Flood Risk Management

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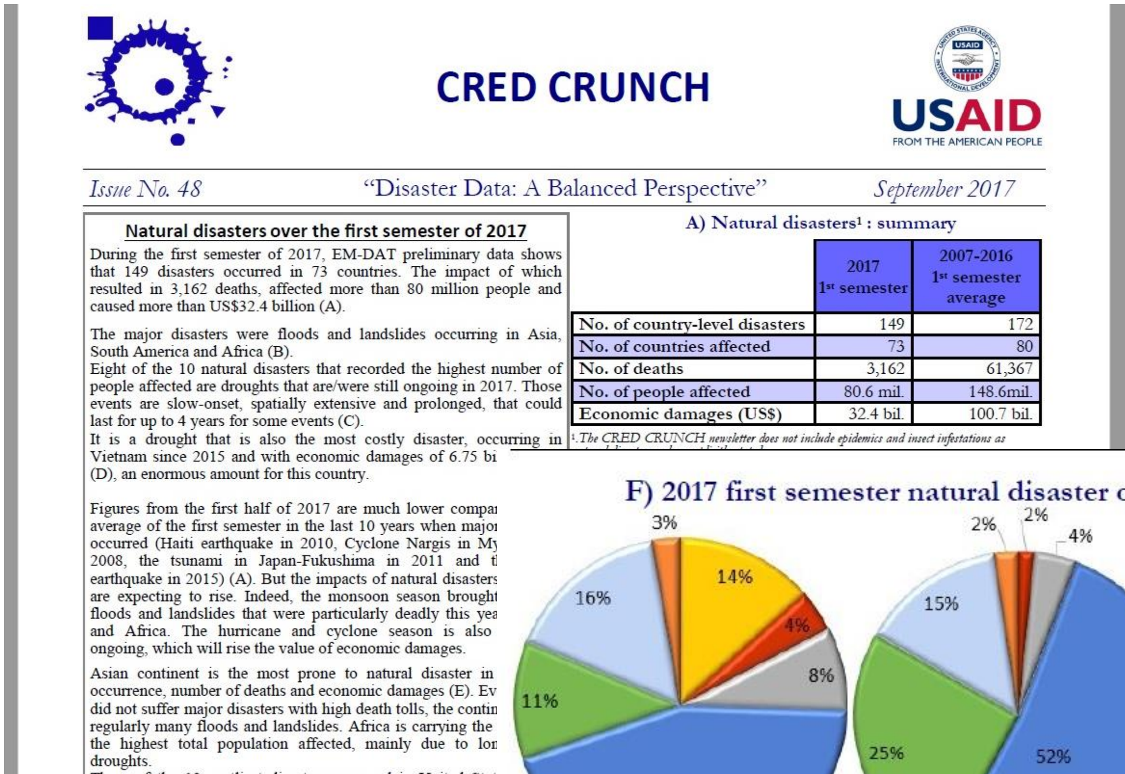
Introduction

A flood is defined by the Oxford English Dictionary as “An overflowing or irruption of a great body of water over land in a built up area not usually submerged.”



CRED CRUNCH

USAID
FROM THE AMERICAN PEOPLE

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Natural disasters over the first semester of 2017

During the first semester of 2017, EM-DAT preliminary data shows that 149 disasters occurred in 73 countries. The impact of which resulted in 3,162 deaths, affected more than 80 million people and caused more than US$32.4 billion (A).

The major disasters were floods and landslides occurring in Asia, South America and Africa (B).
Eight of the 10 natural disasters that recorded the highest number of people affected are droughts that are/were still ongoing in 2017. Those events are slow-onset, spatially extensive and prolonged, that could last for up to 4 years for some events (C).
It is a drought that is also the most costly disaster, occurring in Vietnam since 2015 and with economic damages of 6.75 bi (D), an enormous amount for this country.

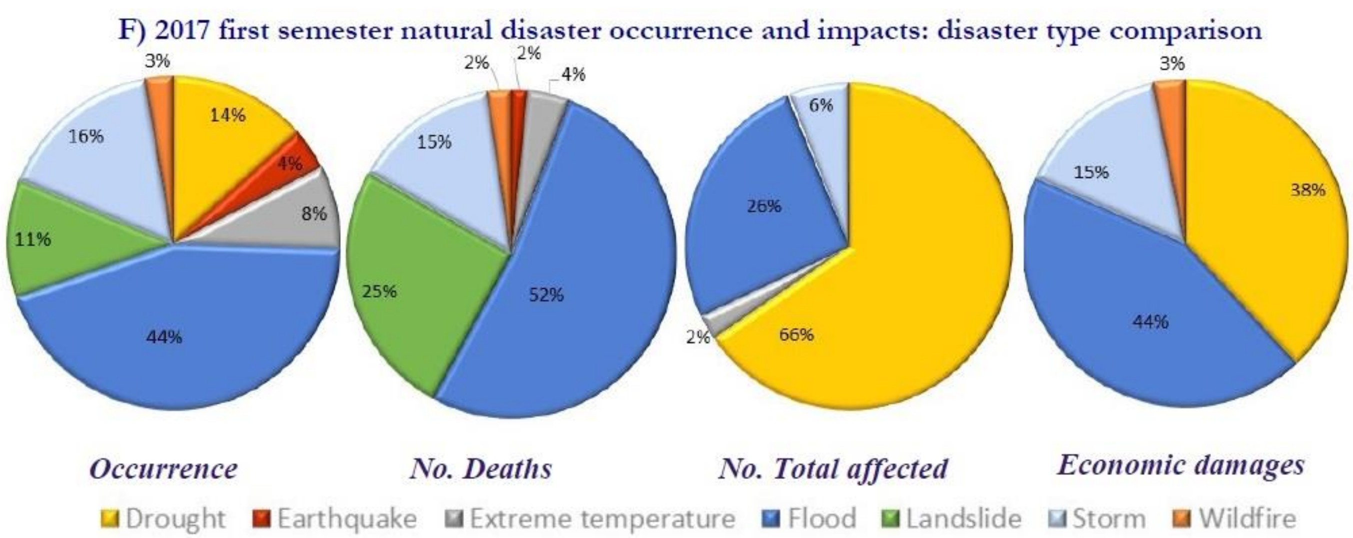
Figures from the first half of 2017 are much lower compa average of the first semester in the last 10 years when majo occurred (Haiti earthquake in 2010, Cyclone Nargis in My 2008, the tsunami in Japan-Fukushima in 2011 and t earthquake in 2015) (A). But the impacts of natural disasters are expecting to rise. Indeed, the monsoon season brought floods and landslides that were particularly deadly this yea and Africa. The hurricane and cyclone season is also ongoing, which will rise the value of economic damages.

Asian continent is the most prone to natural disaster in occurrence, number of deaths and economic damages (E). Ev did not suffer major disasters with high death tolls, the contin regularly many floods and landslides. Africa is carrying the the highest total population affected, mainly due to lo droughts.
Three of the 10 costliest disasters occurred in United Stat

A) Natural disasters[1] : summary

	2017 1st semester	2007-2016 1st semester average
No. of country-level disasters	149	172
No. of countries affected	73	80
No. of deaths	3,162	61,367
No. of people affected	80.6 mil.	148.6mil.
Economic damages (US$)	32.4 bil.	100.7 bil.

[1] The CRED CRUNCH newsletter does not include epidemics and insect infestations as



swarm From flood defence to flood risk management

- Flood risk management can be defined as the "*continuous and holistic societal analysis, assessment and mitigation of flood risk*" (Schanze, 2006).
- Or as "*a process of continuous analysis, adjustment and adaptation of a flooding system (including both structural and non-structural actions) taken to reduce flood risk*" (FLOODsite, 2009a; HR Wallingford, 2007).

Comparison of security approach and risk approach (Heintz et al., 2012; Wagner, 2008).

Main characteristics	Security approach	Risk approach
Aim	protection against threat emanating from flood events	develop a strategy how to handle flood risk, define which level of risk is acceptable
Terminology	danger, threat, security, protection	risk, residual risk, risk evaluation, risk management, risk governance
Scenarios	medium-probability events as the standard level of protection	high-/medium- and low-probability events, priorities regarding level of protection
Measures	focus on structural measures	combination of structural and non-structural measures
Involved parties	sectorial planning (water authority), top-down, implementation gap	interdisciplinary, bottom-up elements
Spatial focus	local solutions for local problems, oriented at administrative borders	across administrative borders, catchment-based
Time aspect	short-term solutions, event-driven, "trial and error"	medium-/long-term solutions, prevention, regular revisions

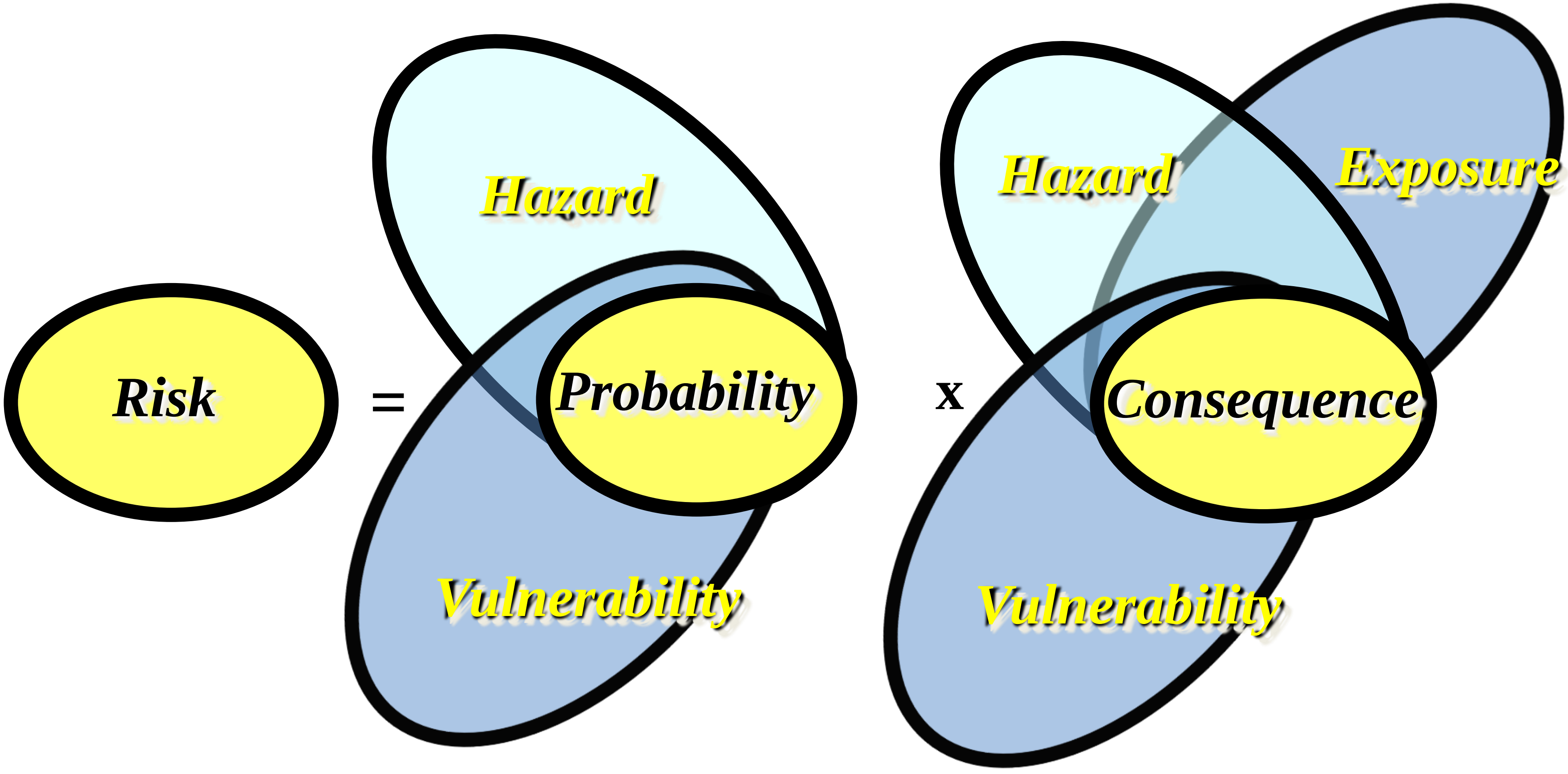
Flood risk management in EU

Flood risk management plans "*shall address all aspects of flood risk management focusing on prevention, protection, preparedness, including flood forecasts and early warning systems*" (European Flood Directive 2007)

How to verify the effectiveness of non-structural measures?

HAZARD AND RISK

- *Distinction between the words "**hazard**" and "**risk**".*



The variables of risk equation

R = H V E

“characteristics and circumstances of a community, system or asset that make it susceptible to the damaging effects of a hazard” (UNISDR 2009)

The variables of risk equation

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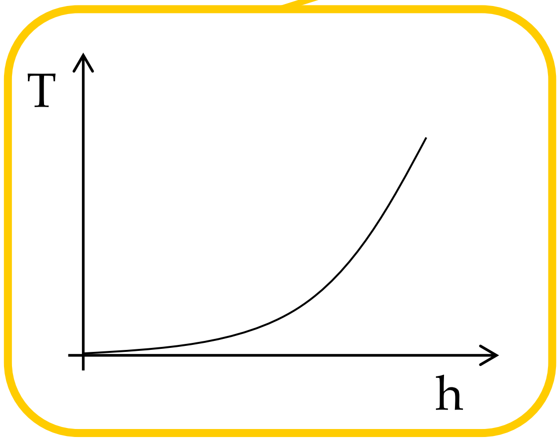
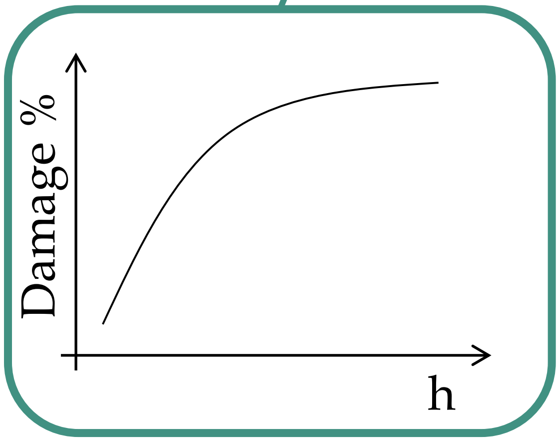
$$R = H \; V \; E$$





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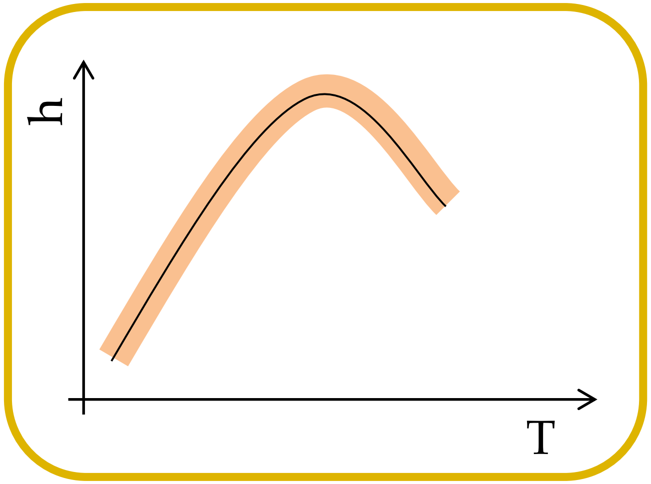
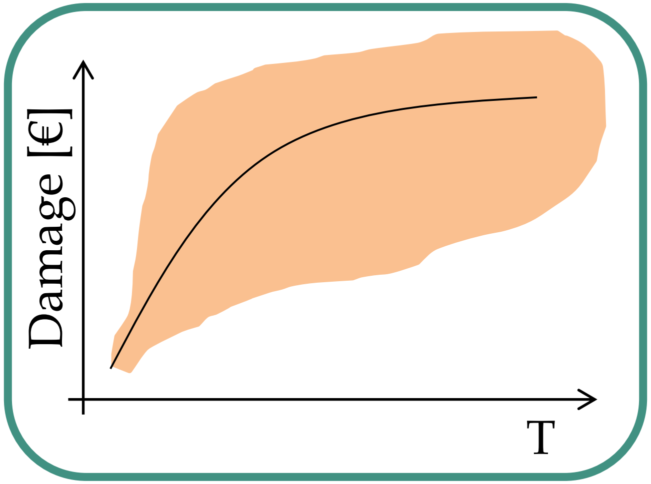
The variables of risk equation

R = H V E

Hydraulic Models



Vulnerability models



RISK

RISK = (probability) x (consequence)

- A large risk may arise because there is a high probability of a flood (say every winter) with only modest consequences.
- A large risk may arise because there is a very small probability of a flood - such as 1/ 1000 per year - but with high consequences.
- *However, in the perception of people, the consequences of events are not only easier to grasp, but also more important than their probability.* ***The consequences are therefore given more weight in the judgment of risk.*** *This means that lay people judge 100 fatalities with a 1/100 per year probability as being worse than 1 fatality every year.*

Floods in urban environment

- Urban environments can be affected by river flooding, coastal floods, pluvial and ground water floods, flash floods, artificial system failures.

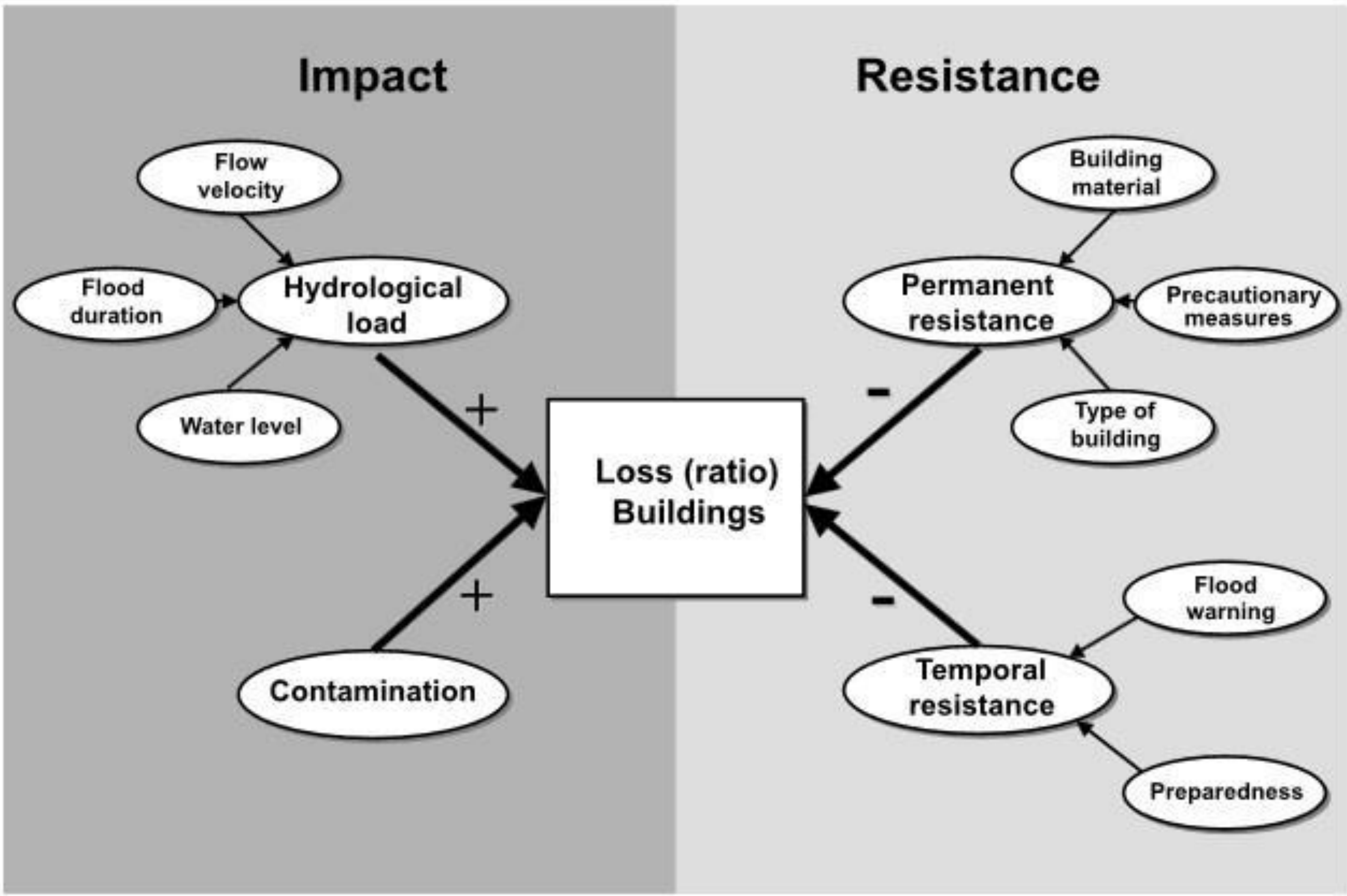
- Urban floods typically stem from a complex combination of causes, resulting from a combination of meteorological and hydrological extremes, such as extreme precipitation and flows. However they also frequently occur as a result of human activities, including unplanned growth and development in floodplains, or from the breach of a dam or an embankment that has failed to protect planned developments.

Flood damages

- Damage assessment of natural hazards supplies crucial information to decision support and policy development in the fields of natural hazard management and adaptation planning to climate change.
- As flood risk management is becoming the dominant approach of flood control policies throughout Europe, the estimation of economic flood damage is gaining greater importance, but it still represents a challenge.

	Direct	**Indirect**
Tangible	Damage to buildings and contents; disruption of infrastructures; erosion of agricultural fields; costs of evacuation and rescue; interruption of economic activities inside the flooded area; clean-up costs.	Interruption of public services outside the flooded area; economic losses of companies outside the flooded areas; costs caused by the interruption of transport infrastructures; businesses migration.
Intangible	Casualties; accidents; loss of objects with an affective value; psycological uneasiness; damages to cultural heritage; environmental impact.	Anxiety; loss of trust in authorities.

Influencing factors in flood damage assessment

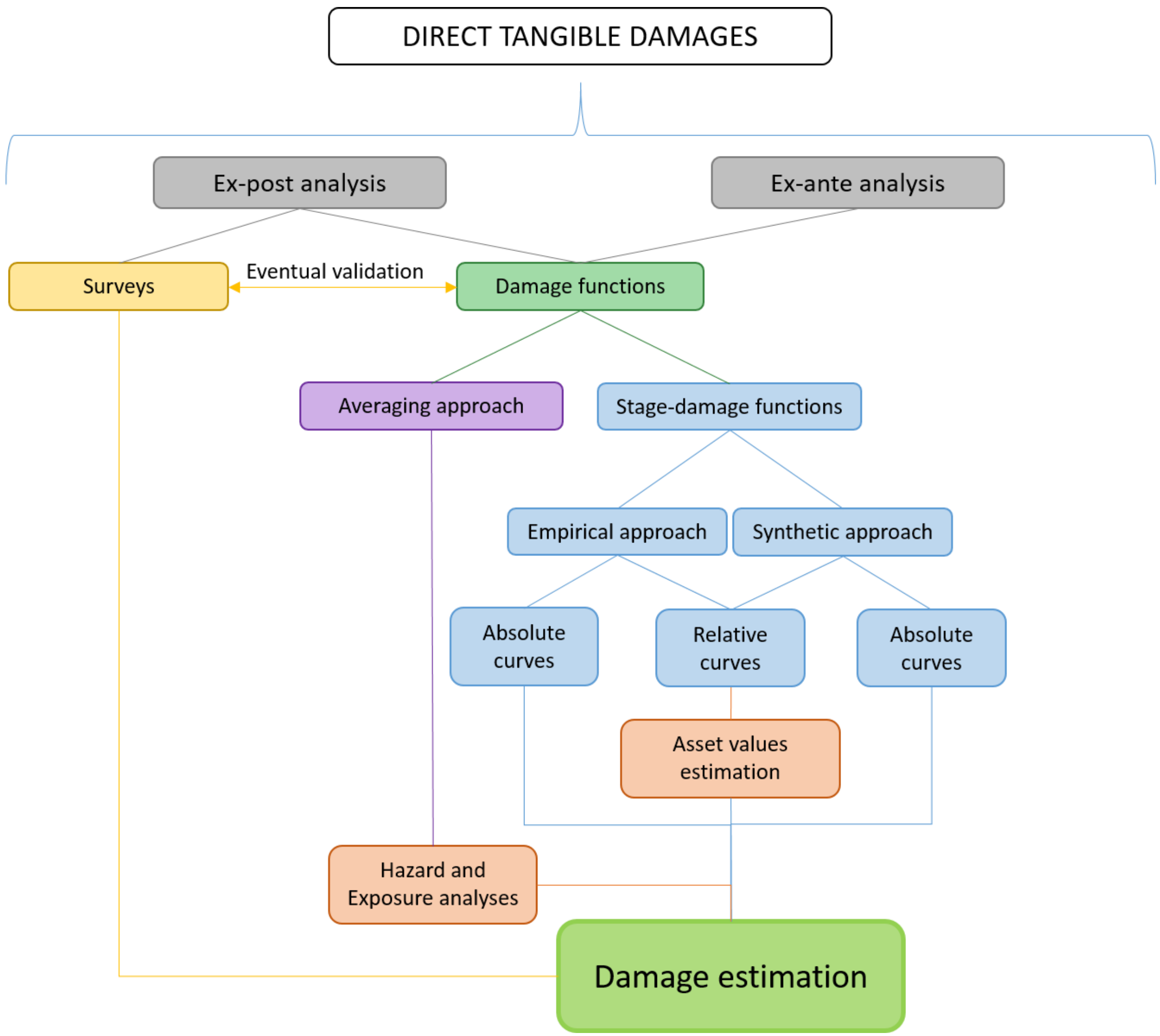


Thieken et al. (2005). Flood damage and influencing factors: New insights from the August 2002 flood in Germany. Water Resources Research

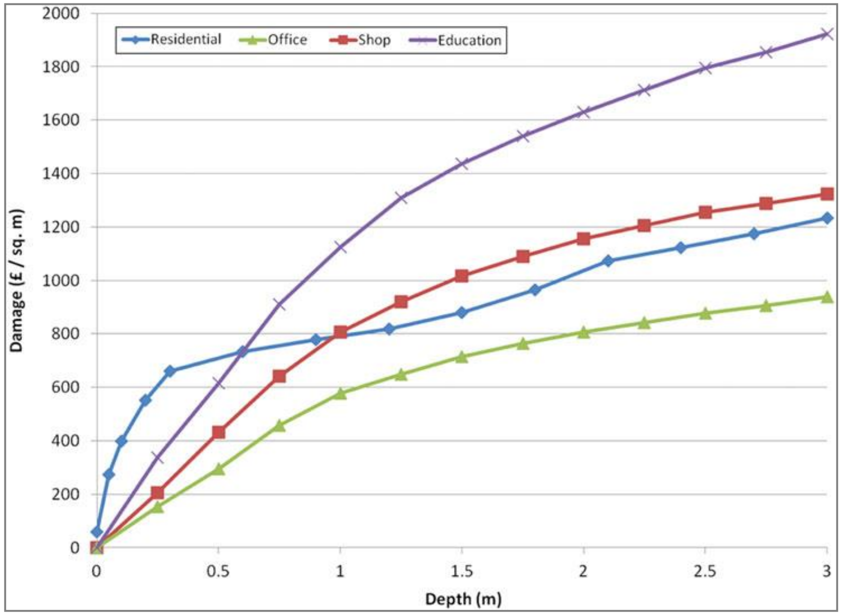
Spatial and temporal scales

- The damage analysis can be carried out at different spatial and temporal scales. This information is important and becomes central when comparing different methodologies and applying them to different contests in respect to the one they are developed for.
- About the spatial scales, the data can be referred to micro-scale, meso-scale, macro-scale.
- Methodologies (e.g. damage functions) developed for a specific spatial scale need upscaling and downscaling procedures to be adapted to other scales' analyses.
- The same attention must be paid when using databases: the data collected have always a spatial scale and the instruments derived follow the same scale.
- Regarding the temporal scale, flood can cause long-term consequences, such as health effects, which are not captured if a too short time horizon of the damage assessment is chosen.
- There are not official or widely recognized definitions for spatial and temporal scales.

Flood damage assessment methods

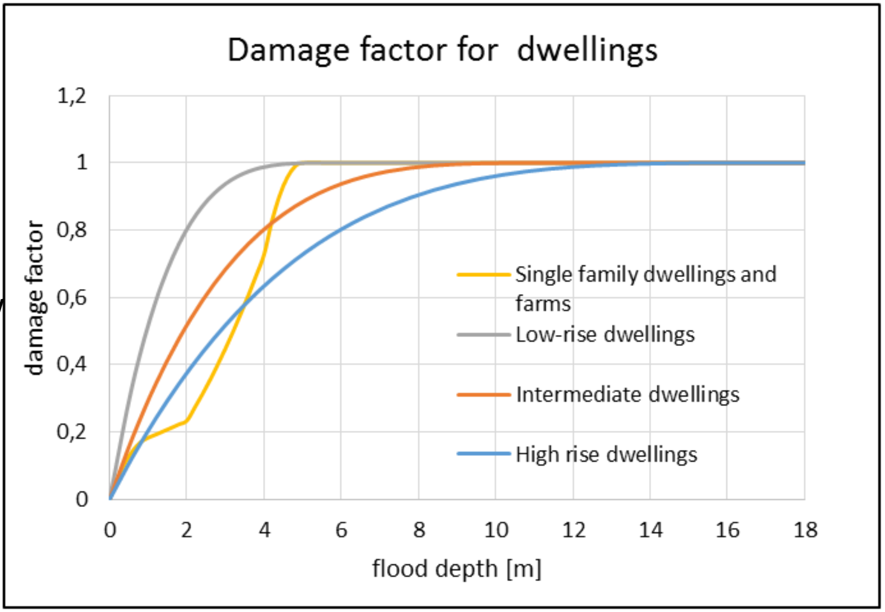


Damage curves



(Penning-Rowsell et al. (2005), *The benefits of flood and coastal risk management: a manual of assessment techniques*. London, UK: Middlesex University Press.)

(Kok, M., Huizinga, H.J., Vrouwenfelder, A.C.W.M, Barendregt, A., (2004). *Standard Method 2004. Damage and Casualties caused by Flooding*. Highway and Hydraulic Engineering Department.)



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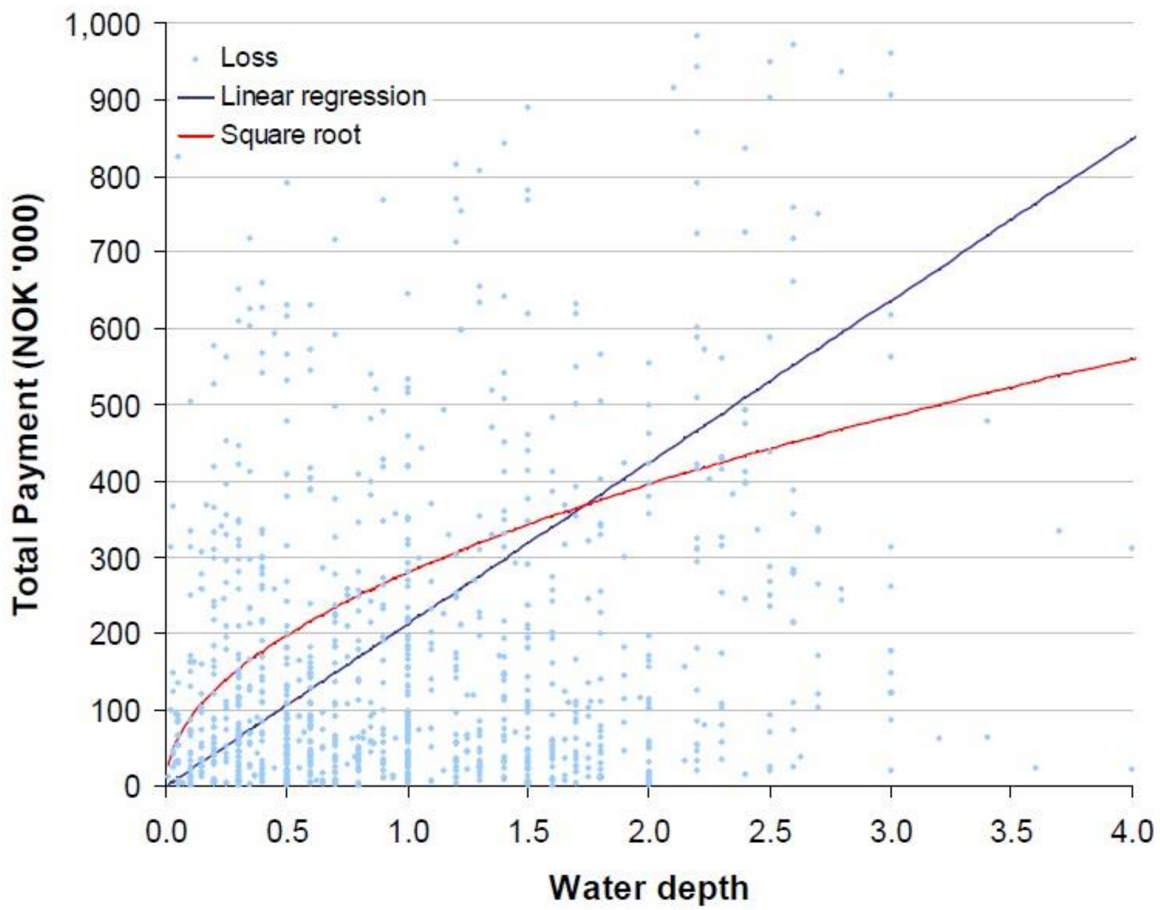
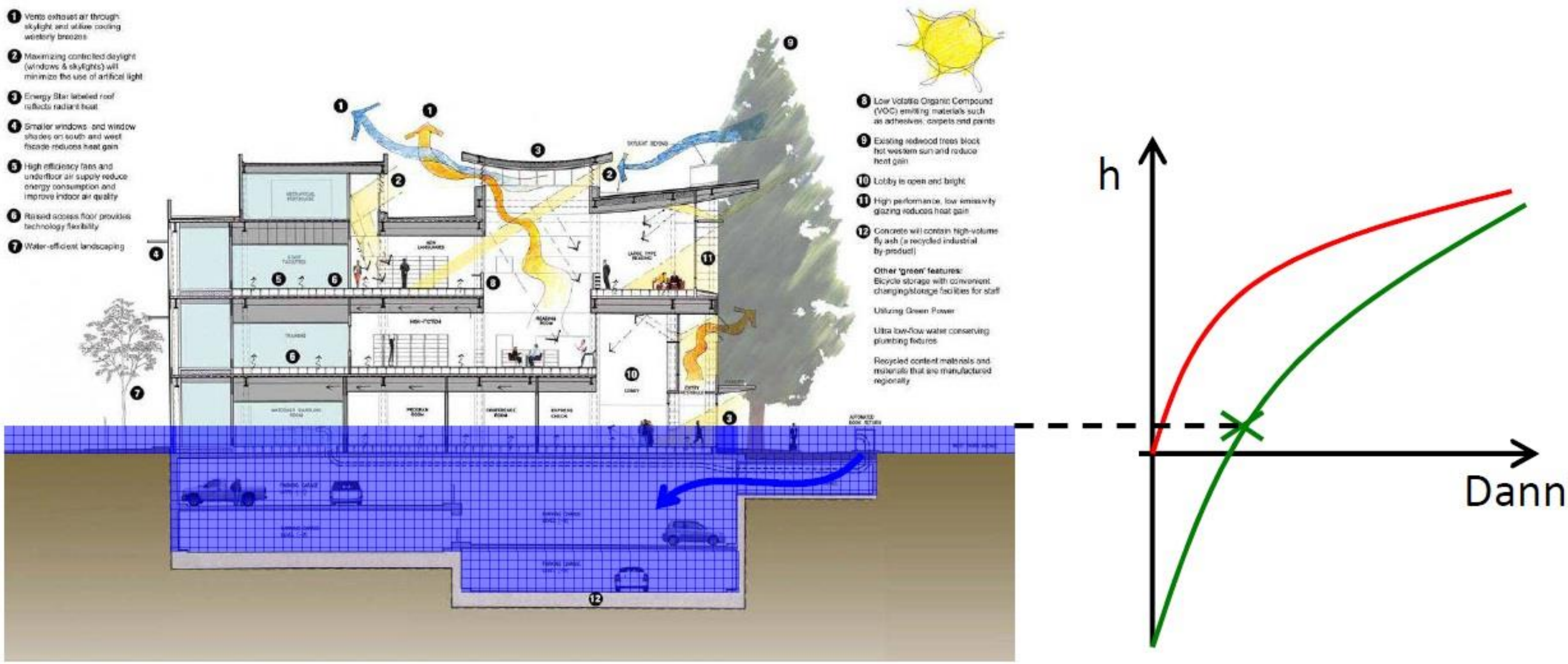
Damage curves and uncertainty



swarm Damage curves and uncertainty



Huge damages to basements can occur for small flood depths in the floodplain. Damages can have no correlation with the event severity in these cases.

