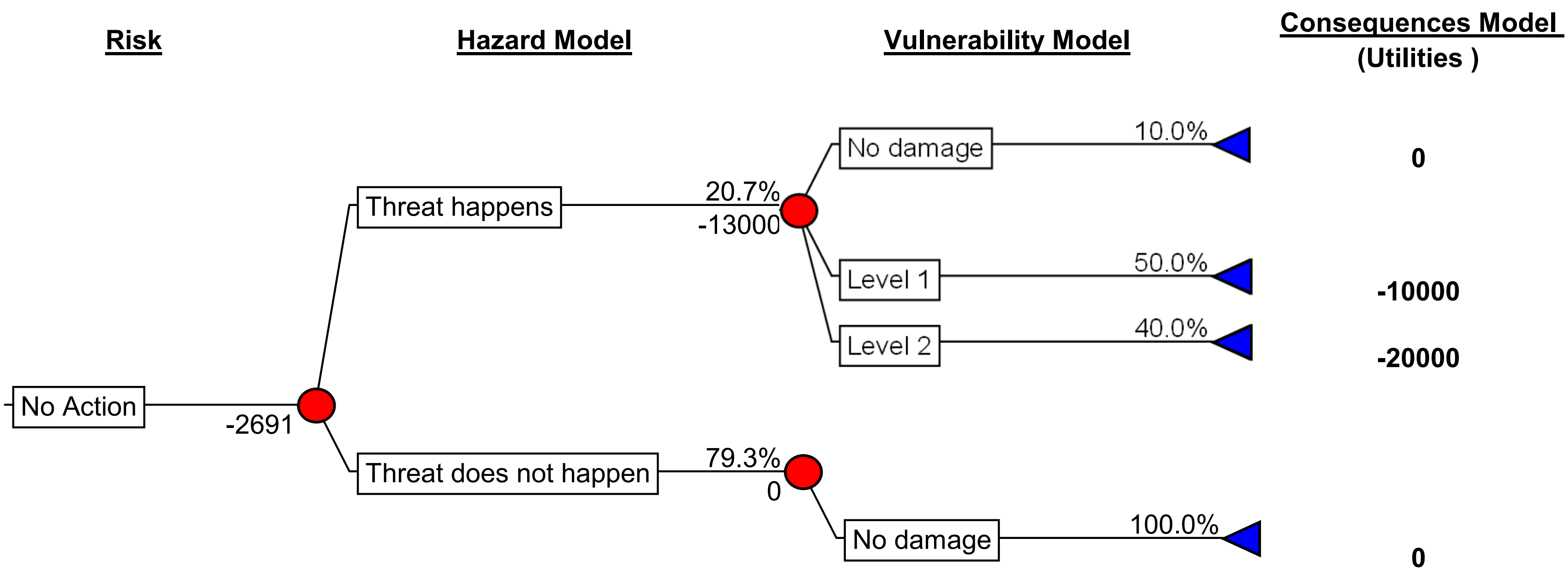
- Easy to understand and interpret: show in detail all different scenarios and paths

Disadvantage:

