Climate-aware Resilience for Sustainable Critical and Interdependent Infrastructure Systems enhanced by emerging Digital Technologies

Massive Open Online Course:

Resilience, Sustainability & Digitalisation in Critical Infrastructure

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Lecture 2

Massive Open Online Course

Resilience, Sustainability & Digitalisation in Critical Infrastructure

Vulnerability and risk and assessment for climate change

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Lecture 2 Outcomes

- Define critical hazards and climate exacerbations for critical infrastructure.
- Define fragility, vulnerability and risk analysis models for critical infrastructure assets and systems
- Apply the risk and loss assessment models to representative transport and energy case studies.

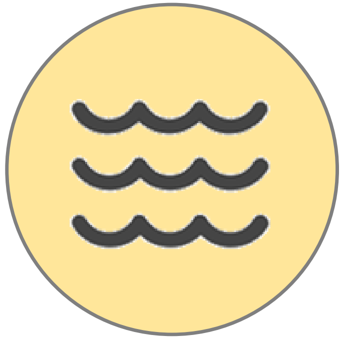
ACTIVITY 1: Natural Hazards and climate projections

- Classification and characterisation of hazards
- Climate projections
- Multiple and cascading hazards and compound events
- Other hazards, human-induced stressors and deterioration mechanisms
- Your country-specific hazards.

Classification and characterisation of hazards

geohazards
(e.g. earthquakes, landslides, volcanic eruptions)

climatic
(e.g. extreme temperatures, hurricanes, wildfires)



environmental & weather
(e.g. floods, rainfall, snowfall)

biohazards
(e.g. bacteria, GMOs)

cyber
(e.g. malware, data breaches, generative AI)

anthropogenic
(e.g. pollution, accidents, contamination)

conflicts
(e.g. wars, political, ethnic/religious)

➡ **threat-agnosticity !**

Classification and characterisation of hazards

- A **natural hazard** is a **natural** phenomenon that **might** have a negative effect on **humans** or the **built/natural environment.**
- **Natural hazards** are the result of naturally occurring processes. In some cases, natural hazards are correlated (**cascading/multiple** hazards), e.g. a tsunami or landslide triggered by an earthquake, a landslide or flood caused by heavy rain








human induced hazards



Classification and characterisation of natural hazards

Geological hazards occur because of geological processes, such as movement in the tectonic plates and volcanic activity: **earthquakes**, **volcanic eruptions**, **lahars**, **landslides**, **mudflows**

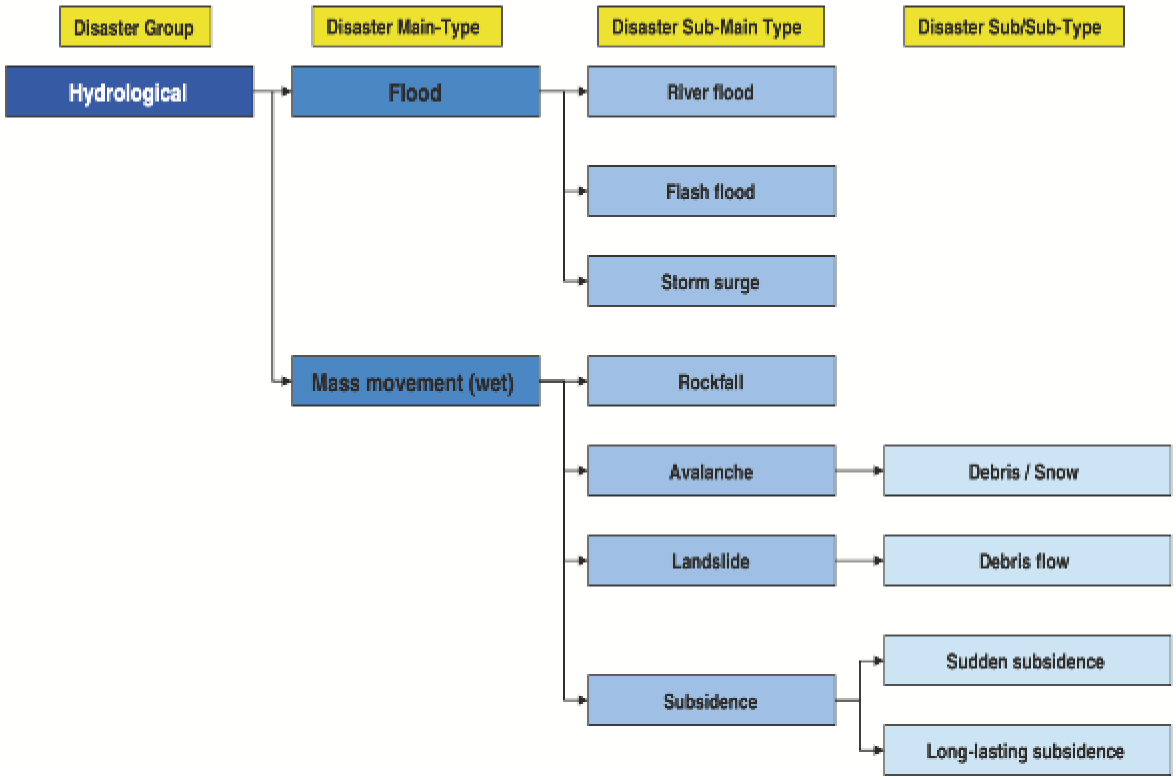
Meteorological hazards occur as a result of processes in the atmosphere: **extreme temperatures**, **hurricanes**, **tornadoes**, **severe storms**, **droughts**

Hydrological hazards are hazards involving water processes: **floods**, **tsunamis**

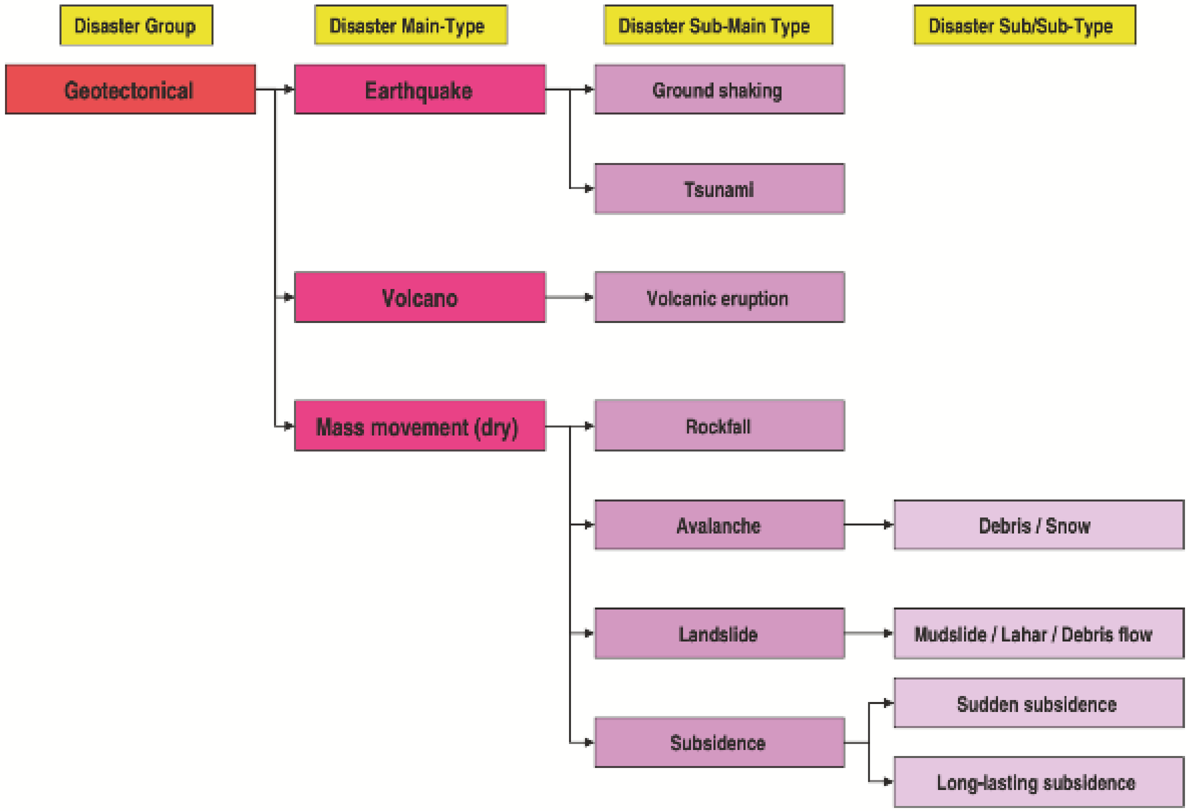
Biological hazards occur due to the biological processes of the earth and primarily involve the spread of diseases and pests: **epidemics**, **pandemics**, **insect swarms**

Classification and characterisation of hazards-examples

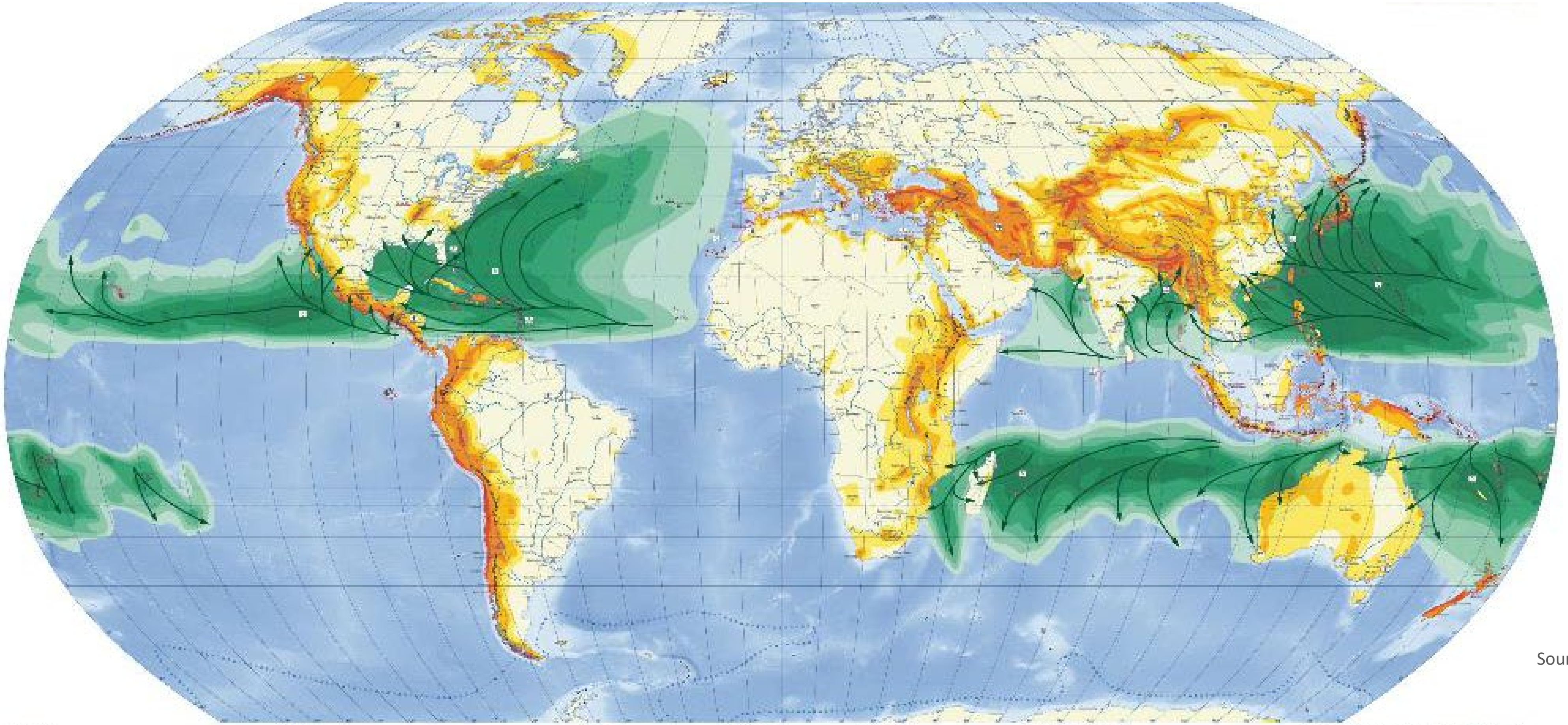
Hydrological



Geotechnical



Natural hazards: Geographical distribution



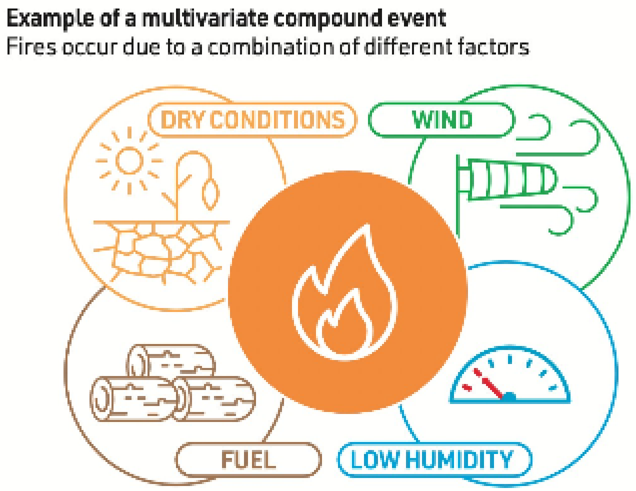
Source : MUNICH RE NATHAN World Map of Natural Hazards

Climate hazards: classification (EU taxonomy)

	Temperature-related	Wind-related	Water-related	Solid-mass related
Chronic	Changing temperature (air, freshwater, marine water)	Changing wind patterns	Changing precipitation patterns and types (rain, hail, snow/ice)	
	Heat stress		Precipitation and/or hydrological variability	Coastal erosion
	Temperature variability		Ocean acidification	Soil Degradation
	Permafrost thawing		Saline intrusion	Soil Erosion
			Sea-level rise	Solifluction
			Water stress	
Acute	Heat wave	Cyclone, Hurricane, Typhoon	Drought	
	Cold wave/frost	Storm (blizzards, dust, sand)	Heavy precipitation (rain, hail, snow/ice)	Avalanche
	Wildfire	Tornado	Flood (coastal, fluvial, pluvial, groundwater)	Landslide
			Glacial lake outburst	Subsidence

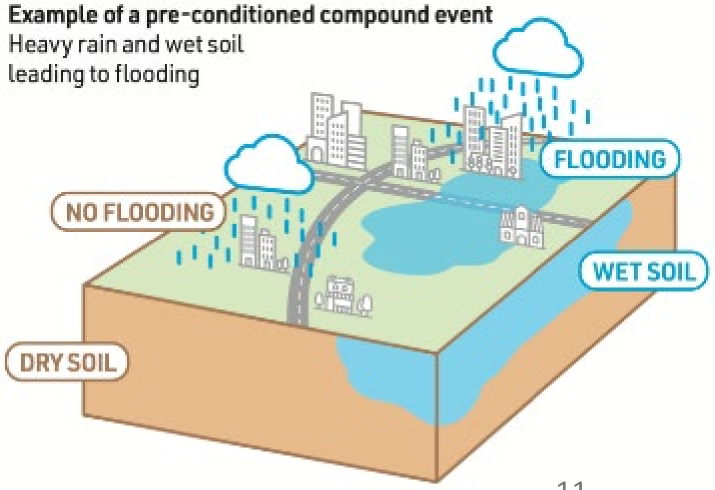
Compound hazards

Compound events occur when multiple climate drivers or hazards, either in one location or across multiple locations, are combined and create greater impacts than isolated events. These can affect ecosystems, infrastructure, public health, and food systems, often straining disaster response efforts.



Example 1 Heat, drought, and wildfires.
A series of compound events stressing communities and ecosystems, causing significant economic damages. Simultaneous heat and drought lead to widespread fires, resulting in infrastructure and property damage, human fatalities, threatened energy and water supplies, and strained firefighting resources. Population is exposed to harmful pollutants in wildfire smoke, impacting public health.

Example 2 Compound flooding
Back-to-back storms can lead to numerous deaths and extensive economic damages. Intense rainfall from hurricanes or tropical storms often results in significant flooding. When one storm follows after another, the cumulative rainfall saturates the soil, causing catastrophic flooding and overwhelming local governance and emergency management systems.



Compound hazards

- **Multivariate**: co-occurring hazards in a location, such as simultaneous precipitation deficits and extreme heat contributed to severe droughts
- **Temporally compounding**: successive hazards in a location, such as destructive wildfires followed by heavy rainfall on burned landscapes, resulted in mudslides and debris flows, damaging ecosystems and infrastructure.
- **Spatially compounding**: similar or disparate hazards occurring simultaneously or within a short time window in multiple locations that are connected by physical processes or complex human and natural systems, such as simultaneous megafires across multiple regions and hurricanes that cause unprecedented demand on emergency response resources
- **Preconditioned:** extreme events superimposed on long-term trends, such as higher sea levels, heavier precipitation, and/or changing storm seasonality causing more frequent and severe coastal flooding
- **Complex events**: non-climatic stressors that exacerbate climate hazards, such as COVID-19, which exacerbated climate-driven food, water, and livelihood insecurities facing Tribes, Indigenous Peoples, and other frontline communities

NCA (2023)

Compound events are expected to become more frequent with continued **climate change.**
The increasing frequency and severity of climate hazards such as extreme heat, heavy precipitation, and severe storms are projected to increase the chances of 1) a sequence of hazards occurring within a short time span and 2) simultaneous independent events in a location or multiple locations.

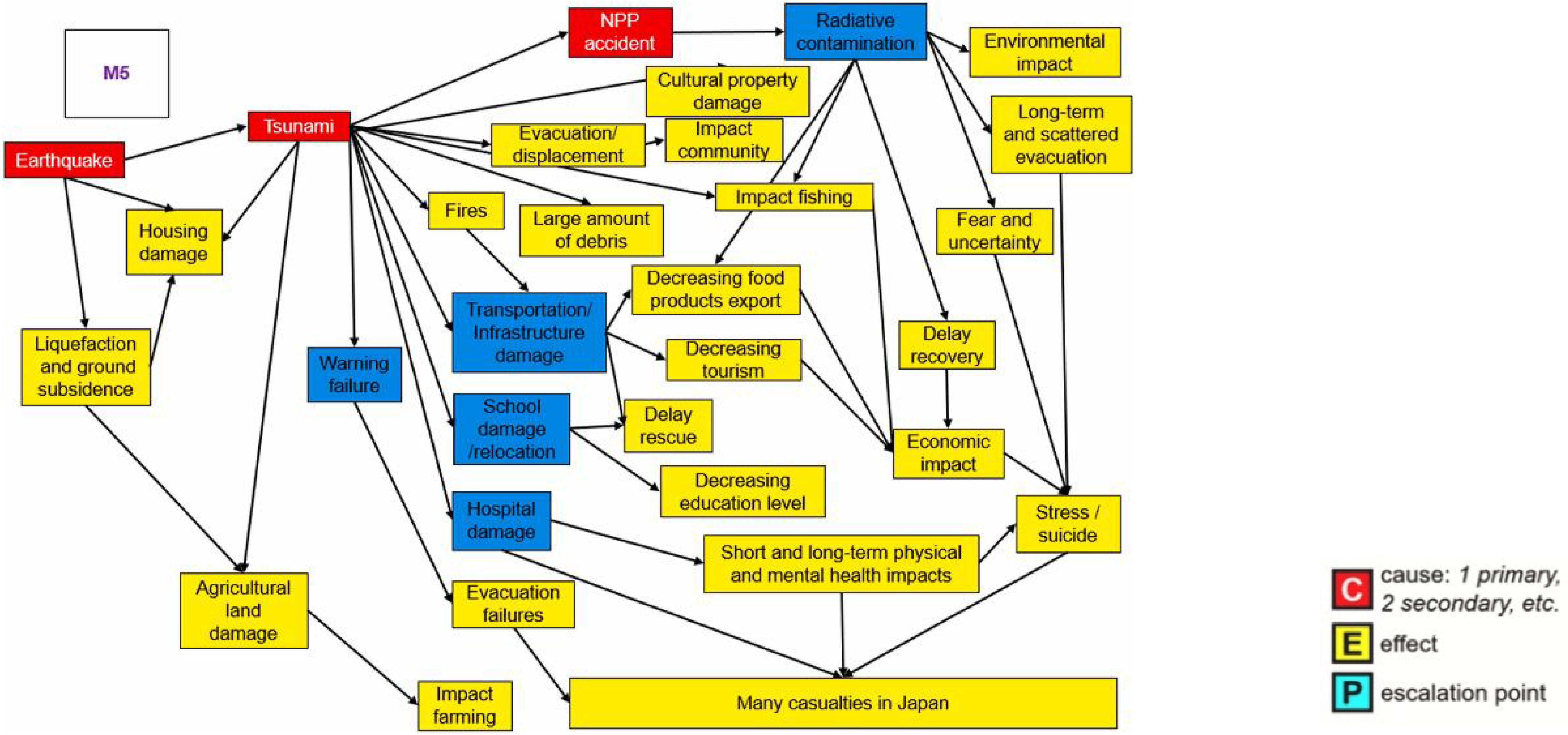
Cascading events

Cascading events refer to a sequence of events where one event triggers another, leading to a chain reaction. These are characterized by:

- **Triggering relationships**: An initial event sets off a series of subsequent events. Each event in the sequence exacerbates the situation.

- **Sequential dependency**: The occurrence of one event depends on the occurrence of a preceding event. This often leads to a domino effect, where the impact grows as the sequence progresses.