Damage data

- In respect to other aspects of flood risk management, flood damage assessment is still a challenge and one of the main reasons of this is the lack of consistent, high-quality, official damage databases.
- Absolute damage functions without any reference to the economic value of the affected buildings, are strictly linked to the contest for which have been derived.
- Another limit in the utilization of flood damage data could be their aggregation in predetermined time intervals (e.g. data that have already been aggregated to a regional or national level are unusable at minor scales).
- Last but not least, the users of these data should always verify their accuracy, as sources of inaccuracy are multiple and difficult to estimate.
- In general, **the lack of high-quality basis data is mentioned as one of the main obstacle to flood vulnerability assessment**.

An integrated exposure-vulnerability approach for flood risk analysis in urban environment

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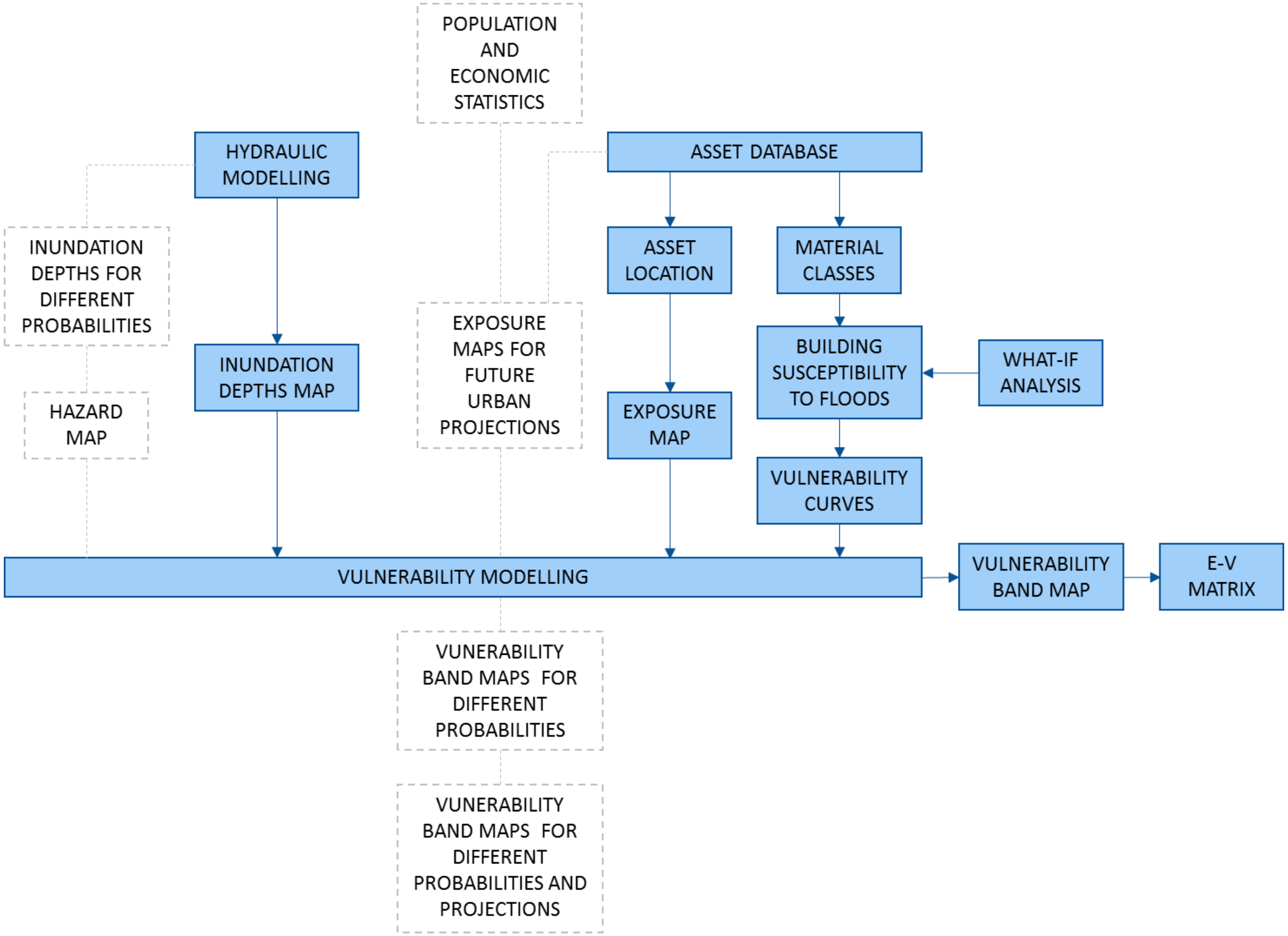

An integrated exposure-vulnerability approach for flood risk analysis in urban environment

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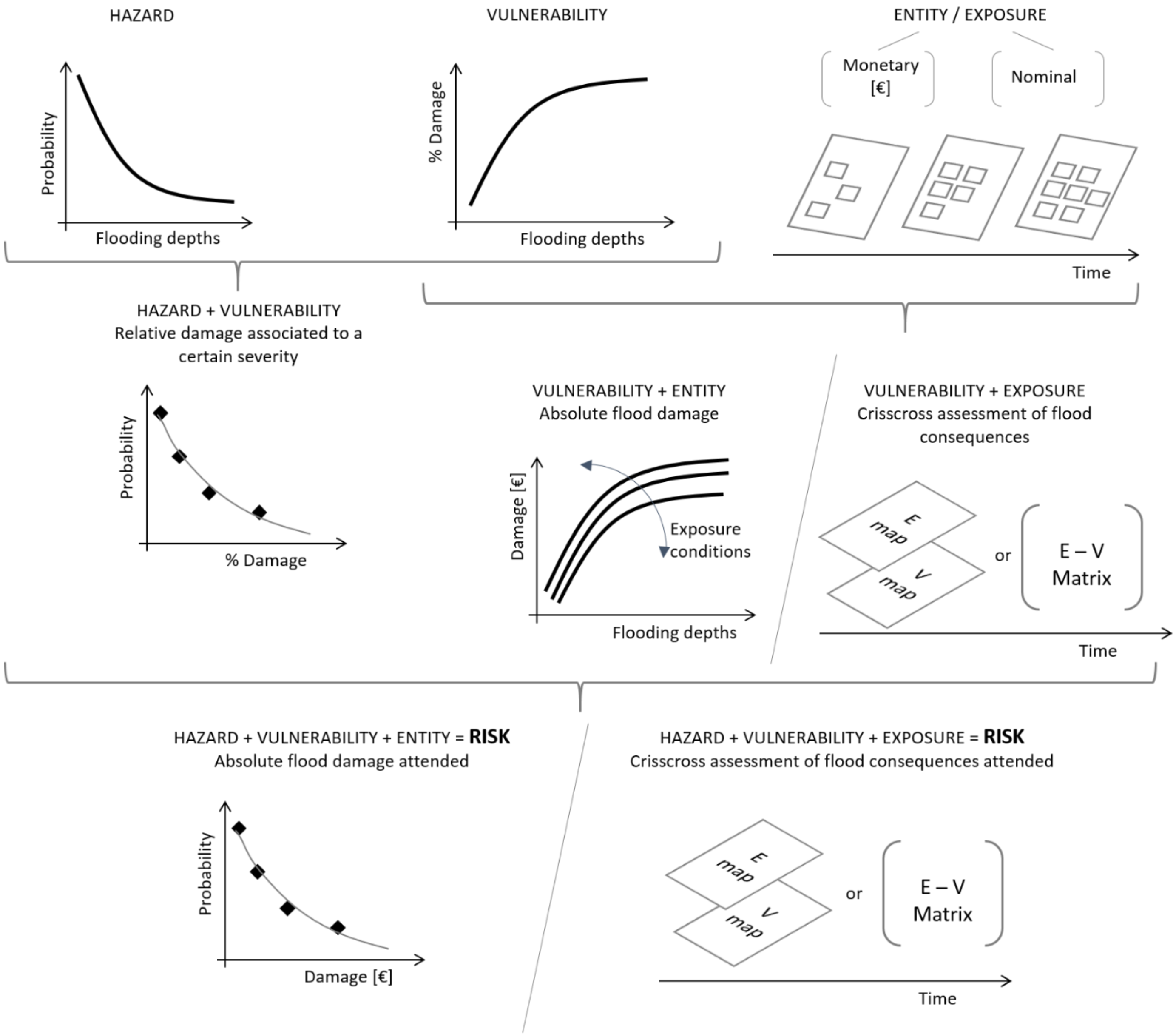
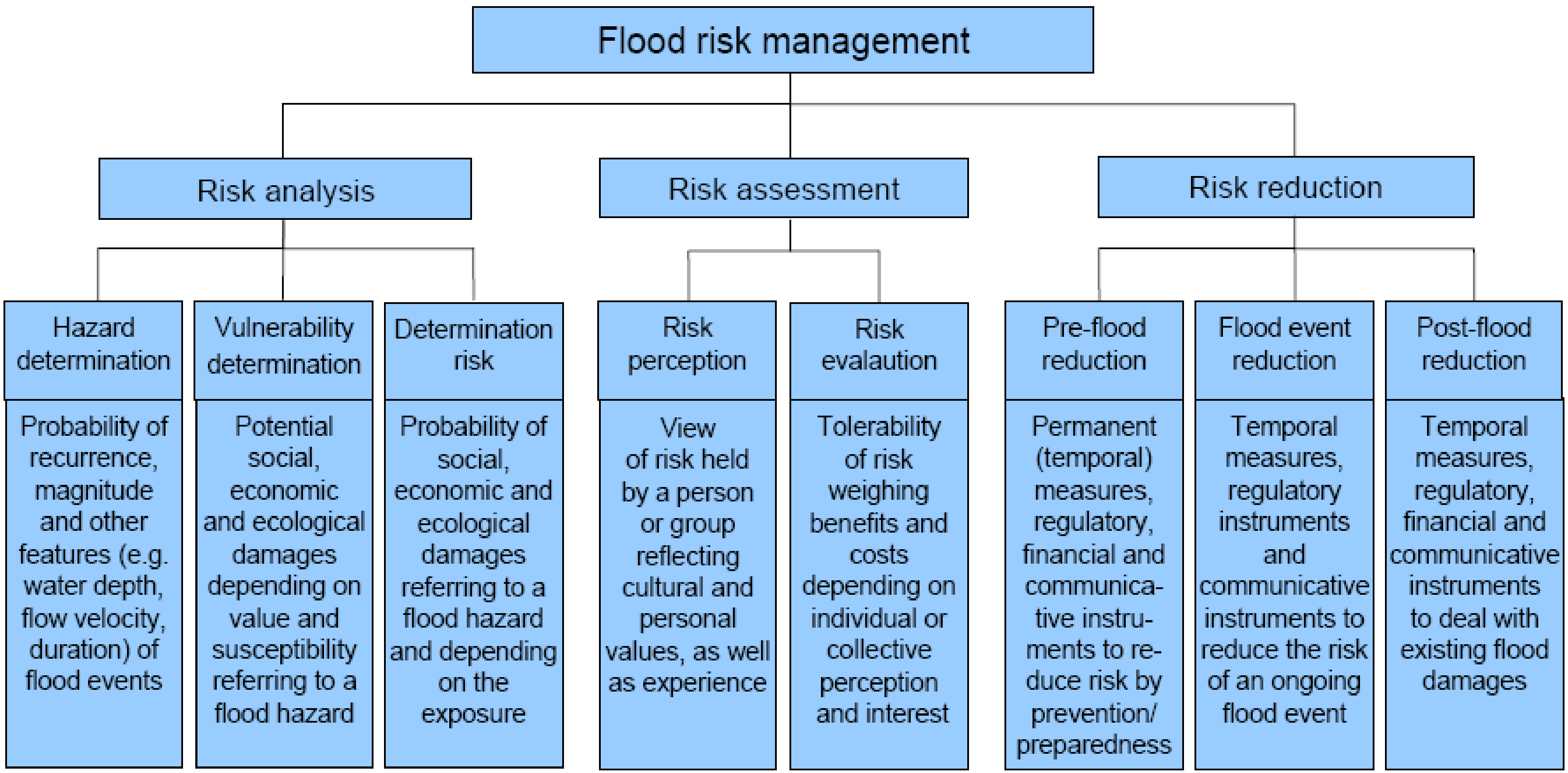


An integrated exposure-vulnerability approach for flood risk analysis in urban environment

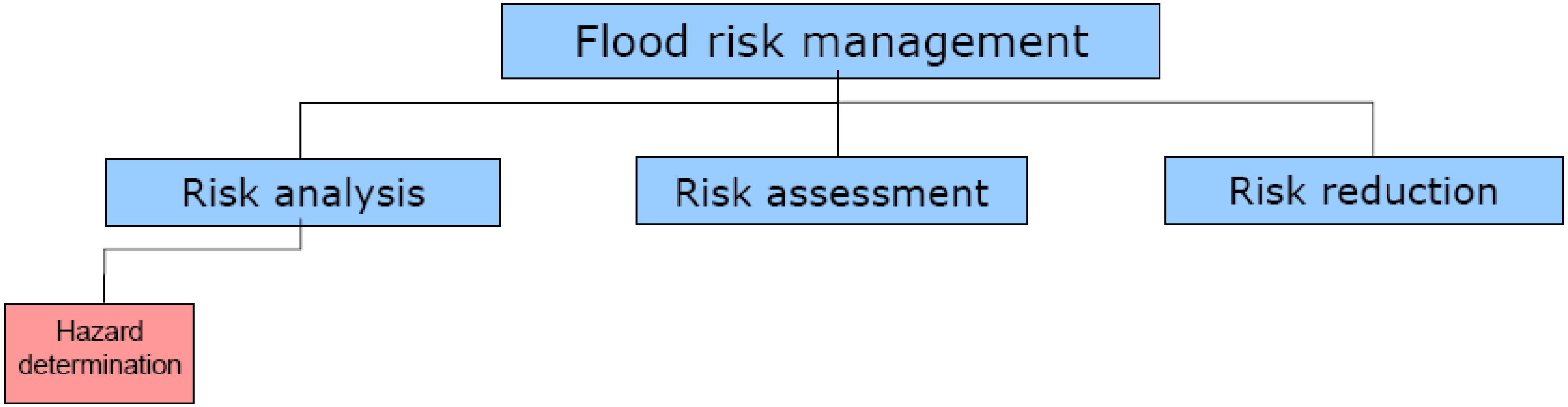
Exposure category	Exposure sub class	V1	V2	V3	V4	V5
Sparse houses	Single houses	low	low	moderate	medium	high
	Flats	low	low	moderate	medium	high
Industrial and craft settlements	Farmhouses	low	moderate	medium	high	high
	Single houses	low	moderate	medium	high	high
	Sheds	low	low	moderate	medium	high
	Box/Garage	low	low	moderate	medium	high
	Flats	low	moderate	medium	high	high
Supermarkets		moderate	medium	high	high	extreme
Residential buildings	Single houses	moderate	moderate	medium	high	extreme
	Flats	moderate	medium	high	high	extreme
	Detached houses	moderate	medium	high	high	extreme
	Villas	medium	high	high	high	extreme
Civil Protection Areas and Police offices		medium	medium	high	extreme	extreme
Important public buildings	Churches	medium	high	extreme	extreme	extreme
	Town hall and municipal offices	medium	high	extreme	extreme	extreme
	Schools	high	extreme	extreme	extreme	extreme
	Hospitals	high	extreme	extreme	extreme	extreme

- low
- moderate
- medium
- high
- extreme

Flood Risk Management

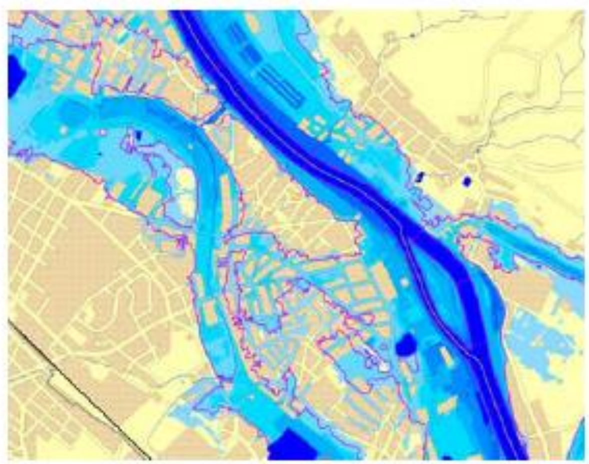


Flood Risk Management



Κίνδυνος πλημμύρας

Ένα φυσικό γεγονός, φαινόμενο, η ανθρώπινη δραστηριότητα που ενδεχόμενα μπορεί να προκαλέσει ζημιά. Ένας κίνδυνος δεν προκαλεί αναγκαστικά ζημία (FLOODsite, 2005)

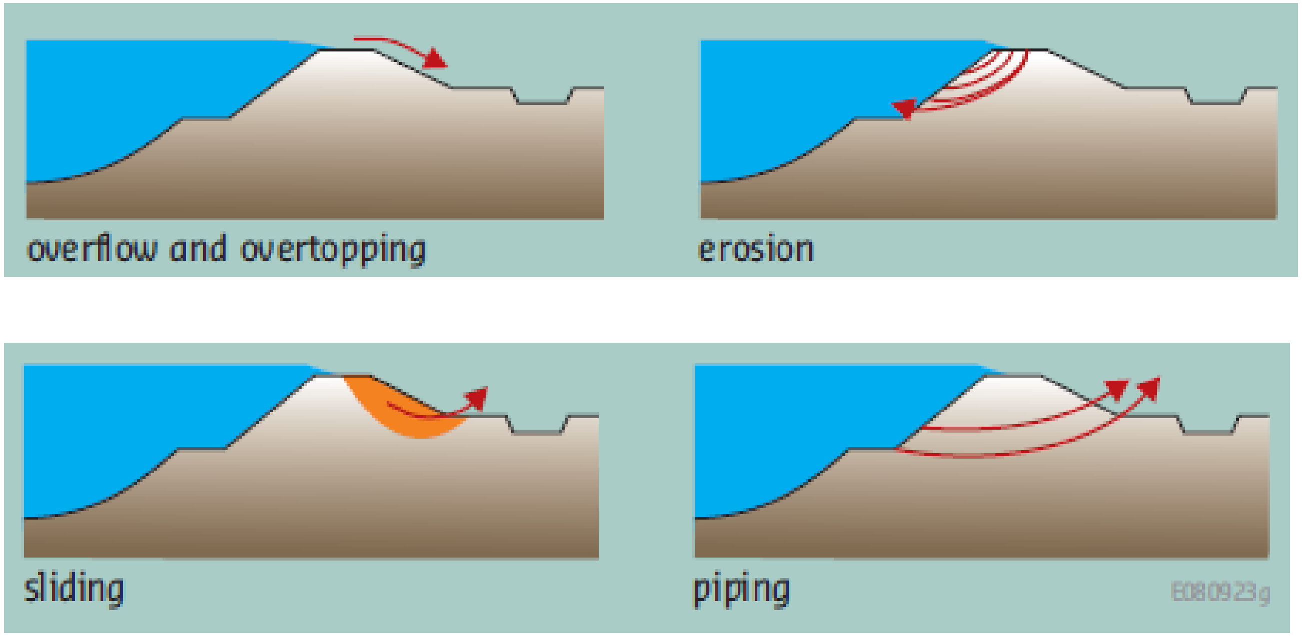


Προσδιορισμός κινδύνου

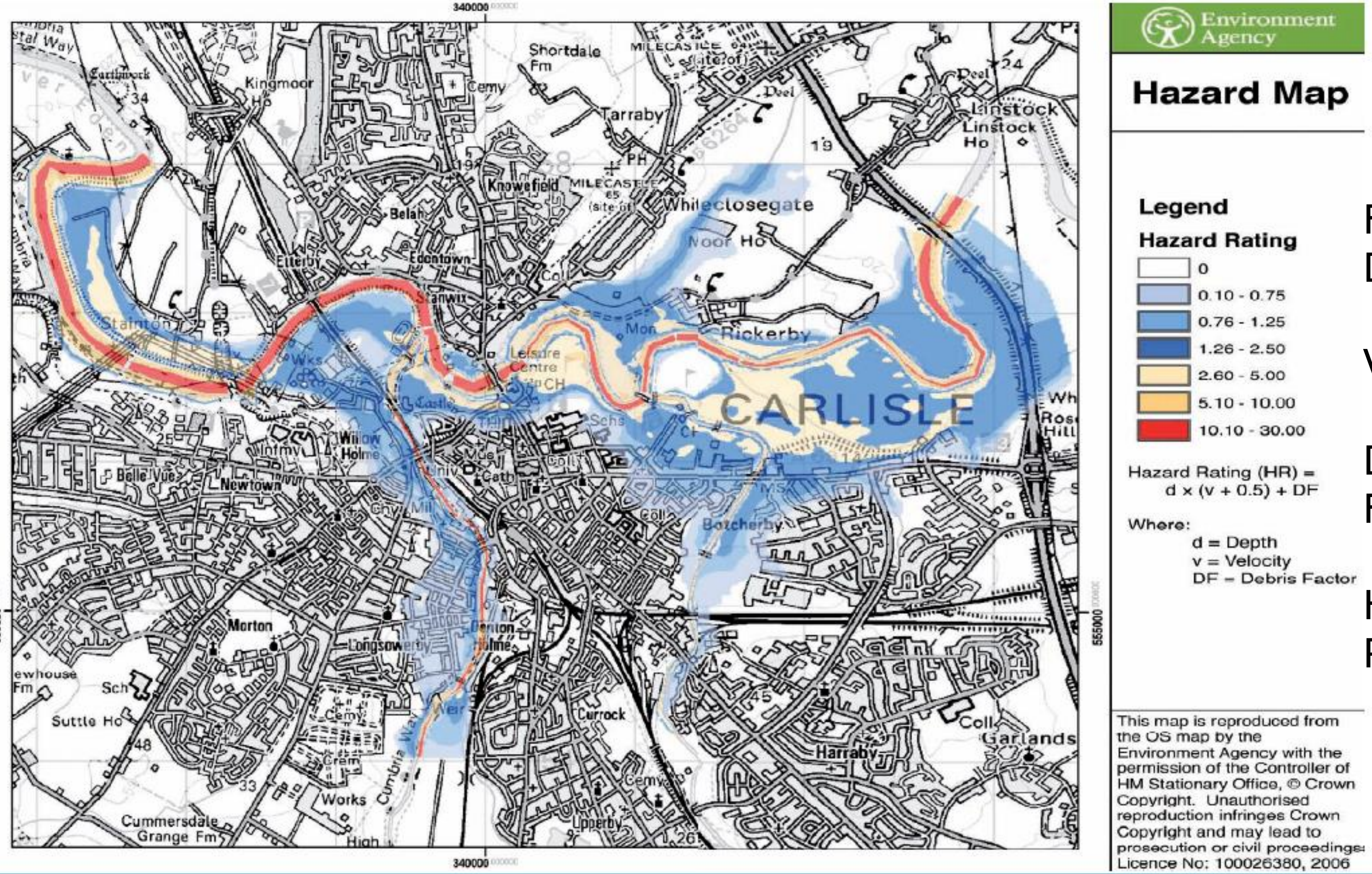
Ποσοτικοποίηση της πιθανότητας Εμφάνισης, μεγέθους και άλλων χαρακτηριστικών της πλημμύρας (Υδρο-μετεωρολογική προσομοίωση)

Reliability and Strength of the defences

❖ To calculate these probabilities we need to know about the reliability (resistance minus the loading) and the strength of the defenses for various failure modes.



Hazard Map



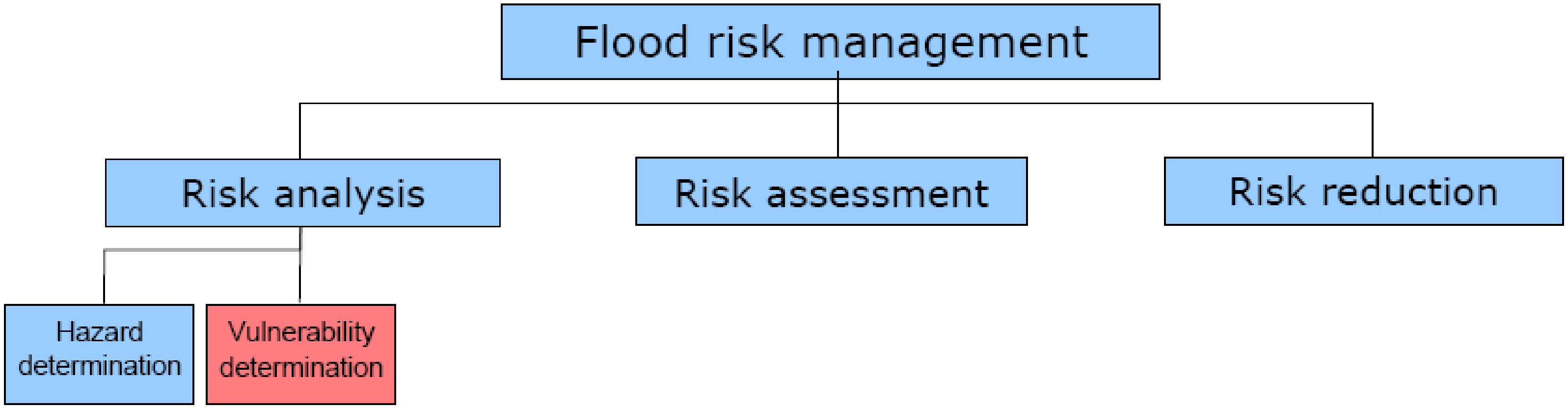
Flow Depth

Velocity

Debris Factor

Hazard Rating

Flood Risk Management



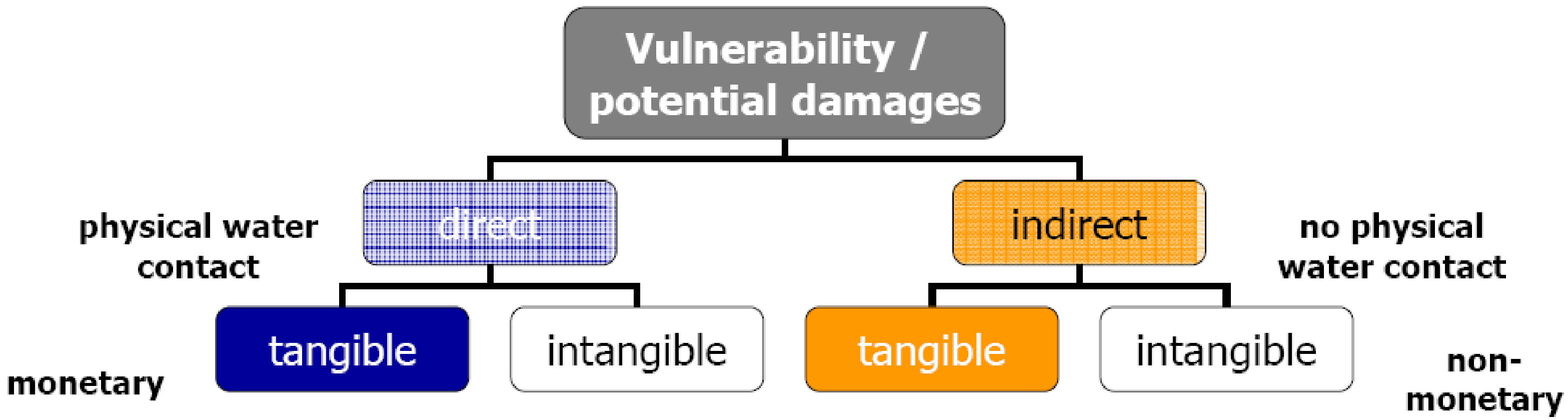
Τρωτότητα

Χαρακτηριστικό ενός συστήματος που περιγράφει το ενδεχόμενο να υποστεί ζημίες (βλάβες). Μπορεί να ορισθεί σαν ο συνδυασμός ευπάθειας και τιμής (αξίας).

Προσδιορισμός τρωτότητας

Ποσοτικοποίηση και αξιολόγηση των ενδεχόμενων κοινωνικών, οικονομικών και οικολογικών ζημιών του πλημμυρικού κινδύνου.

Vulnerability and Damages



e.g.:

Direct – tangible:
- buildings
- infrastructure
- crop, cattle
- capital goods
- consumer goods
- ...

Direct – intangible:
- life
- health
- environment
- unique goods
- art and cultural goods
- ...

Indirect – tangible:
- production losses (in and outside inundation area)
- market discturbances
- loss of time
- ...

Indirect – intangible:
- reduced competitiveness
- migration
- increased vulnerability of economic actors
- ...

Damages/Losses

Direct Damages/Losses
Losses resulting from direct contact with flood water, to buildings and infrastructure

Indirect Damages/Losses
Losses resulting from the event but not from its direct impact, for example, transport disruption, business losses that can't be made up, losses of family income etc.

In both loss categories, there are two clear sub-categories of loss:

Tangible
Loss of things that have a monetary (replacement) value, for example, buildings, livestock, infrastructure etc.

Intangible
Loss of things that cannot be bought and sold, for example, lives and injuries, heritage items, memorabilia etc.

swarm

Categories of Flood Losses

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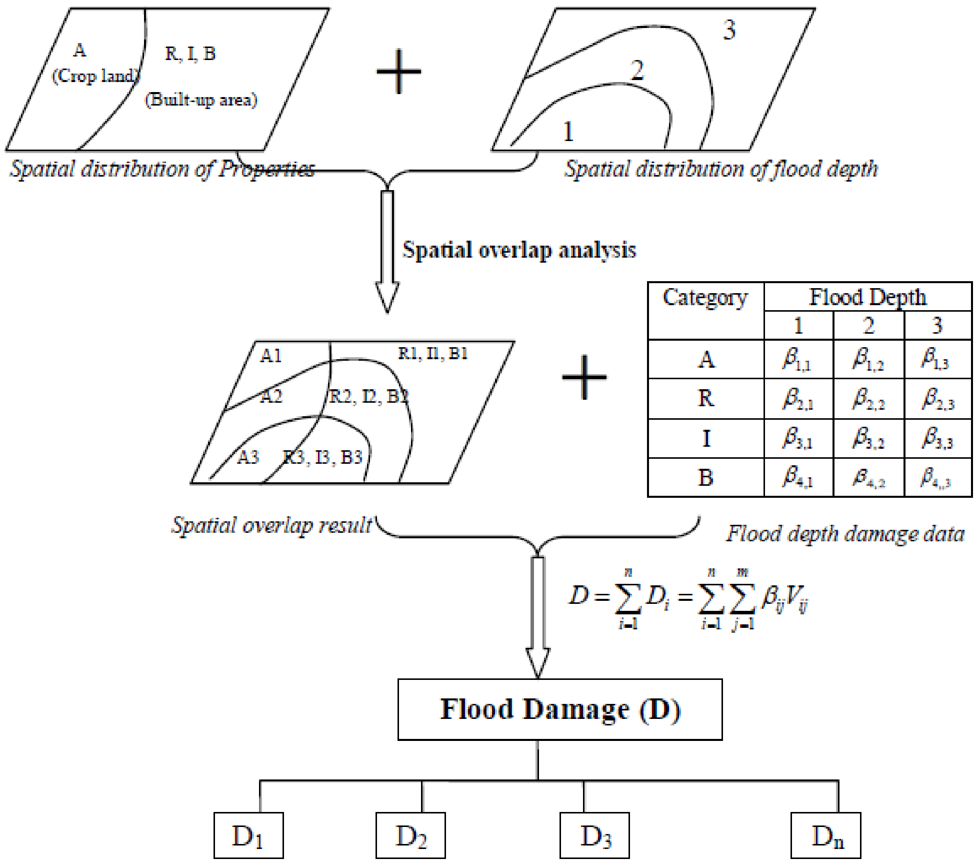
FLOOD LOSSES

	TANGIBLE DIRECT LOSSES	TANGIBLE INDIRECT LOSSES	INTANGIBLE HUMAN AND OTHER LOSSES
PRIMARY	Damage to: • Buildings (e.g. houses) • Contents of buildings • Infrastructure (e.g. roads, bridges) • Crops and animals	Loss of, or disruption, to: • Agricultural production • Industrial production • Communications (e.g. road, rail and telecommunications) • Health care and education services • Utility supplies (e.g. electricity)	• Loss of life • Physical injury • Loss of heritage or archaeological site
SECONDARY	• Flood causes fire and fire damage • Salt in seawater contaminates land and reduces crop yields • Flood cuts electricity supply, damaging susceptible machines and computer runs	• Lost value added in industry • Increased traffic congestion and costs • Disruption of flow of employees to work causing "knock-on" effects • Contamination of water supplies • Food and other shortages • Increased costs of emergency services • Loss of income • Increased household costs	• Increased stress • Physical and psychological trauma • Increase in flood-related suicides • Increase in water-borne diseases • Increase in ill health • Increase in post-flood visits to doctors • Hastened and/or increased mortality
TERTIARY	• Enhanced rate of property deterioration and decay • Long-term rot and damp • Structures are weakened, making them more damage prone in subsequent floods	• Some businesses are bankrupt • Loss of exports • Reduced national gross domestic product	• Homelessness • Loss of livelihoods • Total loss of possessions (i.e. uninsured) • Blighted families • Lost communities where communities are broken up

Flood Damage Assessment model



Category	Flood Depth		
	1	2	3
A	$\beta_{1,1}$	$\beta_{1,2}$	$\beta_{1,3}$
R	$\beta_{2,1}$	$\beta_{2,2}$	$\beta_{2,3}$
I	$\beta_{3,1}$	$\beta_{3,2}$	$\beta_{3,3}$
B	$\beta_{4,1}$	$\beta_{4,2}$	$\beta_{4,3}$

Fig. 6-1 Flow diagram for flood damage assessment model

Note: A=Agriculture output; B=Residential property; I=Industry assets; B=Business assets; Di=flood damage in category i; βij, Vij=Loss rate, assets in category i under depth j, respectively.