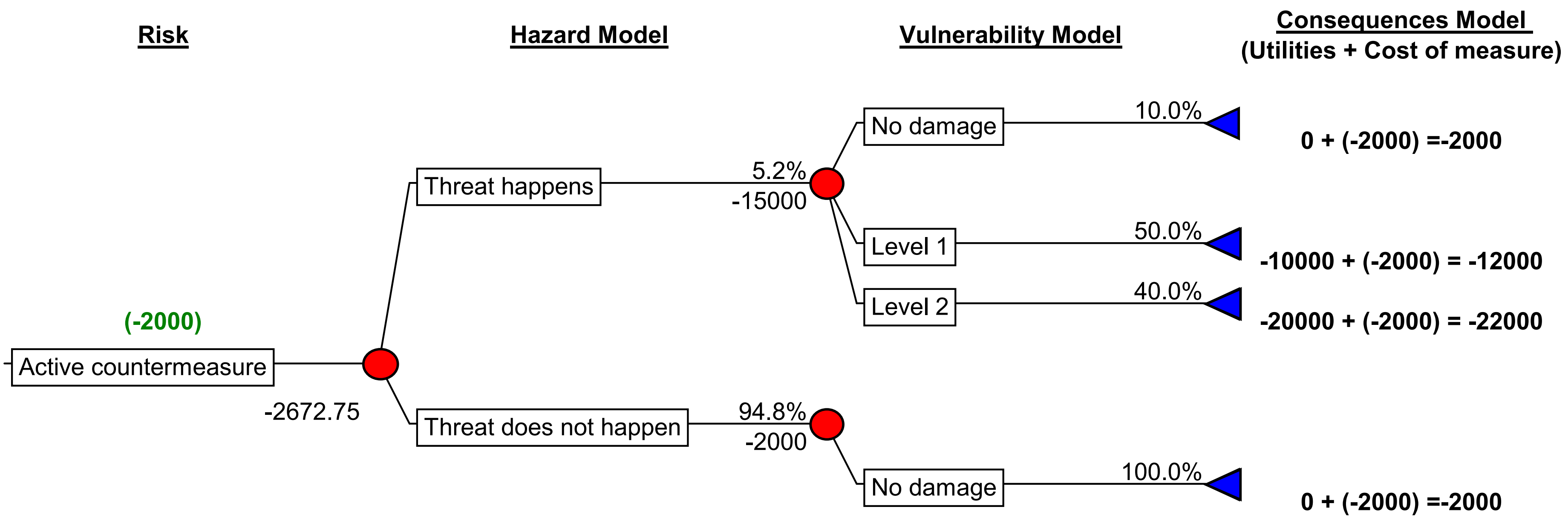
- Can become very large and difficult to read



Example: Decision Tree – No Action

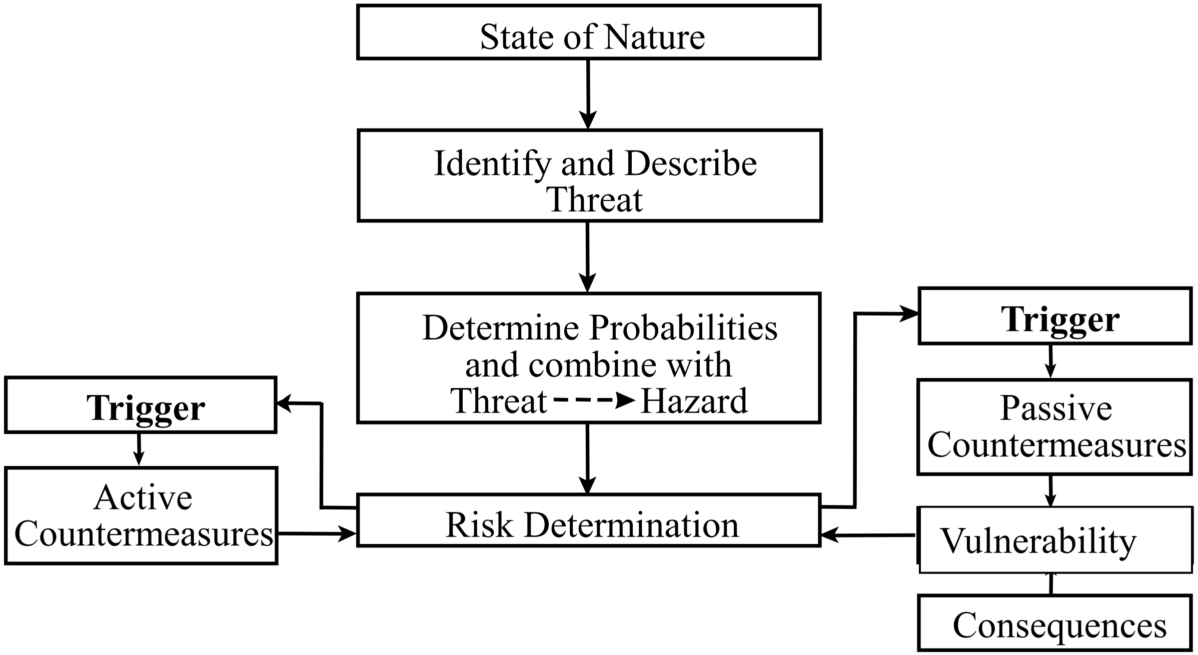


Example: Decision Tree – Active Countermeasure



Reduction in hazard r = 0.25, P′(T) = r x P(T)