Cascading events - example



Cascading impacts of the 2011 Great East Japan Earthquake and Tsunami (Suppasri et al., 2021)

Examples of compound events

Event	Modulators[a]	Associated weather systems	Precondition	Climatic drivers	Hazard(s)	Potential impacts
Preconditioned						
Heavy precipitation on saturated soil	–	Tropical and extratropical cyclones, severe storms, warm conveyor belts[22,23]	Saturated soil	Heavy precipitation	Flood, landslide	Infrastructure
Rain on snow	–	Extratropical cyclones[25,27]	Snow-covered land surface	Heavy precipitation, snowmelt	Flood	Infrastructure
False spring	–	Cold front	Early budbreak due to warm temperatures at end of winter	–	Frost	Crops, natural vegetation
Multivariate						
Compound flooding	–	Tropical and extratropical cyclones	–	Precipitation, coastal water levels, river flow, wind speed, wind fetch, duration of high wind speeds	Flood	Infrastructure, human health
Compound drought and heat	Sea-surface temperature patterns[55]	Atmospheric blocks	–	Temperature, precipitation, evapotranspiration, atmospheric humidity	Drought, heatwave	Wildfire, crops, natural vegetation, power plants, fisheries
Humid heatwave	–	Marine-air advection, tropical moisture export[160]	–	Temperature, atmospheric humidity	Heat stress	Human health, energy demand
Compound precipitation and wind extremes	–	Tropical and extratropical cyclones, severe storms[71]	–	–	Heavy precipitation, extreme wind	Infrastructure
Temporally compounding						
Temporal clustering of precipitation events	Large-scale climate modes[75,86]	Recurrent Rossby waves, blocking	–	Precipitation	Flood	Infrastructure, crops
Temporal clustering of storms	Large-scale climate modes[73,89]	Tropical and extratropical cyclones	–	Precipitation, wind speed	Flood, extreme wind	Infrastructure, human health
Sequences of heatwaves	–	Atmospheric blocks	–	Temperature	Heatwave	Human health, energy demand, crops
Spatially compounding						
Spatially concurrent precipitation extremes/floods at regional scale	Large-scale climate modes[illegible]	Storms, atmospheric blocks	–	Precipitation	Heavy precipitation, flood	Regional trade, (re-)insurance, shipping, emergency response
Spatially co-occurring climate extremes at global scale	Large-scale climate modes[33], circumpolar wave patterns[illegible]	Dependent on the type of extremes	–	Temperature, precipitation, evapotranspiration, atmospheric humidity	Heavy precipitation, flood, drought, heatwave, frost	Global food system, globally operating (re-) insurance

Zscheischler et al. (2020)

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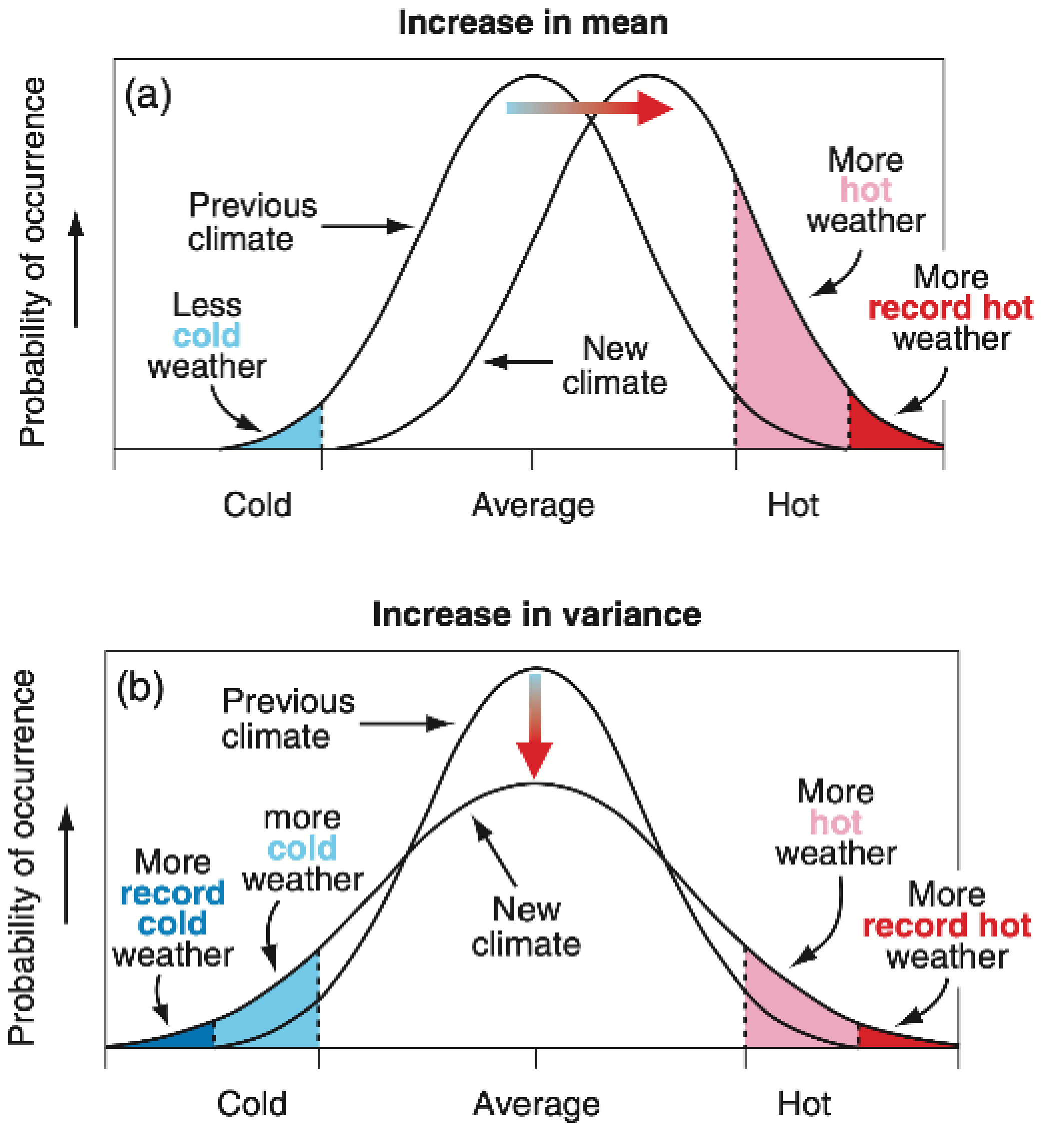
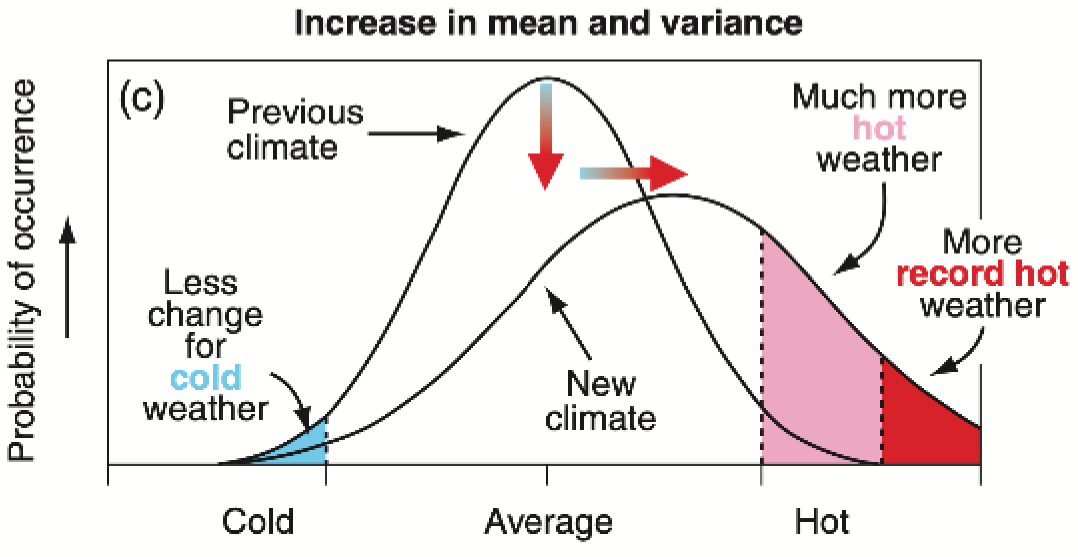
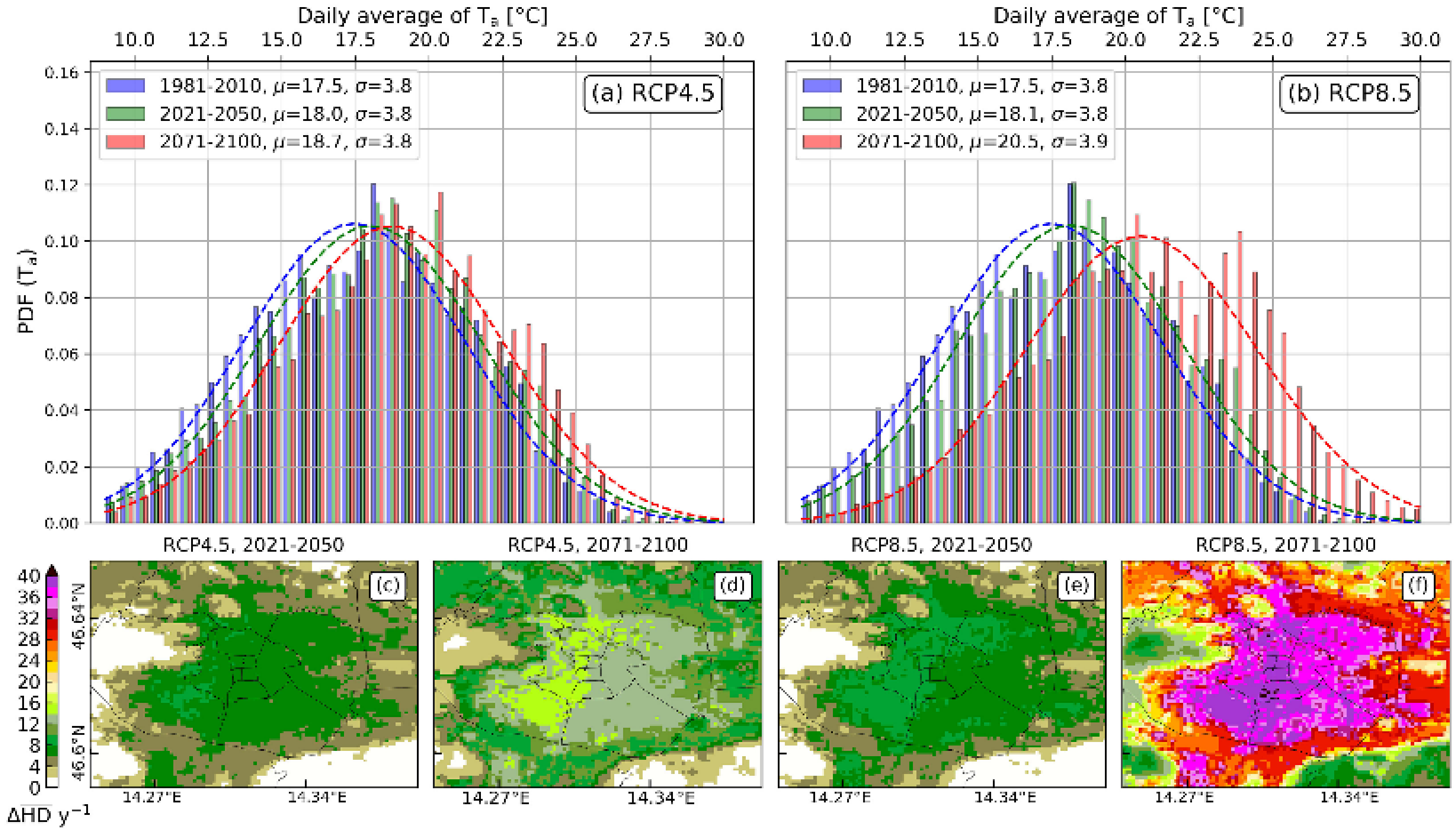
Climate exacerbations and stress-testing





Schematics showing the effect on extreme temperatures when (a) the mean temperature increases, (b) the variance increases, (c) when both the mean and variance increase for a normal distribution of temperature *(IPCC, 2001)*

Climate projections

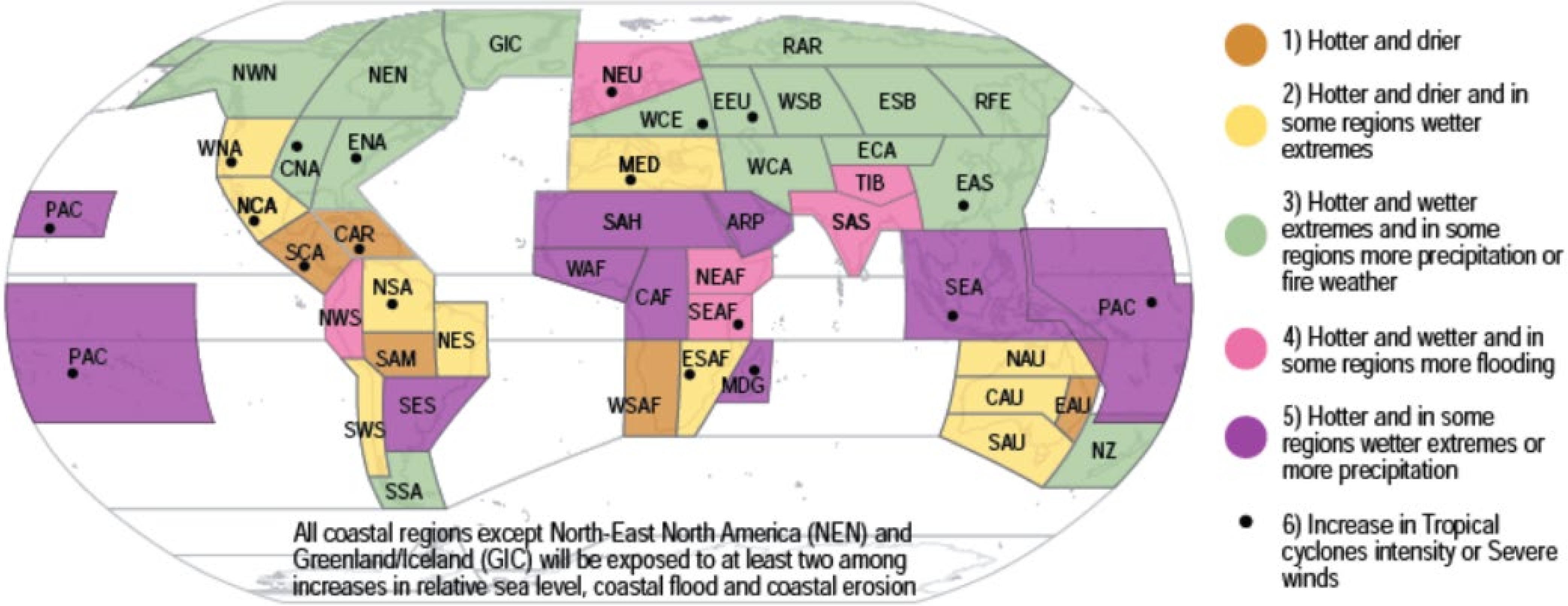


Future climate projections shown as a probability density function (PDF) of the air temperature (Ta) taken from the bias-corrected EURO-CORDEX data set for Representative Concentration Pathways (RCP) of (a) RCP4.5 and (b) RCP8.5 for the extended summer season (MJJAS) *(Oswald et al. 2020)*

Climate exacerbations

(a) World regions grouped into five clusters, each one based on a combination of changes in climatic impact-drivers

Assessed future changes: Changes refer to a 20–30 year period centred around 2050 and/or consistent with 2°C global warming compared to a similar period within 1960–2014 or 1850–1900.



IPCC (2021)

Climate exacerbations

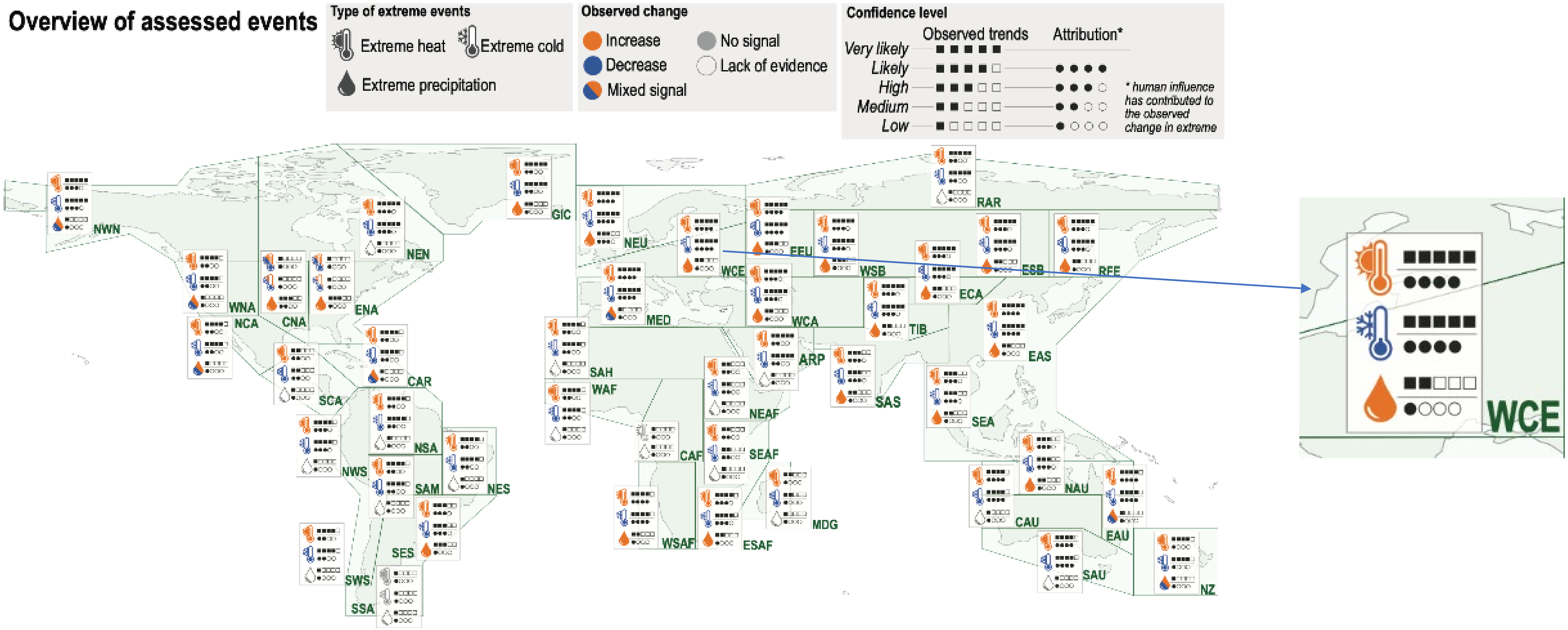


Figure 11.4 | Overview of observed changes for cold, hot, and wet extremes and their potential human contribution. Shown are the direction of change and the confidence in: 1) the observed changes in cold and hot as well as wet extremes across the world; and 2) whether human-induced climate change contributed to causing these changes (attribution). In each region changes in extremes are indicated by colour (orange – increase in the type of extreme; blue – decrease; both colours – changes of opposing direction within the region, with the signal depending on the exact event definition; grey – there are no changes observed; and no fill – the data/evidence is too sparse to make an assessment). The squares and dots next to the symbol indicate the level of confidence for observing the trend and the human contribution, respectively. The more black dots/squares, the higher the level of confidence. The information on this figure is based on regional assessment of the literature on observed trends, detection and attribution and event attribution in Section 11.9.

IPCC (2021)

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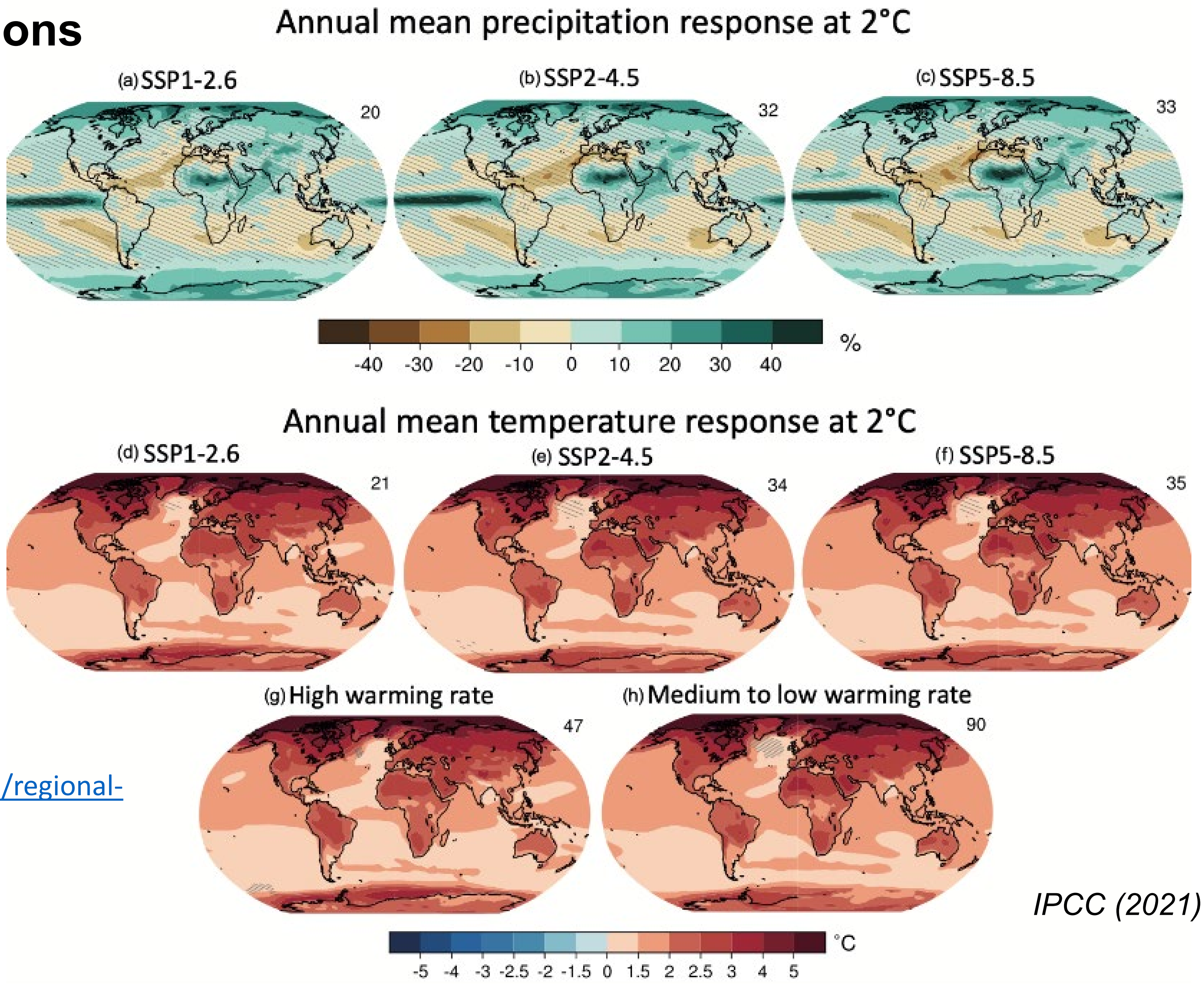
Climate exacerbations



See also ipcc Interactive Atlas:

https://interactive-atlas.ipcc.ch/regional-information

IPCC (2021)

Natural disasters

Impacts of natural hazards on built environment

- Is the effect of a natural hazard on **people and activities**, as well as on the **built and natural environment**

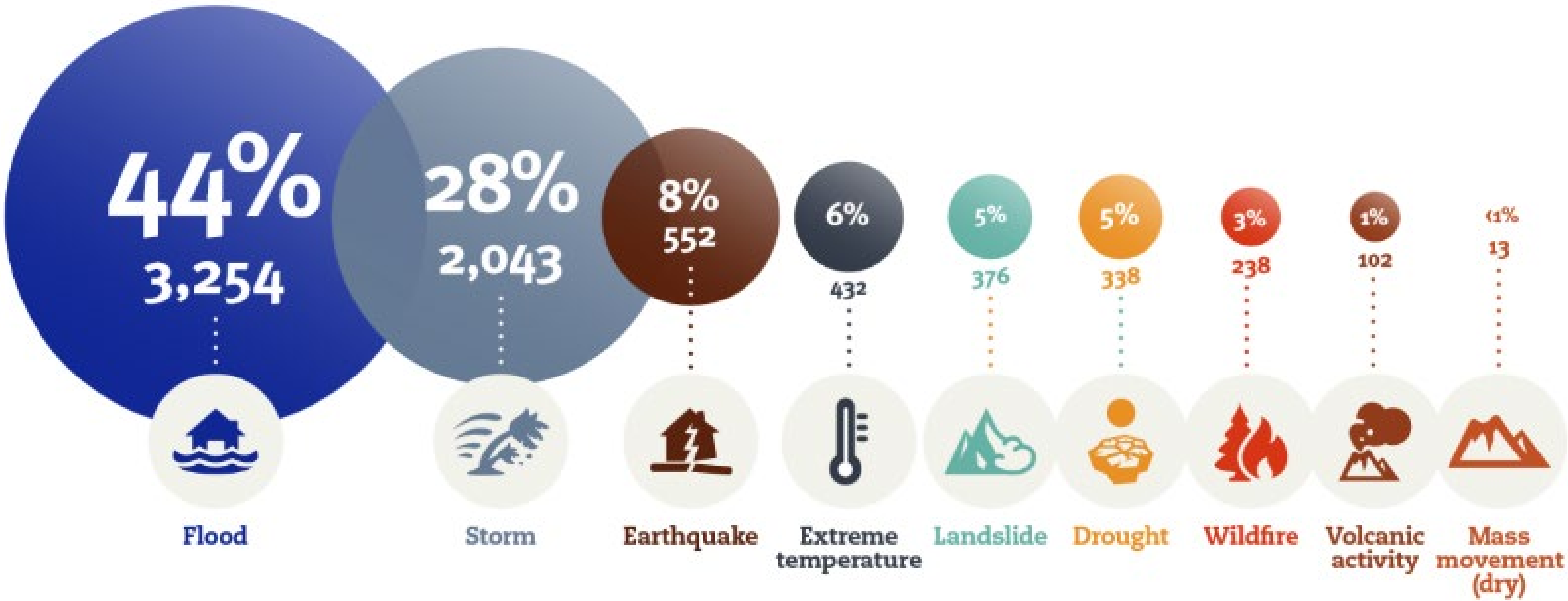
  eg a flash flood will not have any consequences in a non inhabited area (non-catastrophic hazard)


- A natural disaster can cause <u>**loss**</u> of life or property damage and typically leaves some economic damage in its wake. Its severity depends on the **resilience** of the society and infrastructure and their ability to quickly recover **recover**.