Damage Map

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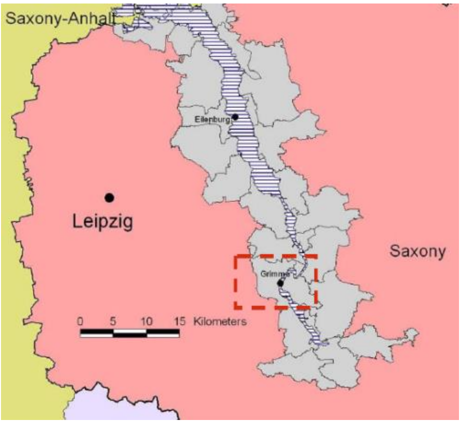

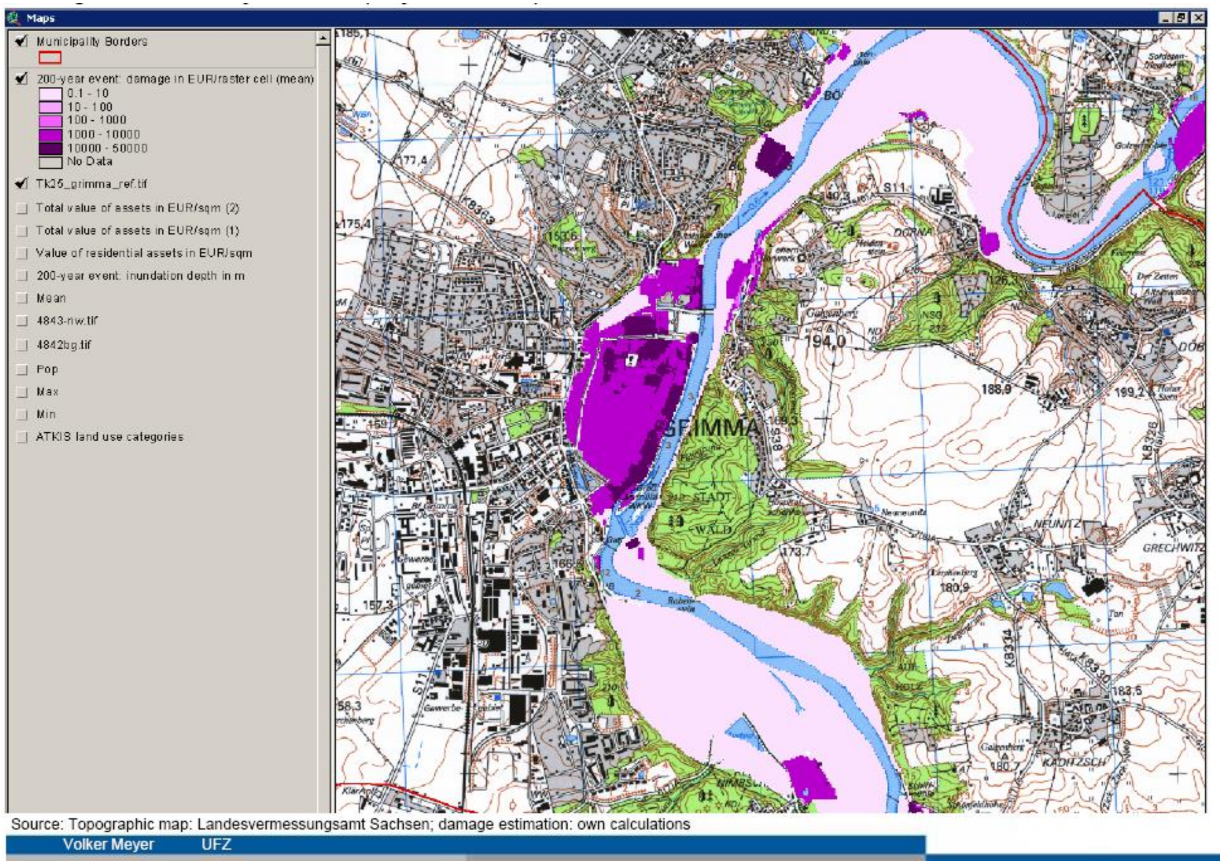

Damages for a 200-year flood event in the city of Grimma, Germany (Meyer, 2007)

Map of affected population

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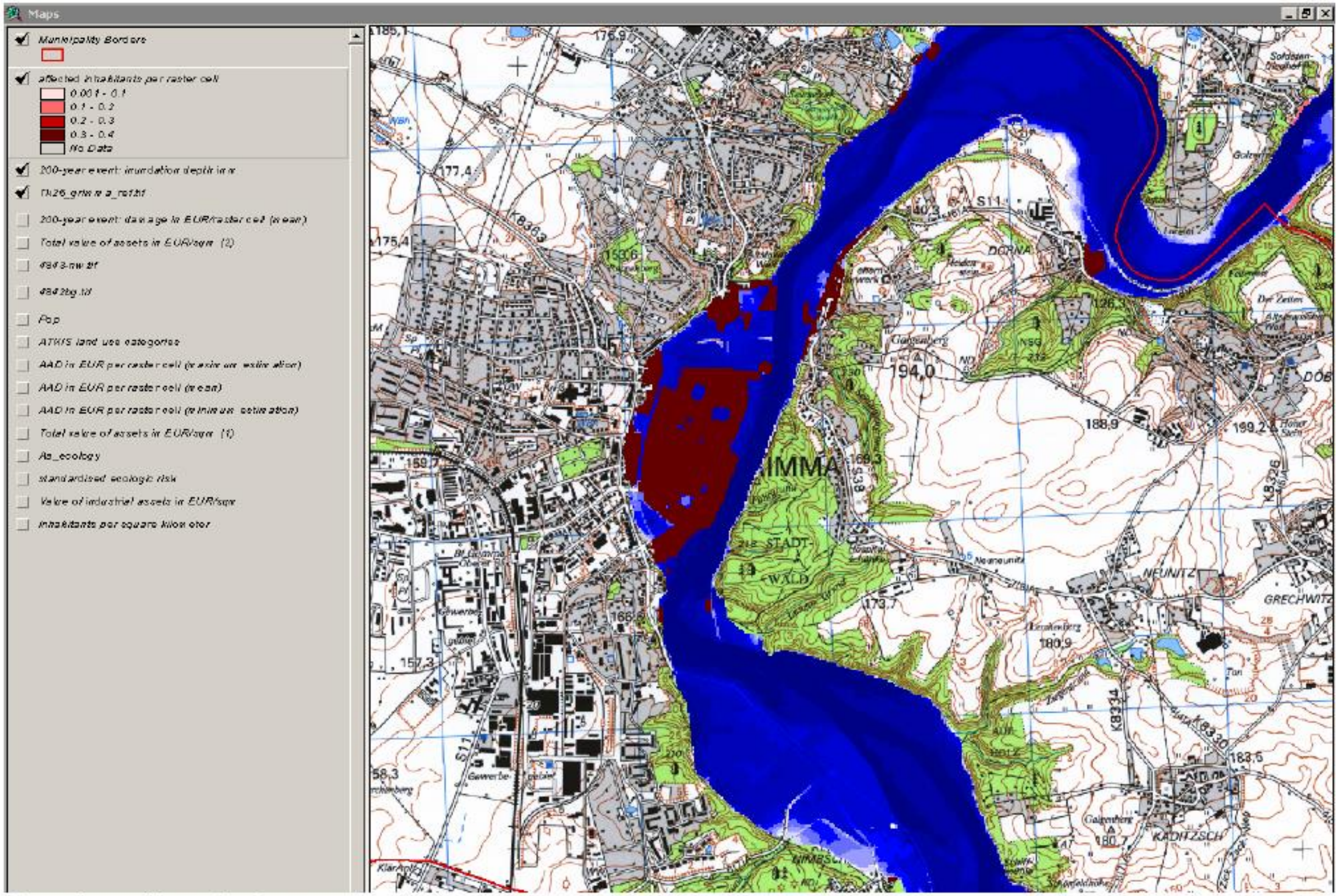
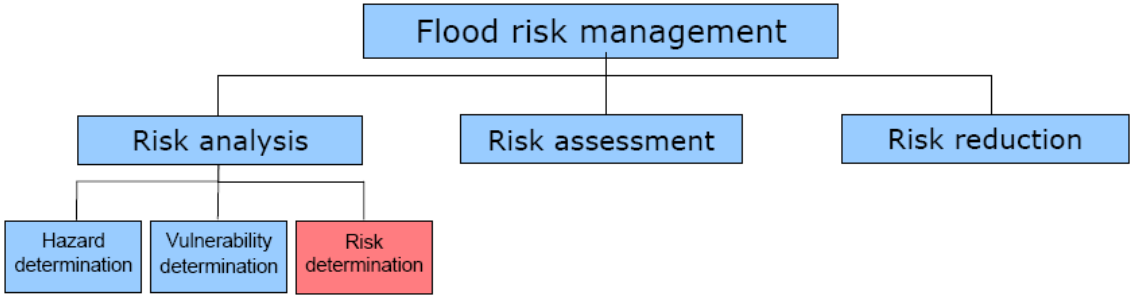


Source: Topographic map: Landesvermessungsamt Sachsen; inhabitants: own calculations

Volker Meyer UFZ

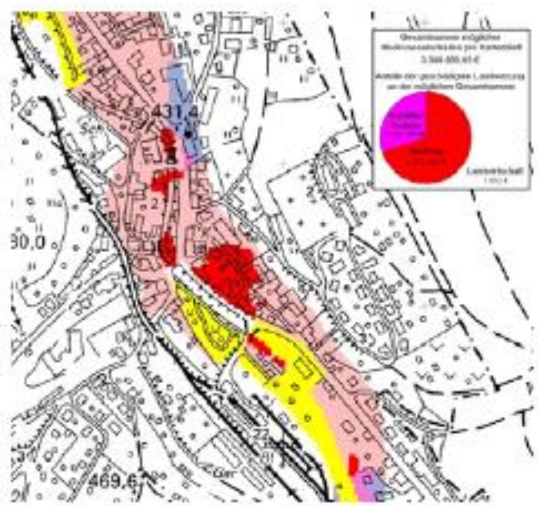
Affected population, 200-year event in city of Grimma, Germany (Meyer, 2007)

Flood Risk Management



Διακινδύνευση πλημμύρας

Είναι συνάρτηση της έκθεσης στο κίνδυνο και της τρωτότητας (Plate, 2001, FLOODsite, 2005)



Προσδιορισμός διακινδύνευσης

Μεθοδολογία για τον προσδιορισμό της φύσης και της έκτασης της διακινδύνευσης πλημμύρας ως πιθανότητα κοινωνικών, οικονομικών και οικολογικών ζημιών από μία πλημμύρα (Χαρτης διακινδύνευσης)

Expected Flood Risk

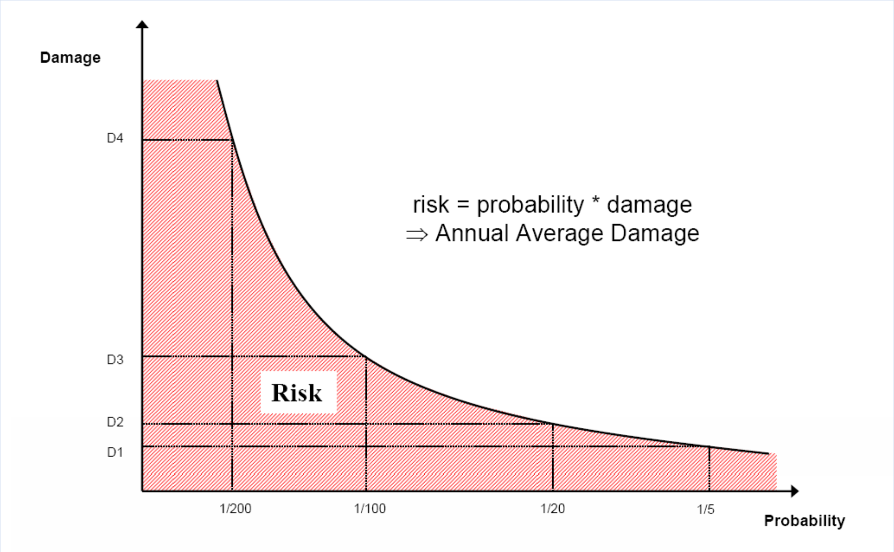
❑ ***Risk*** has a probability and a consequences dimension. This can be represented either by a graph of consequences against probability - termed a '***magnitude-frequency diagram***' - or by calculating the ***average annual consequences***.

❑ The latter gives the Expected Annual Damage (EAD), the Expected Annual Number of Affected persons, and/or the Expected Annual Number of Fatalities (EAN).

❑ ***The full flood risk*** at a site consists of the effects of all floods that can be experienced at that site, not just those of one single event.

Expected Flood Risk

Full flood risk can be represented by a graph of damages (or other consequences) against probability. This yields a 'magnitude-frequency diagram'. The overall Estimated Annual Damage (EAD) is then the area under the curve, which can be accurately calculated as the integral of the probability-consequence curve, or approximated by the sum of a number of 'representative' flood events.



Risk Estimation

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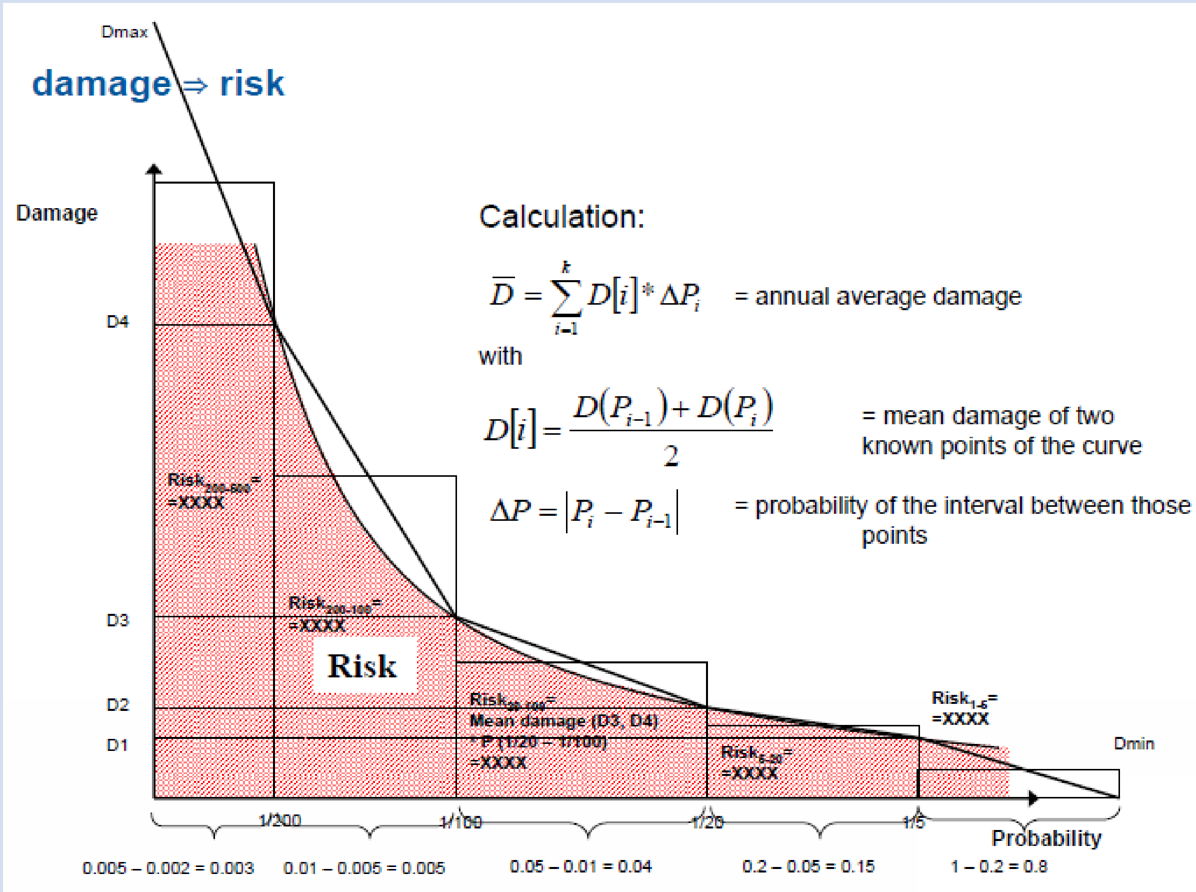


Hazard Map-Vulnerability Map-Risk Map

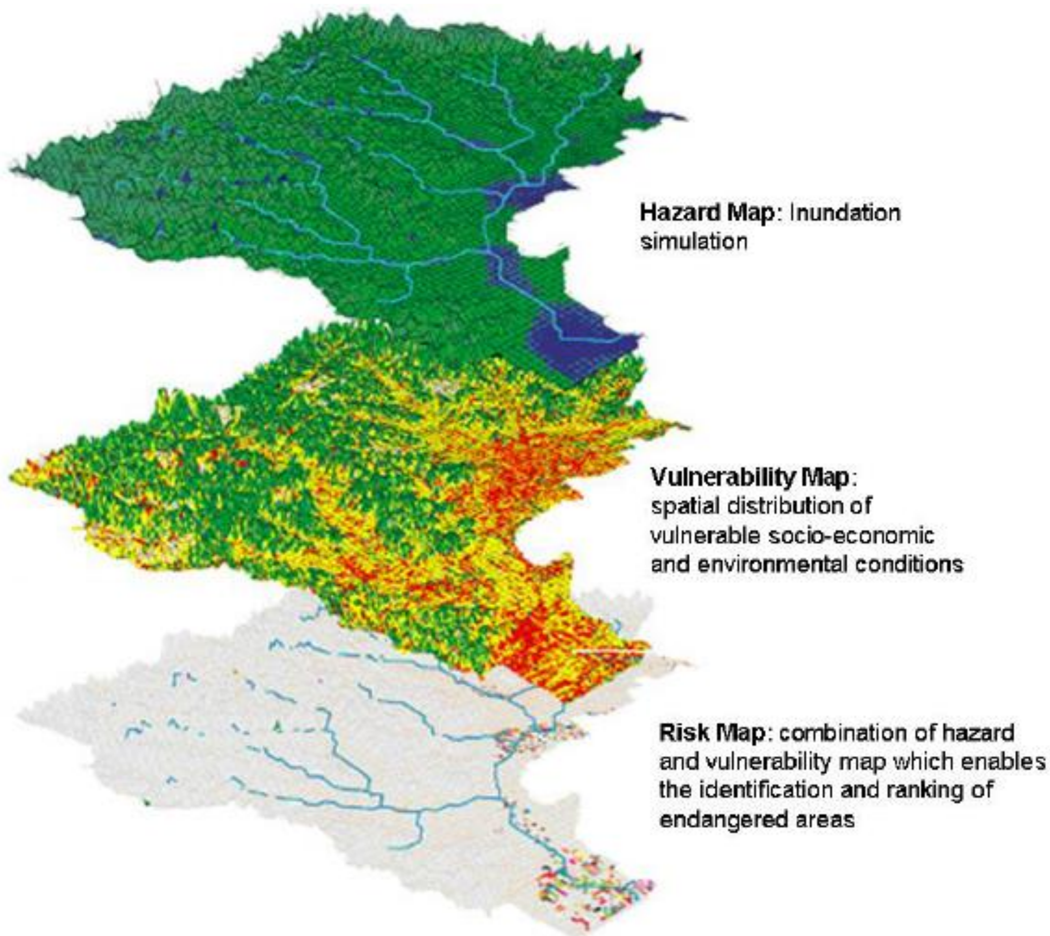
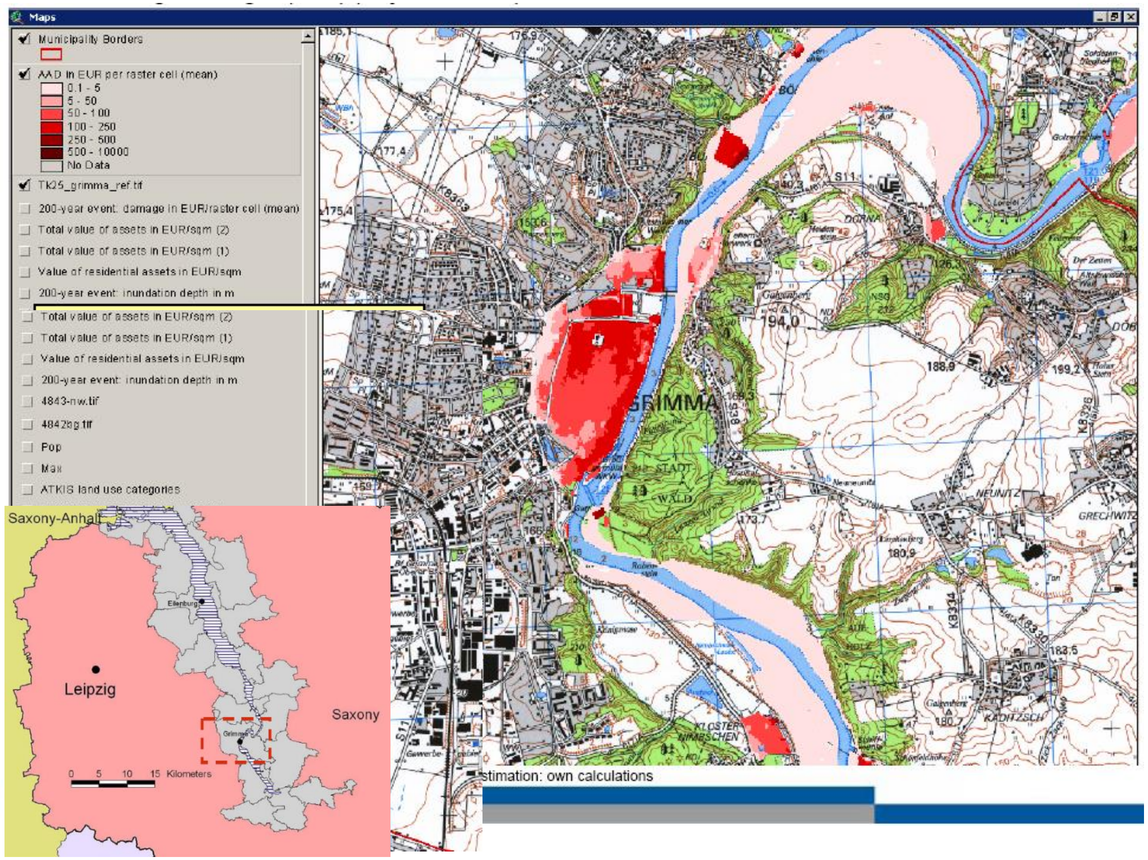


Figure 8: Risk map with a geographical information system (GIS) (adapted from ADRC [15])

Mean Annual Damages



Mean annual damages in the city of Grimma, Germany: mean estimation (Meyer, 2007)

Annual Affected Population

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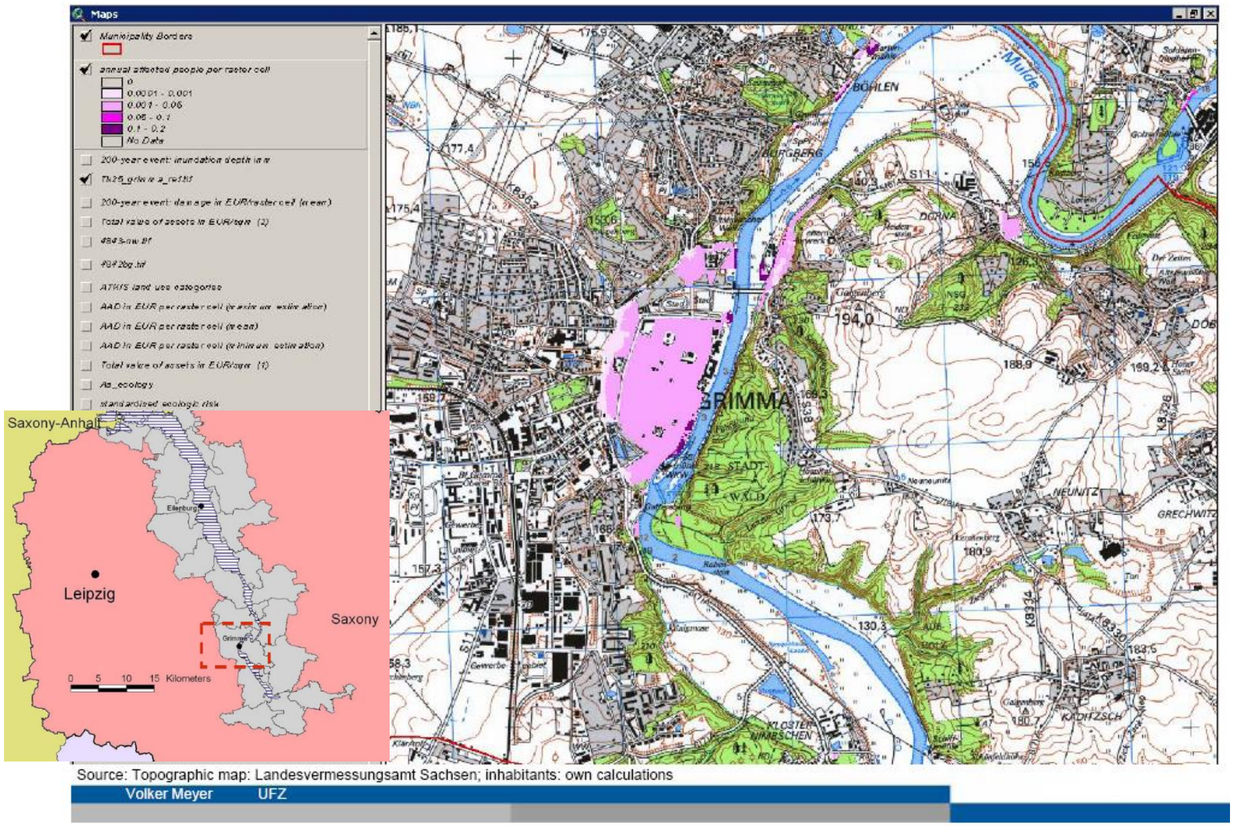
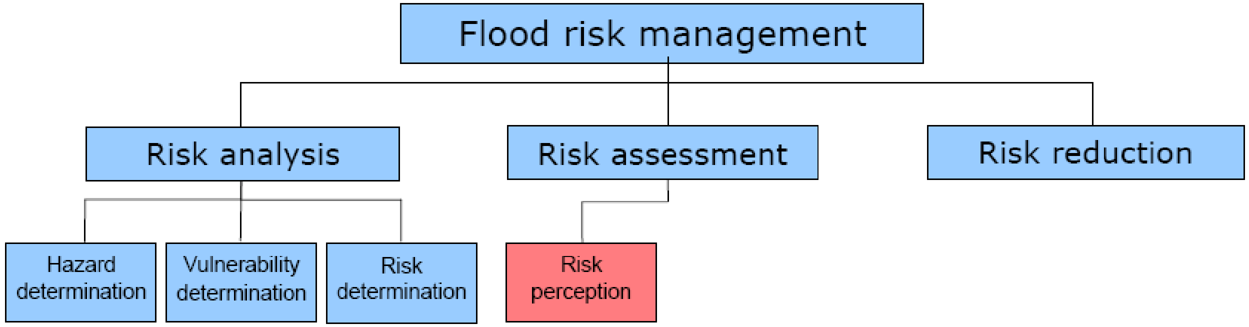


Annual affected population in the city of Grimma, Germany (Meyer, 2007)

Flood Risk Management



<u>Αντίληψη διακινδύνευσης (Perception)</u>

Άποψη που έχει ένας πολίτης ή ομάδα πολιτών για τη διακινδύνευση με βάση προσωπικές αξίες, κουλτούρες και εμπειρία

<u>Διερεύνηση για την αντίληψη διακινδύνευσης</u>

Αναζήτηση πληροφοριών για την άποψη που έχει ένας πολίτης ή ομάδες για τη διακινδύνευση (π.χ. συνεντεύξεις, ερωτηματολόγια)

Tolerable Flood Risk

❑ When performing a flood risk assessment, it is essential to express flood risks in terms which are relevant from:

- An *individual point* of view
- From the point of *view of authorities*.

❑ This requires that one is very explicit about the criteria used, about how they are calculated or estimated, and about how they are judged.

Tolerable Flood Risk

❖ ***The individual 'tolerances' appear to be a function of at least the following:***

✓ The perception and understanding of possible flood risks, and the other risks that the same people face,

✓ The benefits and costs to the communities concerned as a result of the floods,

✓ The ability of individuals and communities to help themselves or reduce the consequences,

✓ The degree to which a flood is seen as an 'Act of God' or as the 'fault' of someone who can then be 'blamed'.

Tolerable Flood Risk

❖ ***For the responsible authorities, it is necessary:***

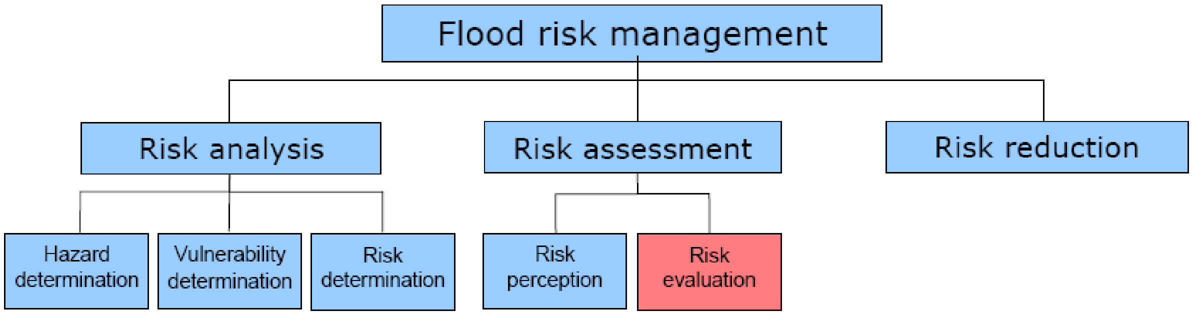
✓ It is necessary to ‘integrate’ or ‘generalise’ the views of individuals, communities and others at risk,

✓ To take into account the view of other parts of society in their judgment of acceptability.

❖ ***Authorities may also be expected to forget less easily and to have, or at least apply, a more steady opinion on acceptability of flood risks than individuals.***

❖ ***Responsible authorities also need to take into account the impact of a possible flood disaster with large numbers of fatalities for the image of the region or entire country.***

Flood Risk Management



Tolerable flood risk

Level of flood risk which is tolerable for a person or group (decision maker).

Evaluating risk

Methods for evaluating the tolerability of a certain risk weighing benefits and costs depending on individual or collective perception and interest (e.g. CBA, MCA).

Flood Risk Management

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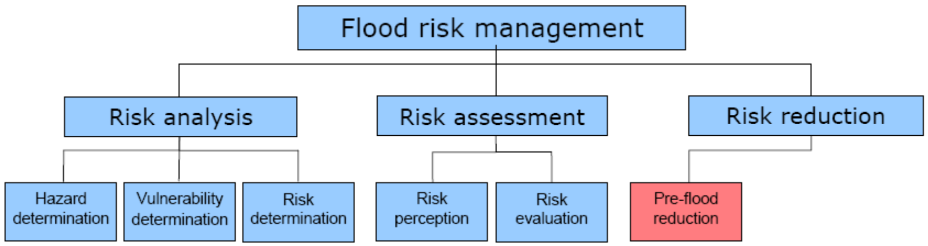
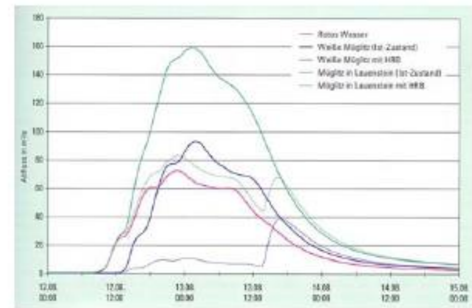
Π. ΠΡΙΝΟΣ





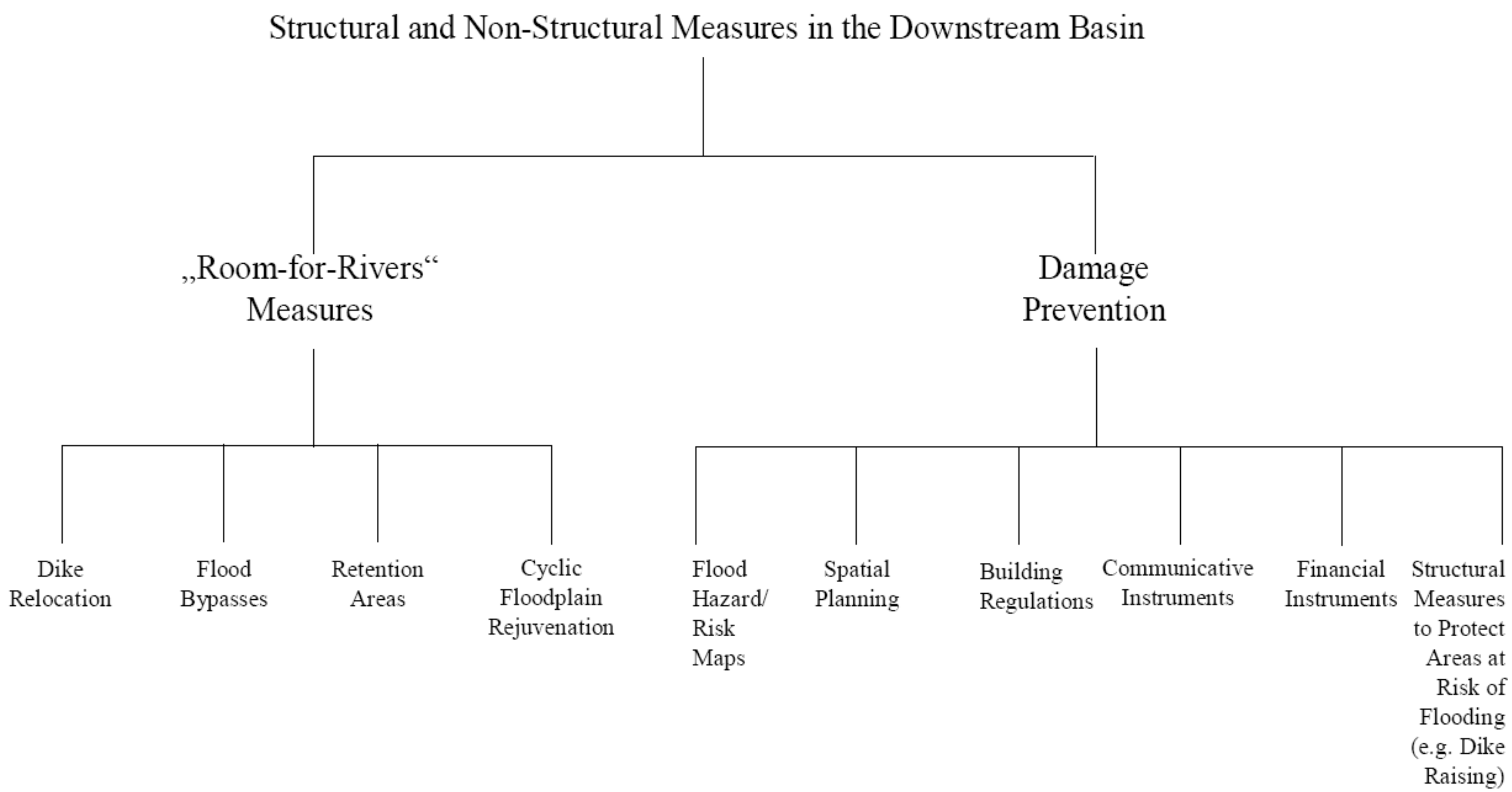
<u>Μείωση διακινδύνευσης πριν την πλημμύρα</u>

Μόνιμα και προσωρινά μέτρα όπως επίσης και κανονιστικά, οικονομικά και επικοινωνιακά εργαλεία για προετοιμασία και πρόληψη της πλημμύρας με σκοπό την μείωση της διακινδύνευσης

<u>Προσομοίωση και αξιολόγηση της μείωσης διακινδύνευσης πριν την πλημμύρα</u>

Ex-ante ανάλυση διακινδύνευσης για τον προσδιορισμό των επιδράσεων και της απόδοσης των προτεινόμενων μέτρων

Risk Reduction



Δομικά και μη-δομικά μέτρα σε κατάντη λεκάνη απορροής (Hooijer et al. 2004)

Risk Reduction

❖ ***Measures*** :

Physical interventions in the environment, which exercise effect directly through their existence. They are usually implemented by the flood risk managing authorities.