Risk Decision Cycle for Natural Threats with Warning System



“Trigger” indicates the triggering of countermeasures by the Warning System

Swiss - Avalanche Warning System (WSL/SLF)

- Meteorological forecast
- Automatic wind and snow stations
- Local observers (80)
- Reports on actual avalanche occurrences
- SNOPACK model

↓

Bulletin (updated daily at 5 p.m. & 8 a.m.)

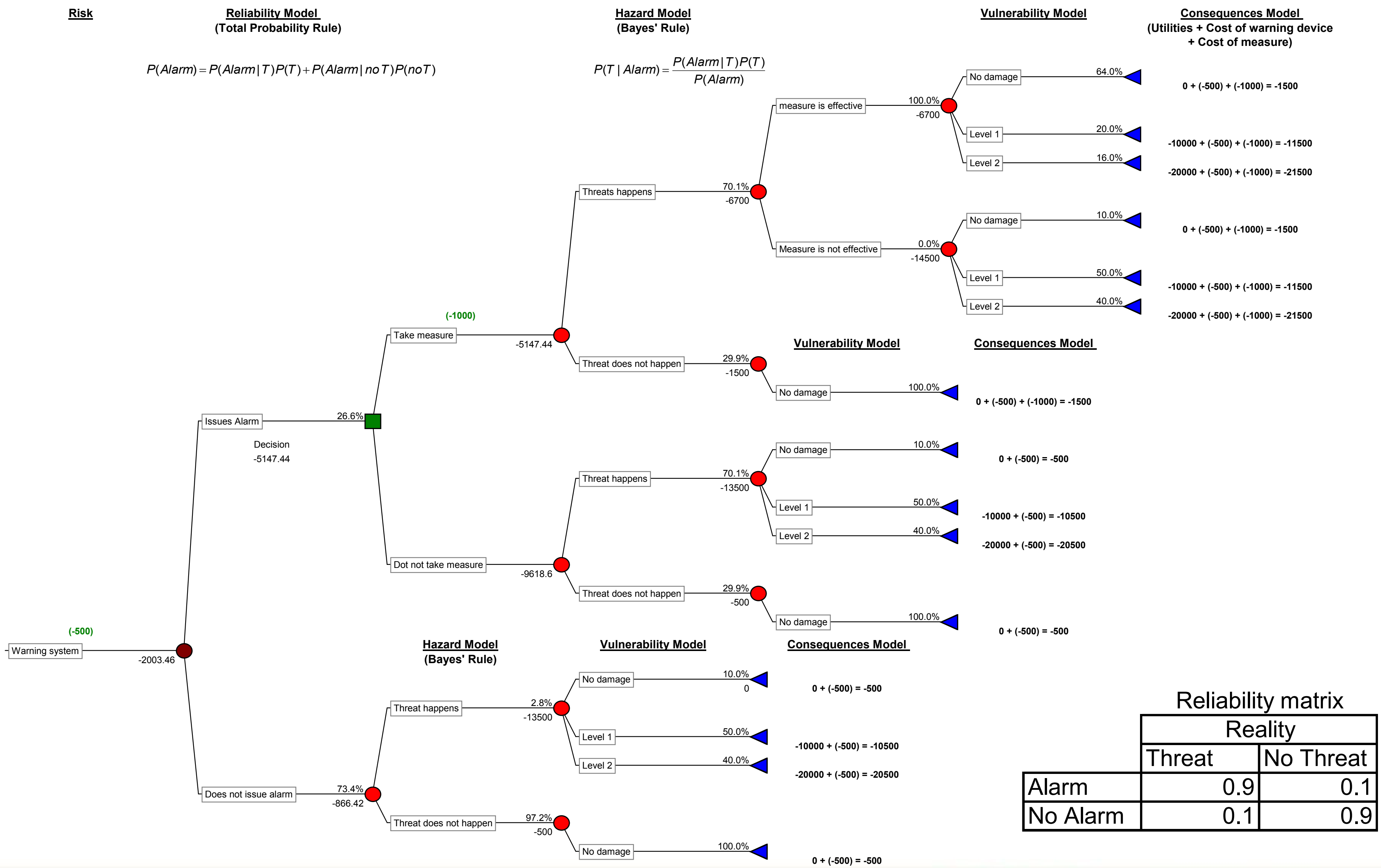
(Accessible by Telephone & Radio)