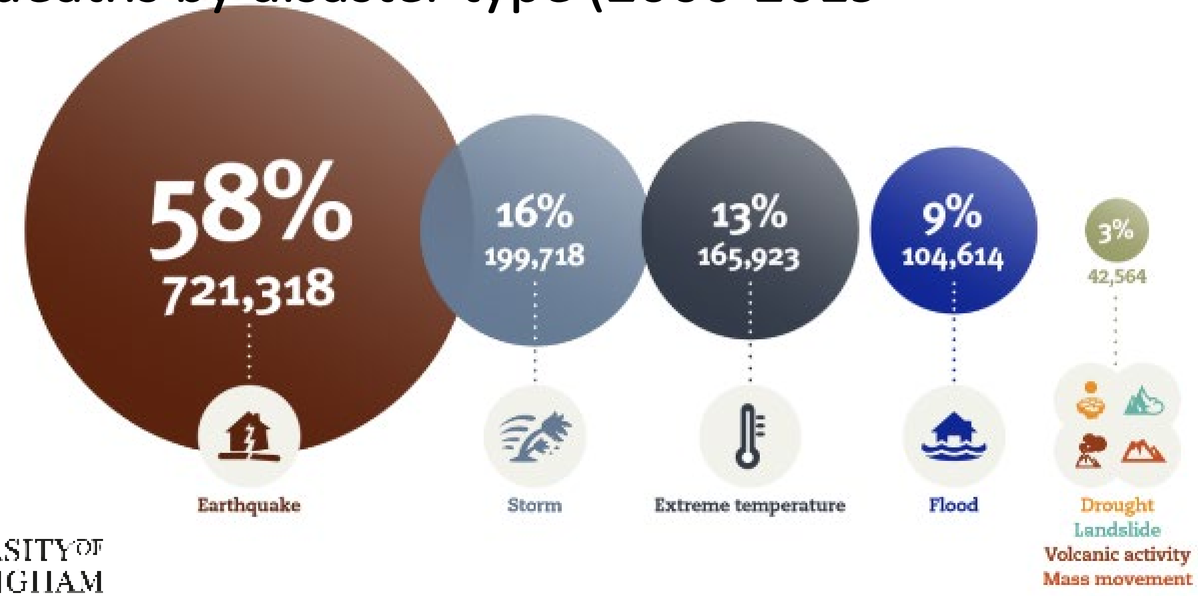
  Therefore, its severity depends on the **robustness**, **preparedness** and **resourcefulness** of the infrastructure, the services and the society.


Which factors may aggravate losses due to natural hazards?

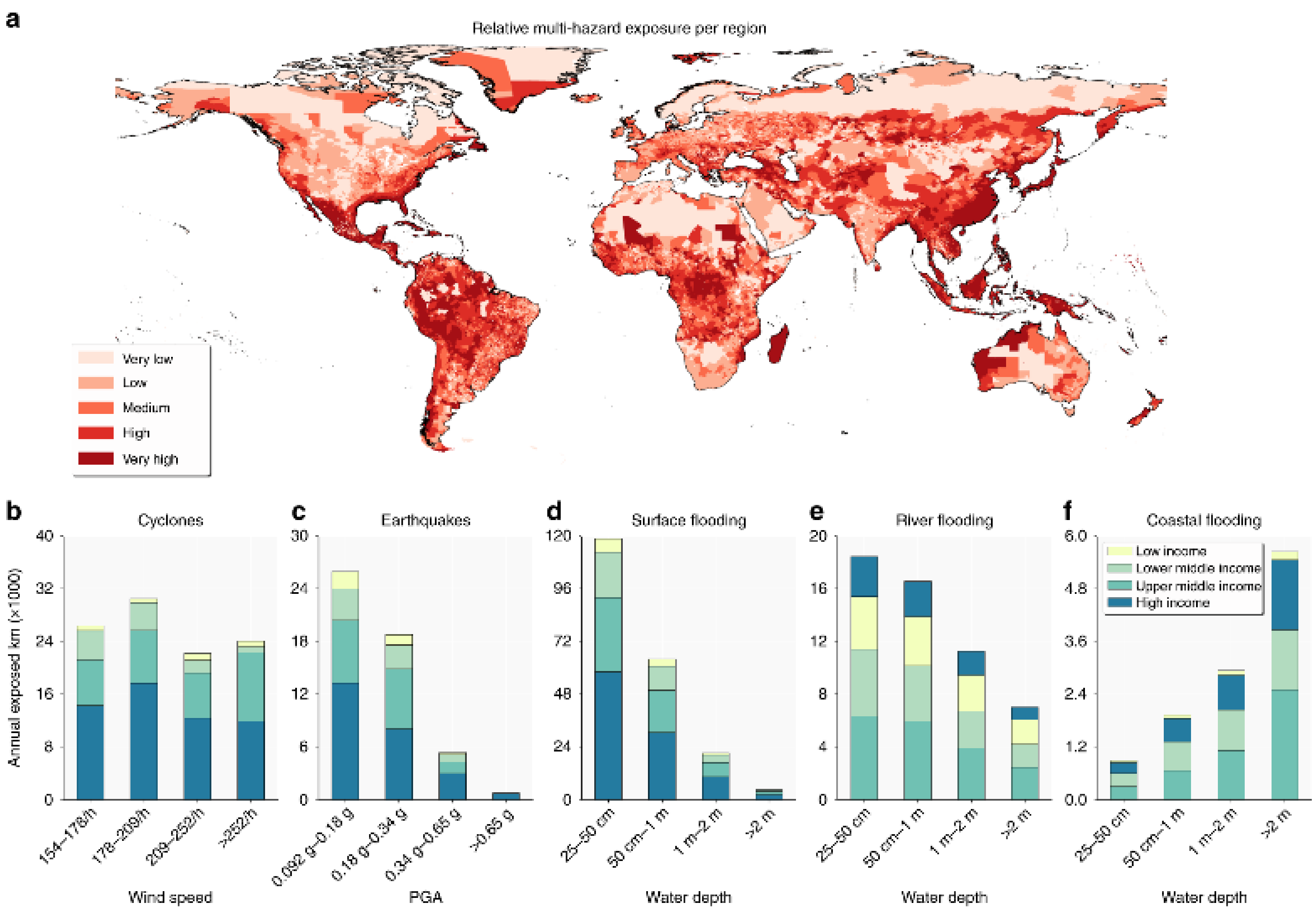
Percentage of occurrences of disasters by disaster type (2000-2019)



Total number of deaths by disaster type (2000-2019



Global multi-hazard transport infrastructure exposure



Koks et al. (2019)

~27% of the network is exposed to at least one hazard with a 1/250 return period

~7.5% of the road and railway assets are exposed to a 1/100 years flood event

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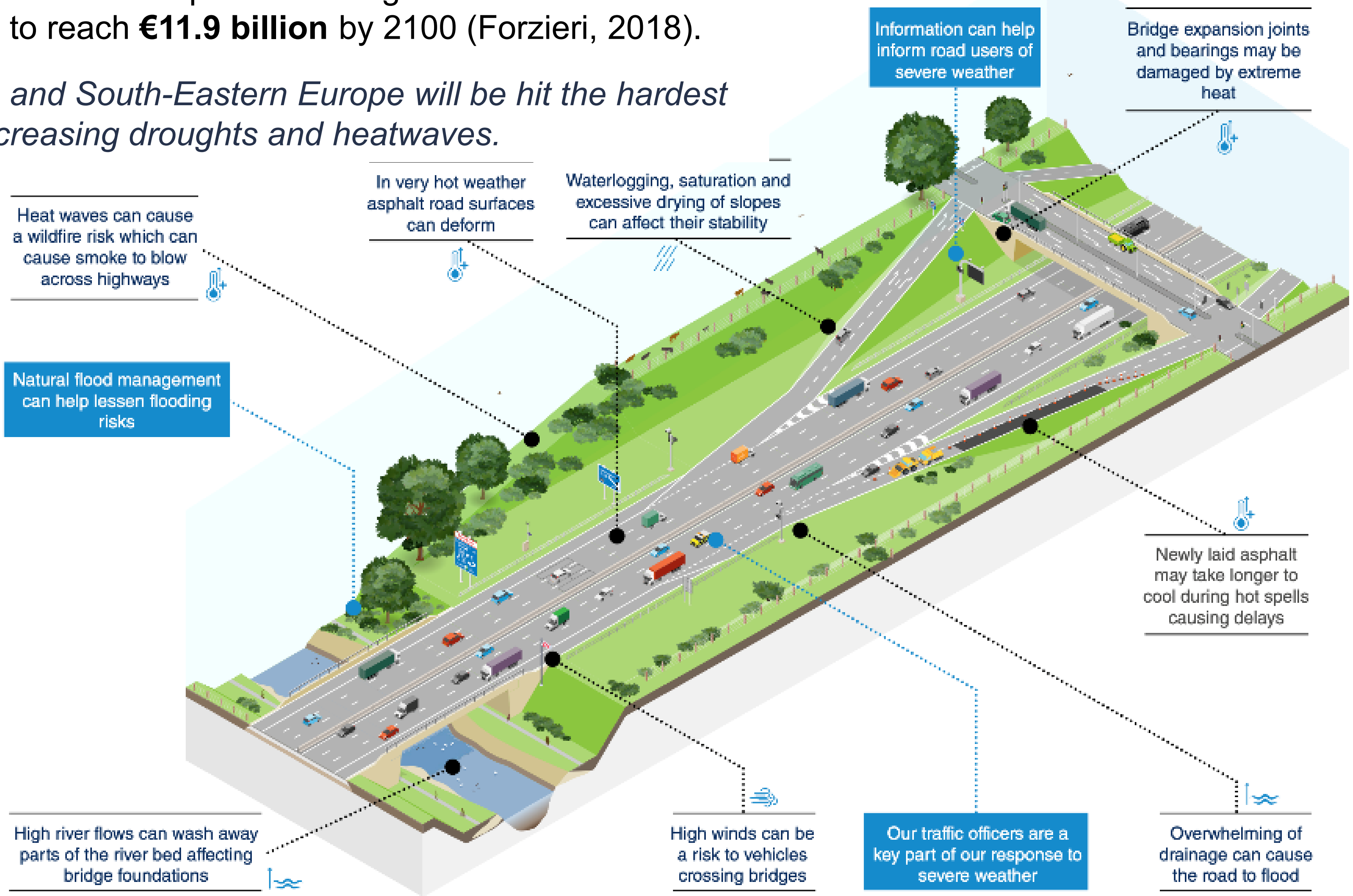
Climate change impacts on transport infrastructure

The current annual expected damage of **€0.8 billion** is expected to reach **€11.9 billion** by 2100 (Forzieri, 2018).

Southern and South-Eastern Europe will be hit the hardest due to increasing droughts and heatwaves.



National Highways (2022)

Impact of interdependent hazards on bridges and road networks

	G1	G2	G3	G4	G5	M1	M2	M3	M4	M5	C1	C2	C3	C4	C5
Earthquake (G1)	×	⇒	⇒	⇔	—	—	—	—	⇒	—	—	—	—	—	—
Tsunami (G2)		×	⇒	⇐	—	—	⇒	⇒	⇒	⇒	—	—	—	—	—
Landslide/rockfall (G3)			×	⇐	—	⇐	⇐	⇐	⇔	⇐	—	⇐	—	⇐	⇐
Volcanic eruption (G4)				×	⇒	—	⇒	—	⇒	—	⇒	⇒	—	—	—
Volcanic ashfall (G5)					×	—	—	—	—	—	—	⇒	⇒	—	—
Extratropical cyclones, windstorms (M1)						×	⇒	⇒	⇒	⇒	—	⇒	—	—	—
Storm surge, coastal floods, wave loading (M2)							×	⇒	⇒	⇒	—	—	—	—	—
River floods (fluvial), pluvial (M3)								×	⇔	⇒	—	⇐	—	⇐	⇐
Avalanches, debris flow, rockfall (M4)									×	⇐	—	⇐	—	⇐	—
Coastal erosion (M5)										×	—	—	—	⇐	⇐
Extreme temperatures (low/high) (C1)											×	⇔	⇔	⇒	—
Wildfire (C2)												×	⇔	—	—
Drought, heat waves (C3)													×	—	—
Sea-level rise (C4)														×	—
Frequent/intense precipitation (C5)															×

× Same hazard

⇒ The hazard of the relevant line can lead to the hazard of the column

⇐ The hazard of the relevant column can lead to the hazard of the line

⇔ Both hazards can cause the other hazard

— No interaction between hazards

Minor consequence

Moderate consequence

Severe consequence

Mitoulis et al., 2022

Power sector vulnerability to natural disasters

Type	Earthquake	Cyclone	Flood	Tsunami	Wildfire	Drought	Extreme Heat
Thermal plants	High	High	Medium	High		High	Medium
Hydropower plants	High	Low	Medium	Low		High	Medium
Nuclear plants	High	Medium	Medium	High		High	Medium
Solar (PV)	Low	High	Medium	Medium		Medium	Very low
Wind	High	Medium	Low	Medium		Very low	Very low
T&D lines	Medium	High	Low	Medium	High	Medium	Medium
Substations	High	High	High	Medium	High	low	Medium

2019 International Bank for Reconstruction and Development / The World Bank

Why?

- lack of disaster risk management capacities
- ageing and poorly maintained assets
- poorly designed networks without adequate level of redundancy

Climate change impacts on energy infrastructure

Tower rupture-snowstorm


Germany, 2005

Tower rupture-windstorm

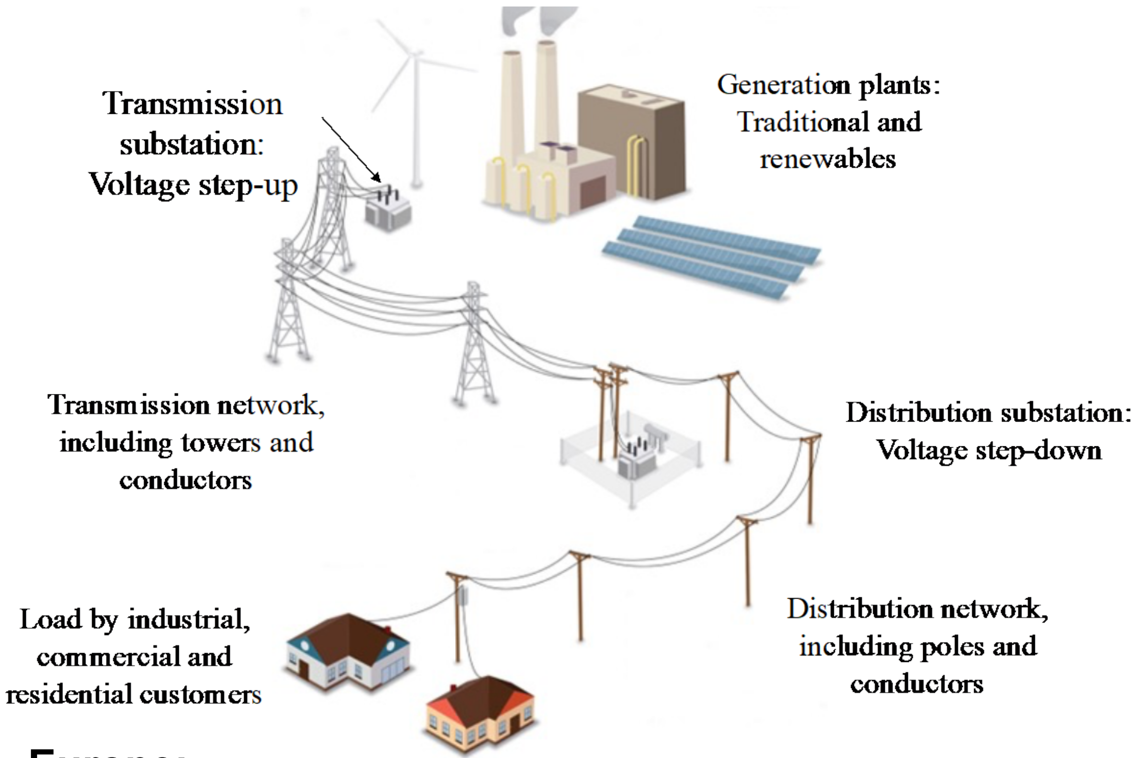

Poland, 2017

Substations-flood


Germany, 2021

Substations and towers-flood


Greece, 2023



Europe:

- 509,000 km **transmission network** and 25,400 **substations** **(**ENTSO-E, 2023)
- **22% of accidents due to climate hazards** (ENTSO-E, 2022)
- **€14.5bn** annual losses in the EU infrastructure in 2010-2020 (Eurostat)
- **€8.2bn** by 2080 only due to **climate change (**Forzieri et al. 2018)

Your country-specific hazards.

Investigation & production:

- Describe in a ~300 word essay the critical hazard(s) in your area/country and give examples of impacts on transport and/or energy infrastructure, including compound and cascading effects

ACTIVITY 2: Fragility and vulnerability

- Fragility models
- Vulnerability and loss models
- Use of fragility models

Terminology

Elements at risk

population, natural and built environment (structures, infrastructure, networks), activities (social, economic etc).







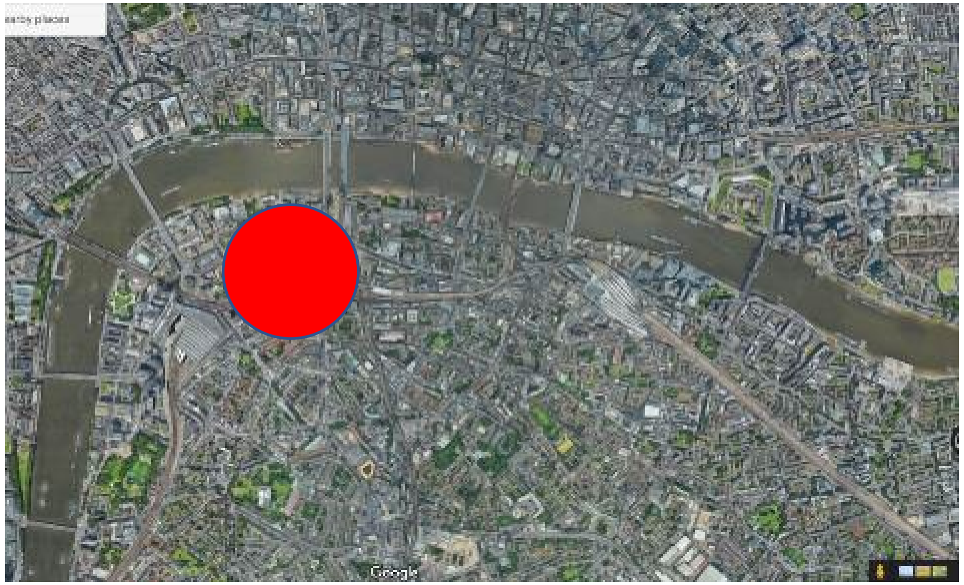

Terminology

Exposure

The status of **people**, **infrastructure**, **housing**, **production** capacities and other **tangible** human assets located in hazard-prone areas.

Measures of exposure can include: number of people, number & importance of assets

Central London



Rural areas

Same hazard intensity different exposure and disruption

Terminology

Exposure - example

London Tower Bridge

Local bridge (Shalford)

Different:

Average daily traffic

Activities in the surrounding area

Cost of repair

Historical importance….

Tools for identifying exposure?

Terminology

- **Hazard:** It is characterised by its location, intensity or magnitude, frequency and probability. Usually described by the **probability** that a hazard intensity (e.g. water discharge or velocity for flood, PGA for earthquake etc) will **exceed a given value, within a certain period** of time and location.
- **Vulnerability:** The conditions determined by physical, social, economic and environmental factors or processes which increase the susceptibility of an individual, a community, assets or systems to the impacts of hazards. The vulnerability of an asset (e.g. a bridge) depends on its structural type, geometry, material etc.
- **Exposure:** The values, infrastructure, connectivities, humans, businesses etc that are present at the location

RISK = **HAZARD** x **VULNERABILITY** x **EXPOSURE**

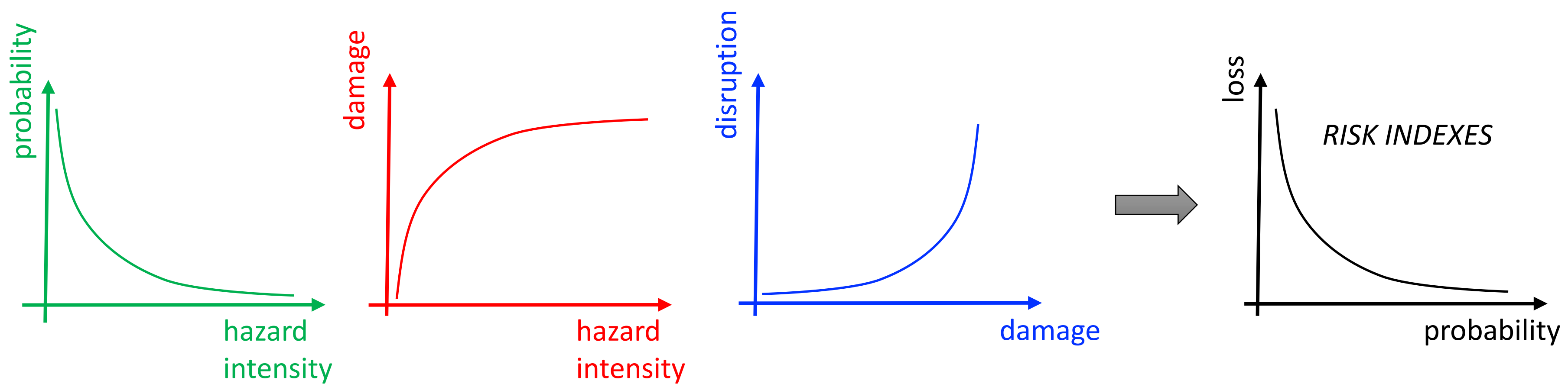
Risk: The potential loss of **life**, **injury**, or destroyed or damaged **assets** which could occur to a **system**, **society** or a **community** in a specific period of time, determined probabilistically as a function of hazard, vulnerability (e.g. structural capacity) and exposure.

Quantitative Risk Analysis (QRA)

Risk analysis for portfolios of infrastructure and networks to given hazards

When dealing with risk analysis it is required to characterize:
the **hazard** of the site,
the **vulnerability** of the analyzed asset, system or network
and the **exposure** in terms of potential impact of damage.

HAZARD x **VULNERABILITY** x **EXPOSURE** = **RISK**

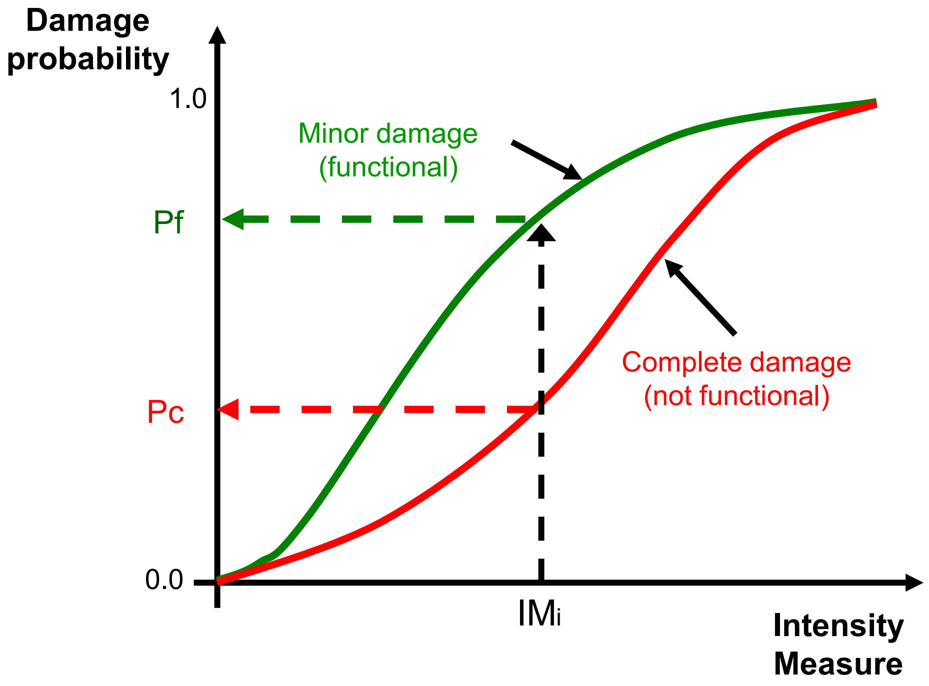


With **R=HxVxE**, it is possible to compute **risk indexes** to **quantify risk levels** and then compare against acceptable **thresholds** (set by infrastructure owners)

Fragility functions

A fragility function specifies the **probability of a state of damage** (e.g. minor, moderate, extensive damage, collapse) of an engineering component (e.g. pier, foundation) or asset (e.g. bridge, tunnel) subjected to hazard stressors (e.g. water flow, ground movement).

It is commonly expressed as a lognormal cumulative distribution function of a representative **Intensity Measure (IM)**, such as water depth, scour depth, water velocity, ground settlement etc.