✓ Measures traditionally include all kinds of permanent structural measures, i.e. river and coastal engineering works, such as dams, flood walls, embankments etc.

✓ Over the last few decades attention for non-structural measures gained ground, such as catchment management to enhance water retention, erosion control by reforestation, river rehabilitation, temporary defences, etc.

Risk Reduction

❖ *There are more innovative structural measures that are more environmentally friendly:*

✓ ***'Room for rivers'*** measures include removing obstacles from the floodplain, the lowering of floodplains, or the construction of bypass channels or 'green rivers'.

✓ ***Temporary defences***

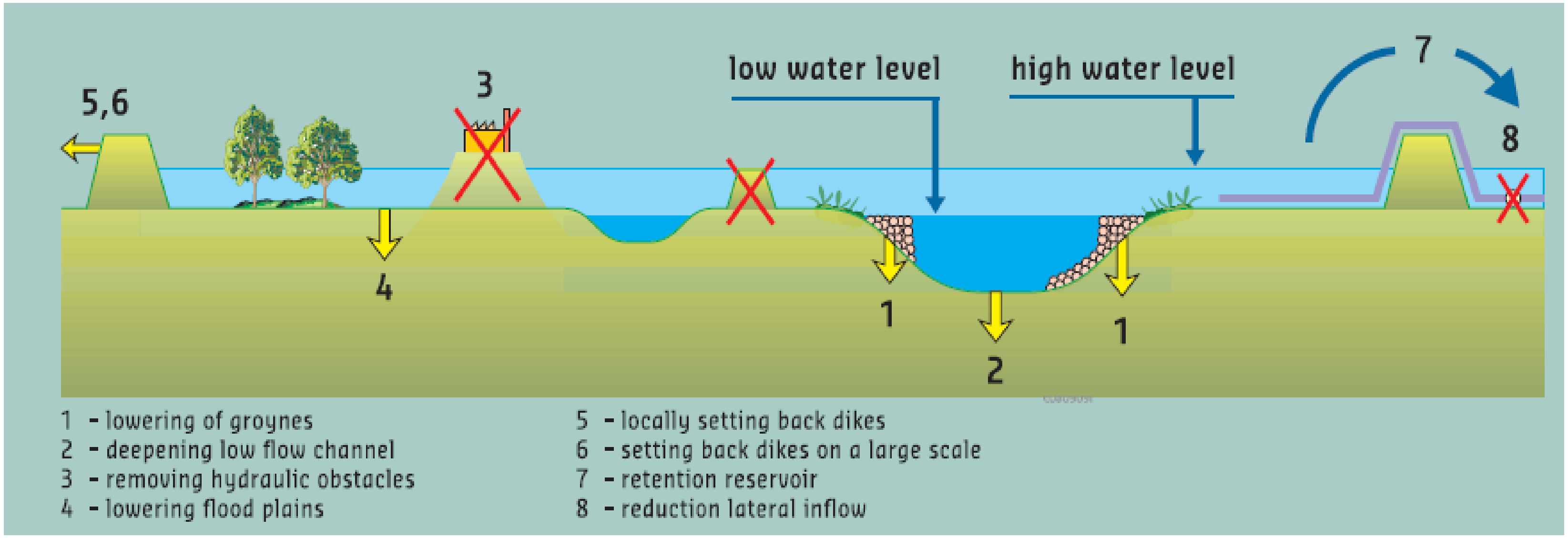
❖ *Non-structural or soft measures:*

✓ ***Re-forestation programs in catchment areas***

✓ ***Adapted agricultural practice aimed at limiting the runoff***

✓ ***The cutting of trees and the dredging of channels to enhance the conveyance capacity of rivers***

Risk Reduction



"Rooms for rivers" measures

Risk Reduction

❖ *There are also measures which aim to reduce the impacts of floods,* ***by reducing exposure*** *or vulnerability of the receptors:*

➢ ***Overtoppable fail-safe embankments*** which guarantee gradual and foreseeable overtopping of dikes when the design level is exceeded, thus reducing the speed of onset and the inflow volume of the flooding process. The expected damage is reduced through the reduced volume of inflow.

➢ ***Compartmentalisation of large polders into smaller ones*** can also reduce the impact of flooding, as the flooded area is delimited.

➢ ***Moving of susceptible goods to upper floors, or entirely out of the flood prone area.***

Risk Reduction

❖ *There are also measures which aim to reduce the impacts of floods,* ***by reducing*** *exposure or* ***vulnerability of the receptors****:*

➢ ***Housing, industries and services can, obviously, be best located on higher ground, i.e. outside the flood prone area.***

➢ ***Flood proofing*** should be done by private property owners to reduce the exposure of buildings or their susceptibility to damage from flood water. This may include the sealing of doors and windows, the waterproofing of walls or the use of waterproof construction material. Up to a certain flood level, and if properly implemented and maintained, flood proofing measures can contribute considerably to the reduction of damage to buildings.

Risk Reduction

❖ *Typical defence measures* ***for coastal areas*** *are:*

✓ ***Embankments and sea walls*** which can resist the forces of the waves and remain intact during overtopping.

✓ ***Sand/ Sediment nourishment to the beach*** to attenuate the wave energy and to the dunes to counteract or compensate for erosion .

Risk Reduction

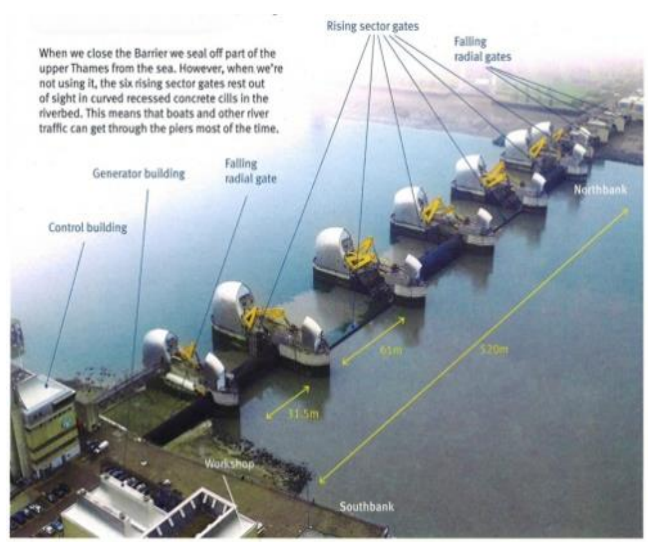
❖ *Typical defence measures* ***to reduce vulnerability for coastal areas*** *are:*

- Compartmentalisation
- Elevation of roads to be used for evacuation
- Safe havens
- Retreat from high risk areas

Risk Reduction

In ***estuaries*** storm surges meet with the discharge of rivers. From a management point-of view estuaries need protection during storm surges, but should also allow fluvial discharge to the sea.

- ✓ Storm surge barriers can be important, particularly in exposed estuaries. This type of barrier is constructed across the estuary mouth to prevent surges from extending into the estuary and causing floods in harbours and cities



Risk Reduction

Flash floods are exceptional due to:

✓Their extreme dynamics and destructive forces

✓Their very rapid onset

Flash floods are mainly generated in small catchments, with steep slopes, impermeable surfaces or saturated soils. These catchments respond very rapidly to intense rainfall, causing floods within a few hours.

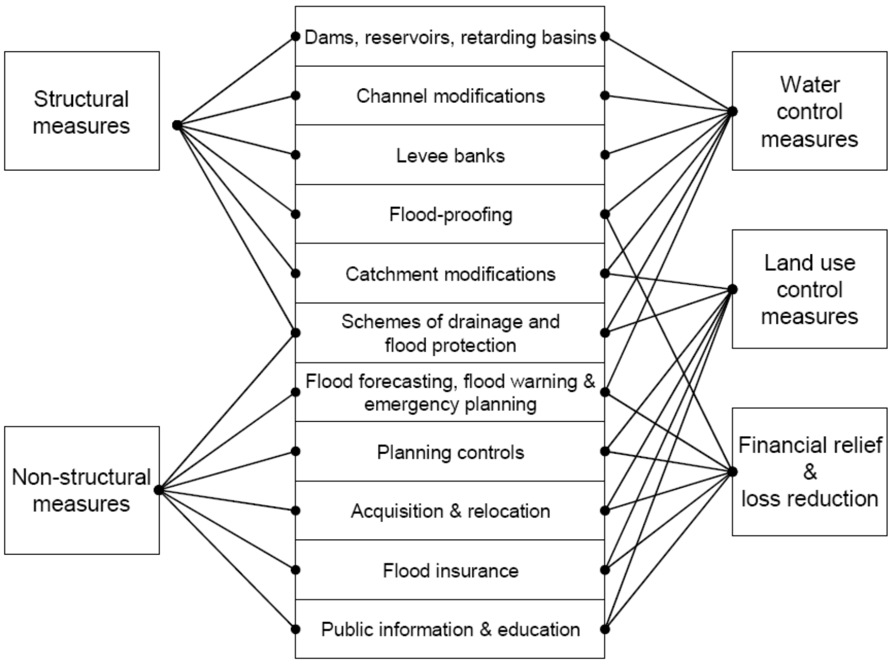
❖ Hazard reduction is not very effective. It is rather advisable to try to ***reduce exposure***:

✓Timely prediction of flash floods (best possible forecasts)

✓ Public awareness of the risk, the available routes and the use of the time available

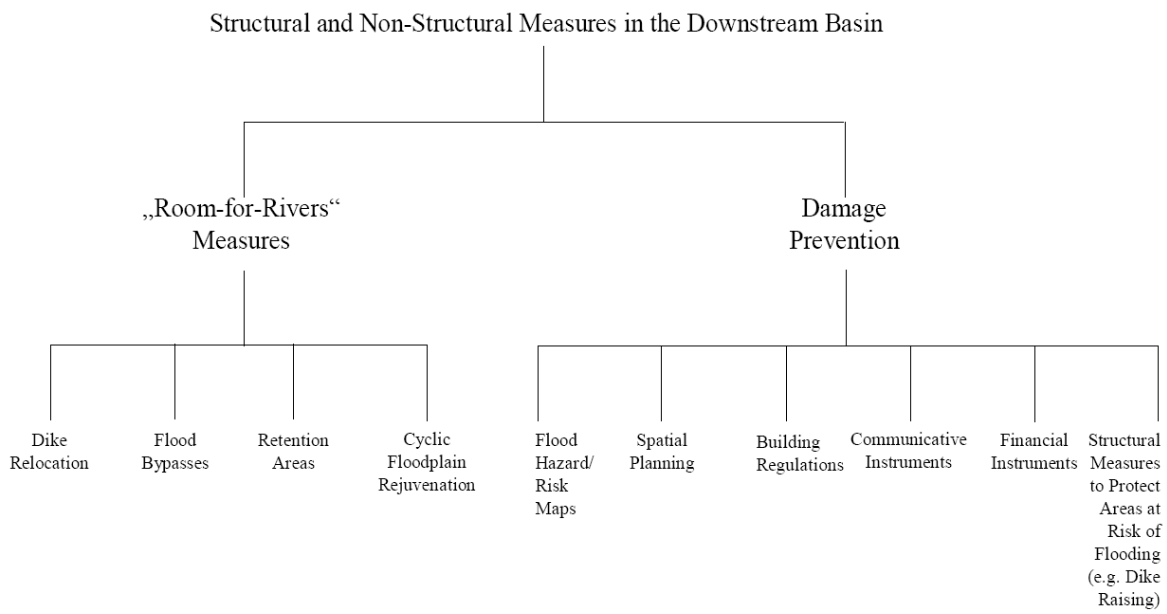
✓ Well organized and rapid response

Risk Reduction



Structural and Non-Structural Measures (Penning-Rowsell & Peerbolte, 1994)

Risk Reduction



Structural and Non-Structural Measures in the Downstream Basin
(adapted from Hooijer et al. 2004)

Risk Reduction

❖ ***Instruments (policy instruments)*** :

No direct physical interventions in the environment but rather means to influence the behaviour of other parties who co-determine the flood risk. For example: communication to warn inhabitants, insurance fees to make companies aware of the flood risk they run, or regulations to force local planners to better take into account flood risk.

✓ Three main groups of instruments can be distinguished:

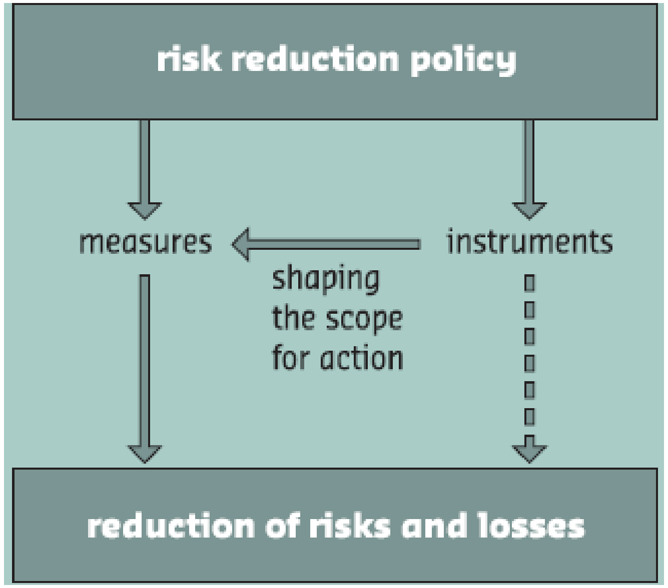
- Communicative : *Enhance the people's risk awareness and preparedness*
- Financial: *May influence people's investments or may encourage them to flood-proof their property*
- Regulatory : *Allow or prohibit certain activities (e.g. land use regulations)*

Risk Reduction

Instruments:

➢ Support the implementation of measures by the authorities

➢ Influence the behaviour of other actors, including the implementation of measures by them.



Relationship between measures and instruments

Risk Reduction

Regulatory Instruments *are the most binding instruments that authorities can apply to influence the behaviours of others. They may include*:

✓Environmental designations and regulations (e.g. coastal zone conservation, catchment protection)

✓ Flood Hazard Zoning, with regulations on allowable land use, cultivations, etc

✓ Spatial planning

✓ Building regulations on constructions, technical layout of installations, etc

✓ Regulations on timely evacuation

Financial Instruments :

✓ *Positive financial stimulation* can be realised by providing allowances or tax reductions for certain behaviour .

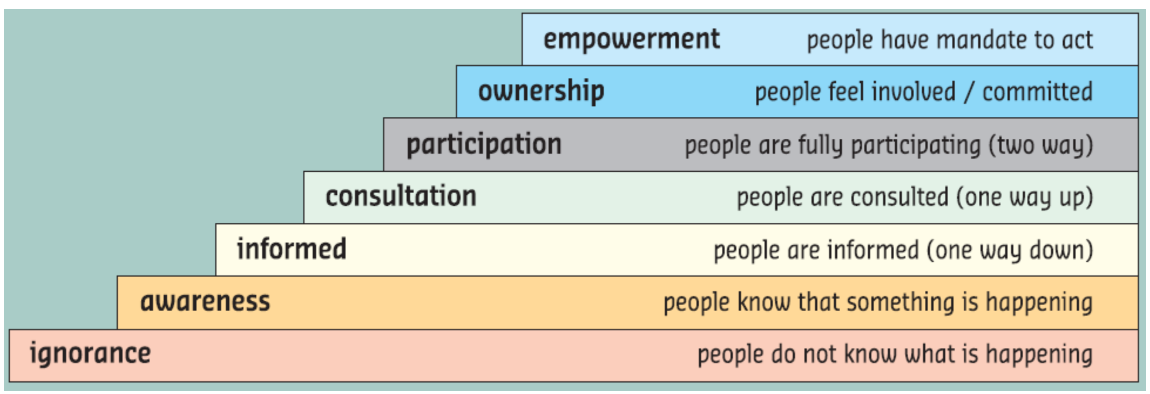
✓ *Negative financial stimulation* can imply fines for certain behaviour.

✓ *Insurance* is not primarily intended to influence the people's decisions or behaviour, but rather to distribute losses over the wider community by involving many more members than can be affected over a period of time.

Risk Reduction

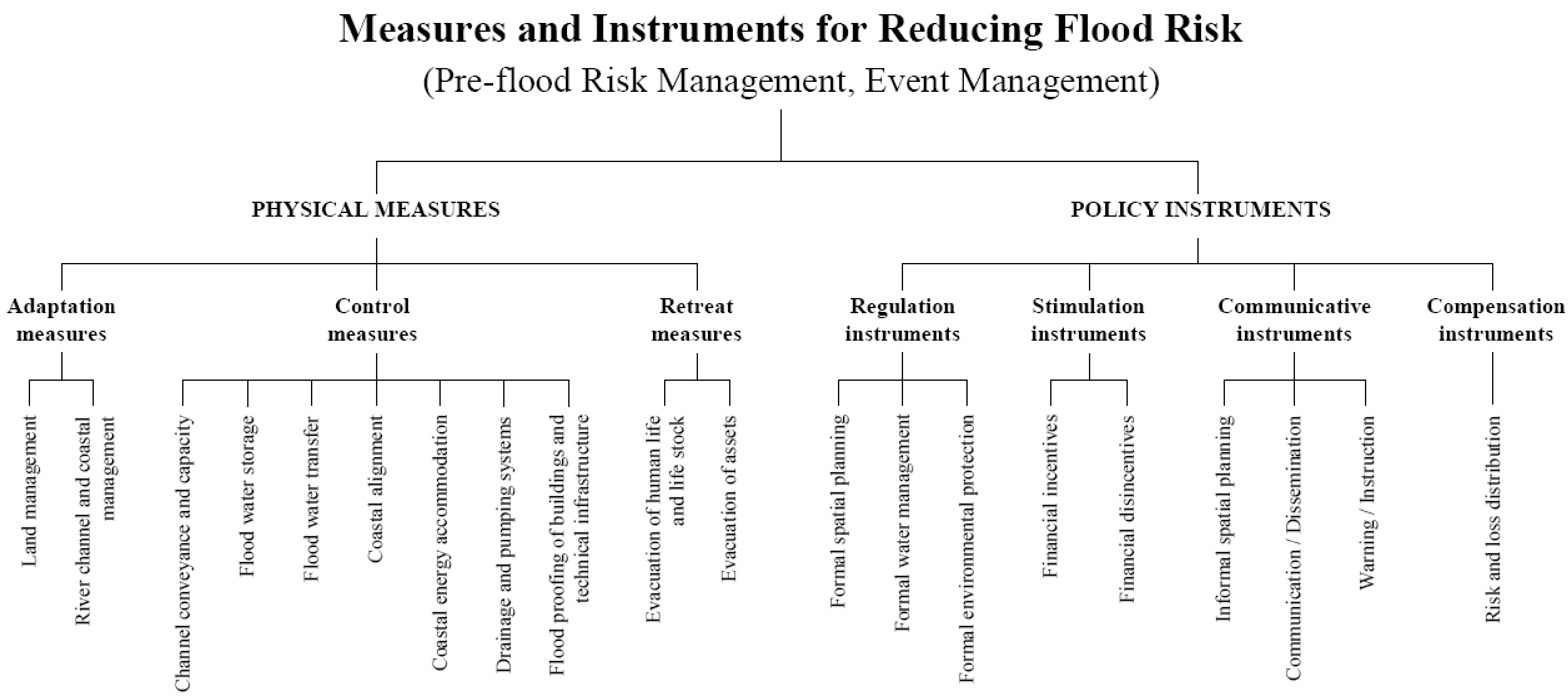
Communication Instruments :

- ✓ Flood hazard maps displaying flood extent, flood frequency, flood depth, etc.
- ✓ Leaflets or circulars containing information on what to do and when to do it, and preferred behaviour
- ✓ Public events, etc.



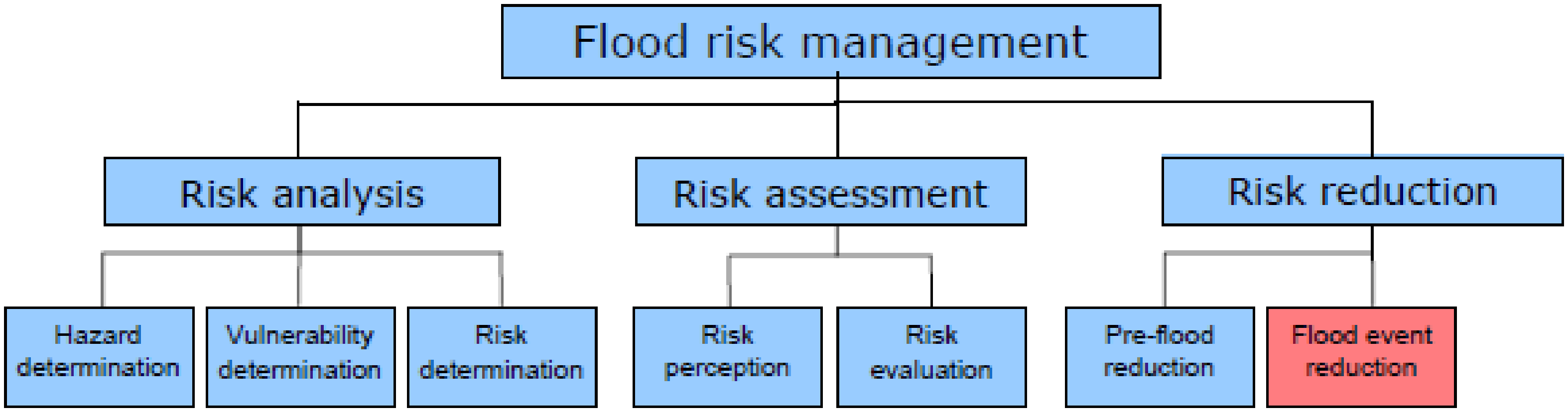
Seven levels of stakeholder involvement

Reducing Flood Risk



Κατηγοριοποίηση μέτρων και μέσων άσκησης πολιτικής (Olfert & Schanze, 2006)

Flood Risk Management



<u>Μείωση κατά την διάρκεια της πλημμύρας</u>

Μέτρα και κανονιστικά εργαλεία για την μείωση της διακινδύνευσης κατά την διάρκεια της πλημμύρας

<u>Προσομοίωση και αξιολόγηση της μείωσης διακινδύνευσης κατά την διάρκεια της πλημμύρας</u>

Ανάλυση διακινδύνευσης σε πραγματικό χρόνο για τον προσδιορισμό των επιδράσεων και της απόδοσης των προτεινόμενων μέτρων

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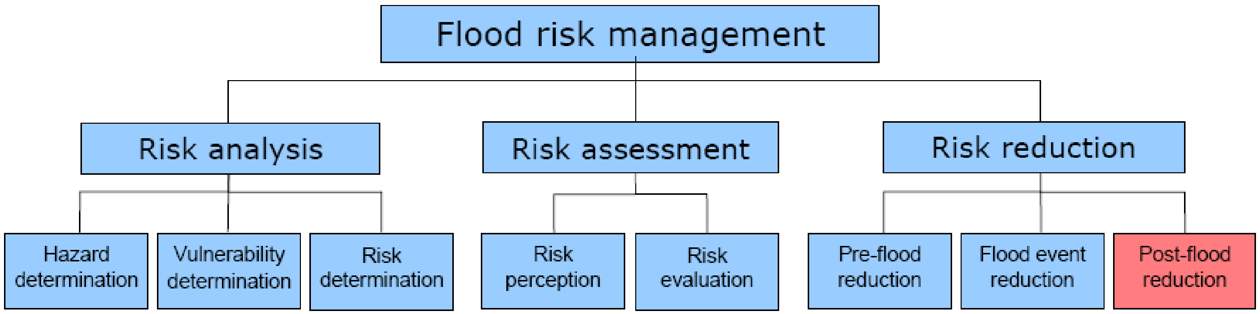
Flood Risk Management



<u>Μείωση διακινδύνευσης μετά την πλημμύρα</u>

Μέτρα και εργαλεία (κανονιστικά, οικονομικά, επικοινωνιακά) για την αντιμετώπιση των καταστροφών

<u>Προσομοίωση και αξιολόγηση της μείωσης διακινδύνευσης μετά την πλημμύρα</u>

Ανάλυση διακινδύνευσης σε πραγματικό χρόνο και ex-post για τον προσδιορισμό των επιδράσεων και της απόδοσης των προτεινόμενων μέτρων

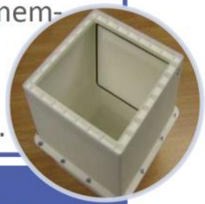
Flood resilient technologies

- Flood resilience of buildings can be defined as their ability to recover easily and quickly from damaging effects
- The enhancement of flood resilience properties is generally aiming at (i) minimising flood damage, (ii) decreasing direct flood repair costs, and (iii) allowing fast re-occupation

flood protection to specific locations up to a certain threshold, e.g. mobile flood barrier systems

Perimeter Technologies

flood protection to roads, railways etc. using surfacing materials, mem-branes, automatic barriers etc.



Infrastructure Technologies

temporary watertight closure of façade openings such as doors, windows or ventilation elements

Building Aperture Technologies

address either resilient building components or resilient engineering solutions

Building Technologies

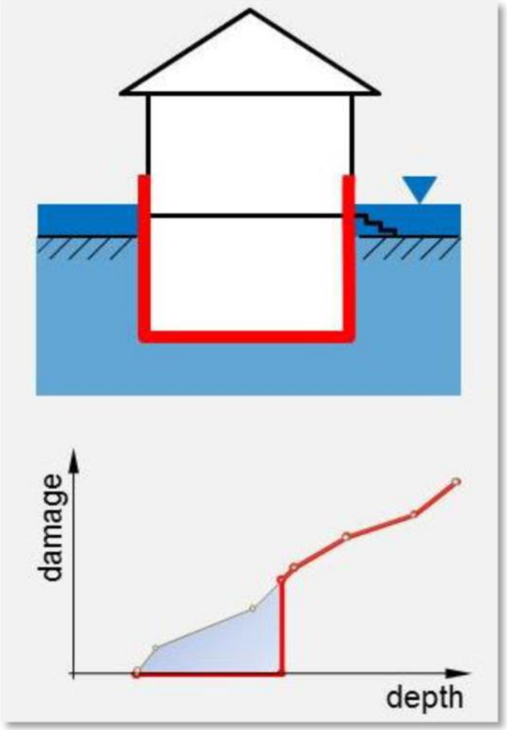
URBAN SCALE (Perimeter Technologies, Infrastructure Technologies)

INDIVIDUAL BUILDING SCALE (Building Aperture Technologies, Building Technologies)

Flood resilient technologies

Impacts on Flood Vulnerability

Dry proofing strategy
Building aperture technologies
Resilient building components

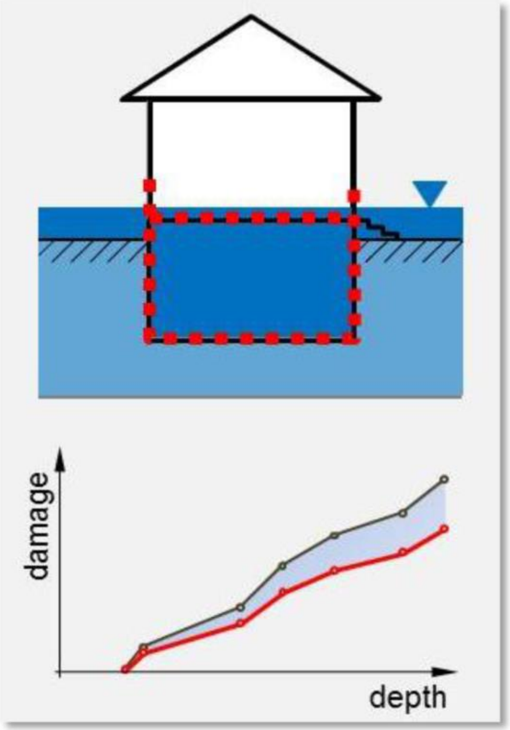


Flood vulnerability analyses considering FRe T implementation

Derivation of adapted depth-damage functions

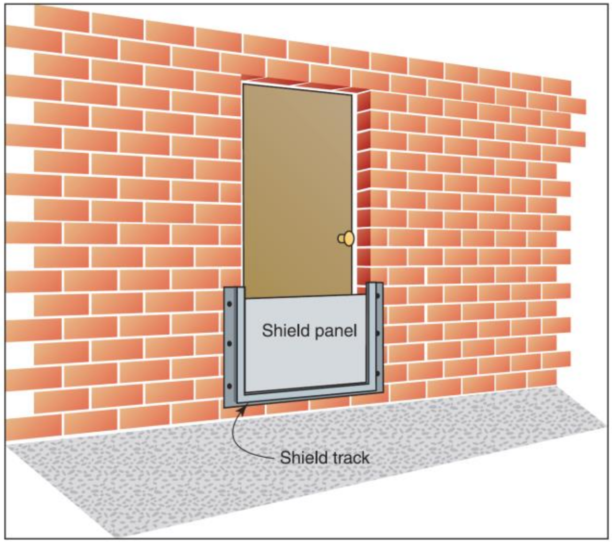
selected **FRe T** to follow the **DRY proofing** strategy	selected **FRe T** to follow the **WET proofing** strategy
temporary flood guards (boards) for doors	modified ground floor construction using e.g. foam glass and mastic asphalt screed
air-brick covers	modified external wall: construction using e.g. polyurethane cavity wall insulation
valves for backflow prevention	

Wet proofing strategy
Resilient engineering solutions



Visualisation: R. Schinke 2010

Flood resilient technologies



Αντιπλημμυρικά διαφράγματα σε θύρες

Flood resilient technologies

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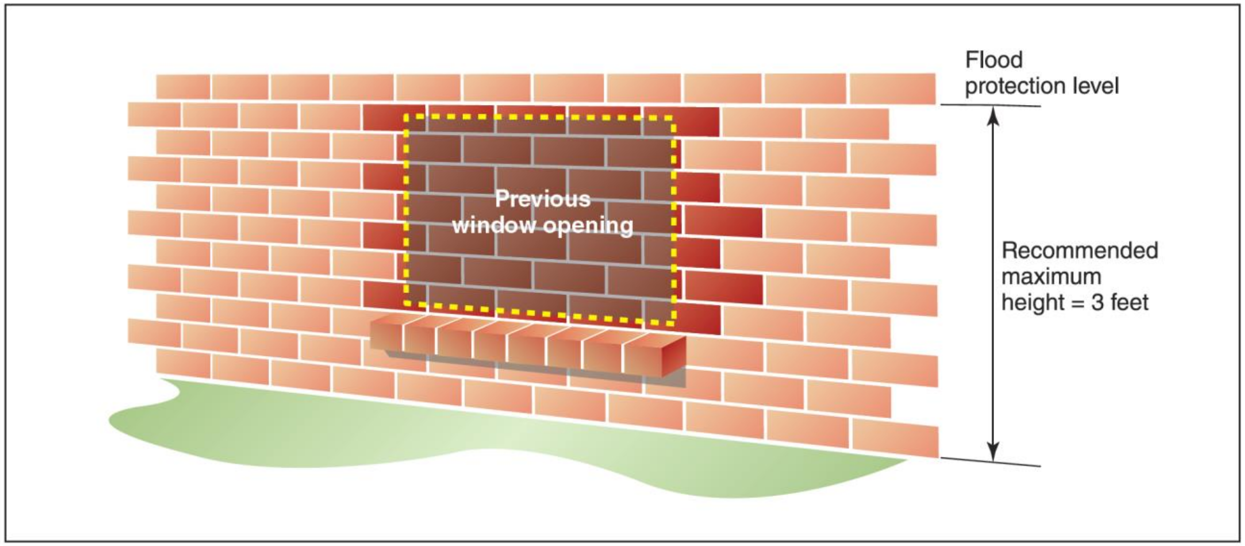
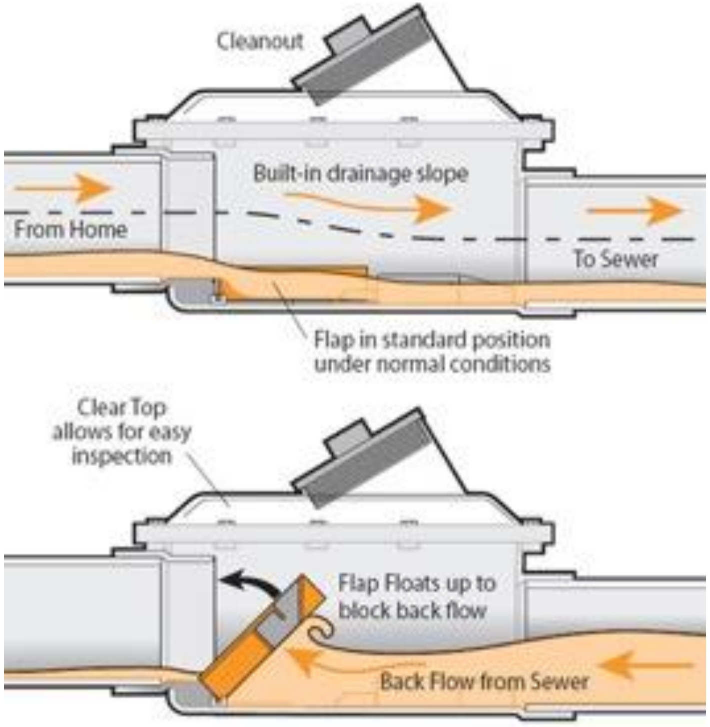


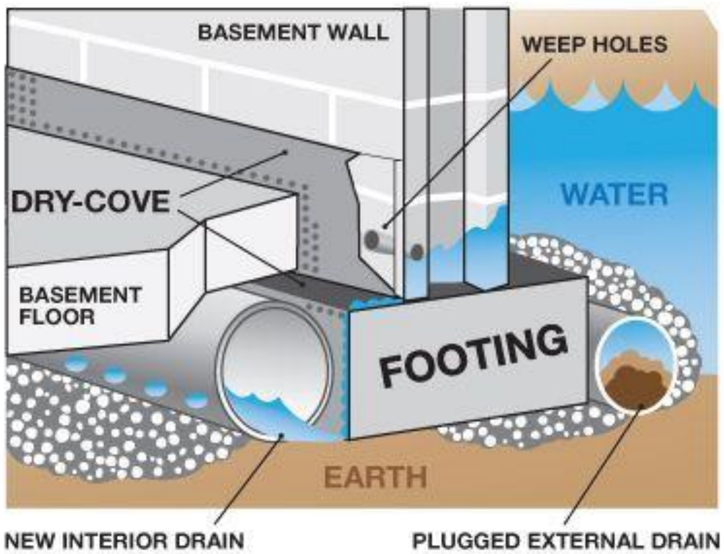
Κλείσιμο οπών

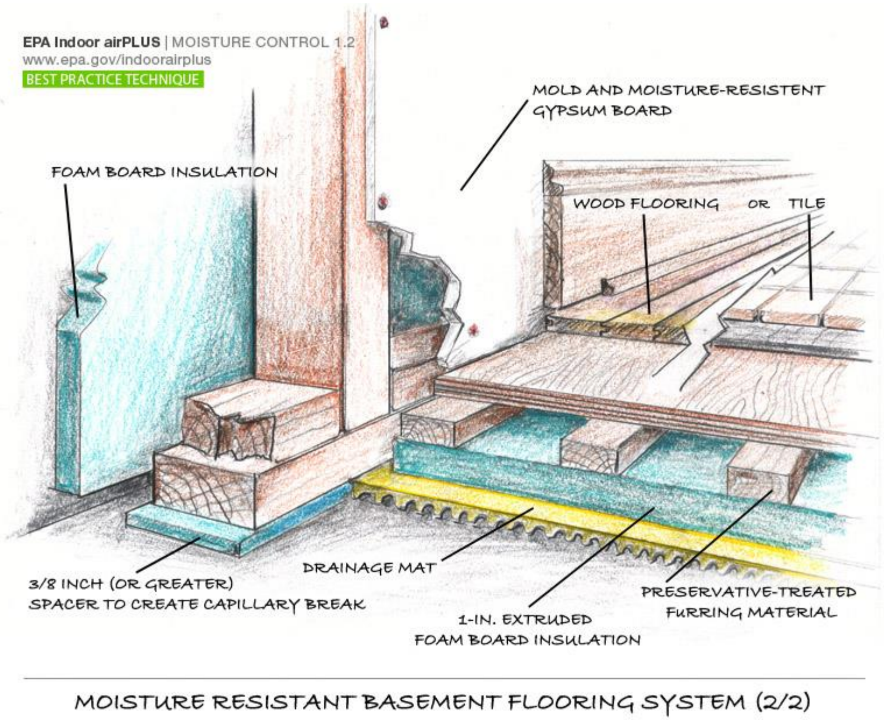
Flood resilient technologies



Αντιπλημμυρική βαλβίδα αντεπιστροφής

Flood resilient technologies





Στεγανοποίηση δαπέδων και τοίχων

Flood resilient technologies

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Π. ΠΡΙΝΟΣ

4. GOOD PRACTICES

- Hot Spot (Critical) Υποδομές
- Μέθοδοι Αδιαβροχοποίησης (Flood Proofing)
- Active and Passive Flood Proofing
- Resilient Technological Solutions
- Emergency Measures

Critical buildings

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Hotspot buildings

Urban systems contain assets of high value, complex and interdependent infrastructure networks.