↓

Local and Regional Safety Experts

Automatic Measurement Station

Decision Tree – Warning System

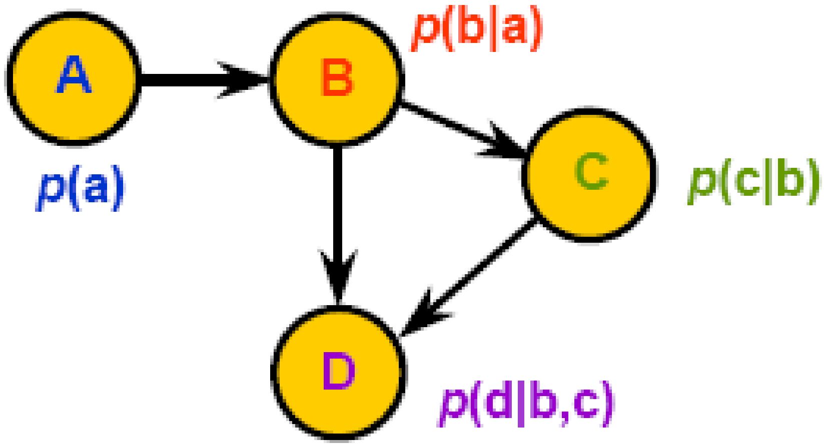


Reliability matrix

	Reality	
	Threat	No Threat
Alarm	0.9	0.1
No Alarm	0.1	0.9

Flow Chart Models (e.g. Bayesian Network) – Chain Rule

Compact and graphical representation of a joint distribution (based on simplifying assumptions)