Developed with different approaches:

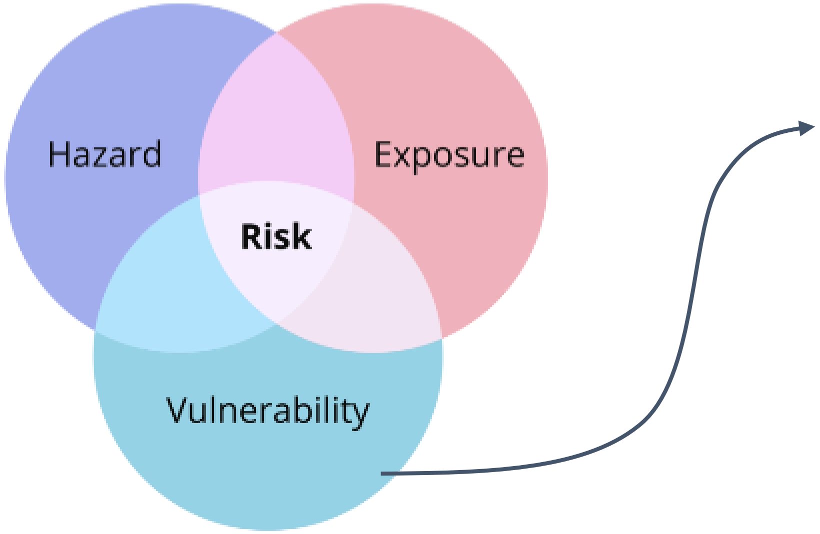
- **Empirical (observed data)**
- **Expert judgment (elicitation data)**
- **Analytical (numerical simulation)**
- **Hybrid (combination of above)**

Commonly & typically expressed with lognormal functions

The need for climate aware fragility models

As **climate change** is likely to increase the frequency and intensity of this type of events, improving the resilience of our infrastructure to natural disasters is becoming essential for economic well-being and quality of life.

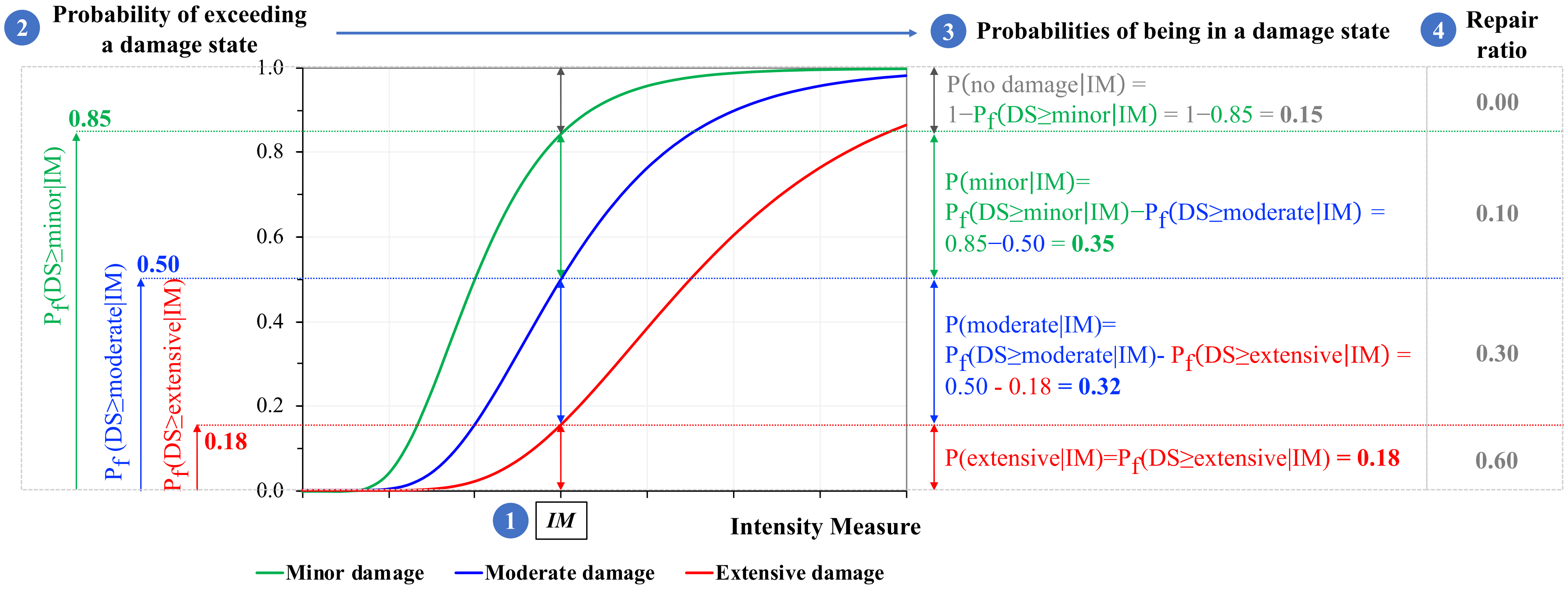
Low-frequency, high-impact events are rarely considered fully in the design of power and transport infrastructure. The implementation of planned management measures is often inadequate.



To improve our understanding of infrastructure vulnerabilities, robust **fragility models are needed**.

Fragility models are useful tools for vulnerability (and loss) assessment of critical infrastructure, and hence, contribute to quantification of infrastructure resilience.

Fragility functions



5 Loss ratio

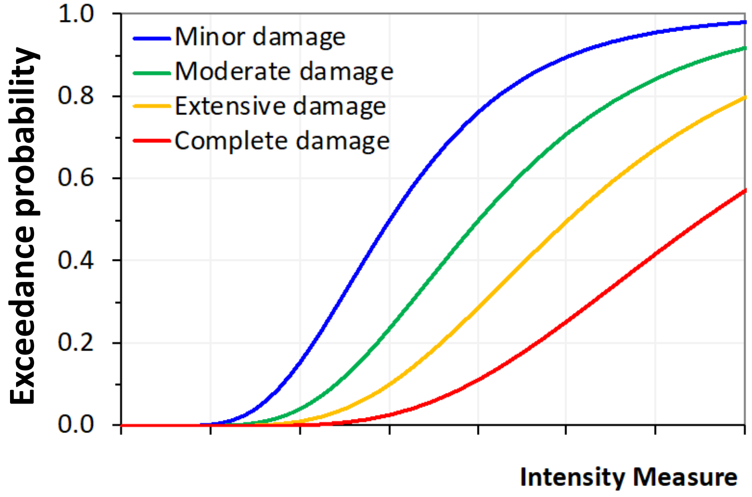
0.15x0.0+0.35x0.10+0.32x0.30+0.18x0.60=**0.239**

6 Direct loss

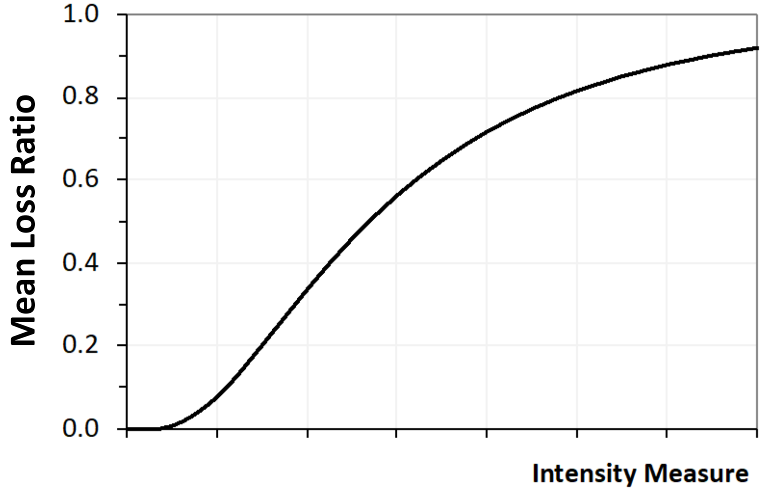
Loss ratio x Replacement cost* = 0.239x 500,000 £

=119,500 £

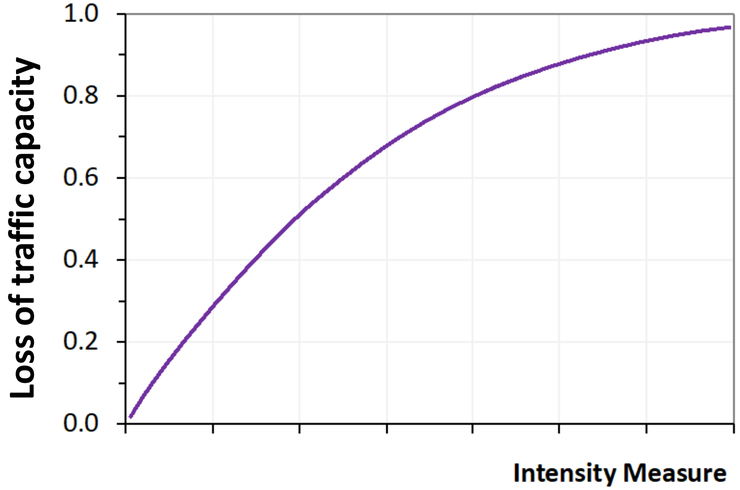
Fragility and vulnerability functions



fragility functions



vulnerability function



functionality loss function

Argyroudis S, Mitoulis SA, Winter M, Kaynia AM (2019). Fragility of transport assets exposed to multiple hazards: State-of-the-art review toward infrastructural resilience. Reliability Engineering and System Safety, 191, 106567.

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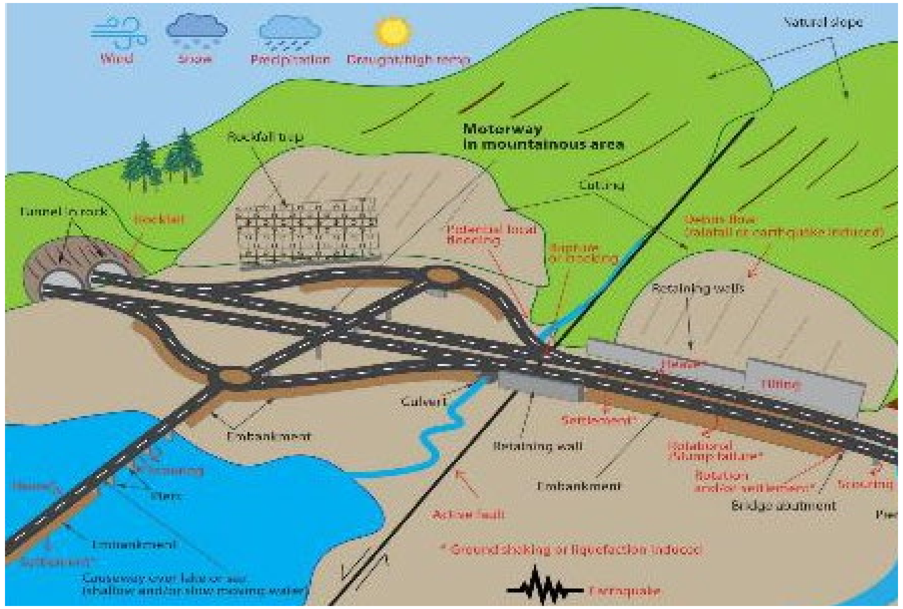
Correlation of damage and functionality

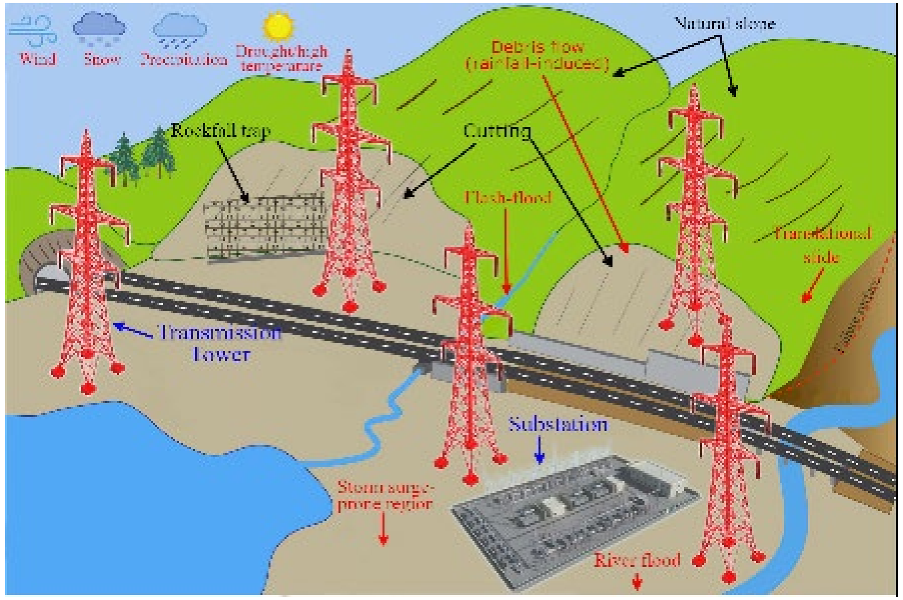
Damage state	Post-damage functionality
No damage	100%
Minor damage	75%
Moderate damage	25%
Extensive damage	10%
Complete damage	0%

FEMA US (2009) for road bridges

Depends on type of infrastructure and infrastructure operator decision, which is influenced by political decisions, redundancies, peoples' reaction etc

Challenges and research needs in fragility modelling



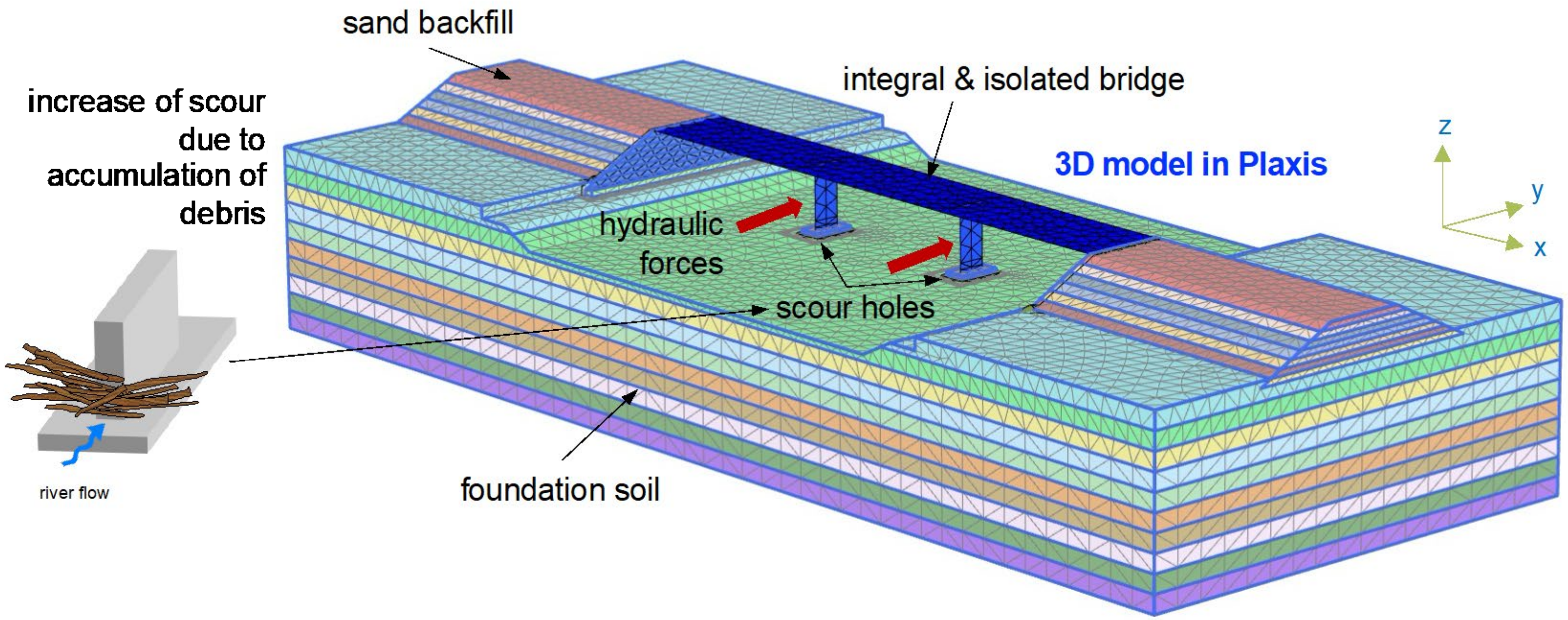


Challenges:

- **Data availability** on extreme weather events and their impacts
- Modelling of **combined hazards**
- **Uncertainties** in climate change
- **Asset** specific vs. **portfolios** of assets fragility
- Integration of **adaptation** strategies
- **Interdependencies** of assets and systems, **cascading** effects

Argyroudis S, Mitoulis SA, Winter M, Kaynia AM (2019).
Reliability Engineering and System Safety

Fragility models based on detailed numerical modelling - Bridges

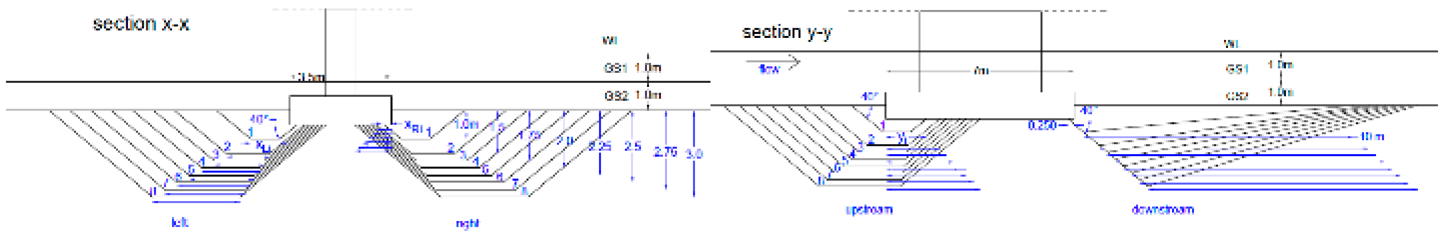


System of Assets: bridge-embankments-foundation soil

Hazards: flood/scour, hydraulic forces

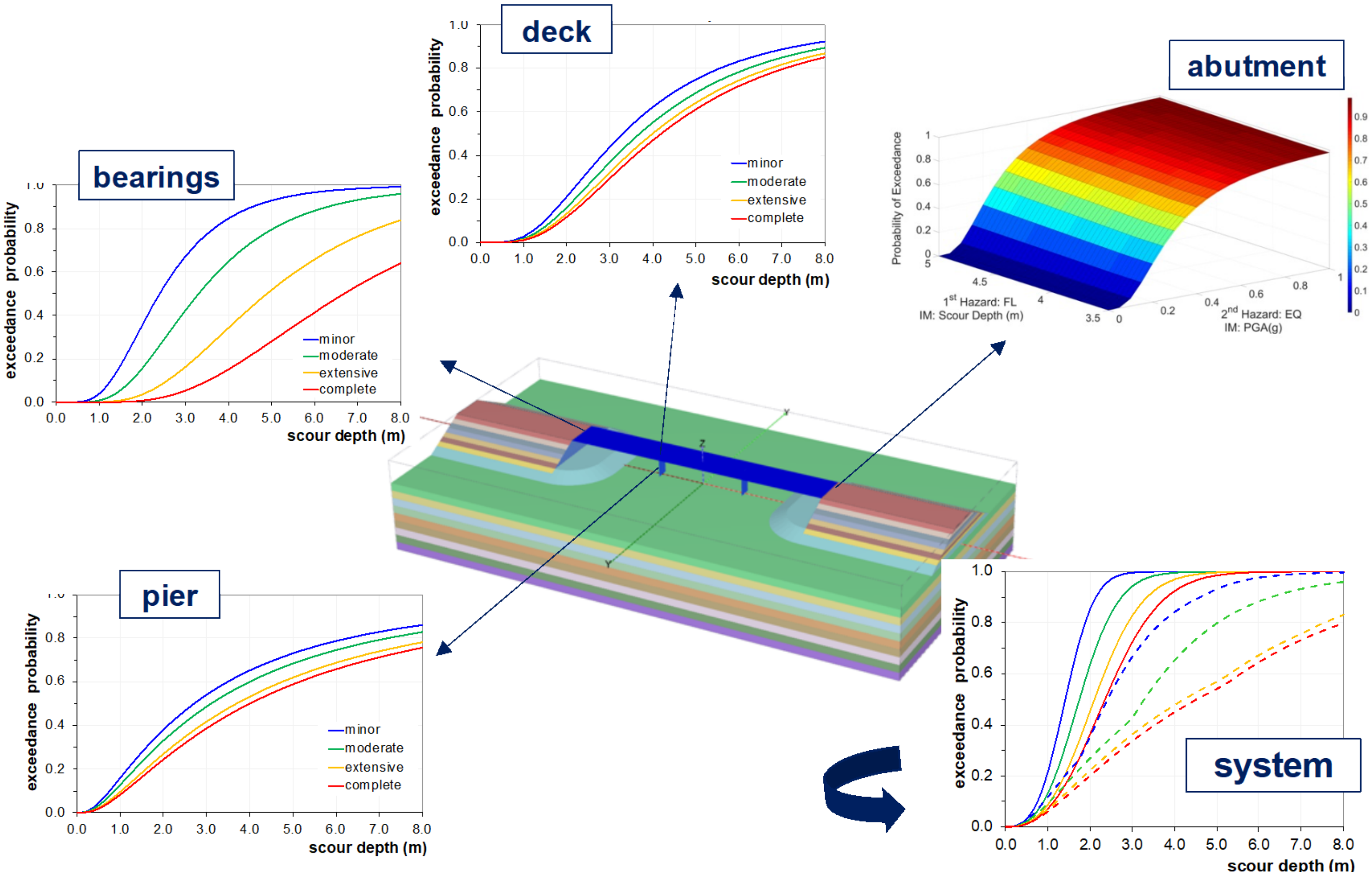
IM: scour depth (m)

Scour models with variable geometries



Argyroudis and Mitoulis (2021)

Fragility models based on detailed numerical modelling – Bridge specific



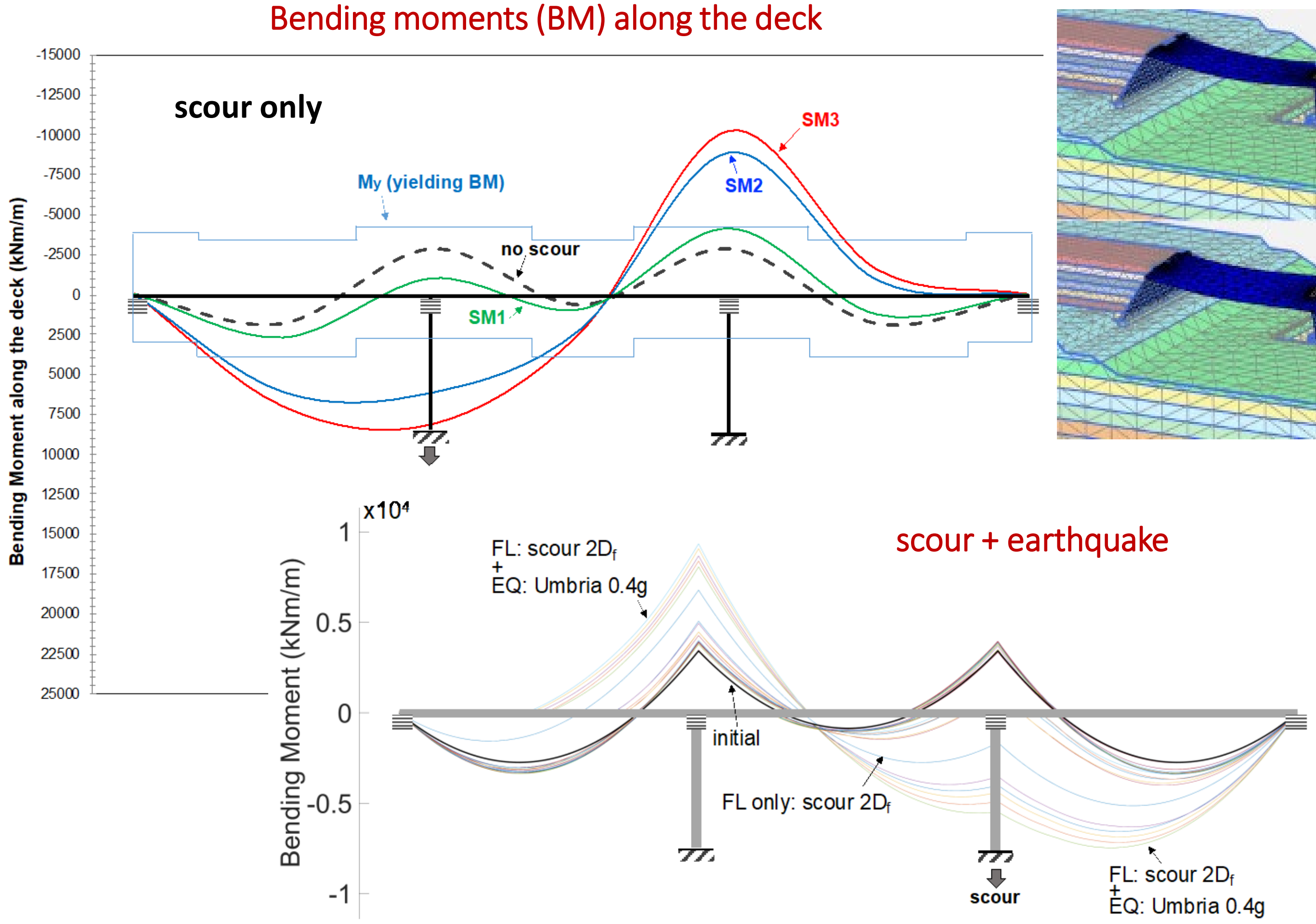
Argyroudis SA, Mitoulis SA (2021). Reliability Engineering and System Safety