Hotspot buildings are defined as essential nodes in critical infrastructure on which urban areas depend for their functioning.

Hotspot buildings within these networks include **power stations, water treatment plants, control centres of public transport, waste water treatment plants, fire fighting stations, communication hubs, food distribution centres and hospitals.**

The availability and functioning of hotspot buildings is needed for crisis management, to maintain daily life as normal as possible during floods and is also required for fast and effective recovery after flood disasters.

Table 5.1 Requirements of critical buildings

	Ensure supplies for production	Access to site by workers	Ensure water and sanitation	Energy supply	Food supply	Ensure flood safety	Ensure waste collection	Indoor climate control	Connection to network vital to deliver critical function, inc. communications
Water treatment	✓	✓	✓	✓		✓	✓		
Sewage treatment	✓	✓	✓	✓		✓	✓		✓
Electricity substations		✓		✓		✓			✓
Energy storage	✓	✓		✓		✓			
Hospitals	✓	✓	✓	✓	✓	✓	✓	✓	
Fire stations		✓	✓	✓	✓	✓	✓		✓
Police stations		✓	✓	✓	✓	✓	✓		✓
Communications		✓		✓		✓		✓	
Food distribution	✓	✓	✓	✓	✓	✓	✓	✓	
Financial centres	✓	✓		✓		✓			
Airports	✓	✓		✓		✓			
Bus stations	✓	✓				✓			✓
Train stations		✓		✓		✓			✓
Metro stations		✓		✓		✓		✓	✓

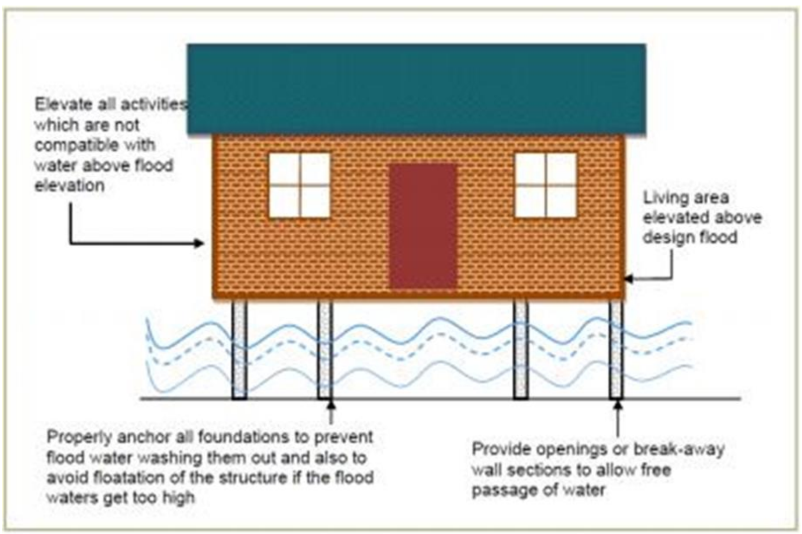
Flood proofing methods

Flood-proofing measures are widely applied where two types of flood-proofing are widely recognized: wet and dry.

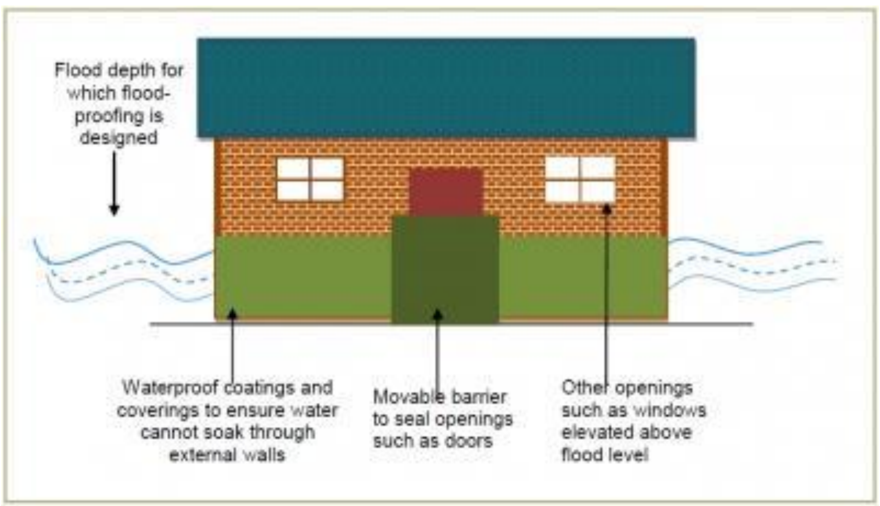
Wet flood-proofing reduces damage from flooding in three ways;
(1) allowing flood waters to easily enter and exit a structure in order to minimise structural damage;
(2) use of flood damage resistant materials; and
(3) elevating important utilities.

Dry flood-proofing is the practice of making a building watertight or substantially impermeable to floodwaters up to the expected flood height (FEMA, 2008).
.

Wet flood-proofing



Dry flood-proofing



swarm

Wet Flood proofing

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Π. ΠΡΙΝΟΣ

Wet flood proofing

Wet flood proofing or wet proof construction is a building method that **allows temporary flooding of the lower parts of the building.**

Structural measures

(1) Properly anchoring structures against flood flows
(2) Flood resistant materials below the expected flood depth,
(3) Protection of mechanical and utility equipment and
(4) Use of openings or breakaway walls to allow passage of flood waters without causing major structural damage (FEMA, 2010)

Table 5.2 Flood resilience characteristics of finish materials
Source: CIRIA, 2006

Material	Resilience characteristics*			Overall resilience performance
	Water penetration	Drying ability	Retention of pre-flood dimensions, integrity	
Timber board				
OSB2, 11mm thick (Oriented Strand Board)	Medium	Poor	Poor	Poor
OSB3, 18mm thick (Oriented Strand Board)	Medium	Poor	Poor	Poor
Gypsum plaster board				
Gypsum Plasterboard, 9mm thick	Poor	Not assessed	Poor	Poor
Mortars				
Below DPC (Damp Proof Course) 1:3 (cement:sand)	Good	Good	Good	Good
Above DPC (Damp Proof Course) 1:6 (cement:sand)	Good	Good	Good	Good

Table 5.3 Flood resilience characteristics of insulation materials
Source: CIRIA, 2006

Material	Resilience characteristics*			Overall resilience performance
	Water penetration	Drying ability	Retention of pre-flood dimensions, integrity	
Cavity insulation				
Mineral fibre	Poor	Poor	Poor	Poor
Blown-in	Poor	Poor	Poor	Poor
Rigid PU foam	Medium	Medium	Good	Medium

*Resilience characteristics are related to the testing carried out and exclude aspects such as ability to withstand freeze/thaw cycles, cleanability and mould growth

Tables 5.2 and 5.3 give indication of the resilience of some finish materials and insulating materials, respectively, based on laboratory tests).

Wet Flood Proofing

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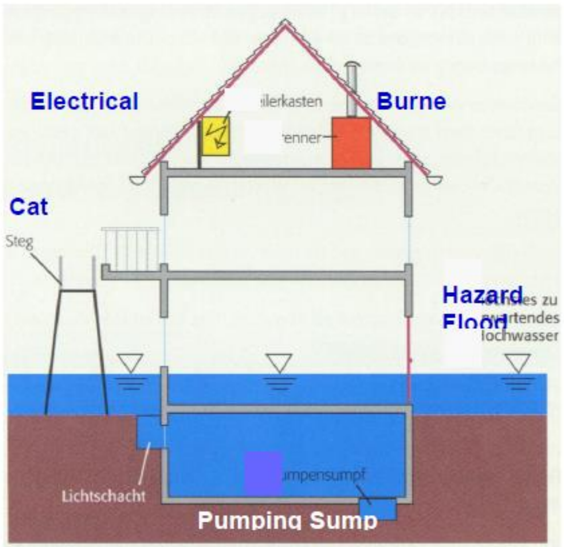
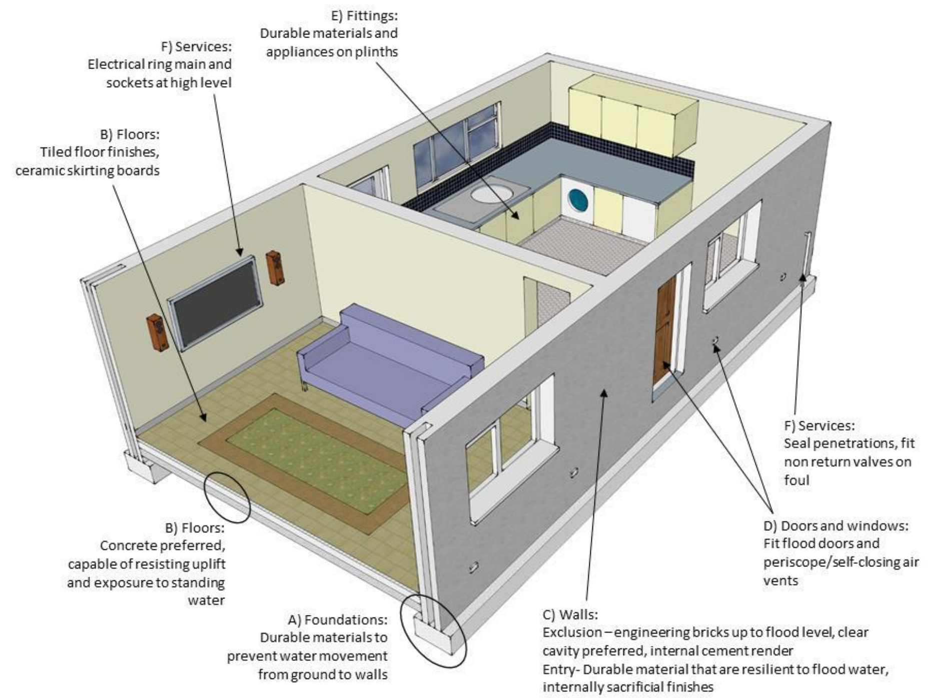


Figure 5.11 Schematic of wet proof method

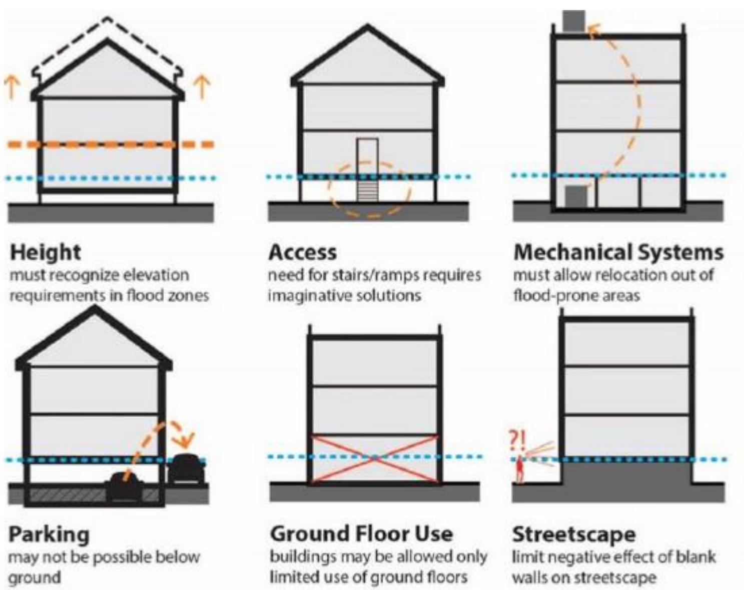
Source: Pasche, 2008



Dry Flood Proofing

Dry flood proofing

With dry flood proofing or dry proof construction, **the water is prevented from entering the building.**
The building is made waterproof by treating the facades with coatings, using resistant materials or buildings with a low permeability
In addition, the building materials should have good drying ability and integrity. Openings in the facades can be closed off with flood shields, panels or doors. These can be temporarily installed or can be permanent features, but in both cases, dry proofing is an integrated part of the building. An alternative approach is to erect temporary barriers located outside and around the building in order to prevent the floodwater reaching it.



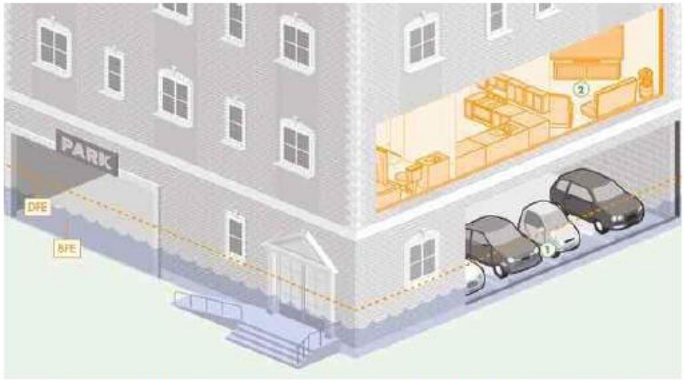


Figure 10. Example of dry-floodproofed building in a city.

Figure 5.12 Example of dry proofing Hamburg, Germany

Active/temporary

Temporary flood barriers are placed only if a flood is expected to damage buildings. After the flood the barrier is removed again. Temporary barriers can protect high value buildings, infrastructure nodes or hotspots. Temporary barriers are made from wood, steel, aluminium or plastics (Figure 5.17).

Figure 5.17 Temporary barriers in Prague, Czech Republ

Source: VRV company, 2007

Passive/permanent flood proofing

Permanent flood barriers that are specifically constructed to protect one or a couple of buildings are another strategy to prevent flooding. Permanent flood barriers can either be a dike around the hotspot or an integrated flood defence in the surrounding area of the hotspot such as walls, gates or other structures (Figure 5.18).

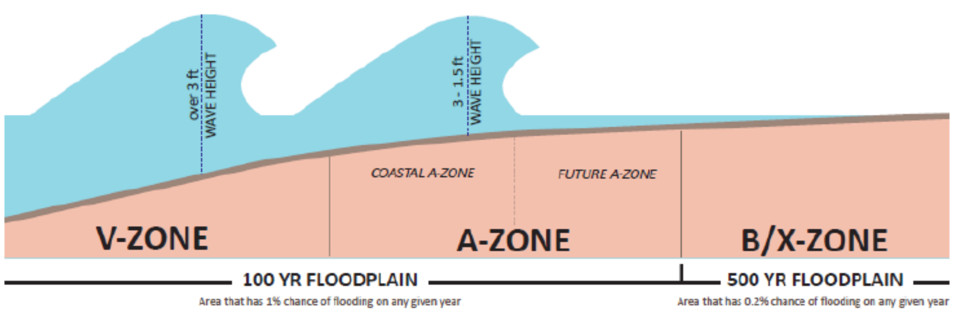
Figure 5.18 Permanent flood gate Meppel, The Netherlar

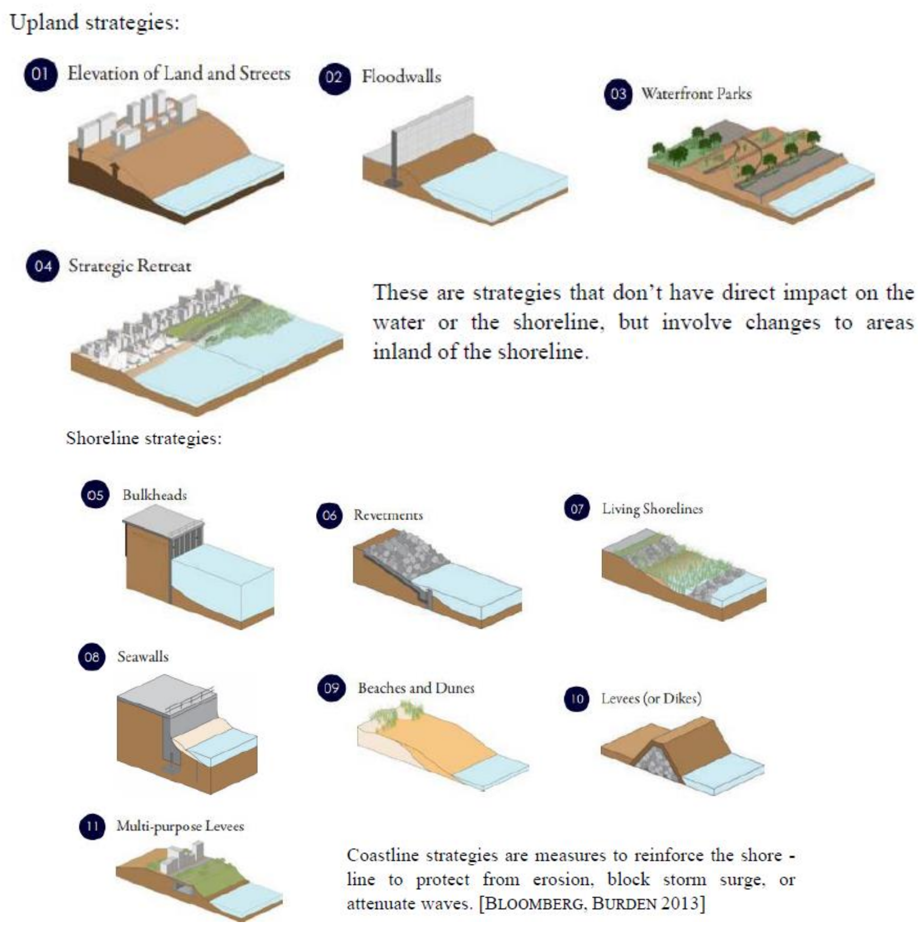
Source: Floodbarrier.nl, 2011

Examples of resilient technological solutions in cities

New York

Adapting a dense, urban environment of New York City to increased flood risk requires a broader set of design strategies. After the Sandy Hurricane that took place in 2012 and was cruel reminder of the importance of flood-resistant construction standards, the city's coastal regions focus of the city's climate resilience planning. Proposed solutions integrate multiple properties in order to address the flood protection and building access.
The city is operating within 3 major flood zones that determine the building requirements and technical solutions for defense against flooding. The specific zone designations describe the extent and severity of the coastal flood hazard.





Examples of resilient technological solutions in cities

In water strategies:

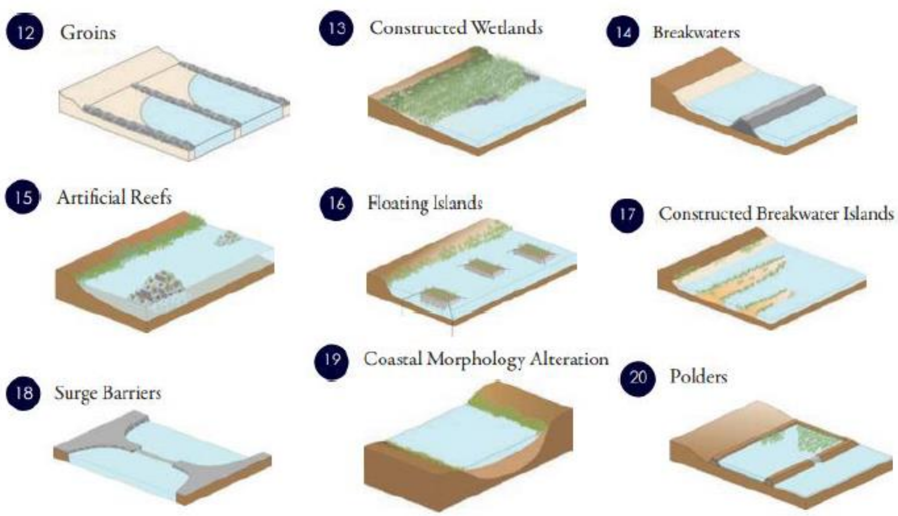


Figure 22. Resilient waterfront development in Williamsburg, Brooklyn located within V-zone.

Figure 23. Brooklyn's P.S. 261 before

Figure 24. Brooklyn's P.S. 261 after

Examples of resilient technological solutions in cities

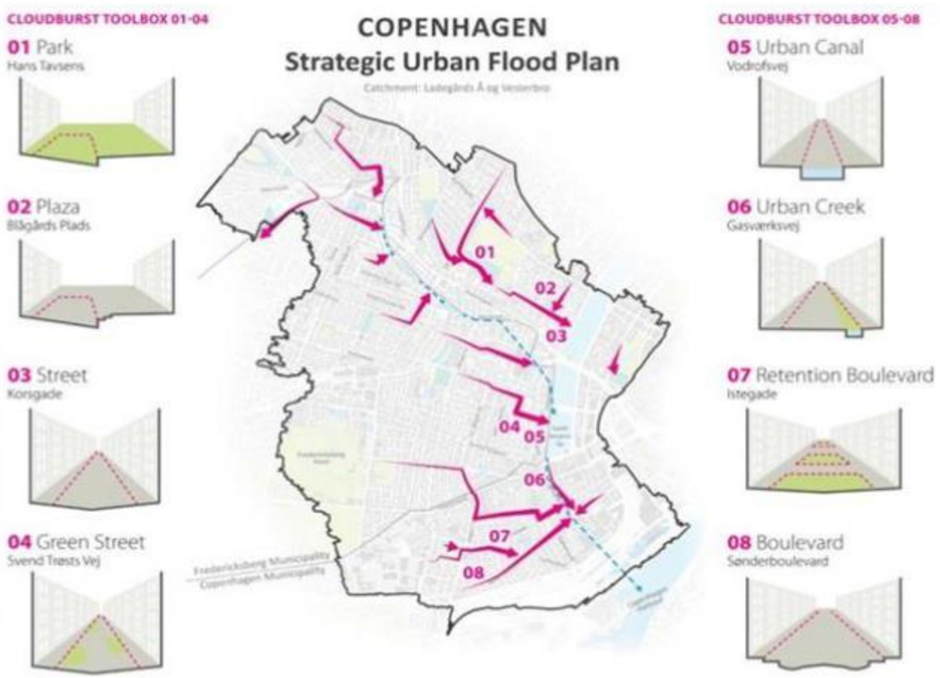


Figure 27. Copenhagen's plan to transform streets into water boulevards.

Figure 28. Tansinge Plads - square and a water retention basin, designed to hold back

Examples of resilient technological solutions in cities

Figure 29. Water Square Benthemplein in Rotterdam. [GOOGLE GRAPHICS]

https://www.youtube.com/watch?v=lviZpuoCTW8

Figure 30. Benthemplein Square filled with water. [GOOGLE GRAPHICS]

Emergency Measures- Smart shelters

Various and diverse mitigation plans have been implemented across the world to reduce the consequences of flooding. In addition to structural measures, emergency measures such as flood shelters are also needed immediately and urgently when flooding occurs, to provide a survival place for flood victims.

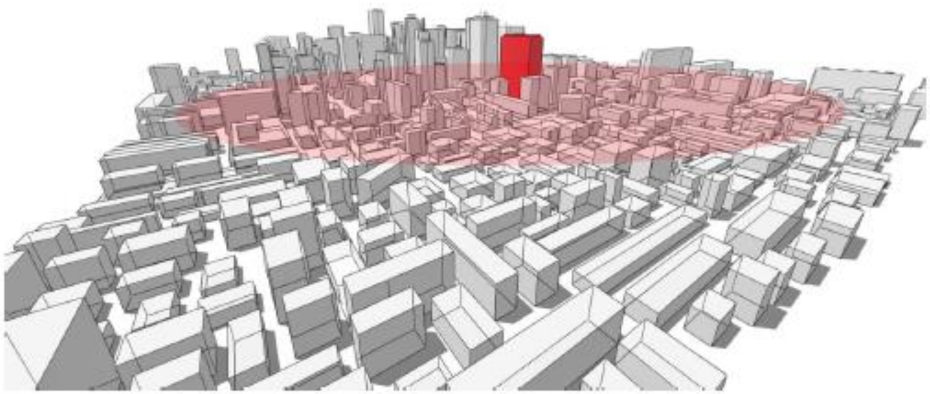


Figure 5.25 One large smart shelter covering a large area

Figure 5.26 Multiple smaller smart shelters covering several smaller areas

Table 5.9 Usable floor space (in m^2) for shelters

Smart Shelter Capacity								
Smart Shelter building type			Cinema		School		Conference Hall	
Gross Floor Area			5000	m^2	5000	m^2	5000	m^2
Spatial Requirements + 10%			500	m^2	500	m^2	500	m^2
Total Gross Floor Area			5500	m^2	5500	m^2	5500	m^2
Useable net. Area (50% / 65% / 80%)			2750	m^2	3575	m^2	4400	m^2
Capacity short-term	1,86	m^2/pers.	1478	pers.	1922	pers.	2365	pers.
Capacity long-term	3,72	m^2/pers.	739	pers.	961	pers.	1182	pers.

Dam Risk Management

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Tuesday, 7/12/2021

DAM CLASSIFICATION

Various classification systems are used to categorize dams based on size, hazard potential, and construction material, among others. Types of classifications include:

- **By size**

Major dams are defined as those 50 ft (15 m) or more in height with a normal storage capacity greater than 5,000 acre-ft (~6 million m3), or a maximum storage capacity of 25,000 acre-ft (~31 million m3) or more.

The International Committee on Large Dams (ICOLD) defines a large dam as one with a height of at least 15 m (from lowest foundation to crest) or a dam between 5 and 15 m impounding at least 3 million m3 of water (interpreted as maximum storage).

Despite these differing definitions, analysis of the 2016 data from the National Inventory of Dams7 (NID), maintained by the USACE, reveals that nearly the same number of US dams fall into each of these two categories—around 8,300 large dams (per USGS definition) and around 8,700 major dams (per ICOLD definition).

•

DAM CLASSIFICATION

- **By hazard potential**

US federal agencies classify dams by hazard using a three-level approach (FEMA 2004b). Failure or misoperation of low-hazard dams is expected to result in no human life loss and low economic and/or environmental losses. Similar failure or misoperation of significant hazard dams is expected to result in no human life loss but may cause economic and/or environmental losses, disruption of lifeline facilities, or other impacts. High-hazard dam failure or misoperation is likely to cause at least one human life loss. In this classification system, a dam that may result in loss of one human life is classified in the same way as a dam that may result in loss of thousands of lives.

- **By construction material**

From a construction standpoint, dams generally fall into a few categories, including earthfill, rockfill, concrete gravity, concrete arch, concrete buttress, and timber dams. Most dams in the US are earthfill; however, many of the larger dams, including those posing flood hazards to NPPs, are of rockfill or concrete construction.

Other classifications

Dams are also classified into different categories based on use and hydraulic design, as described in USBR (1987). They can serve as storage, diversion, or detention structures, which may serve one or multiple purposes . A dam may also include multiple structures with varying hydraulic designs meant to operate as either overflow or non-overflow structures.

DAM PURPOSES

- FEMA and USACE identify recreation, flood control, water supply (including fire protection), and irrigation as leading benefits of dams (Figure 2). Although most dams were originally constructed for a single purpose (Figure 3), some provide multiple beneficial services (especially large dams, as shown in Figure 4). For example, Bonnet et al. (2015) indicates that roughly 94% of all federal hydropower reservoirs serve more than one purpose. The following provides descriptions of the various common benefits of dams.

Use	Description
Multipurpose	Provide multiple benefits. Many dams in the US are multipurpose
Recreation	Offer numerous recreation opportunities, including boating, fishing, skiing, camping, picnicking, and so on
Flood control	Impound water bodies and may be designed to store significant flood volumes or operated to reduce flood impacts
Water supply (including fire and farm ponds in Figure 2)	Supply water for various industrial, municipal, and agricultural purposes
Irrigation	Divert water to provide approximately 10% of the water supplied to croplands in the US.
Tailings and debris control[8]	Retain mine tailings (e.g., coal slurry, minerals, uranium mills) and control debris.
Hydropower	Include power production facilities to generate electricity as water flows from upstream to downstream.
Navigation	Provide infrastructure for inland river navigation.

DAMS-PURPOSES

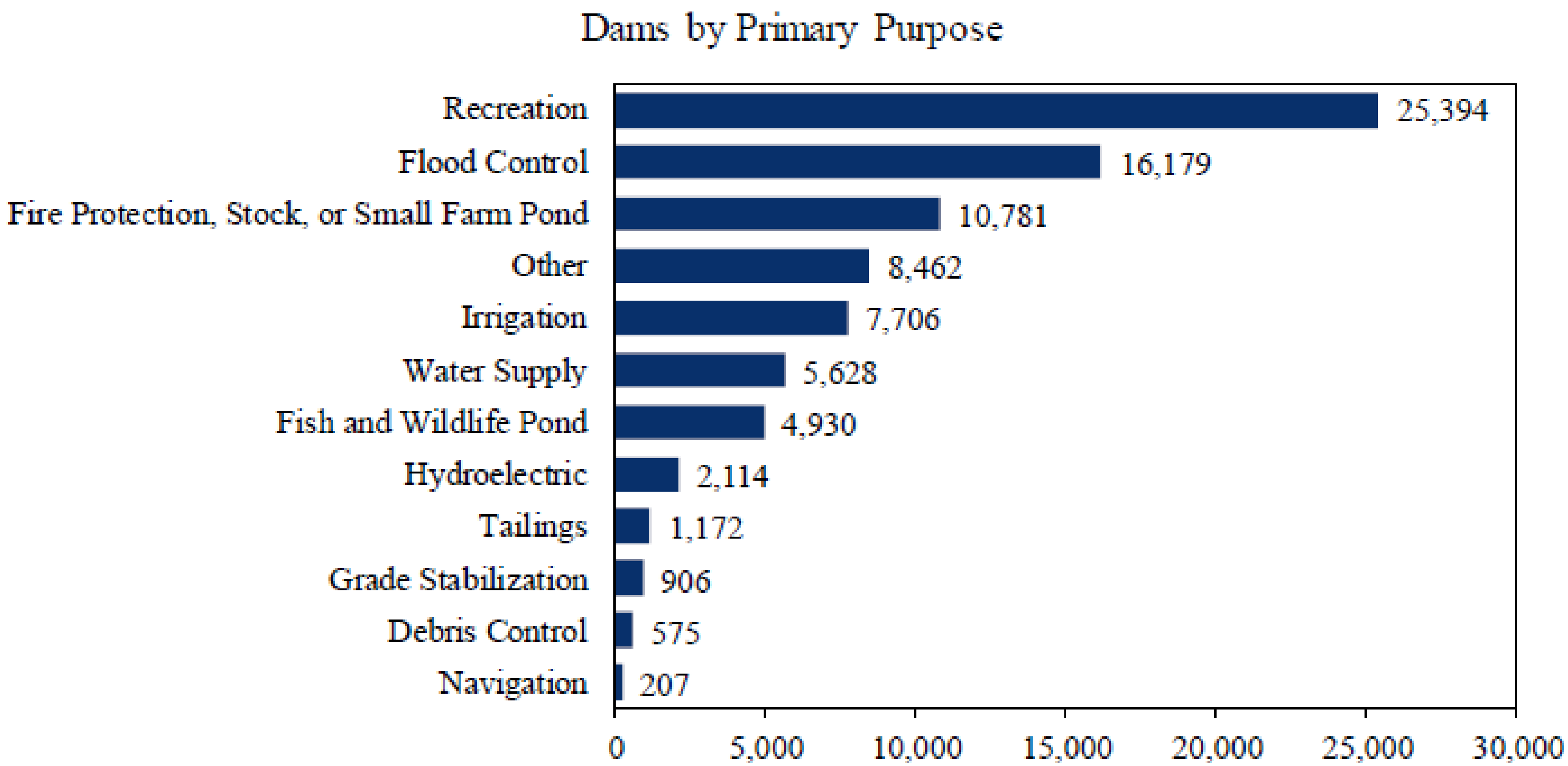

Figure 2. Number of US dams by primary purpose based on 2016 NID data.[7]

DAMS-PURPOSES

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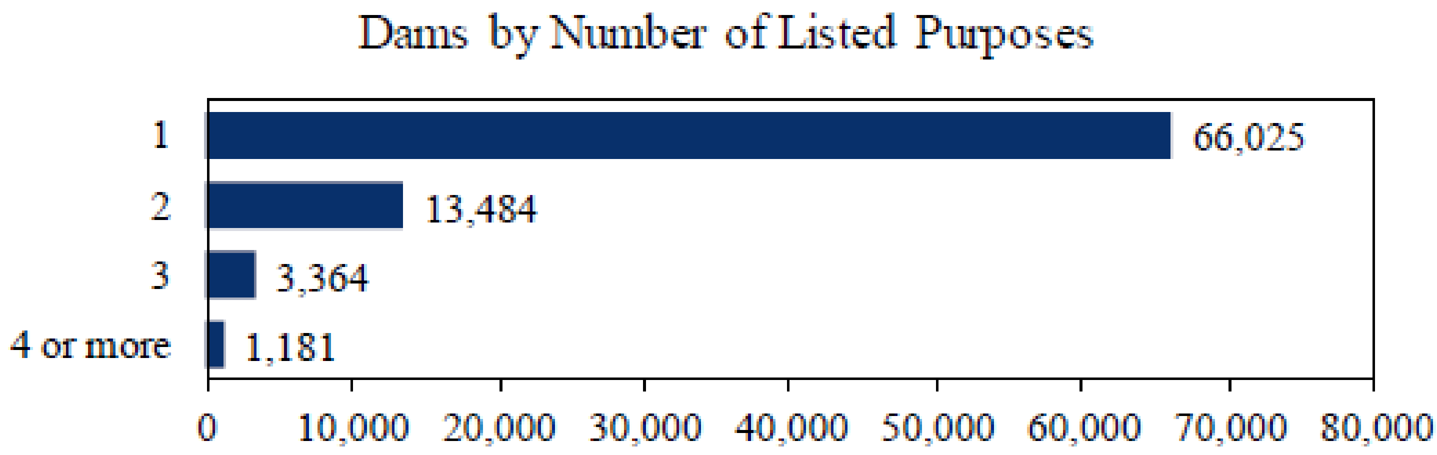


Figure 3. US dams by number of listed purposes based on 2016 NID data.[7]

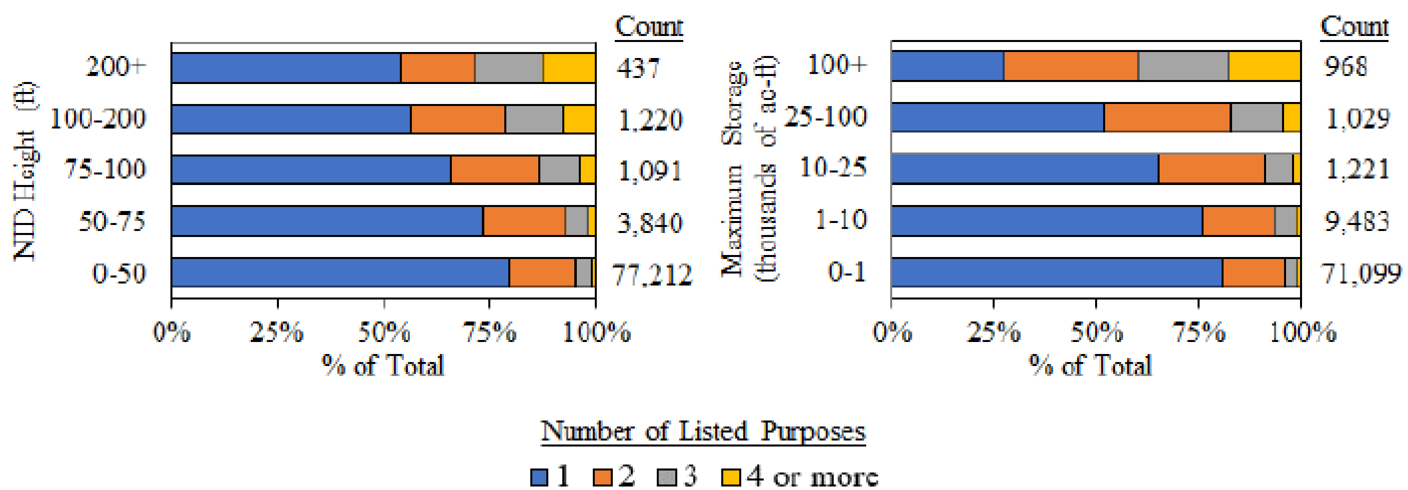


Figure 4. Number of listed purposes by NID height (left) and maximum storage (right) based on 2016 NID data.[7]

DAM FAILURE CAUSES

What constitutes a dam failure can prove somewhat subjective.