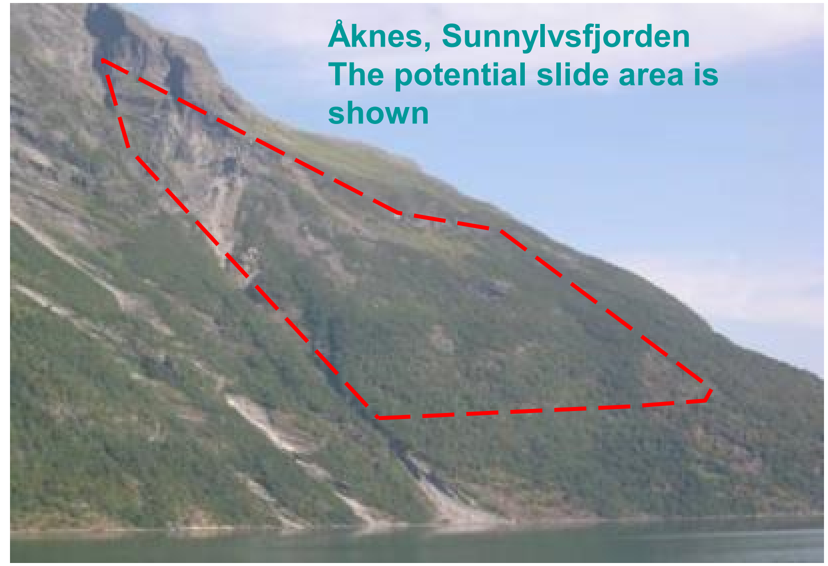


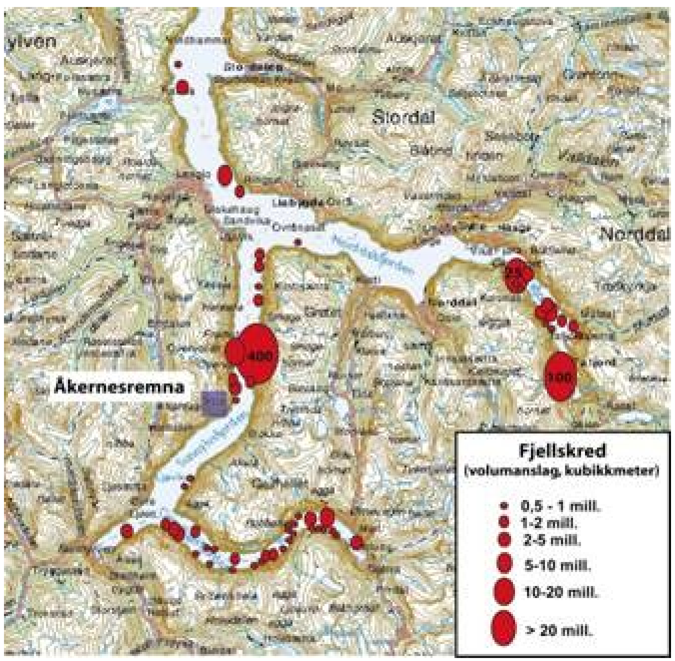
Chain Rule (with independency assumptions):