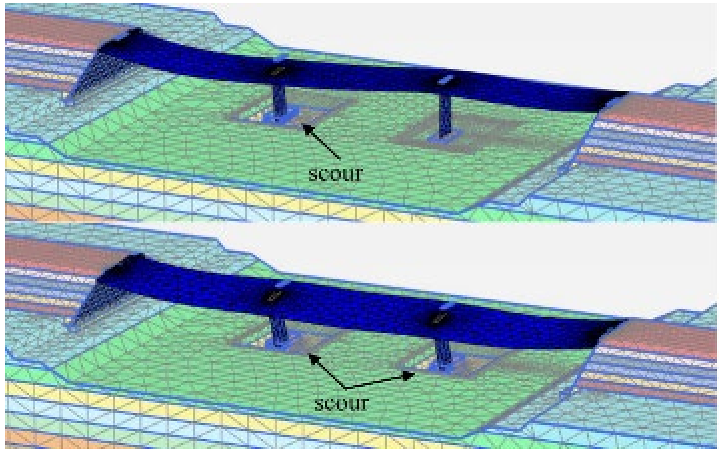
System of Assets: bridge-embankments-foundation soil

Hazards: flood/scour, hydraulic forces

IM: scour depth (m)

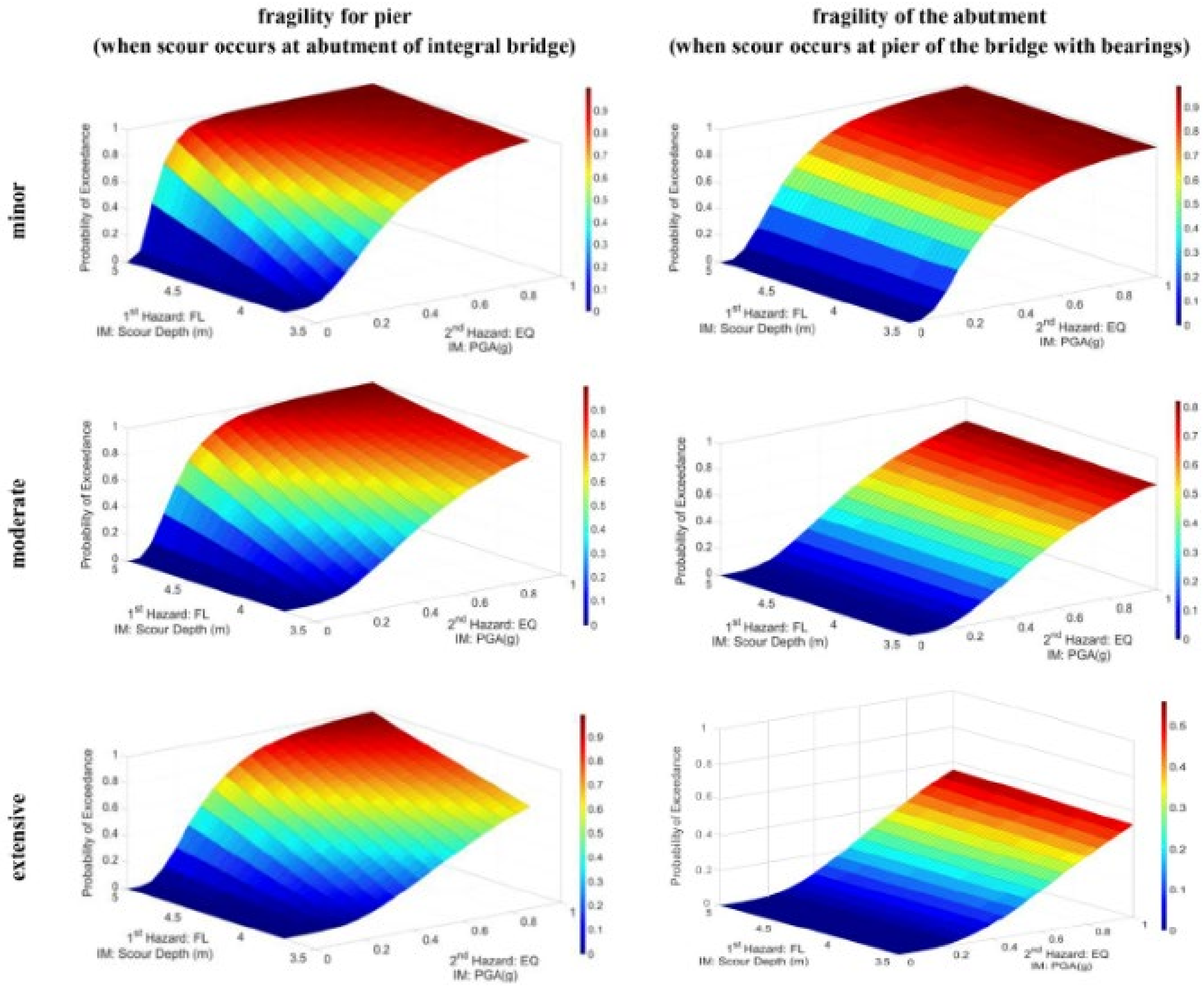
Fragility functions for transport assets under multiple hazards





Argyroudis SA, Mitoulis SA (2021). Vulnerability of bridges to individual and multiple hazards – floods and earthquakes, Reliability Engineering and System Safety, https://doi.org/10.1016/j.ress.2021.107564

Fragility functions for transport assets under multiple hazards



Argyroudis SA, Mitoulis SA (2021). Vulnerability of bridges to individual and multiple hazards – floods and earthquakes, Reliability Engineering and System Safety, https://doi.org/10.1016/j.ress.2021.107564

Typology & Classification

Classification

Bridges with similar characteristics are considered to be of the same **class**

Engineered assumption

Bridges having similar characteristics and similar geotechnical conditions are expected to perform similarly for a given hazard intensity

Vulnerability factors toward representative typologies

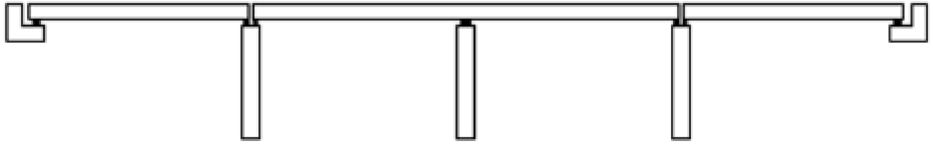
Usual **typology** parameters that reflect the vulnerability:

Geometry, material properties, morphological features, age, design level, soil conditions, foundation details…

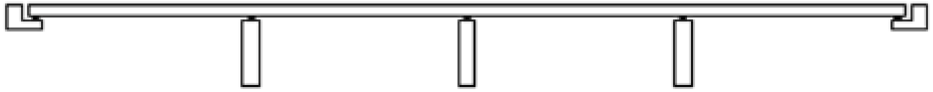
Fragility curves for each typology of assets

What if you have 1000 assets?

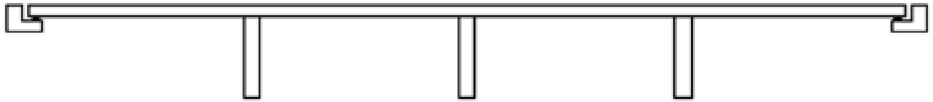
common bridge typologies



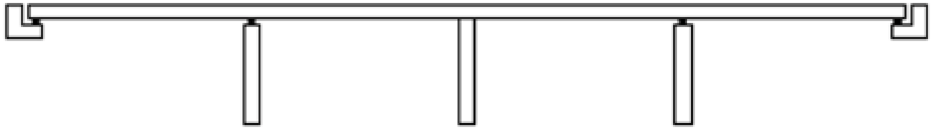
Simply supported (internal hinges) through bearings



Continuous, supported through bearings



Continuous, monolithically connected to piers



Continuous, combination of monolithic and bearing connections

One-span bridge supported through bearings

Fragility curves for each typology of bridges

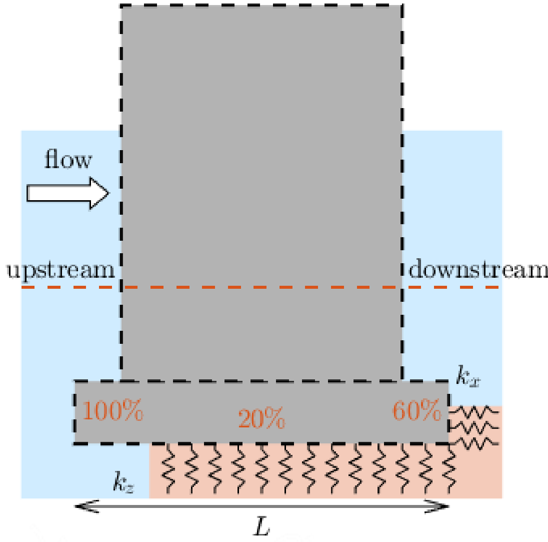
Flood fragility models based on simplified numerical modelling – portfolio of bridges

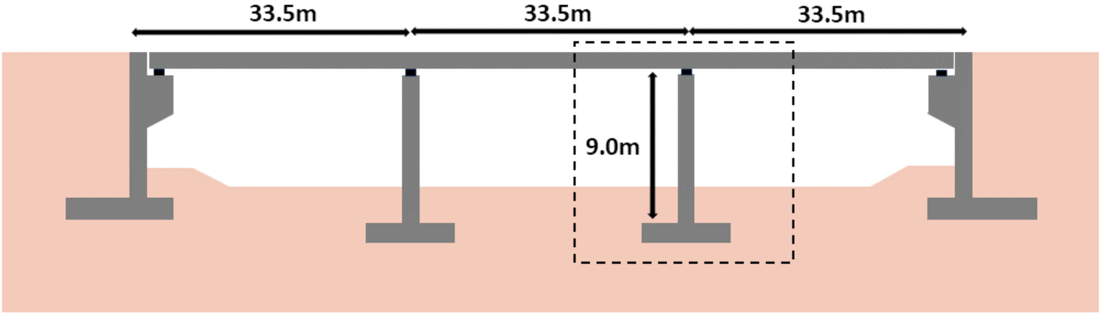
Unified **quantitative** bridge flood fragility framework

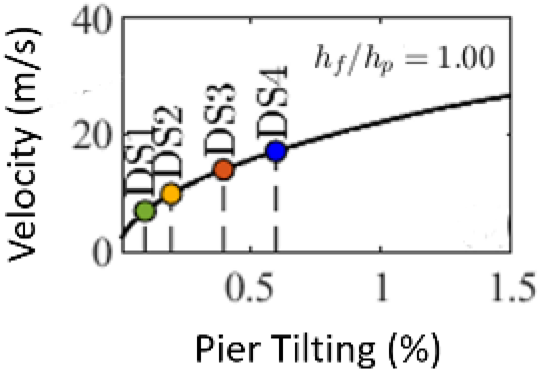
- ❑ Suitable for flood fragility assessments with:
- ✓ Specific bridge assets
- ✓ Bridge portfolios

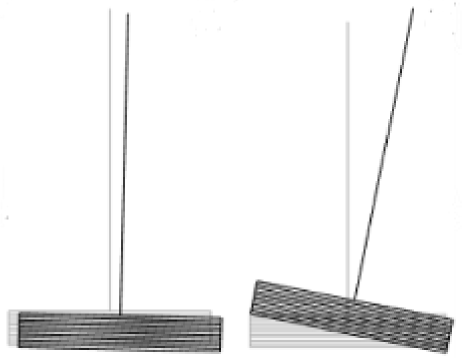
- ❑ Accounts for:
- ✓ different local scour scenarios + intra-scour scenario variability
- ✓ uncertainties in soil properties, traffic loads and capacity definition

- ❑ Response statistics of piers assessed via incremental static analyses







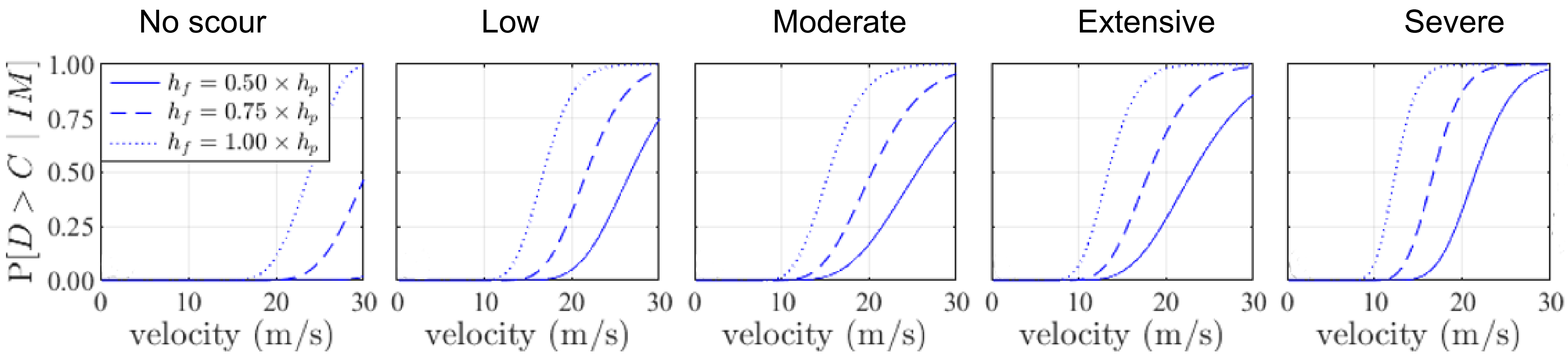


Kazantzi et al. (2024)

Flood fragility models based on simplified numerical modelling - portfolio of bridges

Bridge flood fragilities for different Damage States and:

- ❑ Various scour severity scenarios (No scour, Low, Moderate, Extensive, Severe)
- ❑ Three inundation depths that with water velocity define a vector flood IM



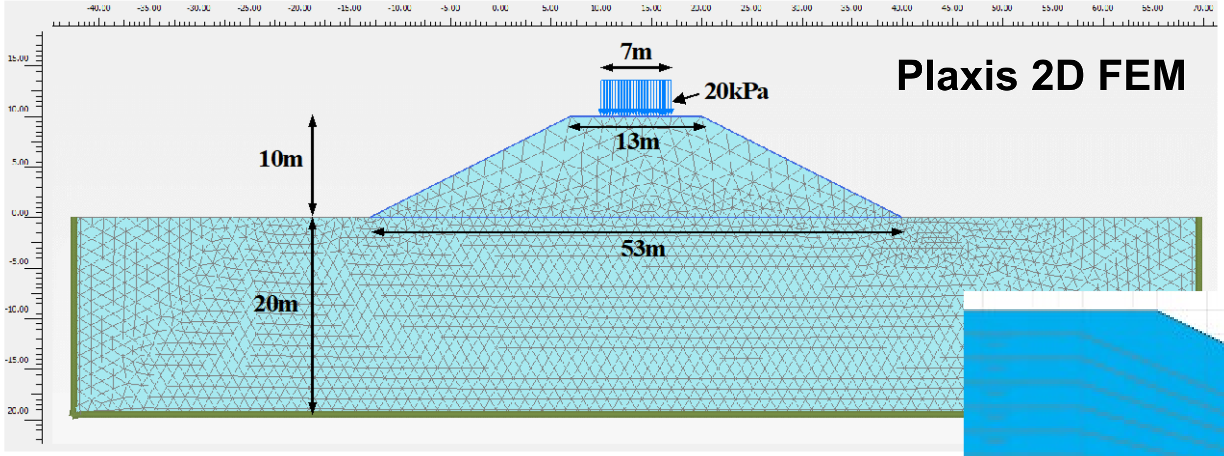
Kazantzi et al. (2024)

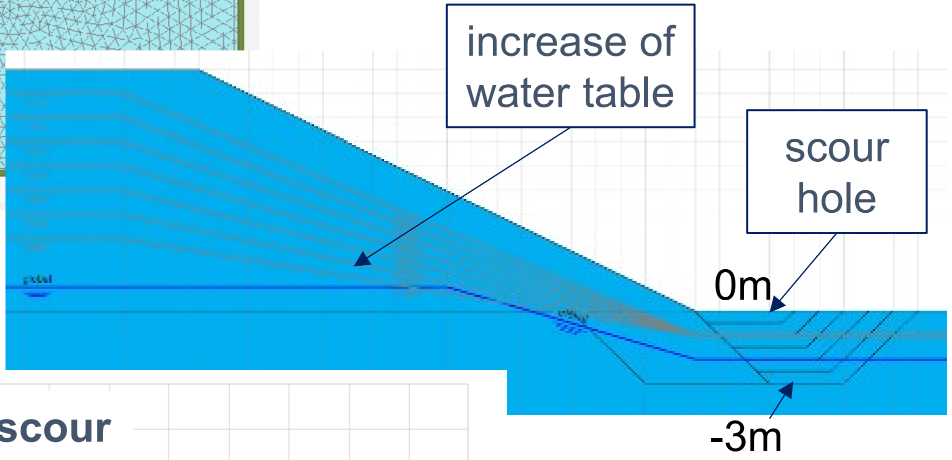
Assets: bridge (pier)

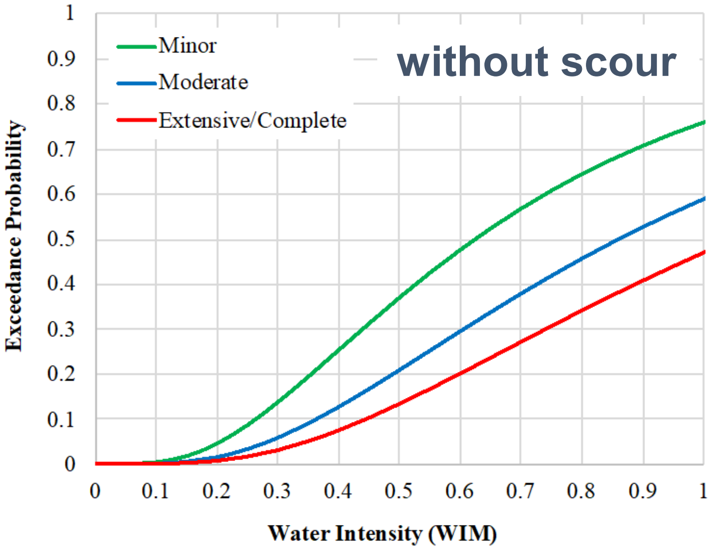
Hazards: flood/scour, hydraulic forces

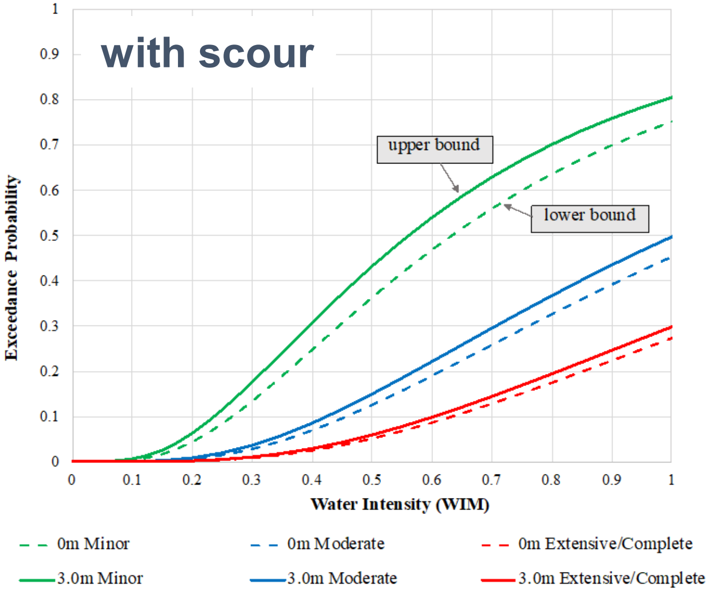
IM: water velocity (m/s)

Fragility models based on numerical modelling - Embankments









Asset: embankments/slopes,

Hazards: moisture ingress, scour

IM: water level, scour level

McKenna G, Argyroudis S, Winter MG, Mitoulis S (2021). Transportation Geotechnics

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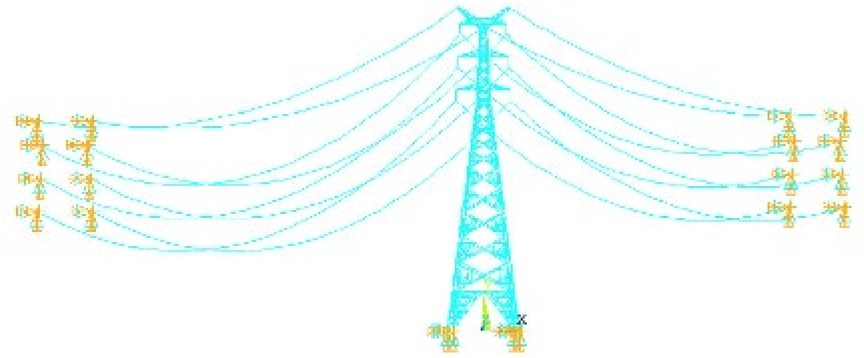
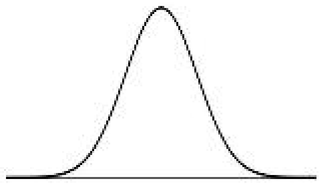
Fragility models based on numerical modelling: transmission tower-line systems under combined wind and rain loads

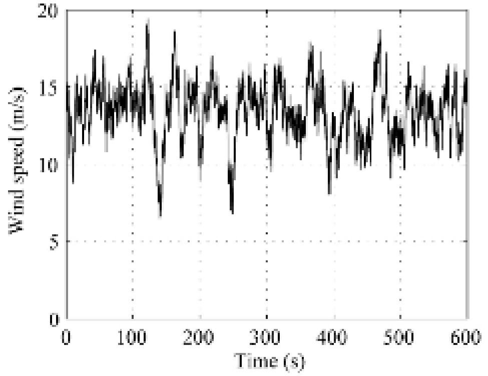


FEM of the transmission tower-line system

Uncertain variables (material, geometrical properties of steel members): Elastic modulus, Poisson's ratio, Yield strength, Damping ratio, Drag coefficient, Web thickness, Width

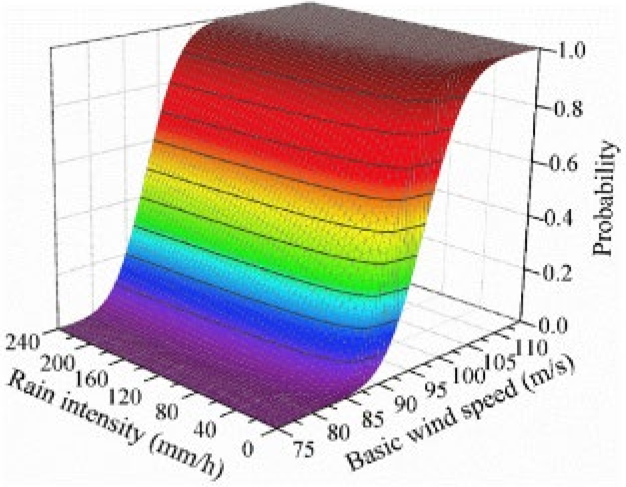


Uncertainty in loading:
combinations of wind and rain loads, and wind attack angles

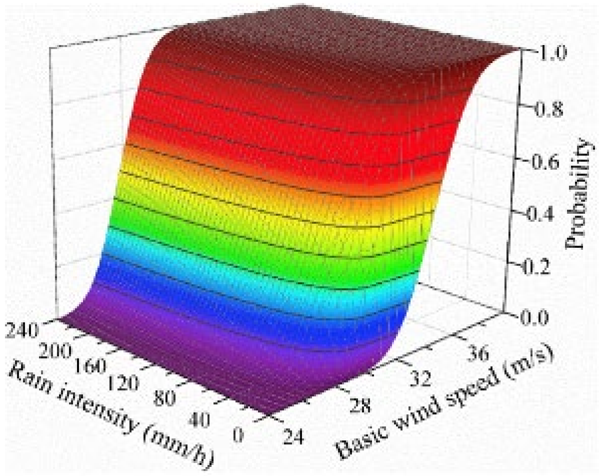


IMs: wind speed (m/s), rain intensity (mm/h)

Fragility surfaces for Collapse (buckling point)