FEMA (2015) defines *dam failure* as

the sudden rapid and uncontrolled release of impounded water or liquid-borne solids. It is recognized that there are lesser degrees of failure and that any malfunction or abnormality outside the design assumptions and parameters that adversely affect a dam's primary function of impounding water could be considered a failure.

While a sudden uncontrolled dam release can pose a significant flood hazard to downstream populations and facilities, the NRC's Interim Staff Guidance JLD-ISG-13-01, *Interim Staff Guidance for Assessment of Flooding due to Dam Failure* (NRC 2013) notes

there may be instances where a controlled release of water from a dam can also lead to the inundation of an NPP site. Examples include, but are not limited to: (a) releases performed in order to prevent dam failure during flood conditions; (b) releases performed to rapidly drawdown a reservoir to prevent incipient failure after a seismic event; and (c) releases performed to rapidly drawdown a reservoir to prevent incipient sunny day failure.

DAM FAILURE CAUSES

Dams may fail for various reasons, including high reservoir inflows (hydrological), earthquake faulting or ground shaking (seismological), internal erosion, mechanical failures of gates and electrical systems, maloperation, and combinations of these causes. Severe natural hazards such as strong earthquakes and large floods have a relatively low annual probability of occurrence; and many incidents, and sometimes failures, are attributable to operating issues. Failures due to internal erosion and mechanical or electrical failures (e.g., supervisory control and data acquisition, or SCADA) can occur absent a natural hazard initiator and are sometimes termed “sunny day” failures (Ferrante et al. 2011, 2012). Section 4.2 contains more detail on dam failure mechanisms.

DAM FAILURE CAUSES

The following are some of the most common causes of dam failure (Table 2 and Figure 7):

Overtopping and inadequate spillway design

- Overtopping caused by floods that exceed the capacity of the dam (including the spillway, powerhouse, and other outlet works)
- Overtopping caused by operational issues (e.g., gates, human factors, SCADA systems)

Piping or seepage

- Internal erosion of soil in embankment dams

Slides

- Movement or failure of the foundation or abutments

Miscellaneous

- Structural failure of materials used in dam construction
- Settlement and cracking of concrete or embankment dams
- Inadequate maintenance and upkeep

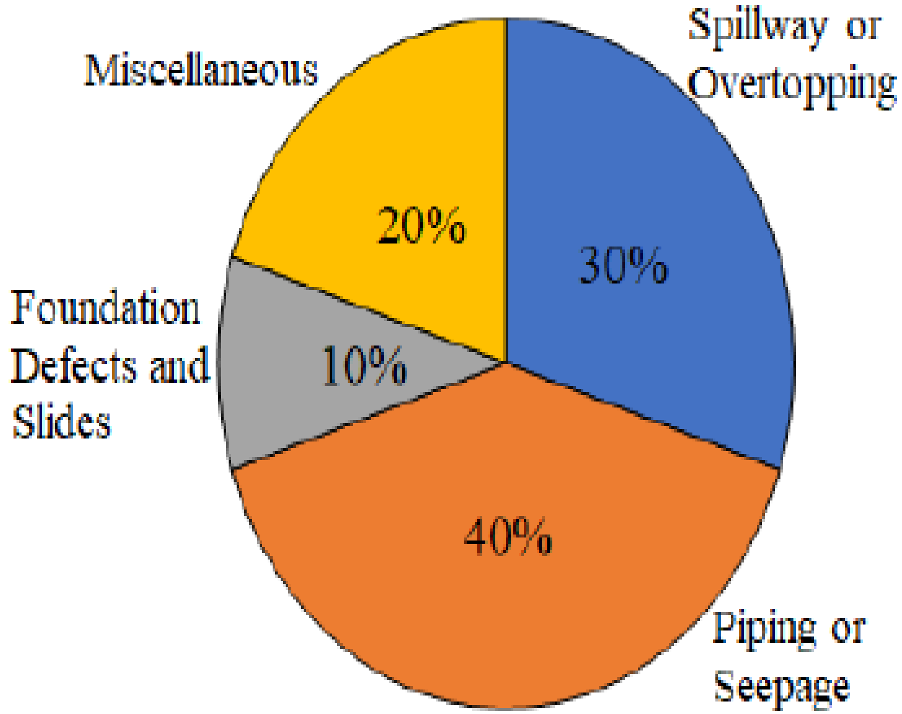


Figure 7. Approximate fraction of international dam failures by proximate cause. (Modified from Baecher et al. 1980)

DAM FAILURE CAUSES - FATALITIES

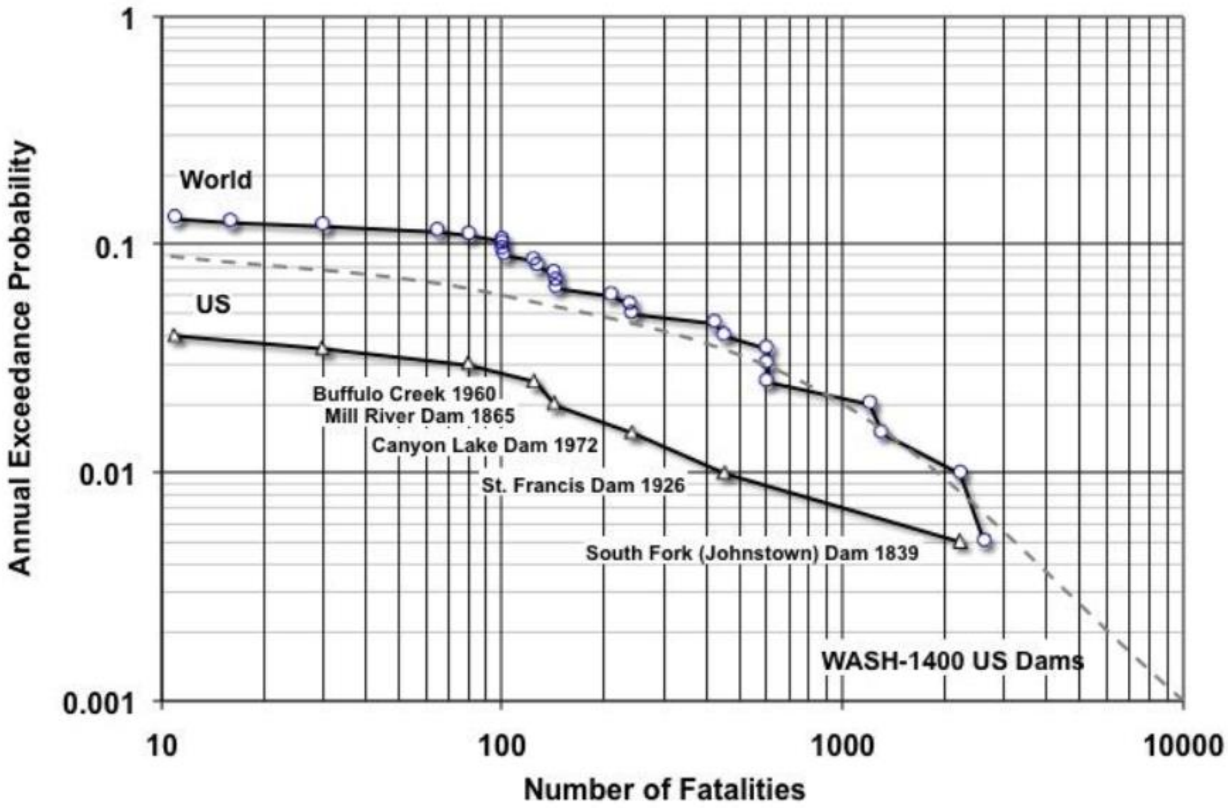


Figure 9. FN chart for fatalities due to historical dam failures in the US and internationally. (Source: Baecher and Christian 2003). Dashed line is the "US Dams" FN curve from *The Reactor Safety Study* [NRC 1975]).

HAZARD POTENTIAL CLASSIFICATION

US federal agencies have adopted a hazard potential classification system for dams, which was published in the FEMA guidelines for dam safety (FEMA 2004b). This system assigns a high hazard potential to any dam for which failure is expected to lead to one or more fatalities (Table 4). It forces many dams into the high-hazard potential classification even if the probability of failure is low, and even if only one individual is exposed downstream. A dam that was originally constructed in an isolated drainage area may become a high hazard potential if one home is constructed in its floodplain. Figure 12 shows that most dams in the US are classified as having low hazard potential, although more than 15,000 fall into the high–hazard potential category..

Table 4. Hazard potential classification system for dams. (Source: FEMA 2004a)

Hazard potential	Loss of human life	Economic, environmental, lifeline losses
Low	None expected	Low and generally limited to owner
Significant	None expected	Yes
High	One or more expected	Yes (but not necessary)

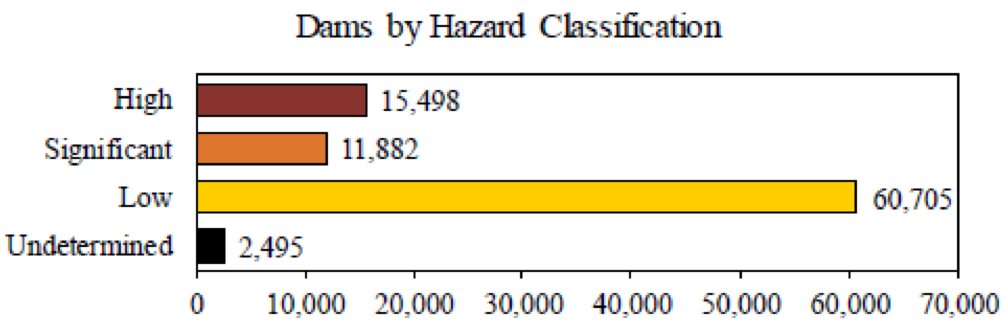


Figure 12. Distribution of US dams by hazard potential based on 2016 NID data.[7]

DAM STRUCTURE

Typical dam structures fall into several categories, depending on the engineering material used in construction. Common structures include concrete gravity dams, concrete arch dams, and embankment dams (e.g., earthfill or rockfill). An understanding of the engineering makeup of these structures is important for informing dam safety risk assessment. Additional information on the various types of dams can be found on the USSD website.27 Figure 18 shows the breakdown of US dams by primary construction type. The overwhelming majority of US dams are of embankment construction (i.e., earthfill or rockfill).

In addition to the dam structure itself, specific co-located structures play an important role in dam safety. Among the sub-system structures that most commonly influence dam safety are the powerhouse, spillways, sluiceways, and other outlet works. The components that interact with and comprise these structures require careful design, operation, maintenance, and monitoring. An overview of powerhouse and spillway engineering is provided in Sections 4.1.4 and 4.1.5.

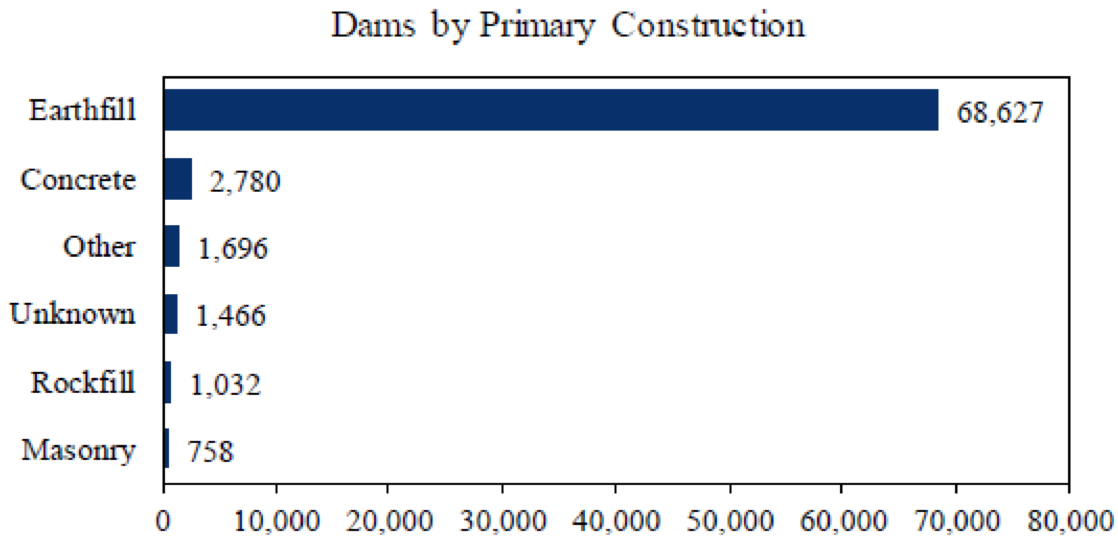


Figure 18. US dam primary construction based on 2016 NID data[7].

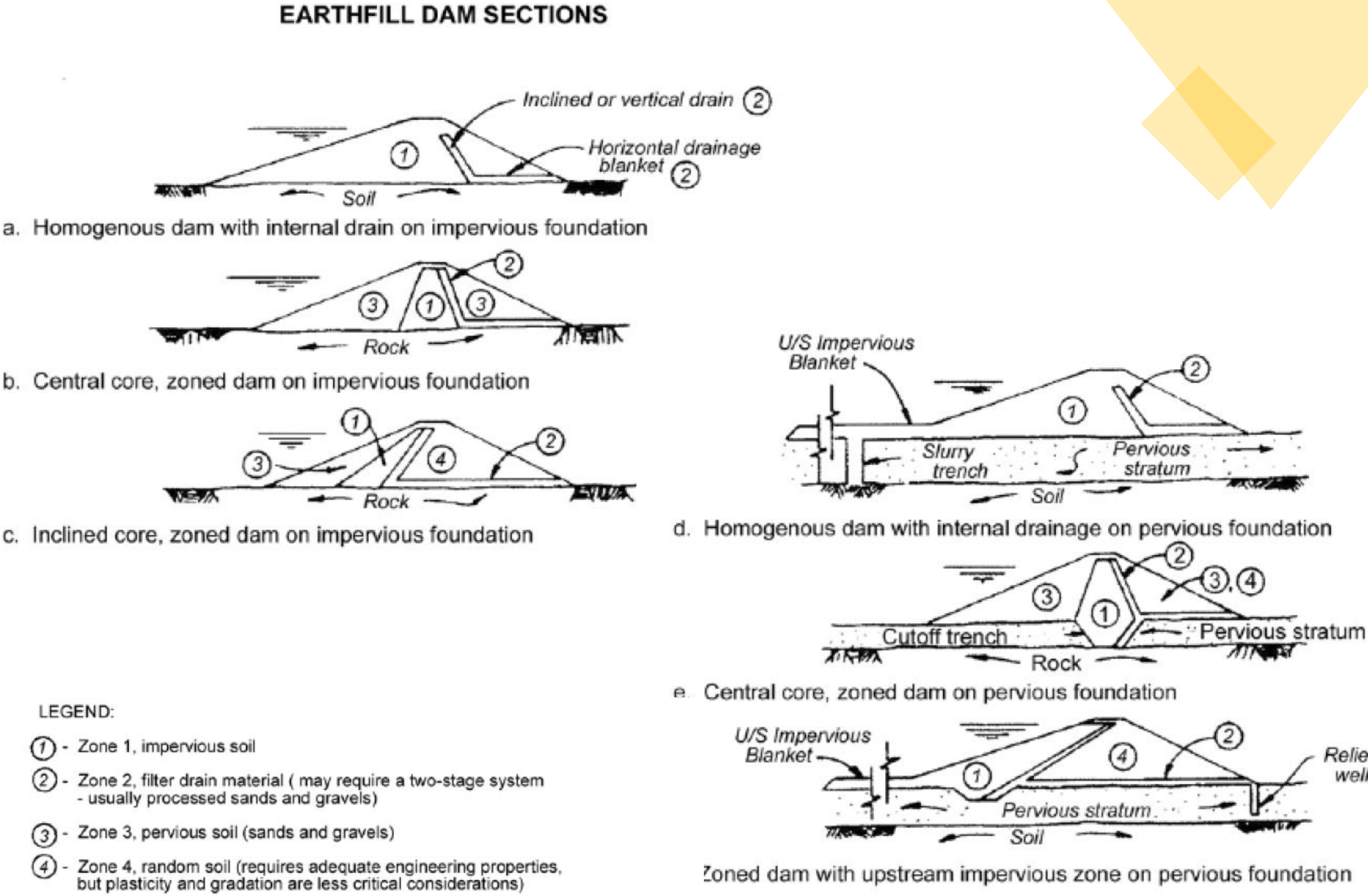


Figure 21. Common types of earthfill dams. (*Source:* USBR 2012)

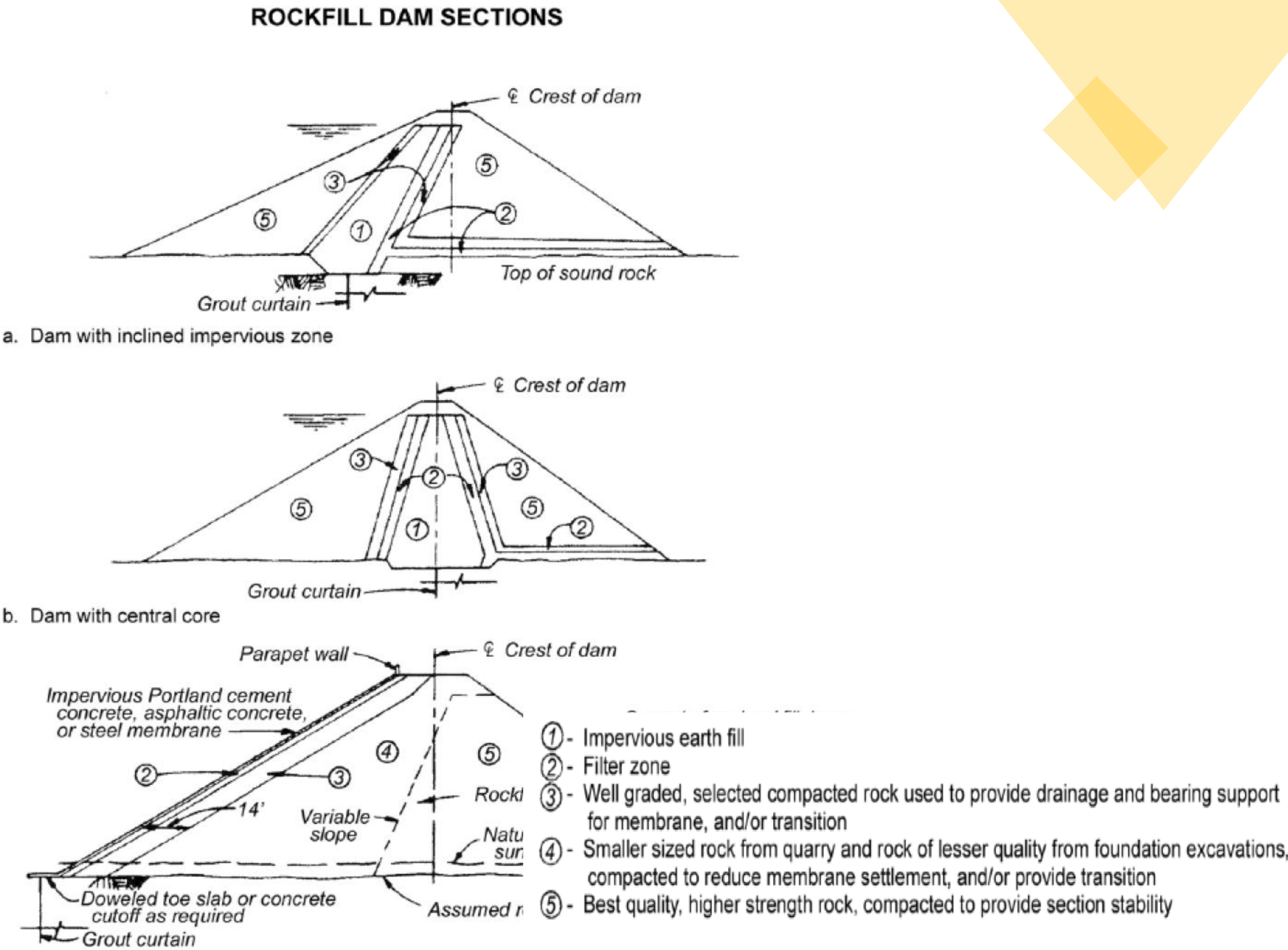


Figure 22. Common types of rockfill dams. (*Source:* USBR 2012)

Powerhouse

For hydropower dams, powerhouses (used to house the hydroelectric machinery and accessory equipment) are typically located at the toe of the dam or at the downstream end of a diversion structure. To prevent large debris or other foreign objects from entering the water conveyance system and potentially damaging flow control or mechanical equipment, a trash rack and control gate are typically placed at the intake. Figure 23 shows a typical layout for a hydropower project co-located with a dam. Many variations of this layout can be found across the US, with arrangements deviating according to site-specific conditions, dam makeup, and project objectives. (USBR 1987)

The operation and integrity of the powerhouse equipment and water conveyance system are essential for dam safety and reservoir management. During flood periods, powerhouses are often used to capacity, with additional water often spilled via a spillway or other bypass. In the case of a power outage, hydropower units equipped with induction generators must be shut down to prevent “freewheel” (i.e., excessive and potentially damaging high rotational speed), thus eliminating flow availability through the turbines. Units equipped with synchronous generators may be designed to continue operating even when grid connection is unavailable.

If flooding occurs during equipment maintenance periods or if operability is limited (e.g., from unplanned outages or equipment malfunction), adverse flow conditions and flow control may result. In addition, rapid drawdown of the headwater through hydropower operations or through flood prevention procedures can alter structural loading conditions on the dam. Thus, clearly defined hydropower and extreme event operational procedures are needed to ensure safe and reliable energy production without jeopardizing dam safety.

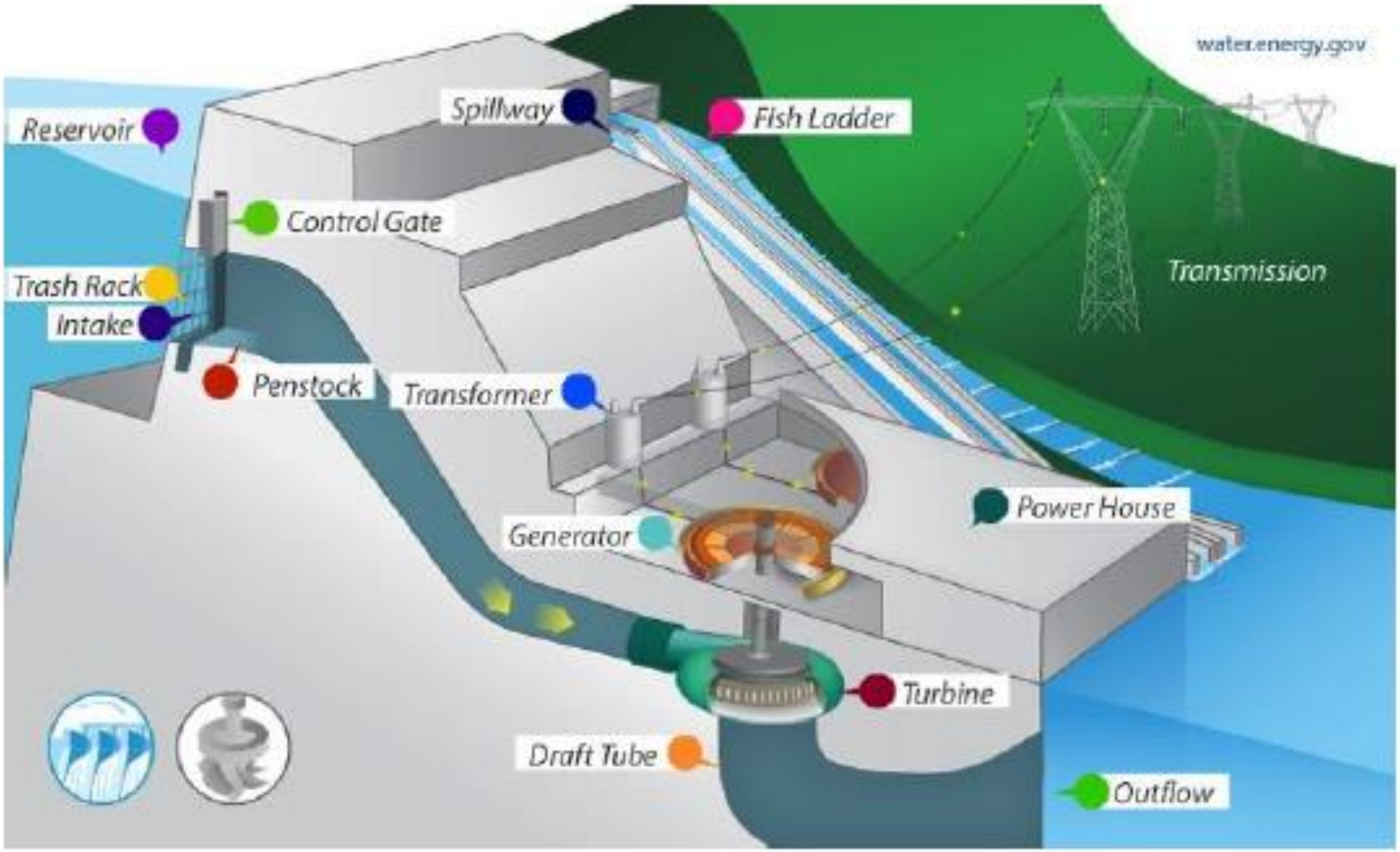


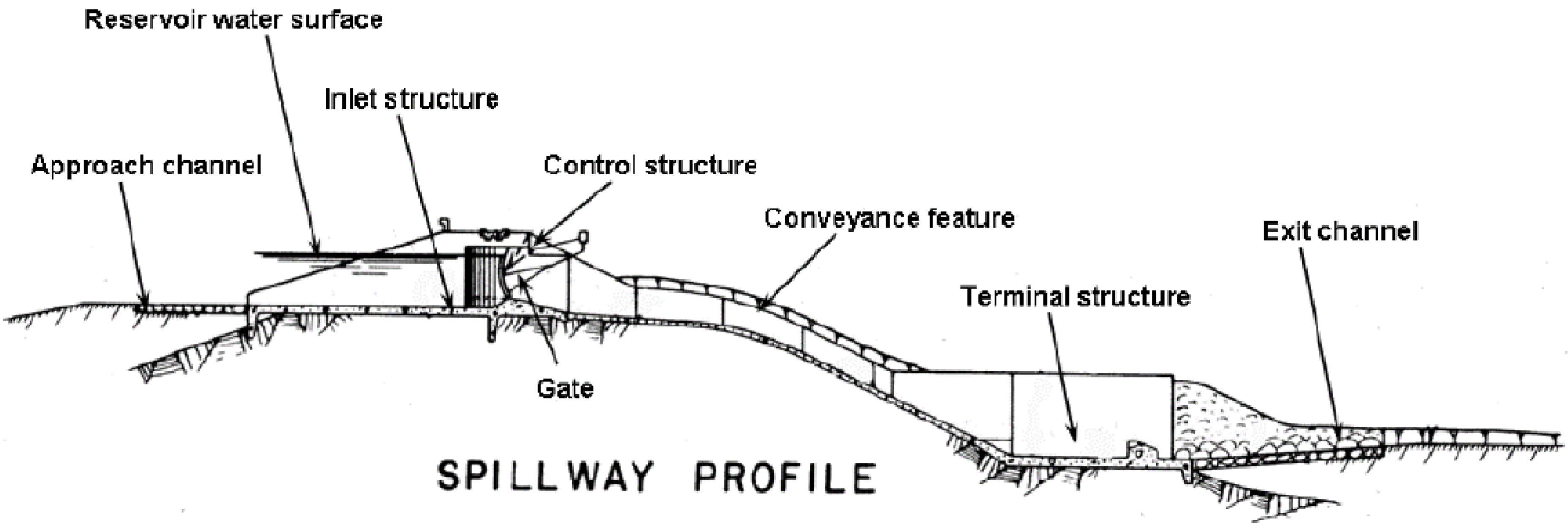
Figure 23. Major components of a hydropower plant. (*Source:* US DOE)

Spillways

For many dam applications, a spillway is used to safely transport non-generating flows over, around, or through a dam. Operationally, spillways and other flow control devices are used to alter flow conditions to meet desired current and future hydraulic characteristics. A desire to meet these operational conditions may be motivated by various purposes, including flood control, hydropower, navigation, recreation, and water supply. To safely pass excess flows, many dams are equipped with gated or non-gated spillways that can safely pass a sizable volume of water; and they are often constructed of concrete or another non-erosive material (Shams-Ghahfarokhi 2014). Such spillways and gates are also subject to failure or misoperation and may incur flow rates exceeding design conditions, as some devices were originally designed based on rare but not extreme flood conditions.

Spillways may be uncontrolled or controlled depending on whether gates or temporary structures are used. Controlled spillways are equipped with various control structures, which may include gates, bulkheads, or stoplogs and their associated operating equipment. Water conveyance via the spillway may be accomplished using a chute, conduit, or tunnel or a combination of multiple features, with the

Spillways



Reservoir water surface
Inlet structure
Approach channel
Control structure
Conveyance feature
Exit channel
Terminal structure
Gate
SPILLWAY PROFILE

DAM FAILURE MECHANISMS

- Dams are designed to withstand a wide variety of environmental loading conditions. When these design loads are exceeded or when unforeseen events or combinations of events occur, the dam structure may fail. Typical dam design includes engineering to prevent failure from multiple mechanisms, including overtopping, internal erosion, sliding, overturning, overstressing, spillway and energy dissipation issues, and other mechanisms. These processes are described in more detail in the following subsections. Several historical dam failure events are noted, with some selected events described in more detail in Appendix A.
- An important consideration for dam safety risk assessment is that some historical dam failures cannot be attributed to a single failure mechanism and may instead result from a chain of events that lead to failure. As noted in the 2018 Independent Forensic Team (IFT) report on the Oroville Dam spillway incident (IFT 2018), there was no single root cause of the Oroville Dam spillway incident, nor was there a simple chain of events that led to the failure of the service spillway chute slab, the subsequent overtopping of the emergency spillway crest structure, and the necessity of the evacuation order. Rather, the incident was caused by a complex interaction of relatively common physical, human, organizational, and industry factors, starting with the design of the project and continuing until the incident.
- This complex series of near-failure forcing mechanisms, as described in detail in Appendix B, does not fit cleanly within a traditional dam safety risk assessment framework and would require thorough systems analysis to predict.

Overtopping

Overtopping occurs when water levels upstream of a dam rise above the dam crest. Such increases in water levels result when inflows exceed the design or effective capacity of the operating water conveyance system. Commonly considered causes of overtopping include rain-induced flooding, landslide-induced tsunamis or seiches, upstream dam collapses, or wind-induced wave run-up; reduced outflow capacity can also contribute to rising headwater levels.