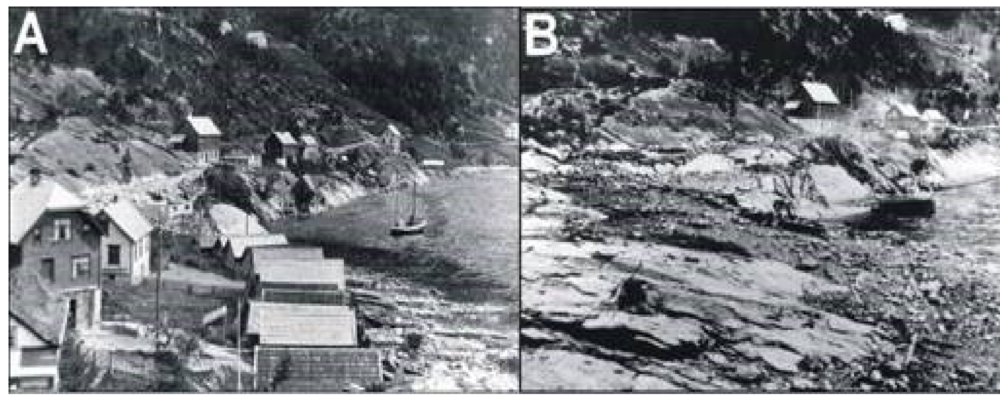
$\Rightarrow$ $p(a,b,c,d) =$

$p(a)\, p(b|a)\, p(c|b)\, p(d|b,c)$

Åknes