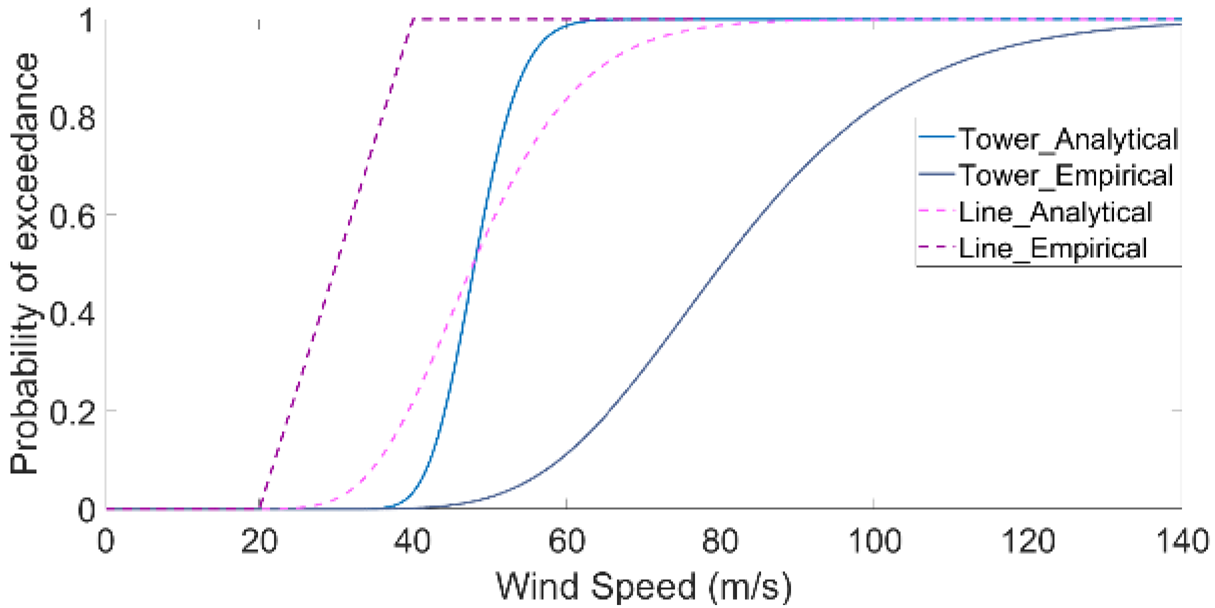
Wind attack angle θ=0°



Wind attack angle θ=67.5°

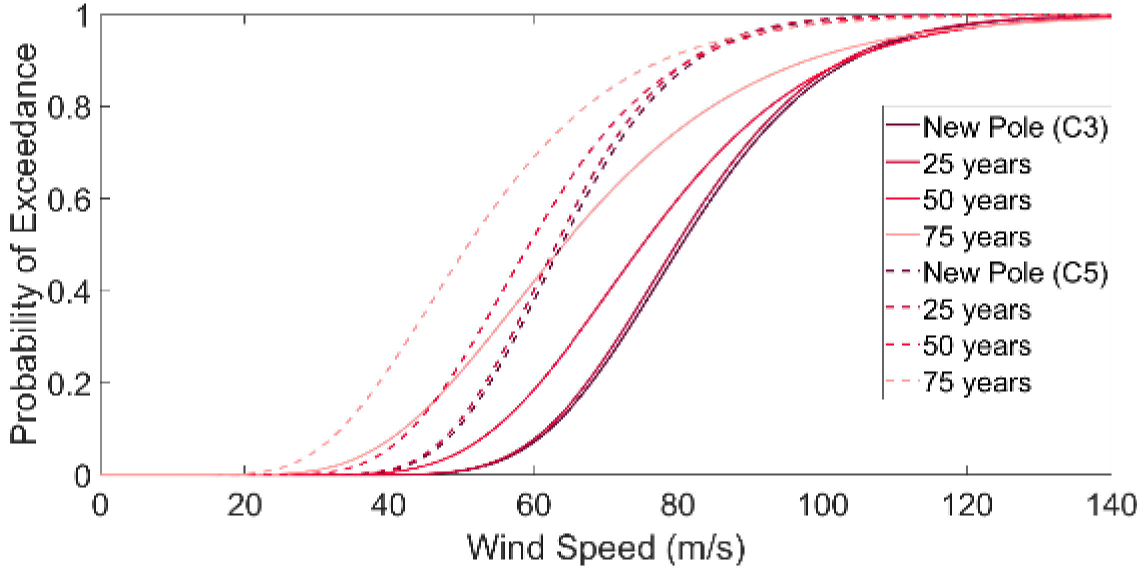
Source: Fu et al. (2020) Journal of Wind Engineering & Industrial Aerodynamics

Fragility models based on empirical and analytical data – power grid under wind hazard



empirical vs. analytical fragility curves for towers
(Dos Reis et al., 2022; Alipour & Dikshit, 2023; Scherb et al., 2019)

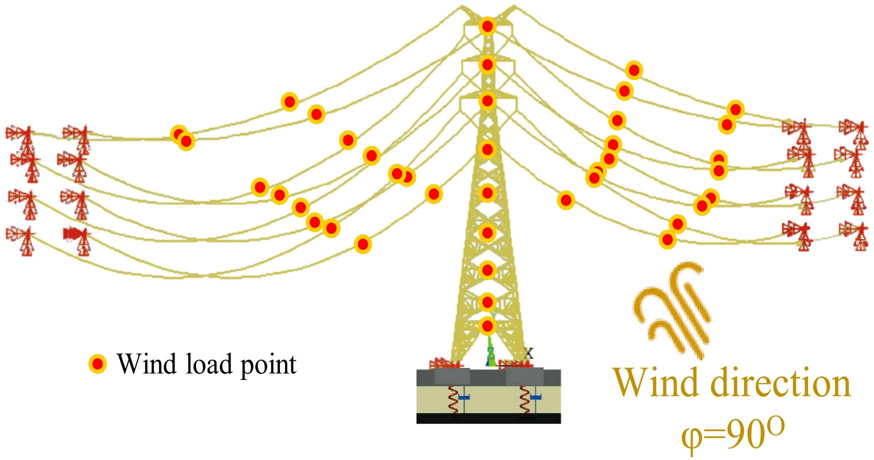
Source: Karagiannakis, Panteli, Argyroudis (2024)



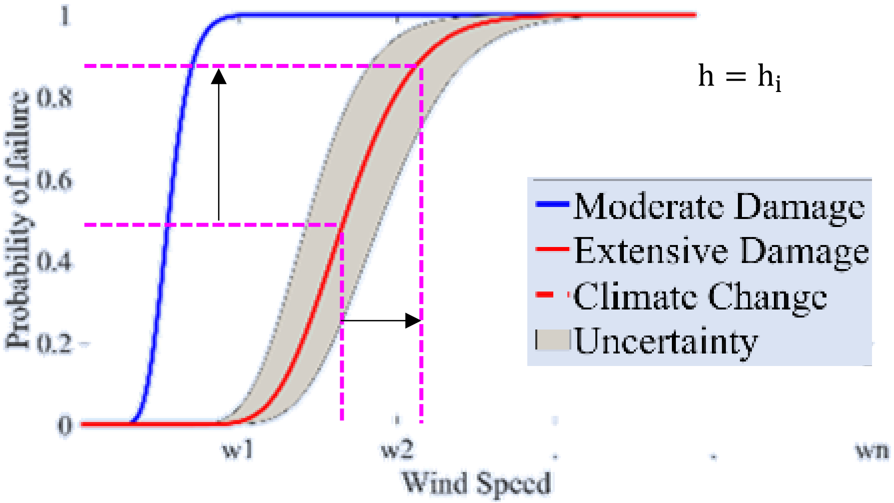
Impact of ageing effects
(Shafieezadeh et al., 2014)

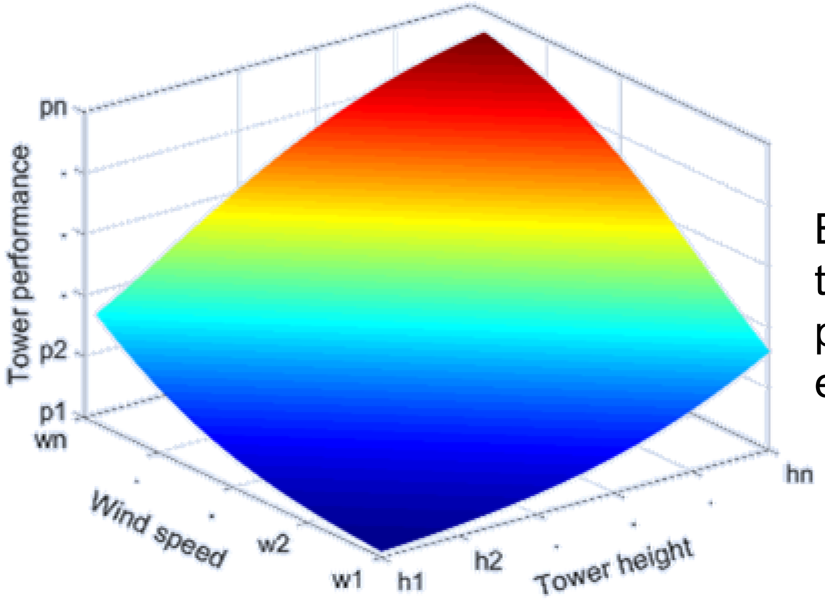
Climate aware fragility modelling

Advanced numerical model



Parameterised fragility functions





Fragility modelling

Best meta-model to map the transmission tower response for potential influential parameters e.g. tower height or span length.

Impact of climate change:

>> Higher intensity of weather events e.g. wind speed or ice thickness

>> Deterioration of infrastructure e.g. scour or aging

>> Change in the probability of occurrence of a baseline scenario

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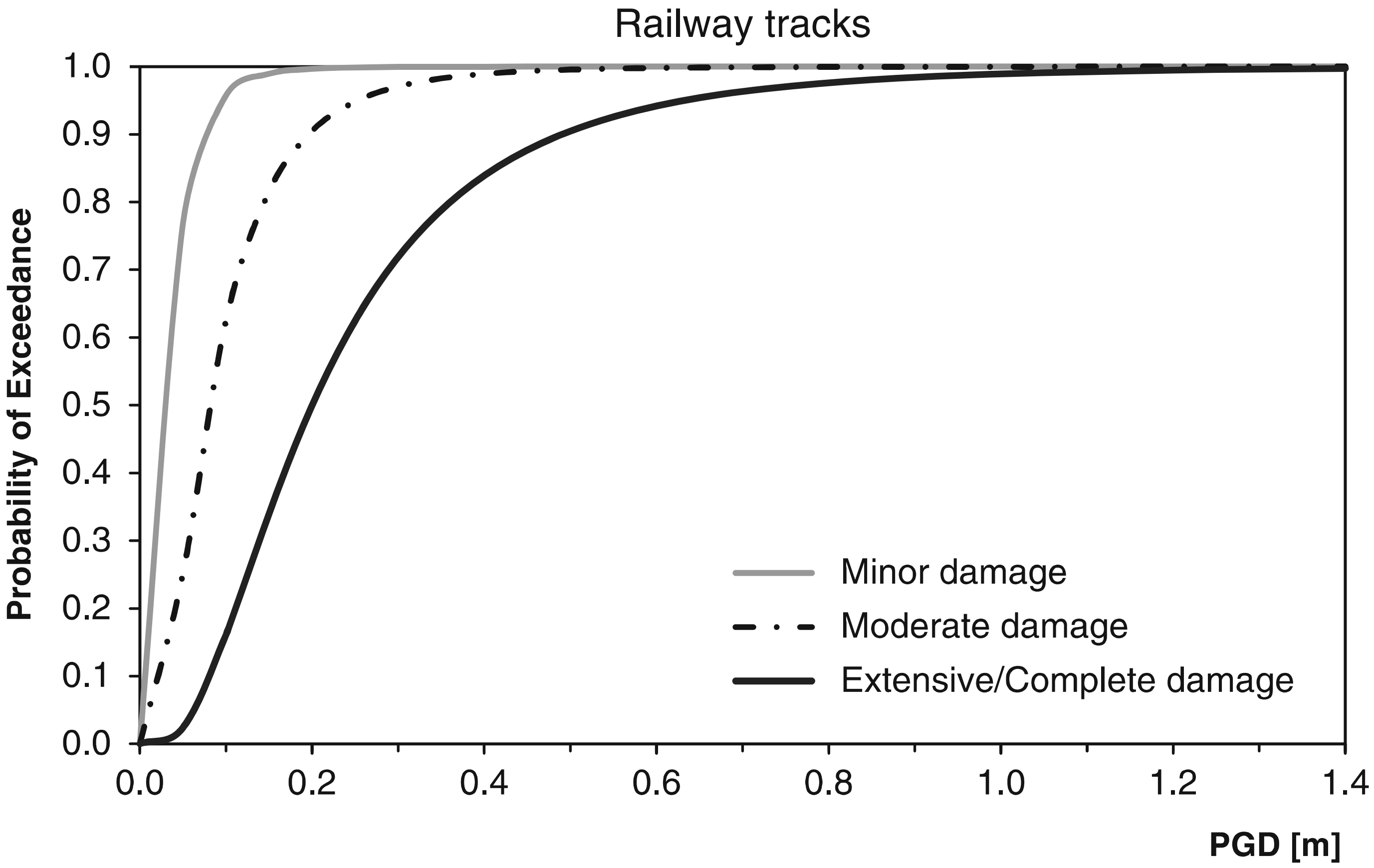
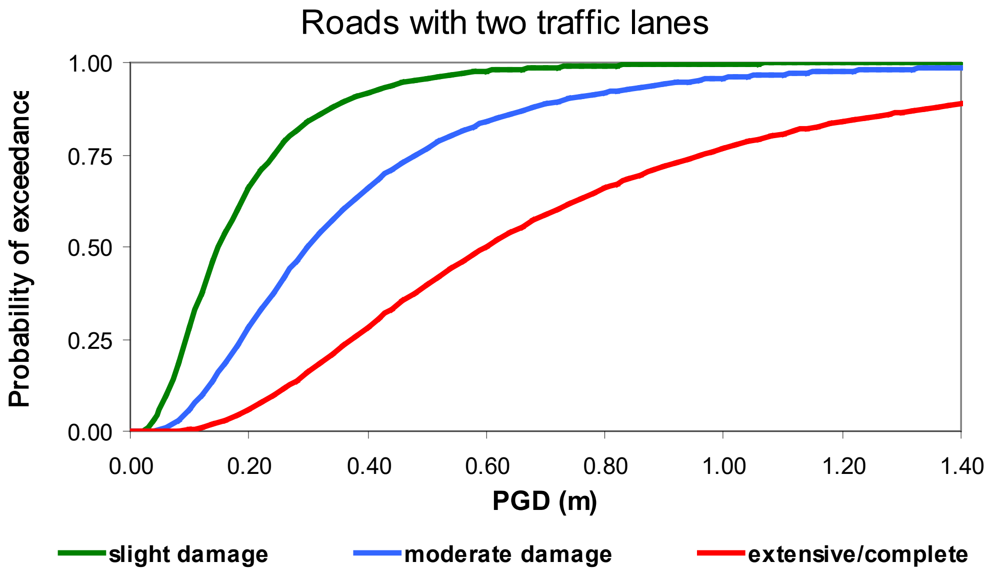
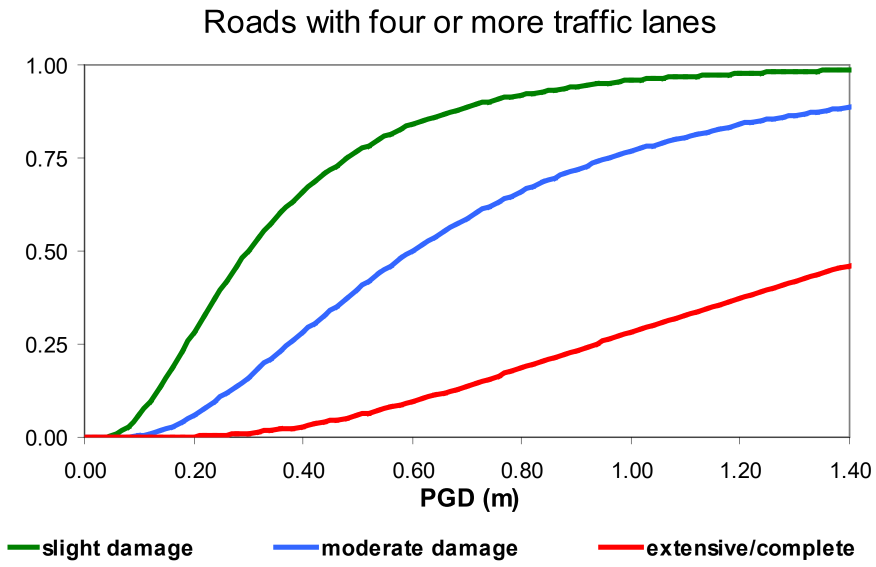
Empirical fragility curves for rail tracks (ground deformation)



Argyroudis & Kaynia (2014)

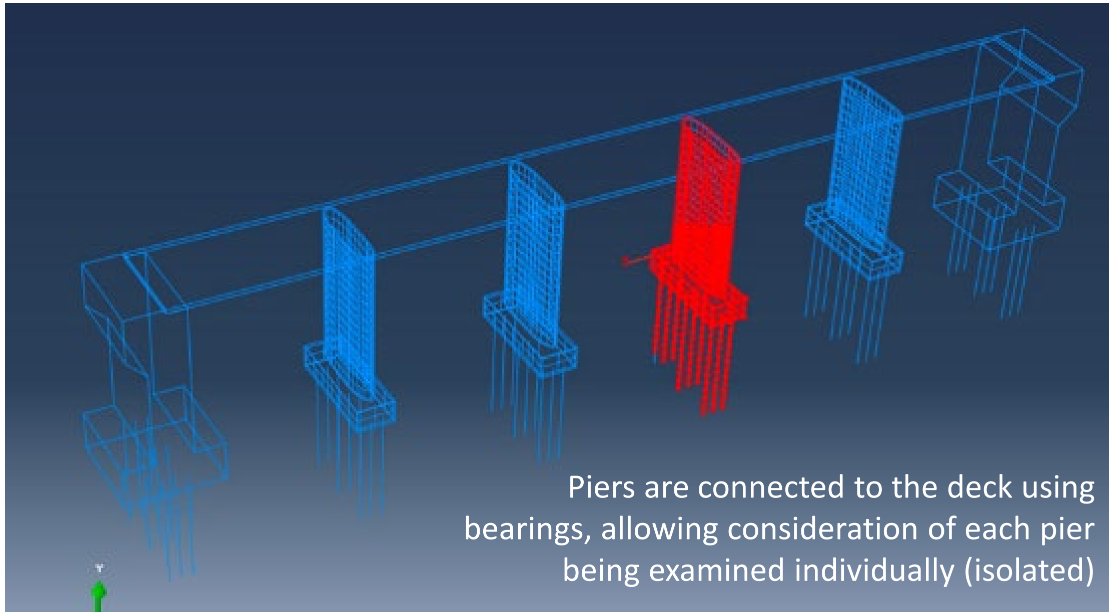
Empirical fragility curves for road pavements (ground deformation)





Argyroudis & Kaynia (2014)

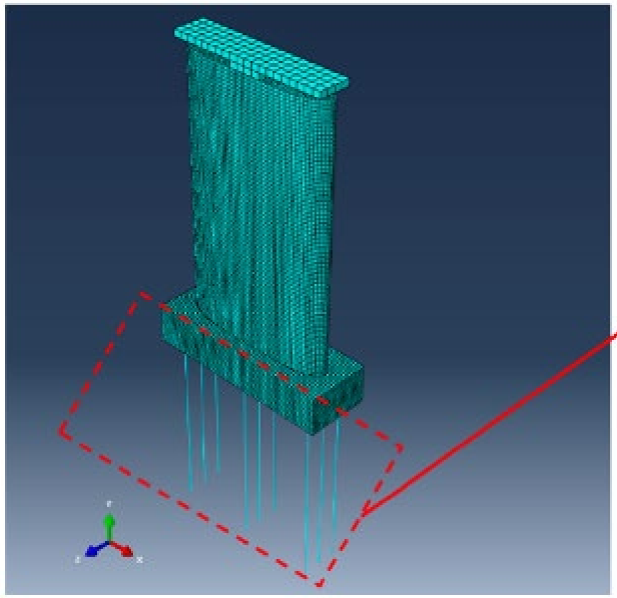
Numerical fragility curves for case specific bridges

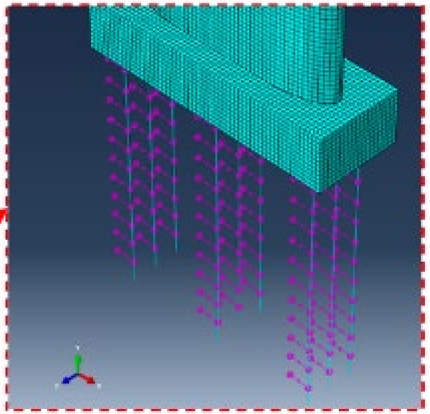


Kim et al. (2017)

Finite element model of a bridge (ABAQUS) exposed to flood (scour)