Internal Erosion

Internal erosion represents one of the leading causes of embankment dam failures and can also affect concrete dams (ICOLD 2017). Seepage occurs when water passes through a body of soil and causes internal erosion of soil particles. Piping occurs when soil erosion begins at a seepage exit point and erodes upstream until a pipe or roof is formed through the dam structure. Internal migration (or stoping) occurs when the soil properties in a voided structure can no longer structurally support a pipe or roof and erosion continues because of internal instability. Other internal erosion processes include scour (including concentrated leak erosion and contact erosion) and internal instability (including suffusion). The internal erosion failure process is typically categorized into four phases: (1) initiation

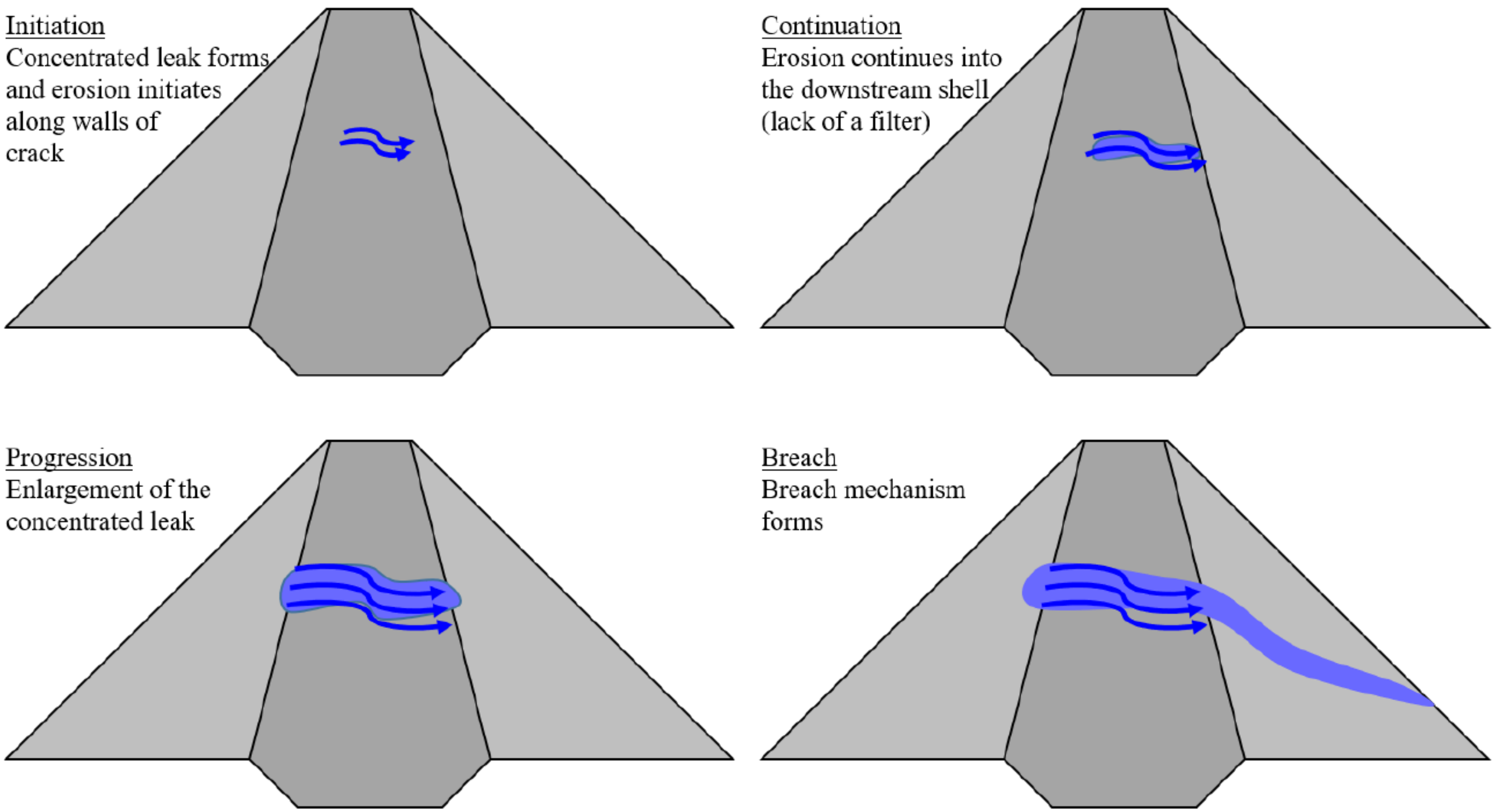


Figure 25. Internal erosion process initiated by a concentrated leak. (*Source*: Adapted from USBR and USACE 2017, Chapter IV-4)

Sliding

As shown in Figure 19, a combination of static and dynamic loads act upon a dam. A well-designed dam will maintain equilibrium under the variety of anticipated design conditions, remaining fixed to the riverbed via adequate foundation and abutment stability and resistive forces. Horizontal "driving" forces resulting from upstream and downstream hydrostatic pressure and from debris, sediment, and ice loadings will (under stable conditions) be balanced by the resistive shear strength of the foundation material and by the frictional forces between the dam and the ground to prevent the dam from moving. Under extreme conditions (including displacement during seismic events), the driving forces may exceed the resisting forces and induce a sliding failure. Uplift pressures along the dam foundation or abutment can reduce resisting forces and contribute to sliding. Often, foundation issues can destabilize the dam and lead to sliding failure. The ratio of the designed resisting forces to the driving forces is considered the sliding factor of safety (Shams-Ghahfarokhi 2014). Sliding failures are equally applicable to both embankment and concrete gravity dams and will occur when the factor of safety decreases to below 1.0 (USBR and USACE 2017, Chapter I-7).

Overturning

Whereas sliding failure occurs from displacement of a dam parallel to the foundation, an overturning failure may occur when overturning moments induced by various driving forces overcome the stabilizing forces (primarily the self-weight of the bulk structure) and cause a rotation of the bulk structure. The overturning moments are often calculated at the dam toe or some other critical joint along the dam body (Shams-Ghahfarokhi 2014). Overturning may be caused by various physical conditions, including insufficient bulk weight or weight distribution, uplift forces from tensile cracking along the dam base, erosion of the dam toe foundation, uplift pressure from inadequate seepage control or pressure relief, and excessive hydrostatic pressures beyond design conditions. As with sliding stability analysis, overturning stability analysis incorporates factor-of-safety calculations to ensure structural stability.

The current state of practice with respect to probabilistic analysis of overturning failures is similar to that of sliding; it is mature.

Several historical dam failures or incidents have resulted from overturning. The following are among the most well-known.

Overstressing

Overstressing presents a risk for concrete dams and occurs when stresses within the structure, foundation, or other components exceed the material capacity. For instance, under flood conditions, increasing reservoir levels can increase the effective stress in a dam, causing tensile forces to exceed the concrete properties and leading to cracking or instability failure (NRC 2013). Such tensile forces are usually of most concern along joints, foundation blocks, and foundation planes. Finite element analysis is often used to compute internal stresses based on dam construction material, and it is typically assumed that if rigid body analysis reveals tensile stresses at the dam toe, a crack will form and allow full uplift pressure to form via water percolation (Shams-Ghahfarokhi 2014).

The current state of practice with respect to probabilistic analysis of overstressing failures is similar to that of sliding; it is mature.

Spillway Failure

- As described in Section 4.1.5, spillway discharge capacity is based on the IDF. IDFs are determined based on inflow hydrographs and operational procedures at the dam. Inadequate spillway design or flooding above the IDF can cause spillway failure and lead to further erosion and structural failure (USBR and USACE 2017, Chapter IV-2).
- Spillway failures may result from various causes, including gates failing to open, improper gate installation, structural gate failure, spillway debris blockage, hoist failure, improper control operation, seal leakage, or ice formation (Hartford et al. 2016). Spillway channels can also be susceptible to abrasion, and high flows can dislodge material. Degradation of a spillway structure can cause unsafe operation at below-design capacity (e.g., 2017 Oroville spillway incident). Erosion can also occur at the spillway discharge point as the high flow velocity of water exiting a spillway to the lower water body creates a trajectory jet. The jet imparts significant kinetic energy into the tailrace; and energy dissipation design measures to prevent downstream scour are often taken, including the construction of a plunge pool and riprap or lined channels (Shams-Ghahfarokhi 2014).
- The current state of practice with respect to probabilistic analysis of spillway hydraulics and spillway gate structures is mature. Spillway hydraulics has been studied for more than a century and is reasonably well understood

DAM SAFETY RISK ASSESSMENT

Risk combines the probability and severity of an adverse event. Kaplan and Garrick (1981) identify a "risk triplet," consisting of three questions used to define risk:

(1) What can happen?

(2) How likely is it that it will happen?

(3) If it does happen, what are the consequences? To answer these questions, both qualitative and quantitative risk assessment approaches may be used, although approaches can vary widely.

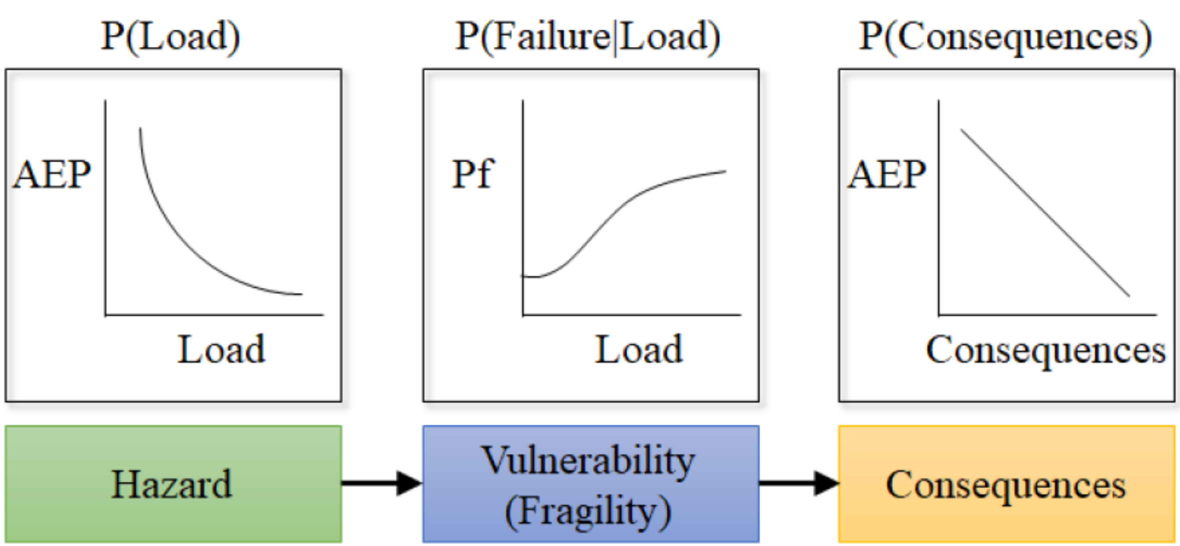
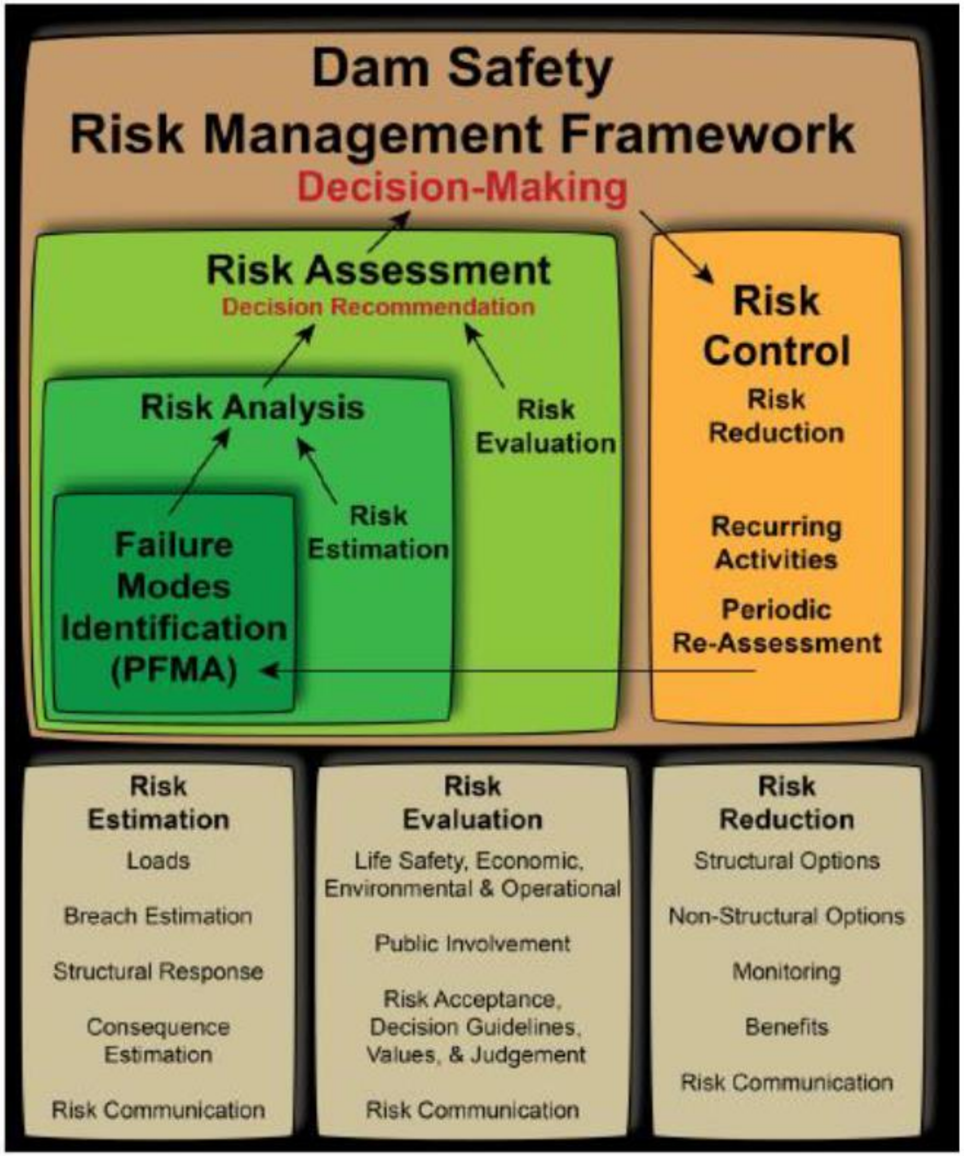


Figure 26. Risk analysis modeling approach. Pf: probability of failure; AEP: annual exceedance probability. (*Source*: Adapted from Baecher 2015)

DAM RISK MANAGEMENT FRAMEWORK



DAM RISK MANAGEMENT FRAMEWORK

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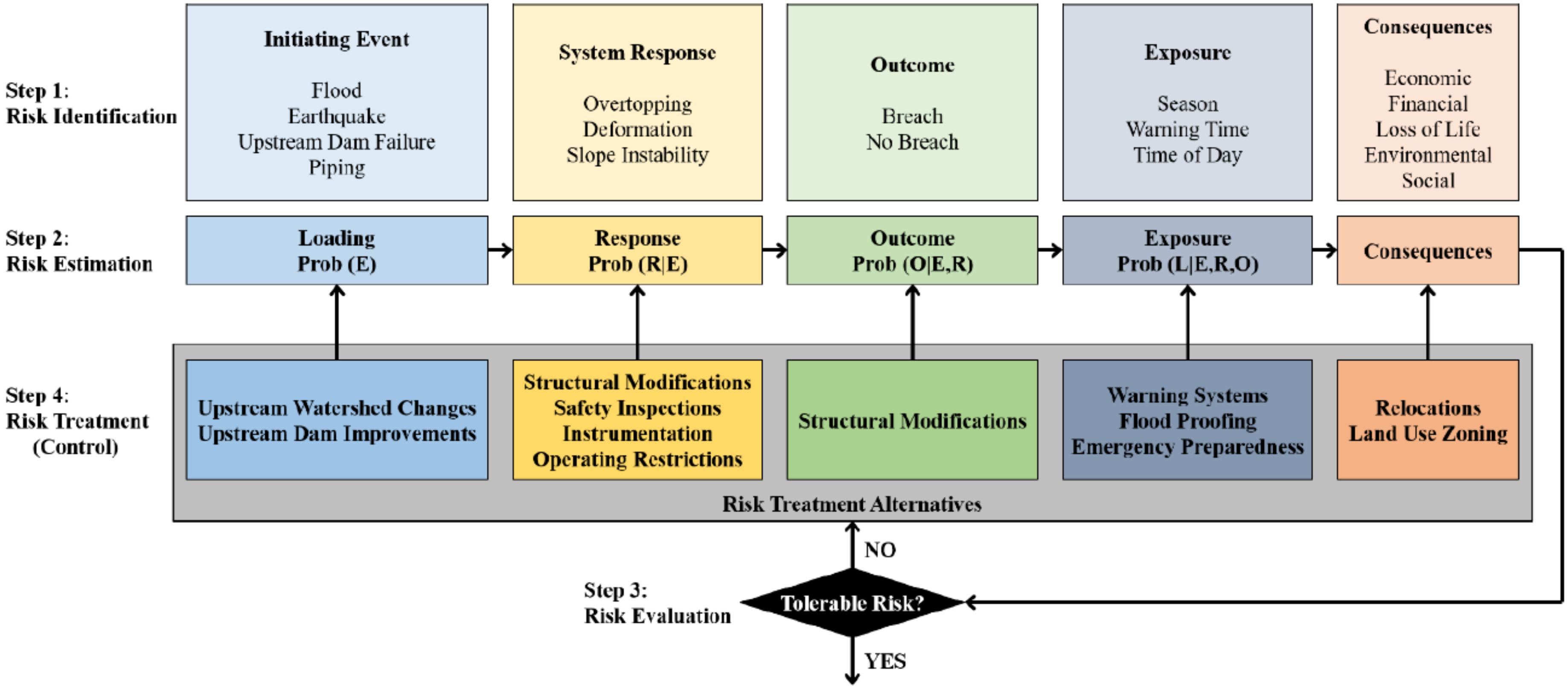
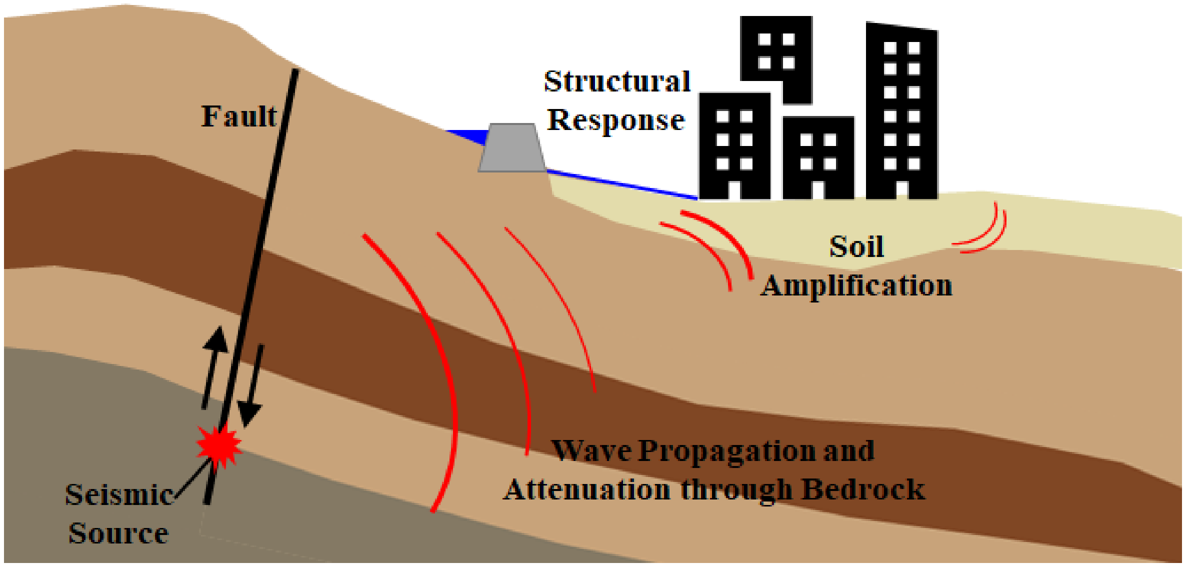


LOADS AND HAZARDS AFFECTING DAM SAFETY

- While scientific dam design has often applied a deterministic standards-based approach in which the dam is designed to withstand certain defined loads, many older dams had no such standards to follow. Still, given the significant number of dams throughout the US, the rate of dam failure is low, as noted in Table 3 in Section 2.5. The sections that follow describe some of the common loads and hazards affecting dam safety. Note that these loads and hazards are not necessarily mutually exclusive (e.g., a sizable flood and a sizable earthquake could co-occur in time). Hence, the frequency of occurrence for various loading events, individually or in combination, is important in a risk assessment framework.
- Hartford et al. (2016) provides detailed information on hazards and disturbances related to dam systems. Among the topics covered are models of time, space, severity, and duration. Readers are referred to that literature for additional insight.

Seismic Hazards

- Seismic hazards (both natural and induced by human activity) are one of the primary hazards for which dams are designed. Failures resulting from seismic activity can be abrupt (e.g., the 2011 failure of Fujinuma Dam [Pradel et al. 2012]). Figure 29 shows a simplified diagram of how seismic hazards propagate through bedrock and result in ground shaking, which can affect structures (including dams and reservoirs) at the Earth's surface.



Large Floods

- Large flood events can induce various different deleterious or extreme loading conditions resulting from increased water levels and higher velocities. The primary threat large floods pose to dams is overtopping failure induced by increased water levels (e.g., 2006 Ka Loko Dam failure [Hartford et al. 2016]), although the risk of damage from seepage/piping and structural overstressing also is increased. In addition to flood hydraulic effects, various types of floating or submerged debris within the water body (common in large floods) can contribute to increased loads on a dam or damaging impacts to system components. While some dams maintain significant storage capacity to accommodate large flood inflow volumes (e.g., dams designed primarily for flood control), others follow run-of-river operation and have little or no storage volume. These rely entirely on gates or other active passage structures to pass increased flows (e.g., dams designed primarily for navigation).
- Under a risk-informed framework, flood loading for dam safety evaluation is often assessed using a hydrologic hazard curve (HHC), developed based on hydrologic hazard analysis (HHA). These HHCs combine peak estimates of flow, reservoir/river stage, and volume probabilities plotted against the AEP. As noted in USBR (2004), the peak discharge and volume estimates resulting from an HHA application may exceed the PMF, in which case USBR assumes that the PMF represents an upper limit of risk. An example is provided in Figure 31, which compares probabilistic reservoir elevation frequency estimates with dam spillway crest and PMF elevations. The dam stage points shown result from modeling water elevations under various analytical approaches, including using streamflow-based (event-based) statistics, precipitation frequency estimates, balanced hydrograph inputs, and inflow design flood hydrograph ratios. Discussion of federal best practices for probabilistic HHA is provided in Chapter II-2 of USBR and USACE (2017).

Other Disturbances

A variety of other disturbances may also pose hazards for dam safety, especially when they are combined. The following are among the most prevalent:

Floating debris

Ice and icing effects

Sedimentation

Reservoir landslides

EVENT AND FAULT TREE ANALYSIS

Most risk analyses begin with a systematically structured model of the events that could, if they happened in a particular way, lead to failure. This type of model is an event tree.

An alternative analytical tool to the event tree is the fault tree, and often the two are used in a reliability analysis to complement each other.

A fault tree starts not with events possibly contributing to failure, but with the failure state itself, and asks what might need to happen for that failure state to occur.

Event Tree Methods

The steps in developing an event tree analysis are

1. **Define what “failure” means.**
2. Identify initiating events.
3. Build an event tree of the system.
4. Develop models for individual components.
5. Identify correlations among component failures or failure modes.
6. Assess probabilities and correlations for events, parameters, and processes.
7. **Calculate system reliability.**

EVENT AND FAULT TREE ANALYSIS

- At the same time, alternative approaches to risk analysis, most specifically **fault tree methods have proved difficult to apply in practical dam safety studies.** Unlike a piece of mechanical equipment, a dam is not easily broken down into a fully enumerated set of components, and it is not easy to link failures among a subset of those components to subsequent failures of others. It may turn out in future research that fault tree approaches shed new light on dam safety assessments; but at present, event trees are the standard approach.
- **Ultimately, event tree analysis is used to inform a decision process by explaining how a dam might be expected to perform.**

It supports considerations that in the past had not been considered formally: the likelihoods of various performance modes and the consequences to the dam and to downstream uses should such performance modes occur. Approached from this perspective, an event tree is a diagnostic tool; it is not intended to generate numbers alone but to draw inferences about how a dam might perform when it is subject to particular service conditions.

EVENT AND FAULT TREE ANALYSIS

- Evolving practice in seismic hazard, nuclear safety, and other risk analysis disciplines is to separate aleatory and epistemic uncertainties into two separate but conjoined trees. **Aleatory uncertainties are those that deal with variations in time or space: randomness in the world. Epistemic uncertainties are those that deal with limited knowledge (i.e., uncertainties in what is known).**

- **The aleatory uncertainties** such as reservoir inflows or the geotechnical performance of an embankment are typically characterized by assumed states of nature, physics-of-failure models, and statistically inferred parameter values. Give the assumed states, models, and parameters, a probabilistic characterization can be made of possible frequencies of behaviors of the real-world systems. These are aleatory uncertainties conditioned on assumptions about nature. **The uncertainties about the assumptions of states, models, and parameters are epistemic.**

EVENT AND FAULT TREE ANALYSIS

- **Two trees are thus created: an *event tree* and a *logic tree*.** The event tree contains only the aleatory events conditioned on possible realizations of states of nature, model validity, and parameter values. The logic tree contains only the epistemic uncertainties about the possible states of nature, models, and parameters. First, a random path is constructed through the logic tree to establish one realization of the possible states of nature, valid models, and corresponding parameter values (Figure 33). This one realization of the epistemic uncertainties is then used as input (conditioning) for all the probabilistic outcomes in the aleatory event tree. This simplifies numerical calculations and ensures that implicit correlations in the event tree due to common dependence on epistemic uncertainties in the logic tree are faithfully maintained.

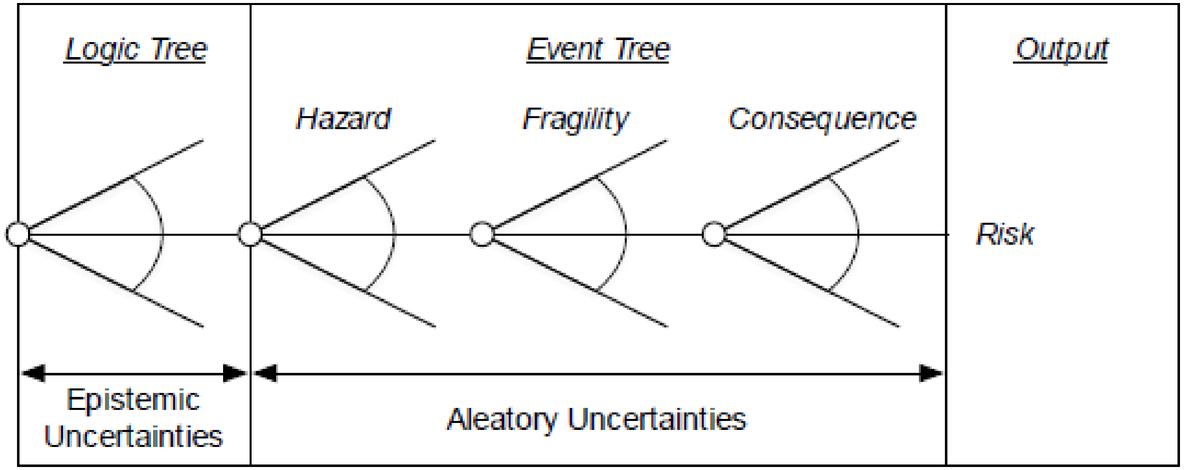


Figure 33. Logic tree describing fixed-but-unknown conditions (states) of nature, as conditioning.

Fault Tree Analysis

- Event trees start with initiating events or causes and progress toward ever more detailed consequences. The ordering of events in an event tree can be rearranged so long as the relationships among conditional probabilities are adjusted; but in concept, the logical progression from cause to effect in a tree is an important, if sometimes concealed, principle of event tree analysis.
- In contrast, **fault trees start with consequences (i.e., failures), and progress backward toward ever more detailed causes (Figure 34).** Thus, the logical structure of a fault tree is reverse to that of an event tree, in that **the logic moves from consequence to cause.** A system failure mode is considered the "top event," and a fault tree is developed in branches below this event, showing causes. Event tree analysts ask what might happen if an initiating event occurs; whereas fault tree analysts ask how a particular outcome can come to pass. In concept, fault trees are photographs showing conditions at an instant in time. They may also show conditions at the transition between two events in an event tree, or the top event may be used as the initiating event in an event tree.

Fault Tree Analysis

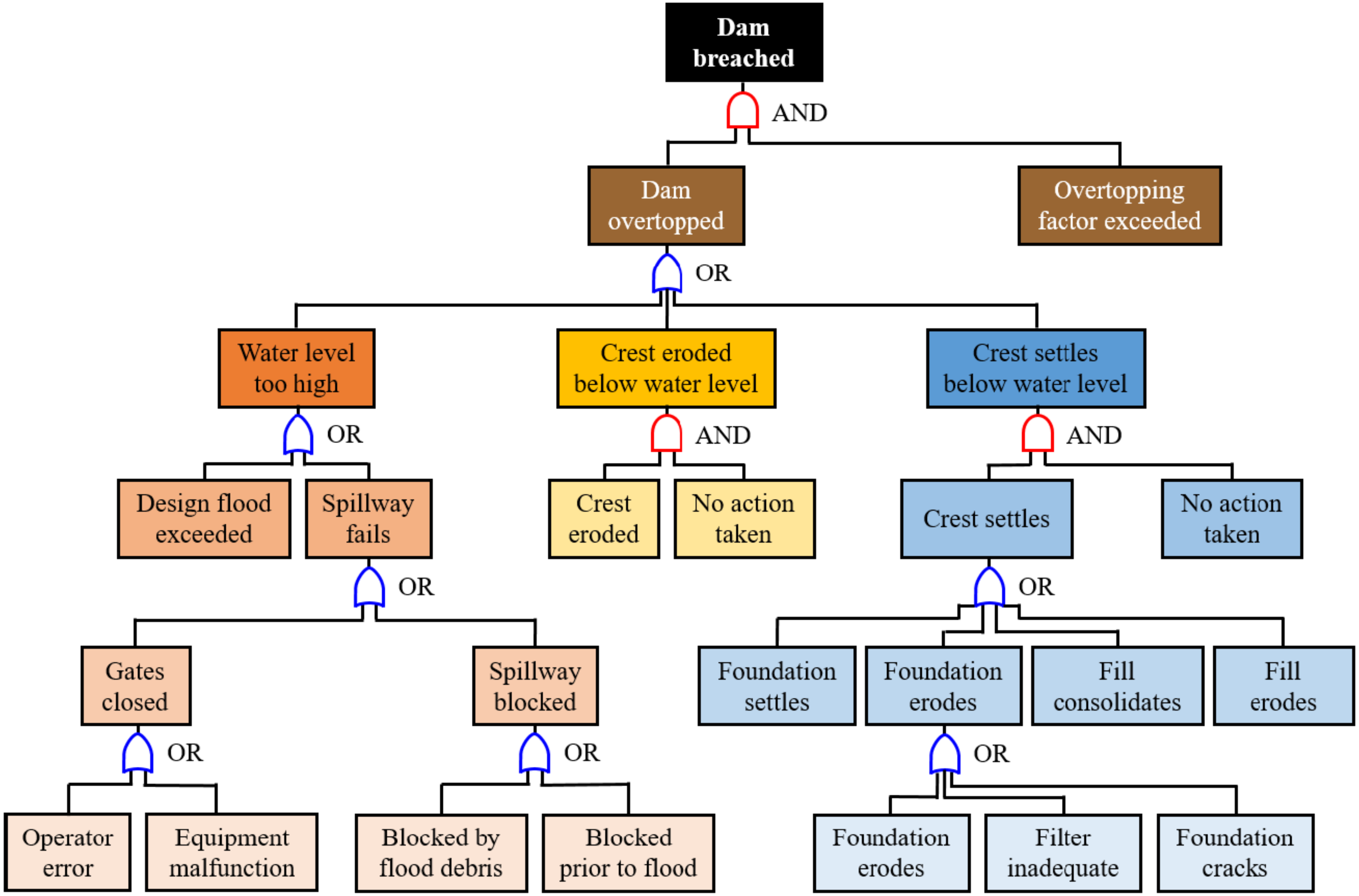


Figure 34. Example of a fault tree applied to the problem of dam failure. (Source: Adapted from Parr and Cullen 1988)

- **Another important difference between fault trees and event trees lies in the distinction between *failure modes* of a system and *failure mechanisms*.** This distinction is clear in classical reliability theory but less clear in dam safety practice.
- **A *mode* is a state or condition of a system or component.** This can be a failing mode if its existence leads to adverse consequences, or it can be a safe mode it its existence does not. The elements of the fault tree of Figure 34 are modes in this sense (e.g., a gate is closed, or it is not; the spillway is blocked, or it is not; the crest is overtopped, or it is not). Modes are described by nouns and adjectives.
- **A *mechanism*, in contrast, is a set of processes or behaviors.** ISO14224 (ISO 1999) defines a failure mechanism as "a process that leads to failure. The process can be physical, mechanical chemical, or a combination thereof." The branching elements in the event tree of Figure 35 used for calculating the probability of internal erosion in an embankment dam mostly describe things that happen: erosion is initiated, erosion continues, erosion progresses further, intervention is unsuccessful. Mechanisms are described by verbs and adverbs.