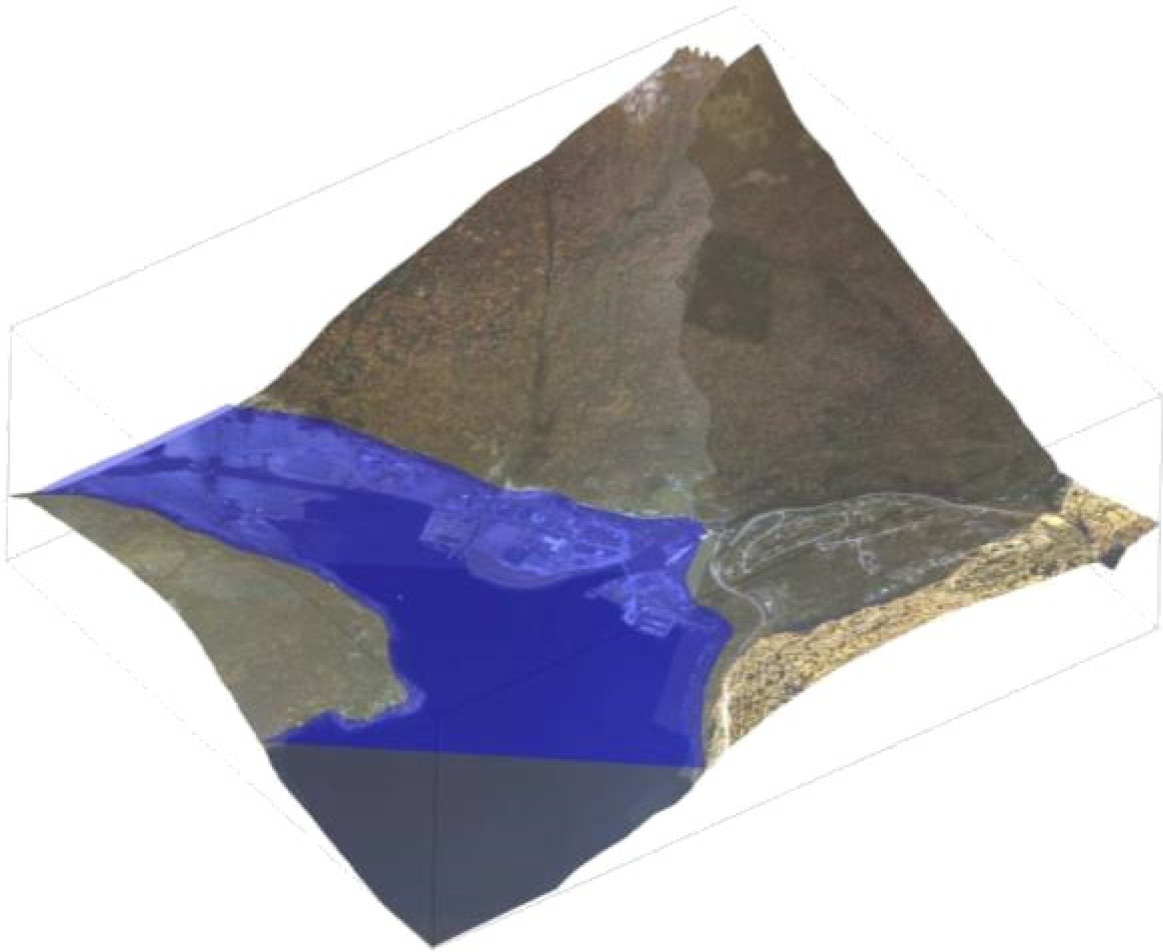


Tafjord, 1934

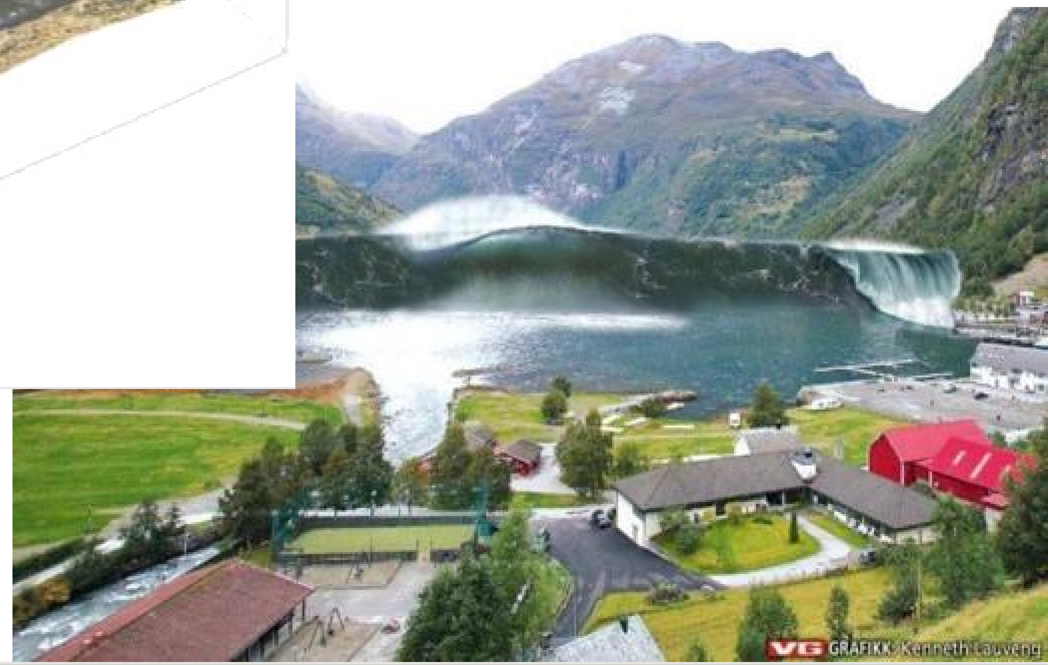
3 million m³ rock mass dropped into the fjord