Pier model



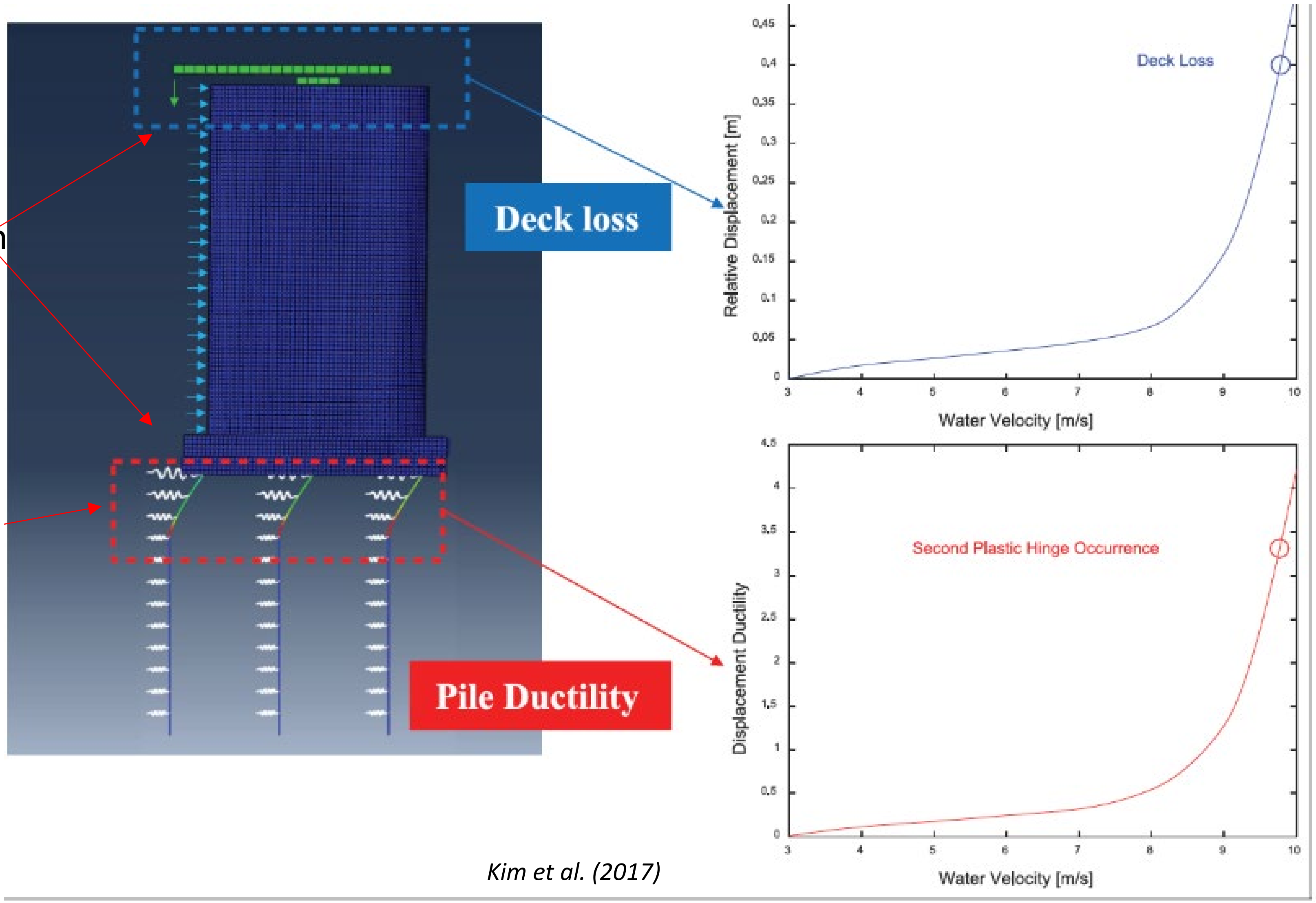


Scour holes around pile foundations are simulated with removal of springs

Numerical fragility curves for case specific bridges

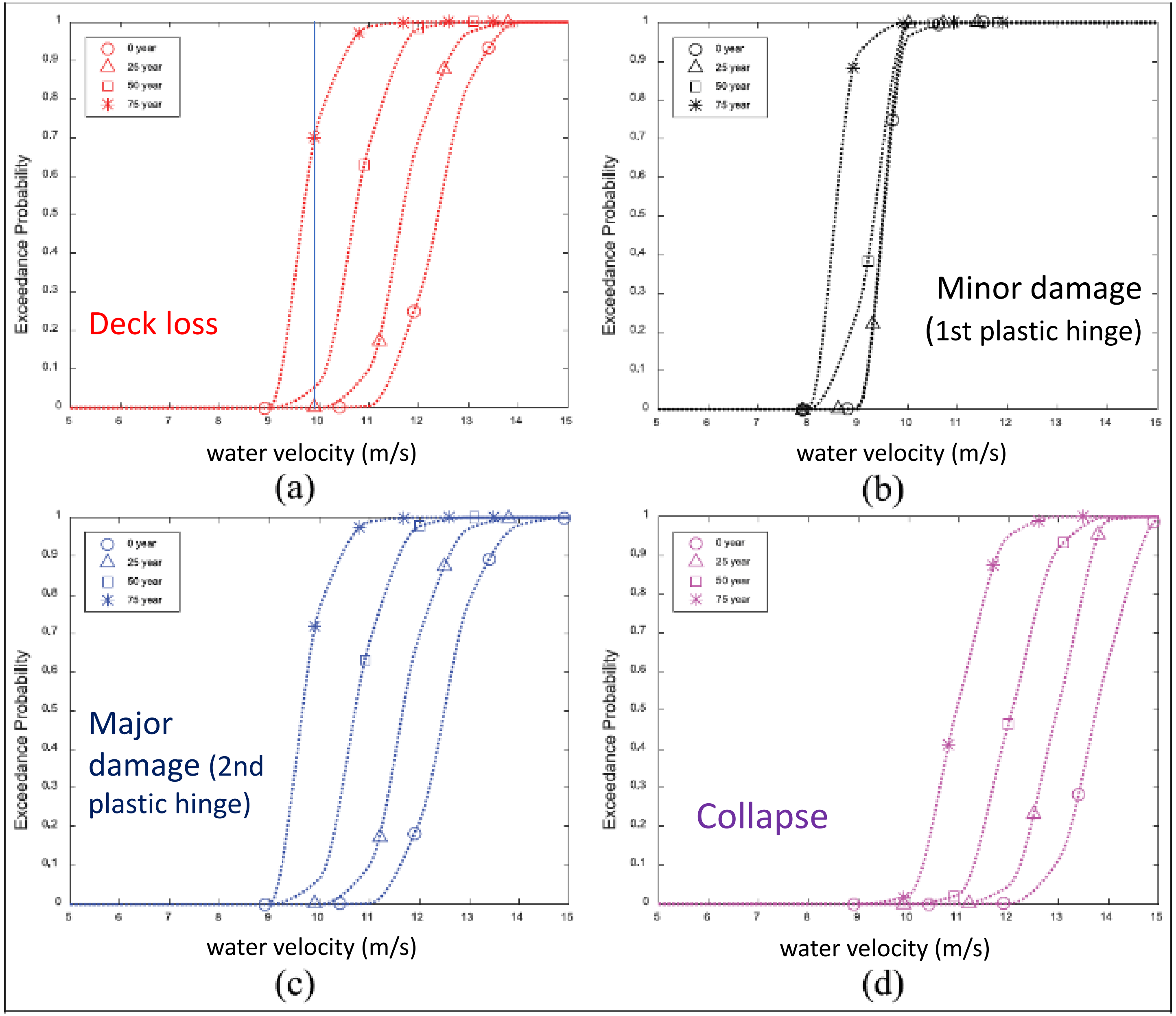
Water pressure on pier

Soil removal due to scour



Kim et al. (2017)

Numerical curves considering structural deterioration



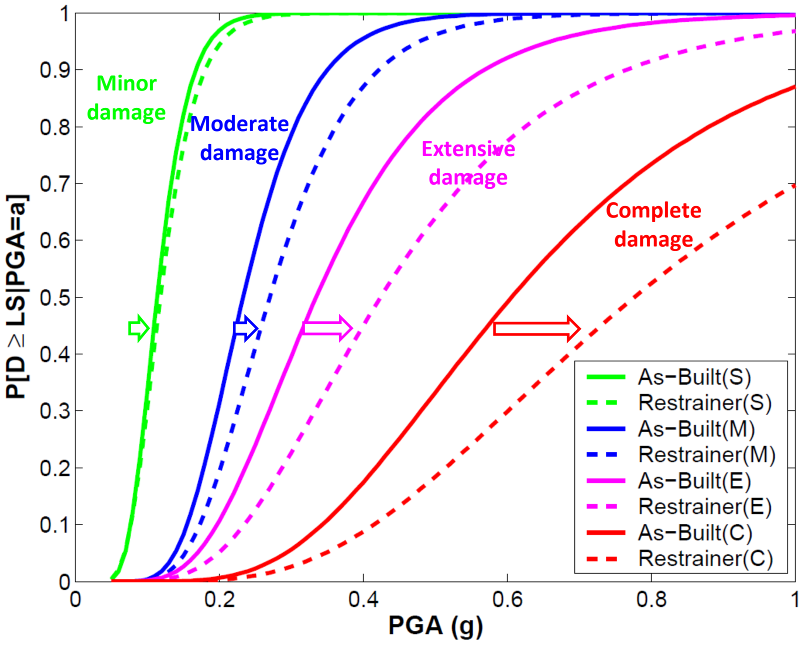
Structural (steel) deterioration due to corrosion is also considered

(as built, 25, 50, 75 years)

Kim et al. (2017)

Fragility curves to facilitate decision making

Retrofitting of bridges
(steel girders on bearings)



Padgett (2005)

a) b) c)

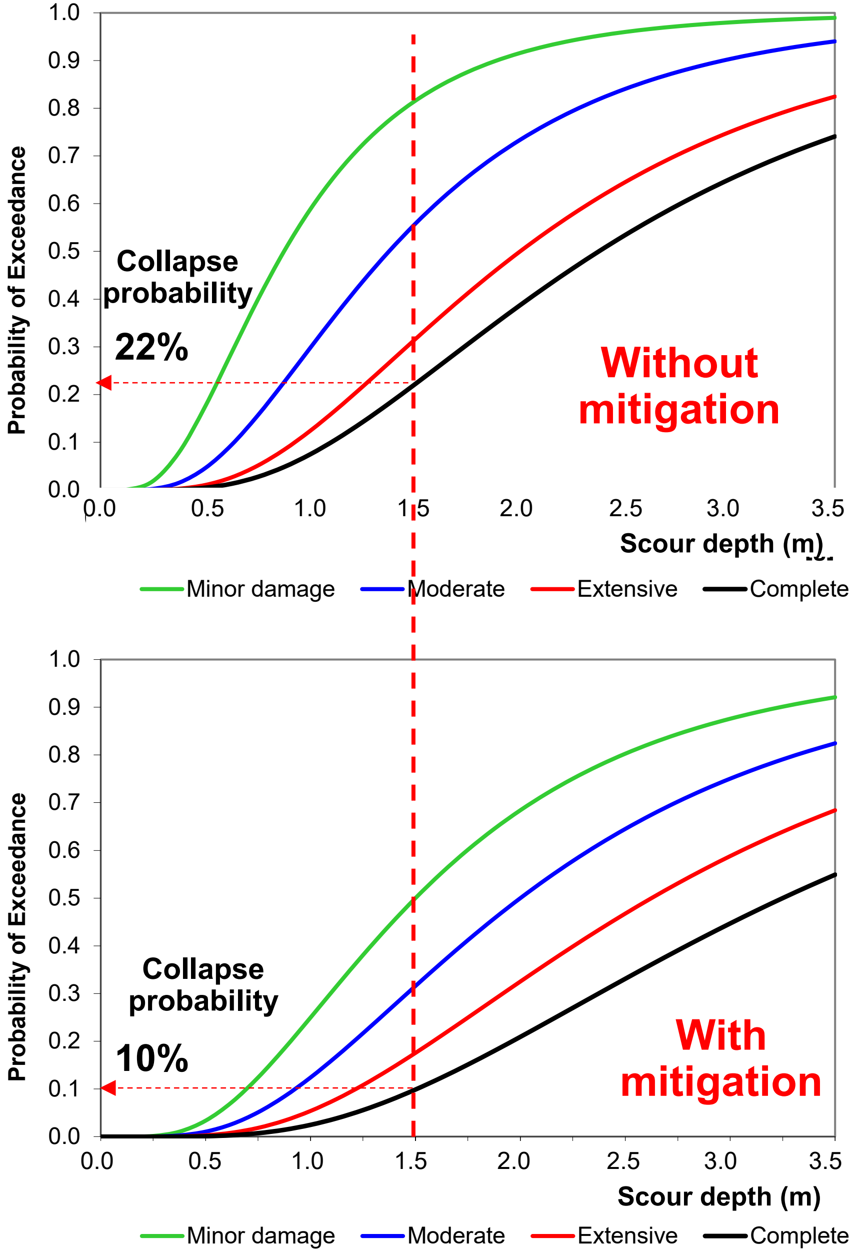
Fig. 9. Restrainer cables (a) in Kentucky connecting two adjacent girders; (b) in Tennessee (SR59 over I-40) connecting girders to the abutment; and (c) in Illinois attached to girders and wrapped around bent beam

US40/I64 in St. Louis, MO retrofit with restrainers and seat extenders

How useful is that? Can we justify investments?

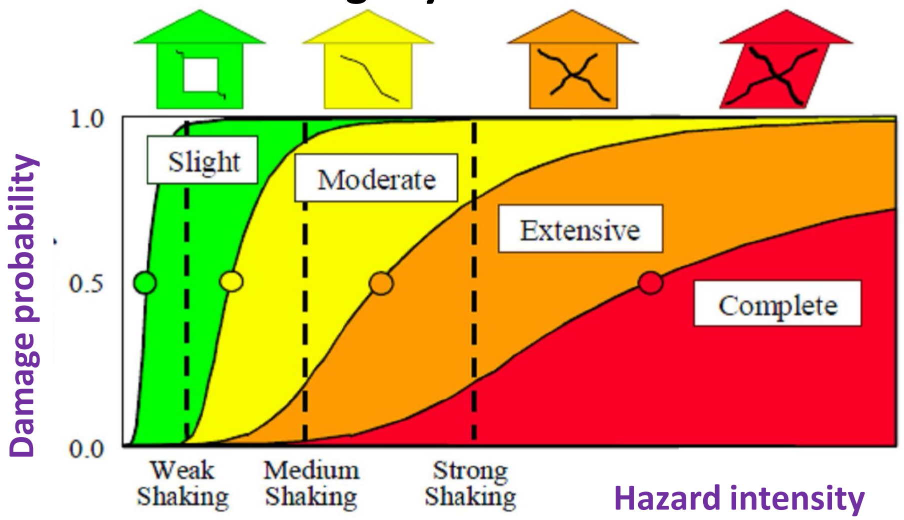
Fragility curves to facilitate decision making

Gabions for scour protection

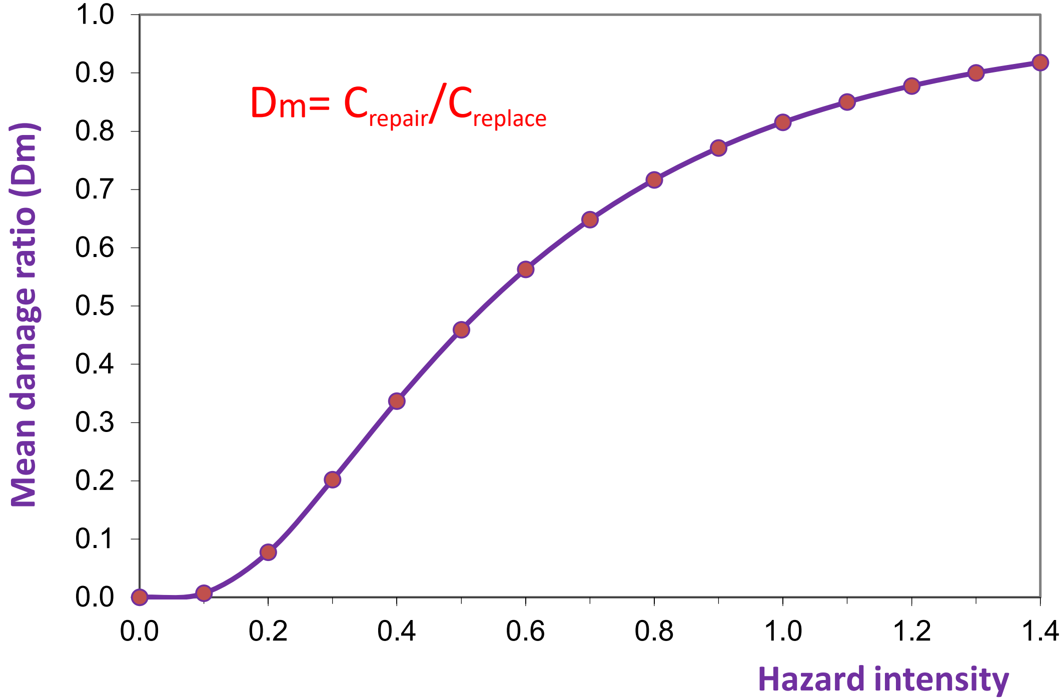


Vulnerability as a measure of robustness

Fragility curves



Vulnerability curves

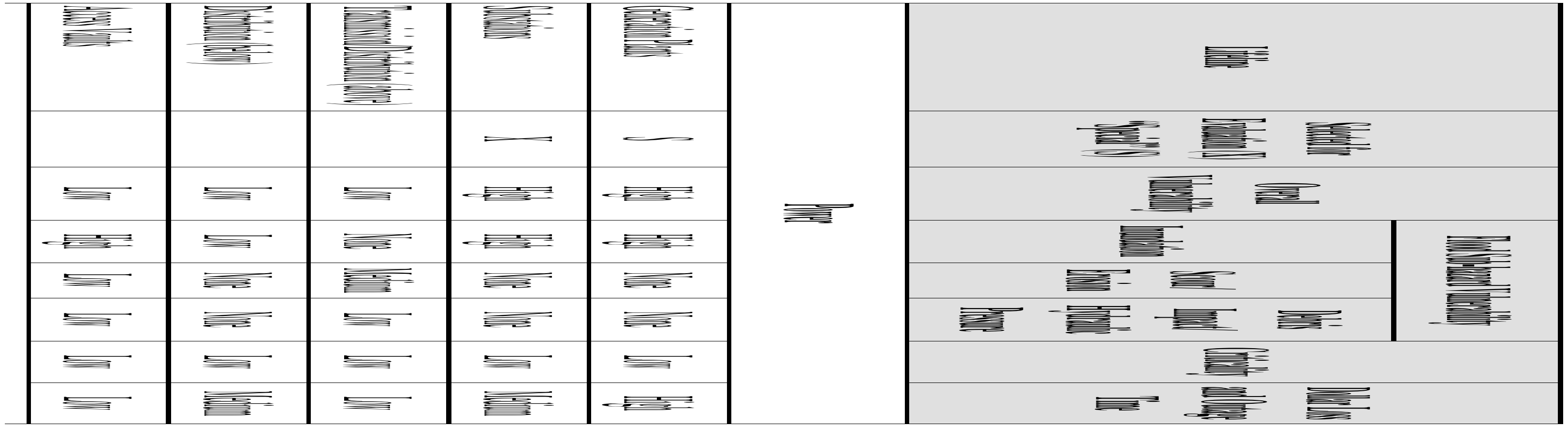


Electric power system: typology & vulnerability (flood)

Table 3.32 Electric Power System Classifications

Flood Label	General Occupancy	Specific Occupancy	Hazus Valuation[1]
ESSL	Substations	Low Voltage Substation	10,000
ESSM	Substations	Medium Voltage Substation	20,000
ESSH	Substations	High Voltage Substation	50,000
EDCE	Distribution Circuits	Distribution Circuits Elevated Crossings	3
EDCB	Distribution Circuits	Distribution Circuits Buried Crossings	3
EDC	Distribution Circuits	Distribution Circuits (non-crossing)	3
EPPS	Generation Plants	Small Power Plants	100,000
EPPM	Generation Plants	Medium Power Plants	500,000
EPPL	Generation Plants	Large Power Plants	500,000

in thousands $



HAZUS MH FLOOD TECHNICAL MANUAL https://www.fema.gov/hazus-mh-user-technical-manuals

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Electric power system: typology & vulnerability (flood)

Table 7.9 Electric Power Classifications, Functionality Thresholds and Damage Functions

Label	Earthquake Classification	Specific Occupancy	Functionality Threshold Depth	Percent Damage by depth of flooding in feet[2]											Comments
				0	1	2	3	4	5	6	7	8	9	10	
ESSL	ESS1, ESS2	Low Voltage Substation	4	0	2	4	6	7	8	9	10	12	14	15	Control room damaged starting at 0 feet, and maximized at 7' depth.
ESSM	ESS3, ESS4	Medium Voltage Substation	4	0	2	4	6	7	8	9	10	12	14	15	
ESSH	ESS5, ESS6	High Voltage Substation	4	0	2	4	6	7	8	9	10	12	14	15	Additional damage to cabling and incidental damage to transformers and switchgear.
EDC	EDC1, EDC2	Distribution Circuits Elevated Crossings	N/A	0	0	0	1	1	1	1	2	2	2	2	Low vulnerability due to flooding of ends of buried cables and possible barge traffic impacting transmission towers
EDC	EDC1, EDC2	Distribution Circuits Buried Crossings	N/A	0	0	0	0	0	0	0	0	0	0	0	No damage due to submergence.
EDC	EDC1, EDC2	Distribution Circuits (non-crossing)	N/A	0	0	0	0	0	0	0	0	0	0	0	No damage due to submergence.
EPPS	EPP1, EPP2	Small Power Plants	4	0	2.5	5	7.5	10	12.5	15	17.5	20	25	30	Support facilities damaged on ground level. Control and generation facilities damaged when water elevation reaches 2nd level.
EPPM	EPP3, EPP4	Medium Power Plants	4	0	2.5	5	7.5	10	12.5	15	17.5	20	25	30	
EPPL	EPP3, EPP4	Large Power Plants	4	0	2.5	5	7.5	10	12.5	15	17.5	20	25	30	

[2] *Assumes electrical switch gear is located 3-feet above grade.*

HAZUS MH FLOOD TECHNICAL MANUAL

damage assessment is modified
for protected vs. unprotected facilities

Electric power system: typology & vulnerability (flood)

($ Loss) = (% Damage) x (Inventory $ value)

(% damage) = damage at (depth of water – equipment height)

Scenario 1: depth of water = **1.5m** (5ft)

Scenario 2: depth of water = **2.7m** (9ft)

Table 7.9

Scenario 1: % damage at (1.5-0.5=1.0m ~3ft): **6 %**
Scenario 2: % damage at (2.7-0.5=2.2m ~7ft): **10%**

Scenario 1: loss= 0.06 x 50,000,000 = **$ 3,000,000**
Scenario 2: loss= 0.10 x 50,000,000 = **$ 5,000,000**

HAZUS MH FLOOD TECHNICAL MANUAL

high-voltage substation/unprotected
equipment height=0.5m

Electric power system: typology & vulnerability (flood)

($ Loss) = (% Damage) x (Inventory $ value)

(% damage) = damage at (depth of water – equipment height)

Scenario 1: depth of water = 1.5m (5 ft)

>>**0.5m** (1.6ft) *(overtops protection wall)*

Scenario 2: depth of water = 2.7m (9ft)

>>**1.7m** (5.6ft) *(overtops protection wall)*

Table 7.9

Scenario 1: % damage at (0.5-0.5=0.0m): **0 %**
Scenario 2: % damage at (1.7-0.5=1.2m ~4ft): **7%**

Scenario 1: loss= 0.0 x 50,000,000 = **$ 0**
Scenario 2: loss= 0.70 x 50,000,000 = **$ 3,500,000**

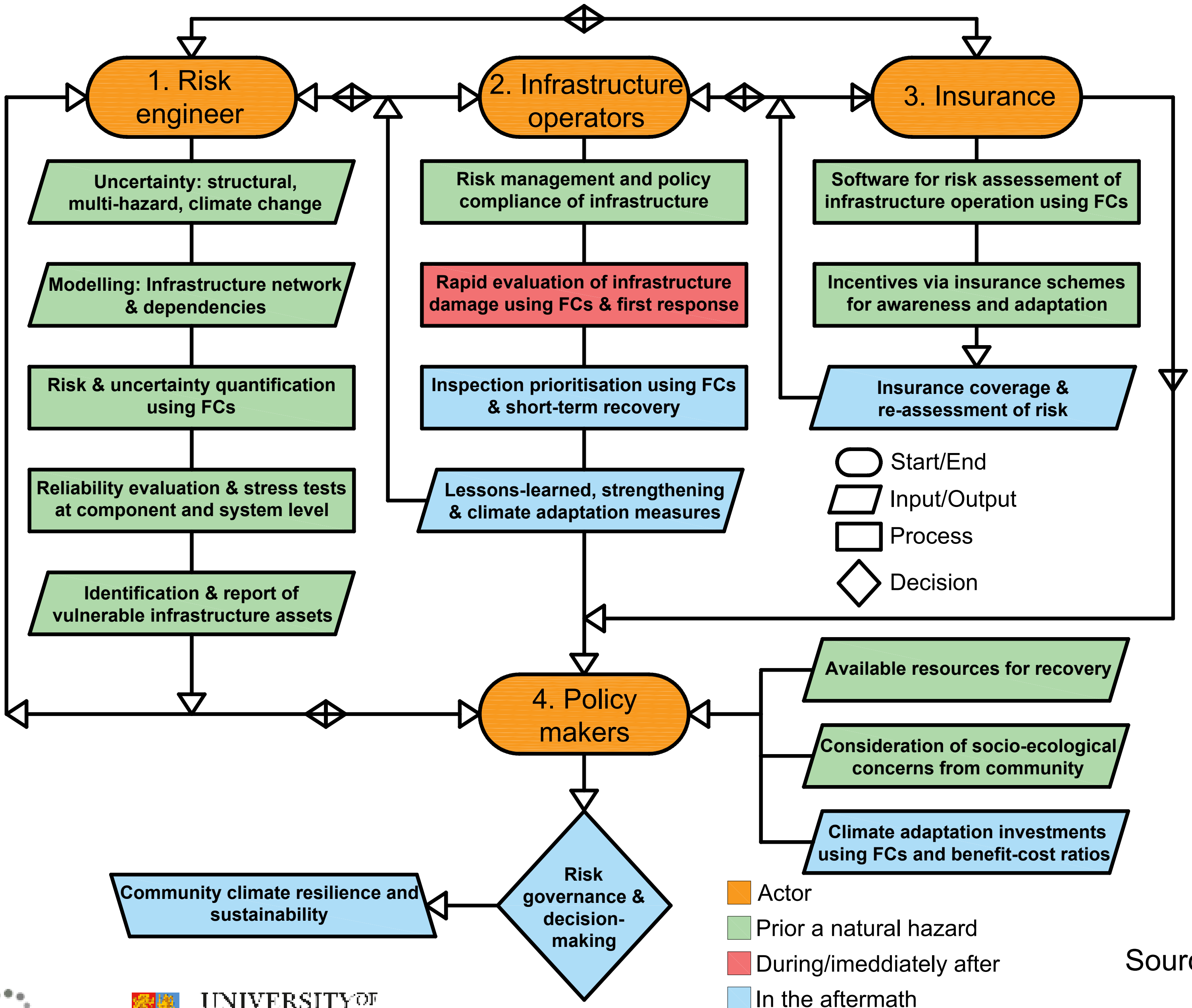
HAZUS MH FLOOD TECHNICAL MANUAL

high-voltage substation/protected

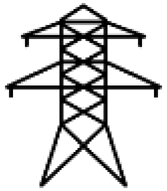
protection wall: 1.0m

equipment height 0.5m

Fragility assessments empower decision-making

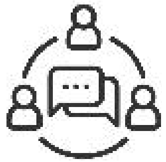


1. Risk analysts: climate uncertainty and modelling



2. Operators: risk management, rapid recovery and adaptation

3. Insurance: incentives with schemes for risk management and adaptation measures.



4. Communication is an adaptation strategy itself

Source: Karagiannakis G, Panteli M, Argyroudis S (2024)

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Practice

Investigation & production:

- Assess the direct losses and discuss other potential losses for a given scenario. A step-by-step guide on how to use and apply models.