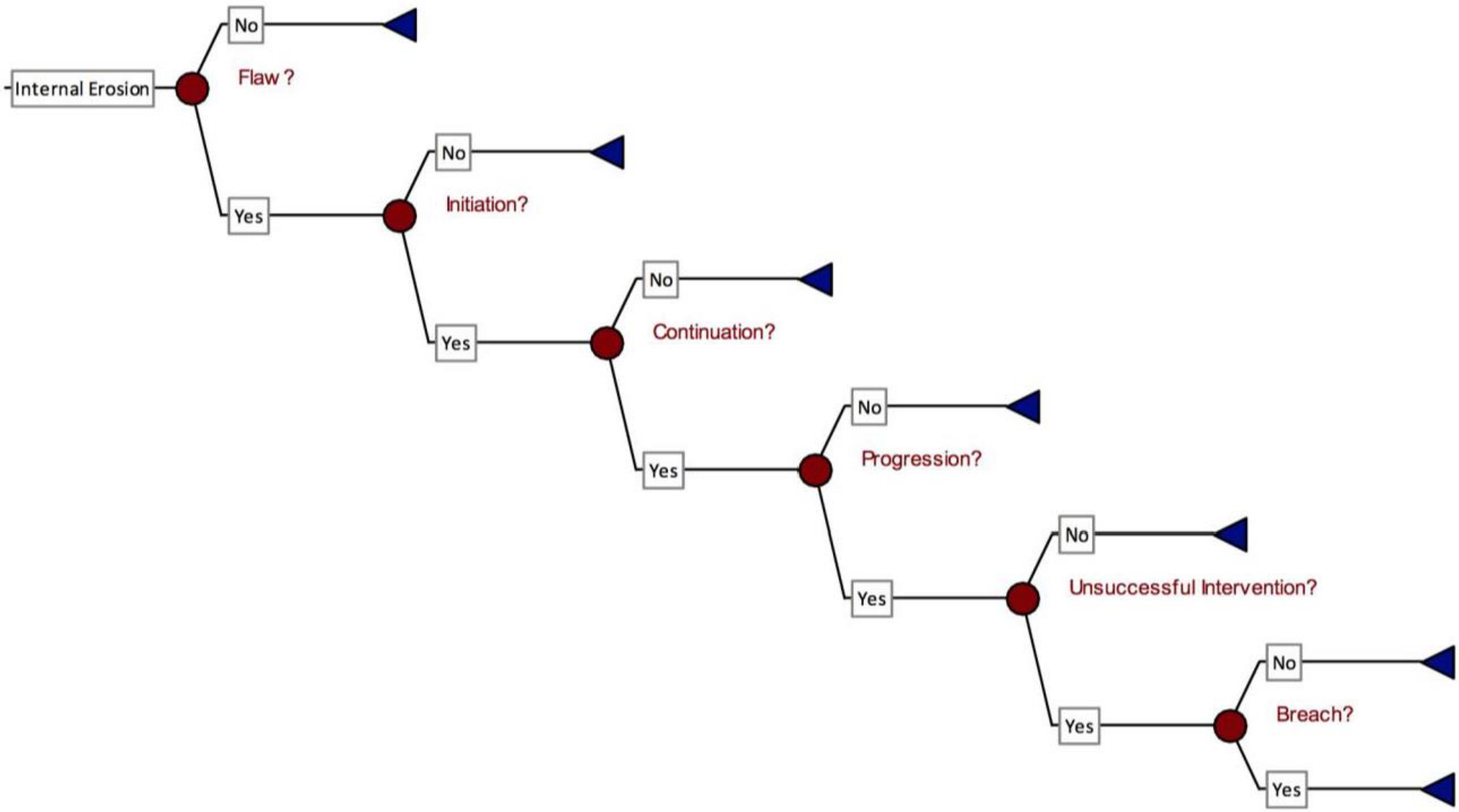


Figure 35. Schematic event tree for internal erosion. (Source: USBR and USACE 2017)

FRAGILITY CURVES

Modeling and analysis of initiating events and failure mechanisms is similar across the many ways a dam behaves. Initiating events are commonly treated as naturally varying in time and space (i.e., as frequencies), even though some uncertainties associated with initiating events may be epistemic, as is the case in PSHA. When included in a risk analysis of dam safety, however, initiating events are most often modeled as due to aleatory uncertainty. Treating initiating events as aleatory implies annual probabilities of events of a given size occurring or being exceeded, as, for example, in flood frequency relations or earthquake recurrence functions.

Initiating events are used as input to an event tree representation of the dam system's response to the corresponding loading. Within the event tree (Section 5.4.1) individual nodes may represent model, parameter, and other uncertainties; or they may represent the performance of components and sub-systems. Increasingly, dam safety practice is to separate out the model, parameter, and other epistemic uncertainties into their own "logic trees" and to leave only the component and subsystem performance uncertainties within the main event tree. These component and subsystem performance uncertainties are often summarized in load-response relationships known as fragility curves (or functions). ICOLD (2005) defines a fragility curve as "a function that defines the probability of failure as a function of an applied load level."

FRAGILITY CURVES

The term "fragility curve" arises primarily in structural engineering, where it is used to mean a summary of structural response, expressed as the probability of failure or of other adverse performance as a function of an applied load. The fragility curve is a simplified, summary model of component or subsystem behavior under load.

Fragility Curves

Porter (2018) defines a fragility curve (Figure 36) as

A mathematical function that expresses the probability that some undesirable event occurs (typically that an asset—a facility or a component—reaches or exceeds some clearly defined limit state) as a function of some measure of environmental excitation (typically a measure of acceleration, deformation, or force in an earthquake, hurricane, or other extreme loading

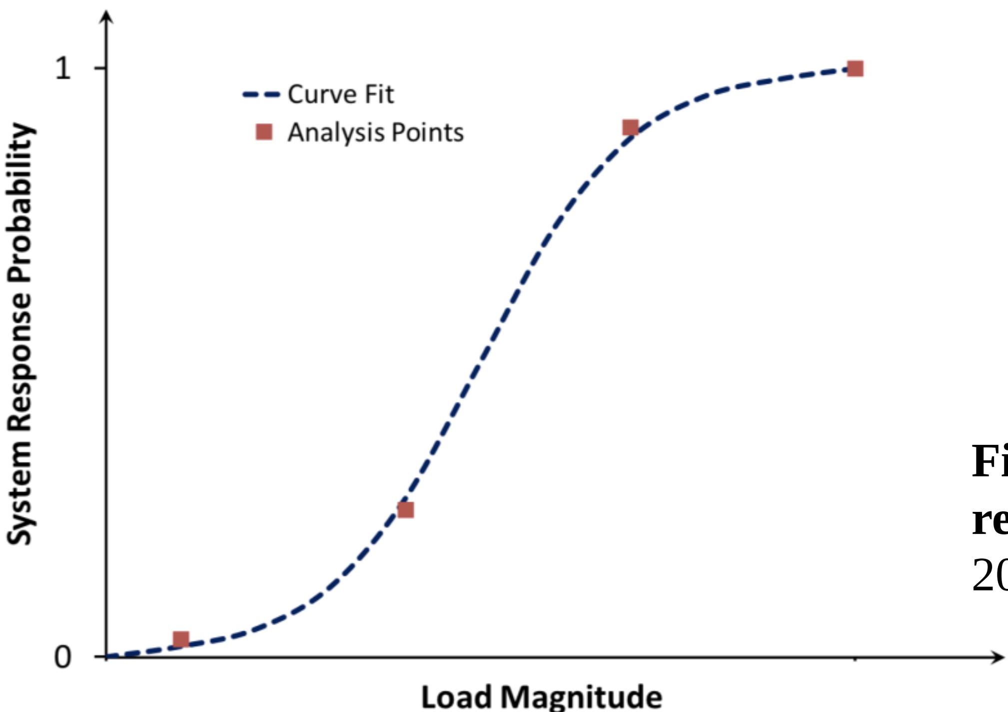


Figure 36. Schematic fragility (systems response) curve. (Source: USBR and USACE 2017).

A more general definition is the conditional probability that a structure or component reaches a limit state (fails or performs adversely), given an environmental load. An example is shown in Figure 36. Fragility curves are also sometimes called “fragility functions.” USACE and USBR use the term “systems response curve” for this relationship (USBR and USACE 2017). Among the first uses of the term “fragility curve” was its use in respect to NPP risk analysis in the paper of Kennedy et al. (1980).

Multiple damage states

In most practical situations, there is more than one damage state; that is, the fragility curve is not a simple Boolean, failure or no-failure, but describes a range of adverse performances from moderate to severe. An example of a fragility curve for multiple damage states (slight-moderate-extreme-collapse) is shown in Figure 37. Fragility curves for multiple damage states are a nested set of curves. The curve associated with the most severe damage state is at the bottom with the least probability, and the curve for the least severe damage at the top with the greatest probability.

The fragility curves in Figure 37 are sequential; that is, post-loading the component exists in exactly one damage state, and the component passes through each damage state to its final level. The component progresses from slight damage to complete damage. There are other possibilities for multiple damage states, but these are less common. For example, the component may exist in more than one damage state at the same time (simultaneous), or there may be exclusive and exhaustive damage states that are not sequential (Porter 2018).

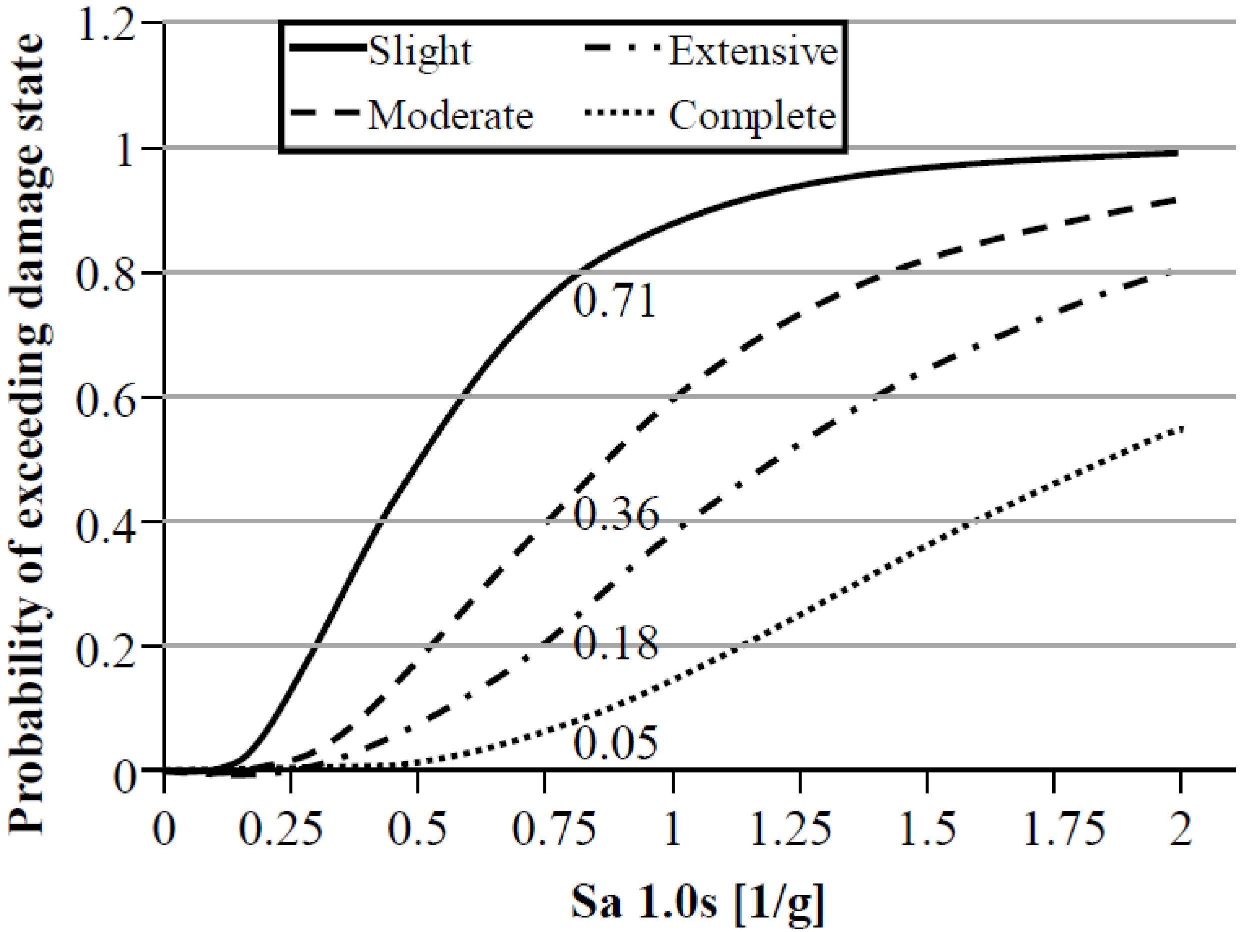


Figure 37. An example fragility curve with multiple damage states for concrete bridges in a database of Northern Italian structures. (Source: Modified from Carturan et al. 2013). Sa 1.0s is spectral acceleration at a frequency of one second.

Reliability curves-Vulnerability curves

Reliability curves describe the time-dependent performance of a system or component, relating failure rates or probabilities to age. These curves are distinct from fragility curves, which relate failure rates or probabilities to the load on a system or component.
For mechanical and electrical systems and components in dams, reliability curves are often modeled as Weibull distributions (Patev et al. 2013), $F(t)=P(T\leq t)=1-exp\{-(t\alpha)/\beta\}$,
where T, t = time to failure, α = scale parameter, and β = shape parameter.
Extensive data on mechanical and electrical gate component reliability from USACE asset management sources are provided in the Appendix to Hartford et al. (2016) as Weibull parameters. The USACE has also collected data and developed reliability models for gate components at its facilities.

Vulnerability curves
Fragility curves relate the probability of exceeding some damage state as a function of the load on the system or component. *Vulnerability curves* relate the extent of loss or the consequence to the load on the system or component. The loss might be repair cost, loss of life, loss of functionality, or some level of environmental degradation. Vulnerability curves are also sometimes referred to as damage functions, loss functions, vulnerability functions. Vulnerability measures loss; fragility measures probability.

Identifying Fragility Curves

As with any estimate, there are only three ways of assigning fragility curves:
(1) statistical analysis of empirical data,
(2) modeling from first principles, and
(3) using subjective judgment (Porter et al. 2007).

The statistical-empirical curve is based on an analysis of historical performance data (Foster et al. 2000). Given the low rate of catastrophic failure of modern dams, however, empirical fragilities for entire dams or major dam subsystems are little used. Historical data for components are more readily available. Large dam-owning organizations such as USACE or large hydropower operators usually maintain asset management data on failures of mechanical and electrical systems such as hydraulic gates and generators. These data are shared through trade groups such as CEATI International in Montreal.

The modeling approach to fragility curves is often used for engineered systems or components, such as the strength of the structural frames supporting spillway gates or the geotechnical stability of embankments. A large collection of literature on structural and geotechnical reliability engineering exists to support these modeling efforts (Baecher and Christian 2003; Ditlevsen 1996; Griffiths et al. 2007; Melchers 1987)

Identifying Fragility Curves

The judgmental approach uses subject matter experts (SMEs) subjectively to assess fragility curves. This has been common for failure mechanisms such as internal erosion for which there are few empirical data and inadequate physics-based models. The use of expert opinion elicitation (subjective probability) in dam safety risk analysis is pervasive. USACE and USBR have developed tailored approaches based on the concept of PFMA (USBR and USACE 2017). The NRC-developed Senior Seismic Hazard Analysis Committee procedure (NRC 2018) has been widely used for conducting seismic hazard analysis related to dam safety (McCann and Addo 2012), but it has been less widely used for general dam safety risk analysis.

Two approaches to the use of expert opinion have evolved in dam safety studies, one principally in European practice and the other principally in US federal practice. The European practice is to use expert judgment to assign values to the input parameters of reliability (i.e., physics-of-failure) models, and then to use the reliability models to propagate those uncertainties to probabilities of failure (Vrijling 2001). The US federal practice, in contrast, is to use expert elicitation directly to assign values to the probabilities of failure without involving a physics-of-failure model.

Examples of Fragility Curves in Dam Safety

Most studies of dam safety risk include some form of fragility curve. The concept and nature of fragility curves are discussed by Porter (2018) and USBR and USACE (2017).

Examples are shown in Figure 36 and Figure 37.

Figure 38 shows four fragility curves for four failure models of a coastal flood levee.

For concrete dams, example fragility curves are provided in Ellingwood and Tekie (2001) and Chase (2012).

For embankment dams involving geotechnical failure mechanisms, example fragility curves are provided in Altarejos-García et al. (2014), Duncan (2000), Fenton and Griffiths (2008), Schweckendiek and Kanning (2016), and Fell (2015).

For internal erosion and piping of embankment dams, example fragility curves are provided in Fell et al. (1992), Foster et al. (1998), Foster et al. (2000), Hartford and Baecher (2004), McDonald (1995), and USBR and USACE (2017).

For spillway structures and systems and key components (e.g., gates, gate hoists, valves), example fragility curves are provided in Langseth and Perkins (1983), Lewin (2001a), Patev et al. (2005), and Patev and Putcha (2005).

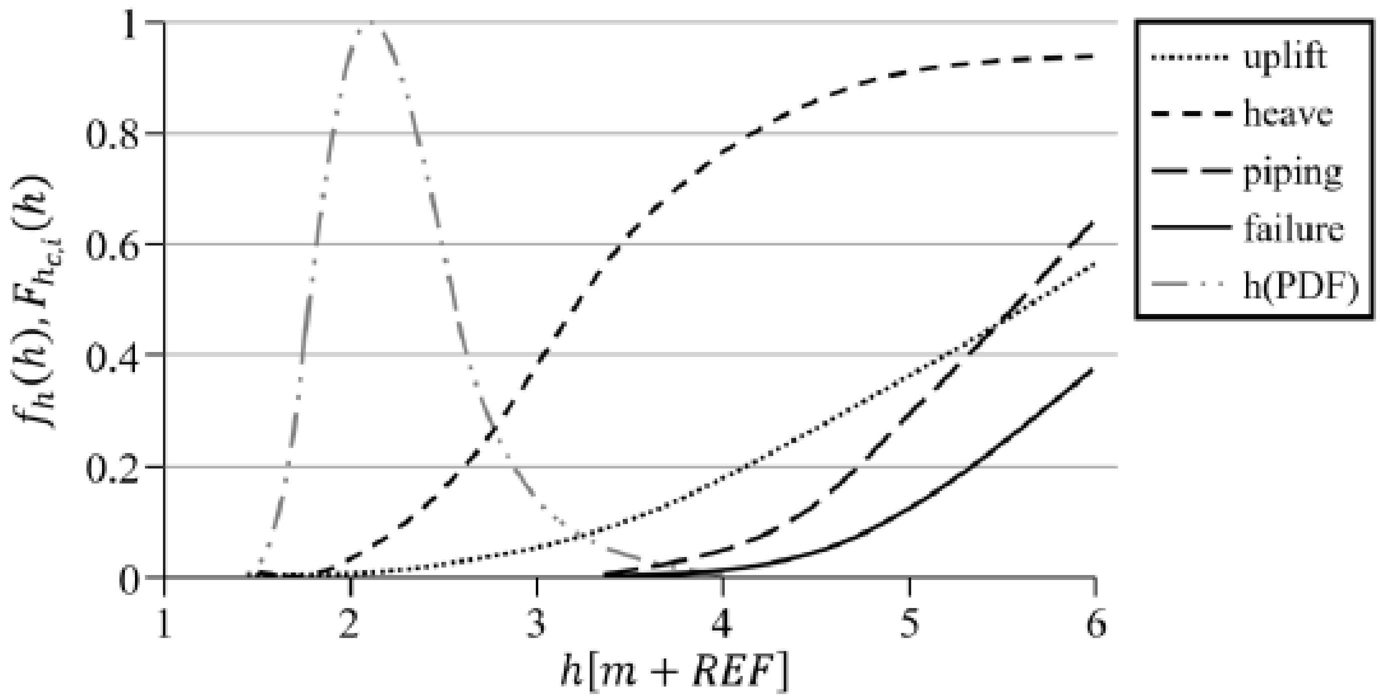


Figure 38. Application example for field observations, dike ring 10 (Mastenbroek) – prior fragility curves for uplift, heave, piping and failure and probability density of the water level. (Source: Modified from Schweckendiek et al. 2014)

DAM BREACH MODELING

Dam breach modeling is a widely used tool for evaluating dam breach impacts. Typical dam breach modeling involves analyzing breach initiation and progression to provide a basis for estimating downstream flows and the consequences of a dam breach. The size and geometry of the breach and the timing of breach development determine peak flows through the breached dam and the breach hydrograph causing downstream flooding.
The analysis of breach initiation and progression focuses on failures of earth dams and embankments, including failures of natural foundation materials beneath or adjacent to constructed dams. Failures of rigid structures, such as spillway gates or a concrete dam section, are typically assumed to occur near-instantaneously, with the size and shape of the breach determined by the size and shape of the structure that fails.

The Wahl review concluded that dam breach models should address the following questions:
1. For a given set of conditions, will a dam breach?
2. How much time is required to initiate a breach?
3. How will the breach develop once it is initiated (e.g., ultimate dimensions, rate of development, total time to reach ultimate dimensions)?

Further, the breach model "should be applicable to both overtopping and piping- or seepage-induced failures, although the initial focus of model development should be on the more tractable problem of overtopping failures."

OPERATIONAL RISK

An operational risk is the potential loss resulting from “inadequate or failed internal processes, people, and internal systems, or from external events.” This definition is adapted from the financial sector, in which operational risk is specifically defined (Basel Committee on Banking Supervision 2004), but it has been widely adopted by the chemical processing, oil and gas, and other hazardous industries (Meel et al. 2007). The aviation industry uses a similar definition of operational risk based on systems engineering (FAA 2000).

Operational risk stands apart from risks associated with physical aspects of the dam, such as its structural integrity or its capacity to withstand earthquakes or landslides. Operational risk is related to the hazardous results occurring from an unusual combination of common operational events (Hartford et al. 2016). It may reflect both errors of commission and of omission. Fully enumerating the many such rare chains of events in a PRA is possible but seldom practicable.

In contrast to the consideration of extreme loads against structural or geotechnical capacities, experience has shown that the majority of dam incidents, and even many dam failures, do not result from extreme loads but rather from operating events. These incidents and failures occur because an unusual combination of reasonably common events occurs, and this combination may have an adverse outcome. Examples of reasonably common individual events include moderately high reservoir inflows, the SCADA system early warning failure, spillway gate(s) unavailability because of maintenance, operator error, and high pool level. When multiple such events occur in combination, the result may be an incident or even a failure, even though none of the individual events was extreme on its own.

DAM OPERATIONS

Dam operations are multidimensional activities influenced by factors including but not limited to: corporate ownership and management structures, regulations, water and power markets, logistics and technology. For example, an individual dam may be owned by one organization and operated by another. In other cases, a series of dams may be owned by a single organization and operated as a system. The retention, release, and allocation of water from dams are influenced by a variety of factors, ranging from power purchasing agreements to public water supplies.

The aspects of a dam system of concern for operating risk include, among other components and processes:

- **Equipment failures (i.e., mechanical and electrical reliability)**
- **SCADA systems**
- **Human factors**
- **External disruptions: debris, ice, reservoir landslides, internal fires**
- **Communication systems availability**
- **Site access during storms or winter conditions**
- **Maintenance practices**

HUMAN FACTORS AND RELIABILITY

The root causes of primary dam failure mechanisms are physical factors that affect dam safety. Human factors, which comprise the decisions, actions, and inactions of dam owners and operators, also influence dam safety. Human reliability failures can originate from decisions made during construction or operation. Hartford et al. (2016) note that, "for spillway systems, many of the human errors occur during the operations phase, but they also occur in design deficiencies, maintenance practices or strategies, lack of updated safety manuals and upper management decisions regarding such systems." Sowers (1993) reports that 58% of civil and geotechnical failures originate from design decisions, with one-third of those failures occurring during construction and two-thirds during operation.

Dams and spillway systems are inherently complex, and human error plays a critical role in the success or failure of these systems. To account for the potential negative impacts posed by human failure events, or ameliorating impacts resulting from mitigating actions, human reliability analysis (HRA) is used. HRA is "a structured approach used to identify potential human failure events and to systematically estimate the probability of those errors using data, models, or expert judgment."35 HRA is typically performed by a multidisciplinary team responsible for assessing PRAs, plant design and behavior, engineering, plan operations, procedures, monitoring and control, and cognitive and behavioral science. These various factors can all play a role in human reliability and are used as input to HRA.

SCADA SYSTEMS

Modern large dams are equipped with automated SCADA systems. These systems combine sensors with industrial controllers, computers and data storage, and communication links and facilitate remote or automatic control of components of the flow-control system.

This sequencing of information from sensors to controllers can increase reliability concerns, particularly since programming may be locally customized. The Taum Sauk failure (discussed later in this section) was related to SCADA misperformance (Regan 2010), and a number of other incidents are summarized in the NPDP.9 Many dam failure precursors may be detected by onsite personnel before equipment detection may occur, and the lack of onsite workers can prove detrimental if site conditions deteriorate (Hartford et al. 2016).

SCADA system reliability is essential for protecting equipment and ensuring dam safety. Some installations use equipment built to military-grade standards to withstand extreme environmental conditions (e.g., temperature, moisture, vibration, and voltage extremes). Programming errors and component failures may still incapacitate SCADA systems and negatively affect the communication of sensor readings to an operator. Consequently, many sensitive facilities are equipped with redundant hardware and communications capability to reduce risk. In addition, many systems rely on external power to activate equipment and are equipped with onsite emergency backup generators in case of loss of offsite power.

CONDITION MONITORING AND MAINTENANCE

Federally owned and non-federal, FERC-licensed dams have condition monitoring and maintenance programs. Condition monitoring primarily involves data collection (visual observation and instrument readings), processing, and evaluation to continuously evaluate dam safety. Visual observation may include inspecting the dam and appurtenant structures to identify any unusual conditions that could jeopardize dam safety. Instrumentation involves the use of electrical and mechanical instruments or systems that measure pressure, flow, movement, stress, strain, and temperature. For example, Table 7 shows the FERC minimum recommended monitoring matrix for existing dams (FERC 2017)
Given the common dam failure mechanisms described in Section 4.2, various methods of visual inspection are typically practiced for identifying safety-related dam issues.

According to the British Columbia *Inspection & Maintenance of Dams: Dam Safety Guidelines* (British Columbia 2016),

- Embankment dams should be inspected for the most threatening deficiencies, which include longitudinal or transverse cracking and misalignment of adjacent dam portions.
- Concrete dams should be inspected primarily for structural cracks, foundation or abutment weakness, or deterioration due to alkali-aggregate reaction (also known as alkali-silica reaction; ASR).
- Spillways, outlets, and gates should also undergo inspection where accessible.
- Safety signage should be inspected for deficiencies resulting from vandalism, readability, overgrowth, or outdated information.

ADDRESSING OPERATIONAL RISKS

Once general categories of operational risk classes have been identified, there are a limited number of approaches to their appraisal and quantification. The different categories of operational risk may best be approached using different methodologies.

The most common methodologies are those based on subject matter expert (SME) judgment. An example is USACE's use of expert panels (USACE-USBR and USACE 2017). The experts have specific knowledge, experience, and information regarding the risks to be appraised. The simplest SME approach is the use of a self-assessment questionnaire. These questionnaires are used to gather information on the impact and frequency of events and on the effectiveness of mitigation or intervention. On the other extreme is the expert elicitation protocols more commonly used for traditional event tree analysis.

An alternative methodology is scenario analysis. It uses hypothetical operational risk scripts as story lines, which are analyzed by groups of experts. While scenario analysis is more common in financial sector risk analysis (Hassani 2016), an example in the dams sector is FEMA's use of dam failure scenarios in estimating potential loss of life (FEMA 2011). This method is usually implemented using workshops involving experts from a variety of disciplines and a professional facilitator. The process starts by defining a hypothetical situation and attempting to achieve a consensus opinion on the likelihood the scenario would occur and the associated consequences.

ADDRESSING OPERATIONAL RISKS

A third methodology is to rely on internal or external databases of historical failures, near-misses, or precursor events, possibly similar to nuclear sector OpE databases. An example is the FERC-supported *National Performance of Dams database*. However, classical statistical approaches tend to be ineffective for chains of low-frequency, high-consequence events both because of their rarity and because so many potential combinations of events may exist. For the dam industry, the NPDP9 provides one such database. In other hazardous industries, such as chemical processing, these databases are often more expansive, and reporting may be legally required, which is not the case for dams.

A fourth methodology is systems simulation, which can be used to model operational risks and to spot emergent behaviors that might otherwise be difficult to identify. An example is Vattenfall's use of Systems Dynamics on its Göte River cascade (Ascila et al. 2015). This approach is newer and less widely used than the others. Systems modeling using simulation (Hartford et al. 2016), systems dynamics (Pavlovic 2016), or related techniques may help to identify potential failure paths.

ADDRESSING OPERATIONAL RISKS

Systems Engineering

A systems analysis approach to dam safety involves comprehensive consideration of all components of a dam and their interactions, wherein not only are the risks and risk mitigation important for safety but understanding how to accommodate the risks is critical as well. The term "system" refers to the set of interacting, interrelated, and interdependent elements that dictates a complex whole; while "systems analysis" refers to determination of the plans, design, and operational strategies through the use of scientific methods (Hartford et al. 2016).

The risks posed by a dam system can be challenging to assess because of the variability of the organization and loading conditions associated with components. Traditional treatment of risk as a "single-component" deterministic issue can be detrimental to the perceived reliability of a dam system. Safety analysis that incorporates probabilistic analysis and simulation techniques for assessing variability in component interaction is crucial for understanding and assessing the risks. In addition, a departure from a single-component focus toward a more holistic approach encompassing a multi-interactive systems analysis is necessary.

ADDRESSING OPERATIONAL RISKS

Flow Control

For risk analysis in the context of systems analysis, **“flow control” refers to the wide array of elements—including structures, equipment, sensors, communication facilities, personnel, management arrangements, and policies—that implement the handling of water through the reservoir and past the subject dam to the downstream reach of the river.** In general, the main components of flow control are the catchment, reservoir, dam, spillway, and other waterways (e.g., emergency outlets, power generation, bottom drain).

Reservoir and dam operation can be controlled with SCADA equipment and human interaction. Although the use of these control mechanisms is intended to impart a culture of safety with respect to reservoir and dam control, human-operator error and programming errors and component failures associated with SCADA systems are possible.

ADDRESSING OPERATIONAL RISKS

System Simulation

Simulation or physics-of-failure modeling can be a crucial part of identifying and predicting operational system risks such as hydrological system inflows, since the operation of the dam functions is dependent on the magnitude and timing of reservoir inflows. Although deterministic models are adequate for predicting systems with a high degree of certainty in their inputs, hydrological systems do not contain such degrees of certainty. Recent research is incorporating stochastic approaches in hydrologic modeling by developing and using probability distributions of the output of deterministic models for random parameters.

Modeling the complexity of a dam system at the systems level is challenging because of the nonlinearity and randomness of the interactions. Modeling using traditional engineering risk analysis does not address the reliability of physical dam components in conjunction with their integration with communication and control systems (Regan 2010). Overcoming these issues requires a simulation approach.

SOFTWARE TOOLS FOR DAM SAFETY RISK ANALYSIS

INTEGRATED DAM SAFETY SOFTWARE

Integrated dam safety software combines the identification of categories of uncertainties, tools for fault tree or event tree analysis, and consequence estimation. Sometimes these integrated applications also combine other analytical or statistical tools. The number of available applications is limited, and most have been developed by dam owners and operators, or regulators.

FEMA Risk Prioritization Tool for Dams

The FEMA Risk Prioritization Tool (URS Group 2008) is a screening tool developed under contract to FEMA as a way for dam owners and operators to quickly prioritize safety risks among dams in a portfolio. It is based on qualitative risk analysis and expert judgment rather than detailed quantitative modeling. A description of this tool is provided at the FEMA website:37

The Risk Prioritization Tool for Dams is a standards-based decision-making tool for risk-based dam safety prioritization to be used by state dam safety regulators throughout the country to identify those dams within a large inventory that most urgently need attention and then allocate resources accordingly. Once priorities are judged, risk acceptance or tolerability is a matter of policy that will vary from state to state. The tool is quick and easy to implement; applicable to any type or number of dams; accommodates the broad differences between owners and information known about each dam; avoids subjectivity and unnecessary bias; and is defensible

DAMRAE-U (USACE)

Based on a generalized event tree algorithm, a deterministic model (DAMRAE) was developed for the US Army Corps of Engineers to support the dam safety risk assessment.

With an objective to incorporate the uncertainty analysis functionality for the event tree-based risk models, we extend the DAMRAE framework to develop a generic uncertainty analysis tool (DAMRAE-U) for dam safety risk assessment.

DAMRAE-U provides a convenient way to efficiently characterize, propagate, and display the outcomes of uncertainty analysis.

DAMRAE-U is structured to analyze knowledge uncertainty for the event tree variables and natural variability associated with flood and earthquake loadings. It also provides for separating the effects of uncertainty in the existing condition of the dam system on which the event tree model is dependent.

DSS-WISE™ Lite (FEMA)

The Decision Support System for Water Infrastructure Security (DSS-WISE)38 is a two-dimensional dam and levee flood modeling and mapping software program developed by the National Center for Computational Hydroscience and Engineering at the University of Mississippi with FEMA funding.

It runs on a browser-based platform providing access to a secure, web-based environment. The program allows a user to set up and run dam and levee breach scenarios. DSS-WISE solves dynamic shallow-water equations and provides results within about half an hour after user inquiries. DSS-WISE Lite is used internally by federal agencies and state dam safety offices for dam safety studies and preparing EAPs. A post-processing module generates flood hazard maps and carries out loss-of-life analysis based on a USBR methodology.

EVENT TREE ANALYSIS SOFTWARE

The use of event tree analysis for dam safety risk evaluation was pioneered by BC Hydro and USBR in the 1980s. Event tree analysis and the related fault tree analysis methods applied to dam safety risk analysis are described in Hartford and Baecher (2004) and in more general terms in Pate-Cornell (1984).
An event tree is a graphical representation of the chains of events that could lead from some initiating event or hazard occurrence to system failure. As the number of events increases, the diagram fans out like the branches of a tree. A presumption of event tree analysis is that data and engineering judgement are most powerful at detailed levels of dam behavior that involve specific models, parameters and assumptions and less powerful at the aggregate level of an entire dam. Thus, a decompositional approach is warranted. Event trees are commonly used to analyze “open systems” in which possible outcomes are inferred inductively, so it is possible that some failure mechanisms will not be captured in a particular analysis. This is in contrast to fault tree analysis. **Today, event tree analysis is the principal analytical approach to dam safety risk worldwide**.

Many commercial-off-the-shelf software products are available to perform event tree analysis. Few of these were developed specifically for dam safety. Most are components of statistical decision theory software, which is a much larger market. PrecisionTreeTM, which is a component of a larger suite of software products—DecisionSuiteTM—provided by Palisade Software Corporation of Ithaca, NY, is perhaps the largest market shareholder in the dam safety community.

EVENT TREE ANALYSIS SOFTWARE

Among the vendors providing event tree analysis software are (alphabetically)

- DATA—TreeAge Software
- DecisionPro—Vanguard Software Cooperation
- Event Tree Analysis (ETA)—SoHaR
- Event Tree Module—Isograph
- PrecisionTree—Palisades Software
- RAM Commander's Event Tree Analysis Module—ALD
- RiskSpectrum—PSA software

FAULT TREE ANALYSIS SOFTWARE

Fault tree analysis, in contrast to event trees, is a deductive logic based on set theory and Boolean algebra. In developing a fault tree model, a top-down approach is used. Beginning with a top failure event, one seeks causes that would lead to its occurrence. Next, failure mechanisms or event occurrences are sought for these causes to be realized. A failure mechanism is a description of how a failure mode can occur: it is a system state. Fault tree analysis is widely used in mechanical and electrical reliability studies of "closed systems," that is, those in which all the complements and their relationships are identifiable.

Among the vendors providing fault tree analysis software are (listed alphabetically)

- EMFTA: Open Source Tool for Fault Tree Analysis—CMU
- Fault Tree Analysis—Isograph
- Fault Tree Analyzer—ALD
- Fault Tree Diagram Software—SmartDraw
- ITEM Toolkit Fault Tree Analysis—Item Software

MONTE CARLO SIMULATION

Monte Carlo methods (or MC simulation) comprise a broad category of numerical methods for solving stochastic models (and complex integrations). They use random sampling and sampling statistics to obtain quantitative estimates with associated numerical uncertainty, which is quantified statistically. They are commonly used for models that are difficult to solve using other approaches. In physics-based problems like dam safety, MC methods are useful for simulating systems with many coupled degrees of freedom, or complex, correlated uncertainties. MC methods are common in risk analysis across a broad range of disciplines, from engineering to medicine to finance.

Among the vendors providing MC simulation software are (listed alphabetically)

- @RISK—Palisades Software 90
- Crystal Ball —Oracle
- GoldSim—GoldSim Software
- Model Risk—Vose Software
- Matlab and Simulink—The Math Works
- Risk Engine for Mac—Engineering for the Real World