The tsunami reached 62m above sea level

More than 40 people were killed

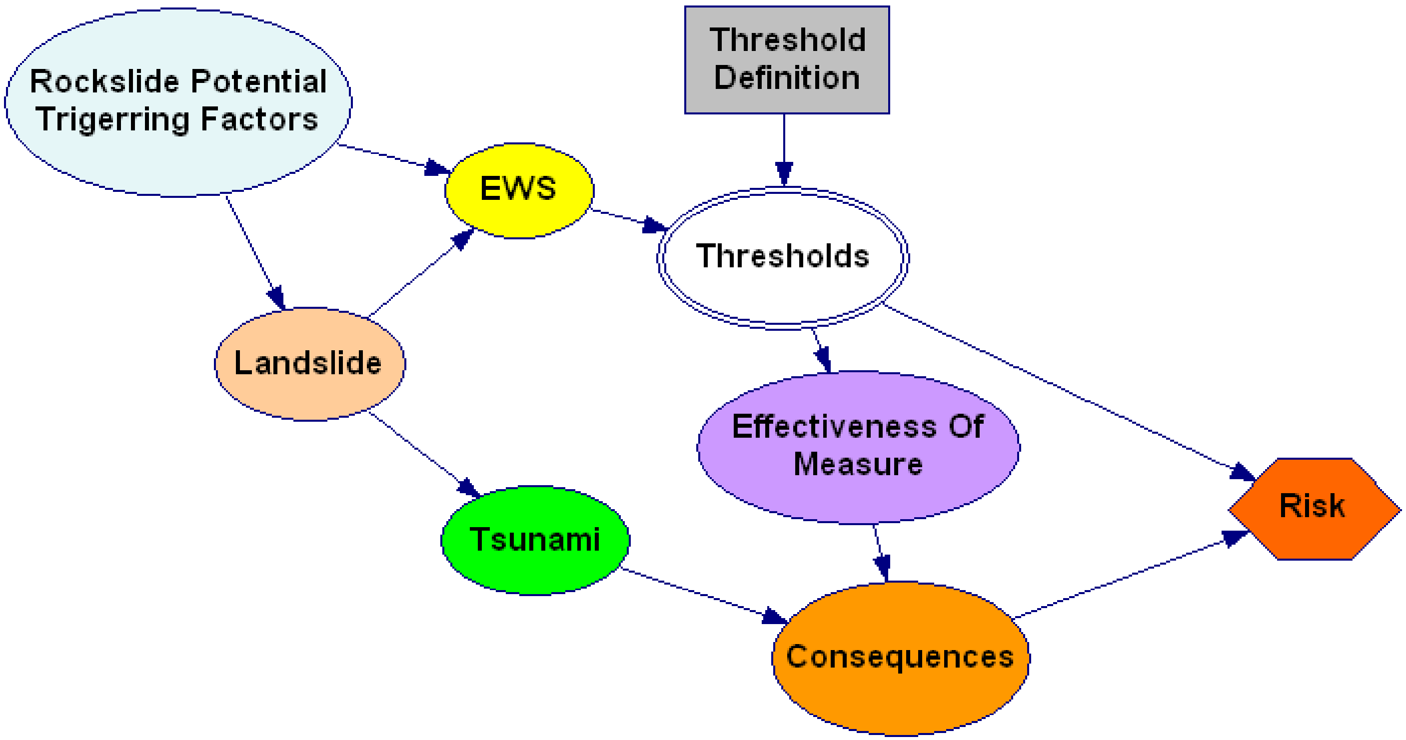


Artist's depiction of a tsunami disaster



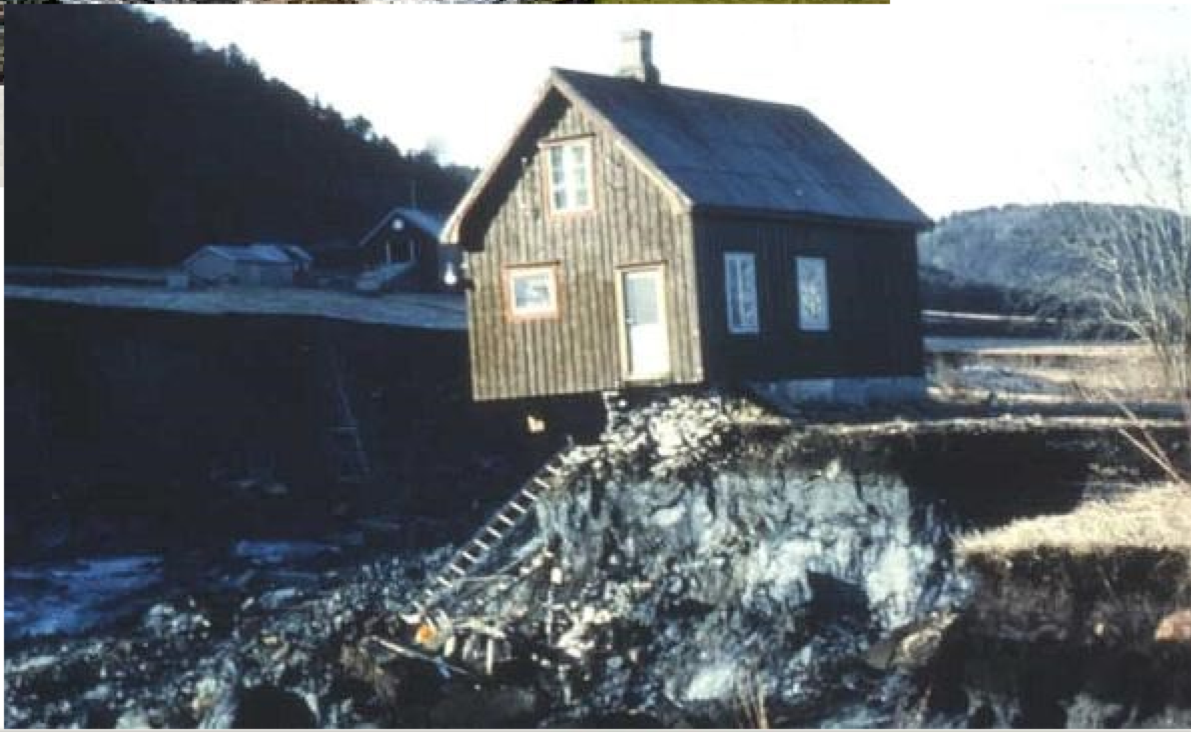
Flow chart model for Åknes Rockslide (with Early Warning System)

- Elements defined into nodes
- Influences defined as arcs
- Non-cyclic network



CONCLUDING REMARKS

- Landslides will happen.
- Landslide risk management involves decision-making under uncertainty.
- The uncertainty has to be reflected in:
  - Predictions of Hazard and Risk
  - Countermeasures - Active, Passive or Warnings
- Quantitative Risk Assessment (QRA) is a useful tool when one is confronted with decision-making under uncertainty.
- The optimal solution on the basis of QRA is not necessarily the most appropriate solution.



Thank you
for your attention!

NGI ICG