ACTIVITY 3: Risk analysis

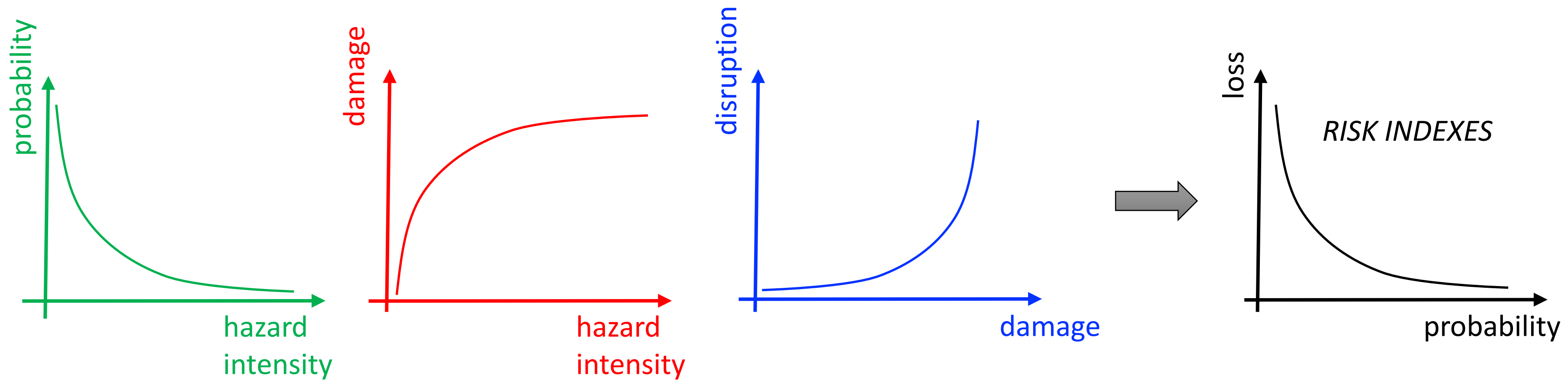
- Risk assessment
- Risk metrics and risk management framework.
- Standards, design guidelines and policies

Quantitative Risk Analysis (QRA)

Risk analysis for portfolios of infrastructure and networks to given hazards

When dealing with risk analysis it is required to characterize:
the **hazard** of the site,
the **vulnerability** of the analyzed asset, system or network
and the **exposure** in terms of potential impact of damage.

HAZARD x **VULNERABILITY** x **EXPOSURE** = **RISK**



With **R=HxVxE**, it is possible to compute **risk indexes** to **quantify risk levels** and then compare against acceptable **thresholds** (set by infrastructure owners)

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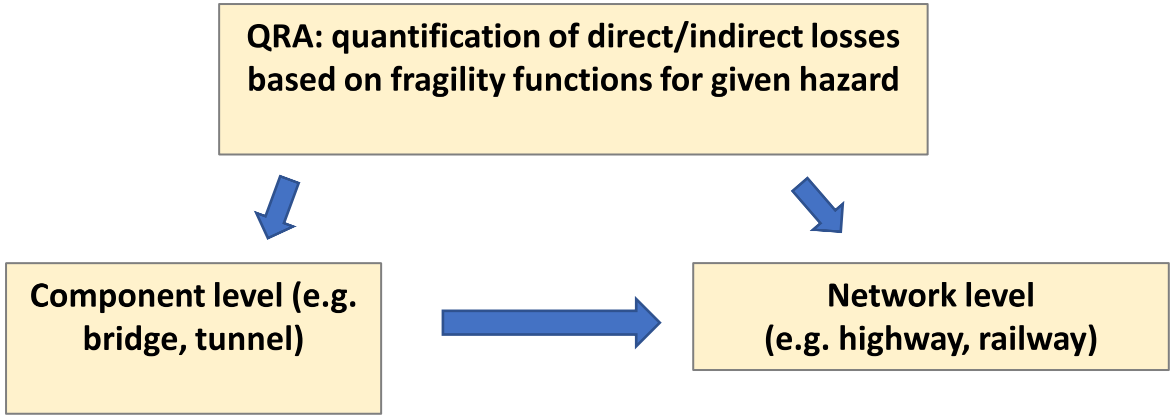
Benefits of QRA

QUANTITATIVE Risk Analysis (QRA):
QRA quantifies the probability of a given level of loss and the associated uncertainties

For scientists and engineers:
QRA allows risk to be quantified in an objective and reproducible manner, and the results can be compared from one location (site, region, etc.) to another

For risk managers/stakeholders:
QRA allows a cost–benefit analysis, and provides the basis for the prioritisation of management and mitigation actions and the associated allocation of resources

For the society:
QRA helps to increase the awareness of existing risk levels and the appreciation of the efficacy of the actions undertaken



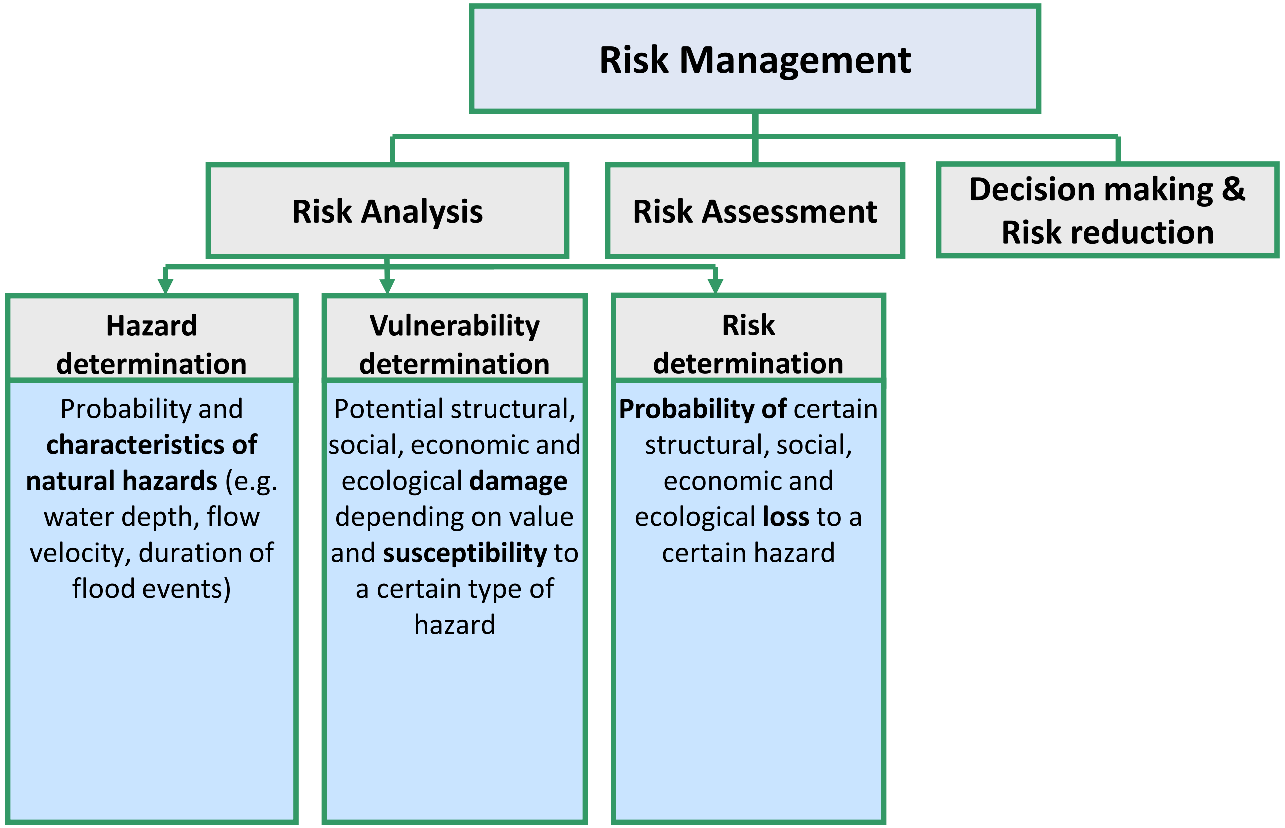
QRA who cares?

Stakeholders and operators

Those (individuals, organisations, authorities) who are involved in the risk management and decision making at international, national or local level, e.g.:

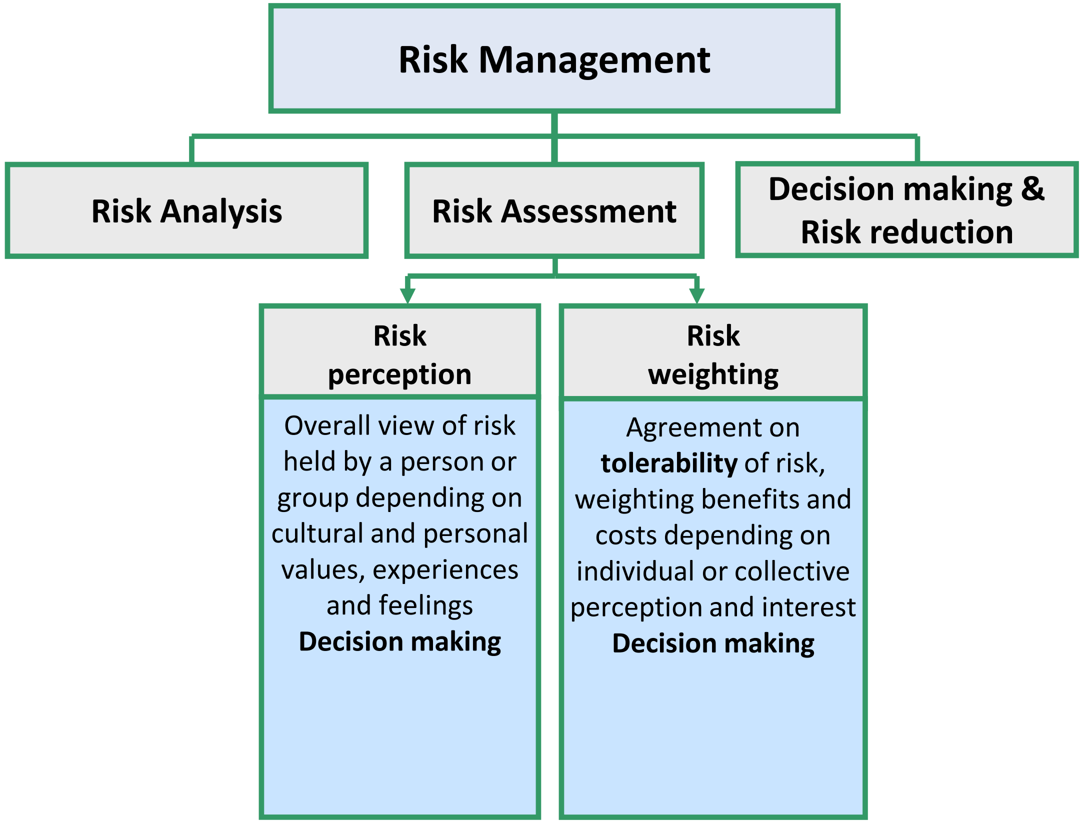
- Governmental bodies, County councils, Municipalities
- Civil protection, Emergency services
- Network owners and operators
  (e.g. National Highways, Network Rail, port authorities, etc)
- Insurance & Re-insurance companies,
- Construction Sector, Land planners, Real estate sector
- Scientists

Risk-based decision-making framework



FlOODsite FP6/EC project
http://www.floodsite.net/

Risk-based decision-making framework



FlOODsite FP6/EC project
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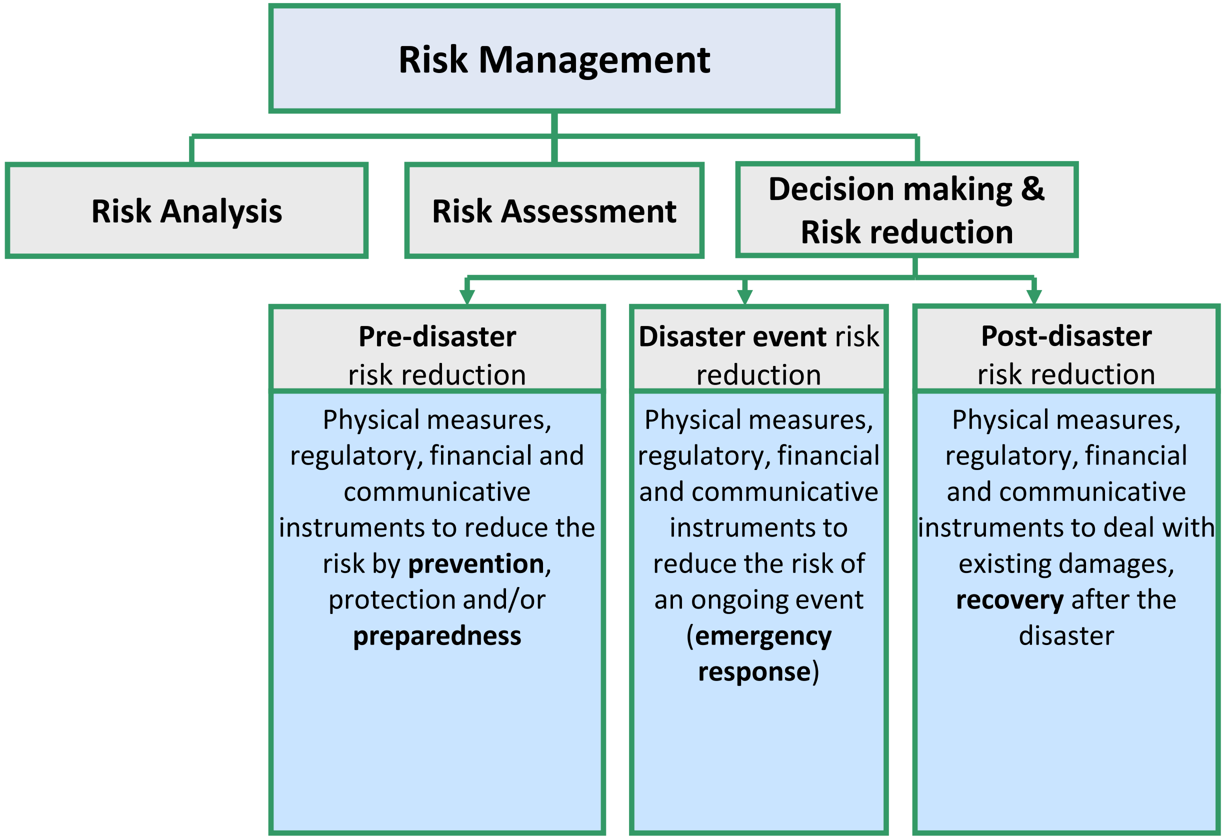
Risk-based decision-making framework

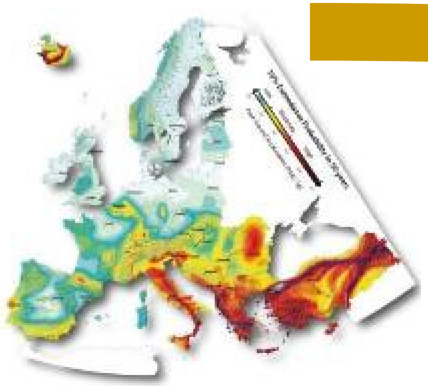


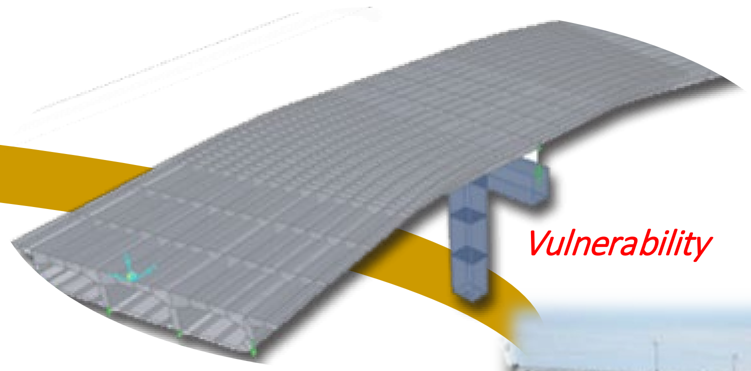
FlOODsite FP6/EC project
http://www.floodsite.net/

the importance of quick recovery → resilience

Risk analysis for portfolios of bridges and transportation networks

The *RISK CHAIN* should be followed:





RISK CHAIN

Risk Indexes
in terms of:

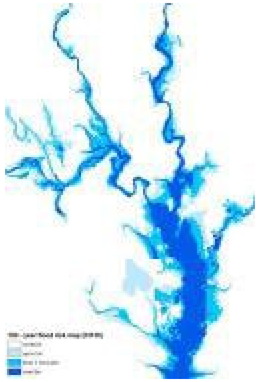
- Replacement cost
- Recovery time
- Resilience
- Business interruption
- Injuries and fatalities
- ...

Risk assessment – QRA for a single scenario

The expected **losses** in a given area and period of time (e.g. annual) for a specific set of elements-at-risk as a consequence of a specific hazard scenario with a specific return period

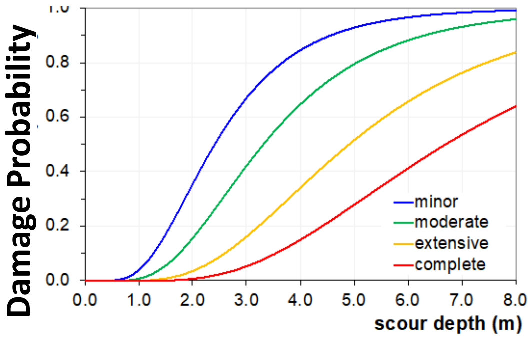
Risk (R_{single}) = Hazard x Vulnerability x Exposure

from hazard maps or site specific hazard analysis



flood depth (Tm=50 years)

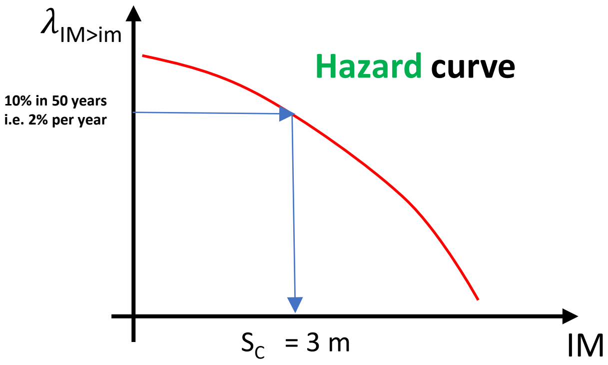
from fragility/vulnerability functions for each asset



Intensity Measure

from inventory (number of assets, monetary costs etc)

- Bridge type;
- Number of spans, Length;
- Average Daily Traffic;
- Detour length;
- Construction cost;
- …



(e.g. flood depth or scour depth)

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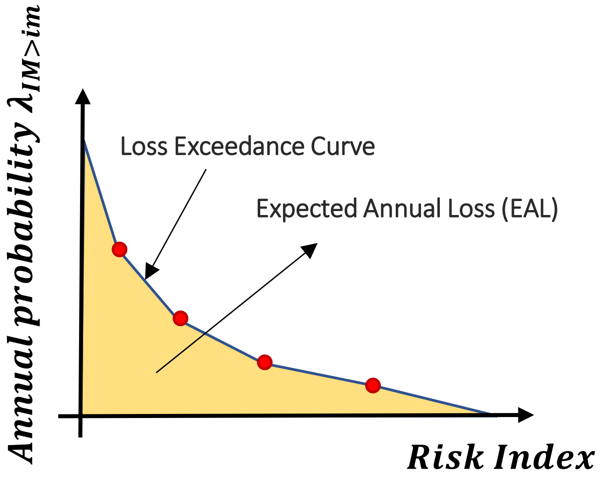
Risk assessment – QRA for all possible scenarios in a given exposure time DT

$\Sigma (R_{Single}) = \Sigma$ (**Hazard** x **Vulnerability** x **Exposure**) = $\int (H * V * E)$
for all **hazard scenarios**, for all **return periods**, for all **elements** at risk

It is normally obtained by plotting **consequences** against **probabilities**, and constructing a **risk curve**.
The area below the curve is the **Expected Annual Loss (EAL)**



EAL = Expected Annual Loss:
risk metric representing average annual costs to be sustained to face damage induced by hazard occurrences.

Based on risk indexes:
- **Replacement cost**
- **Recovery time**
- **Resilience metrics**
- **Business interruption**
- **Injuries and fatalities**
- **…**

The **probability** of expected losses (deaths, injuries, property, economic activity disrupted or environment damaged) resulting from interactions between natural or human induced **hazards** and **vulnerable** conditions in a given **area** and **time** period. It is calculated by analysing all specific **risks**.
It is the integration of all specific consequences over all probabilities.

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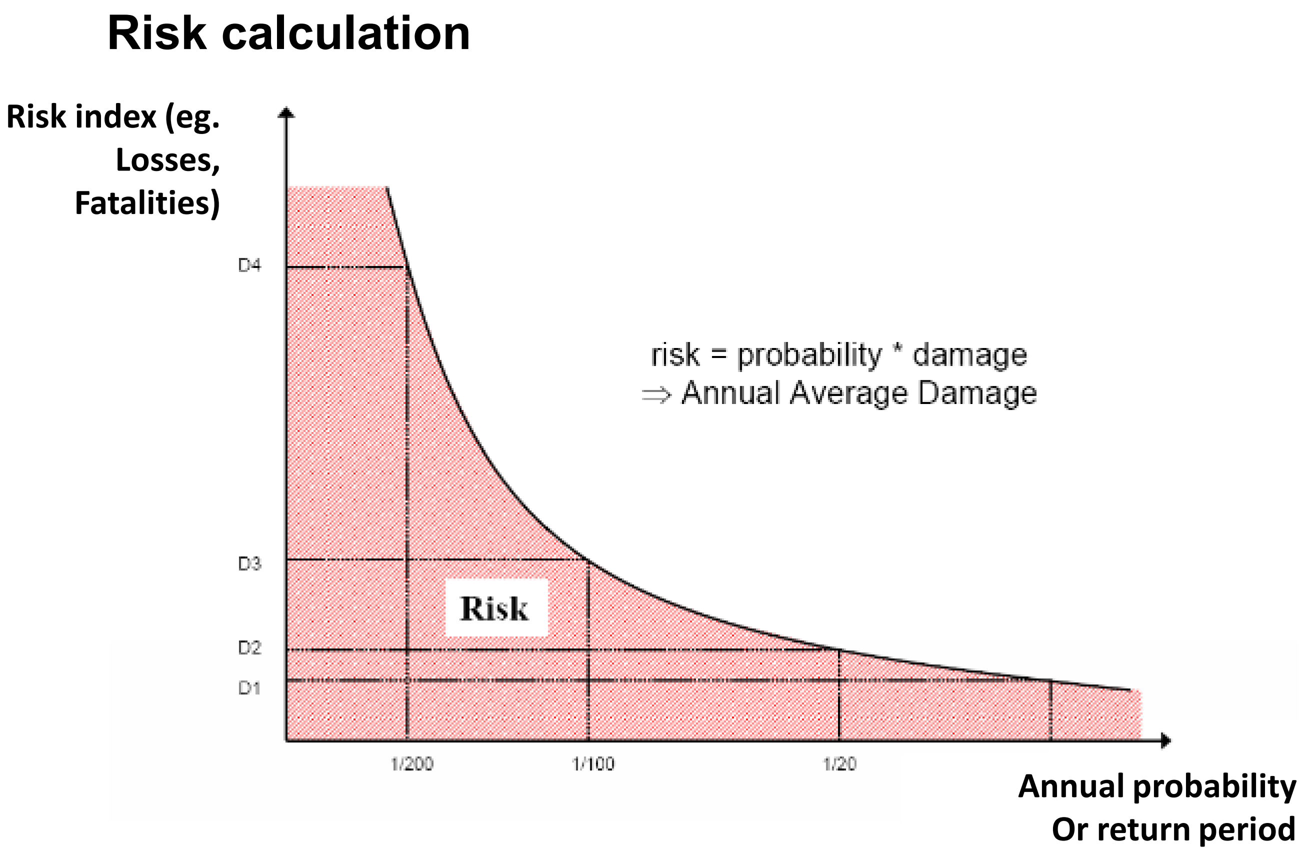
Risk curve


Risk calculation
Risk index (eg. Losses, Fatalities)
D4
D3
D2
D1
risk = probability * damage
⇒ Annual Average Damage
Risk
1/200
1/100
1/20
Annual probability
Or return period

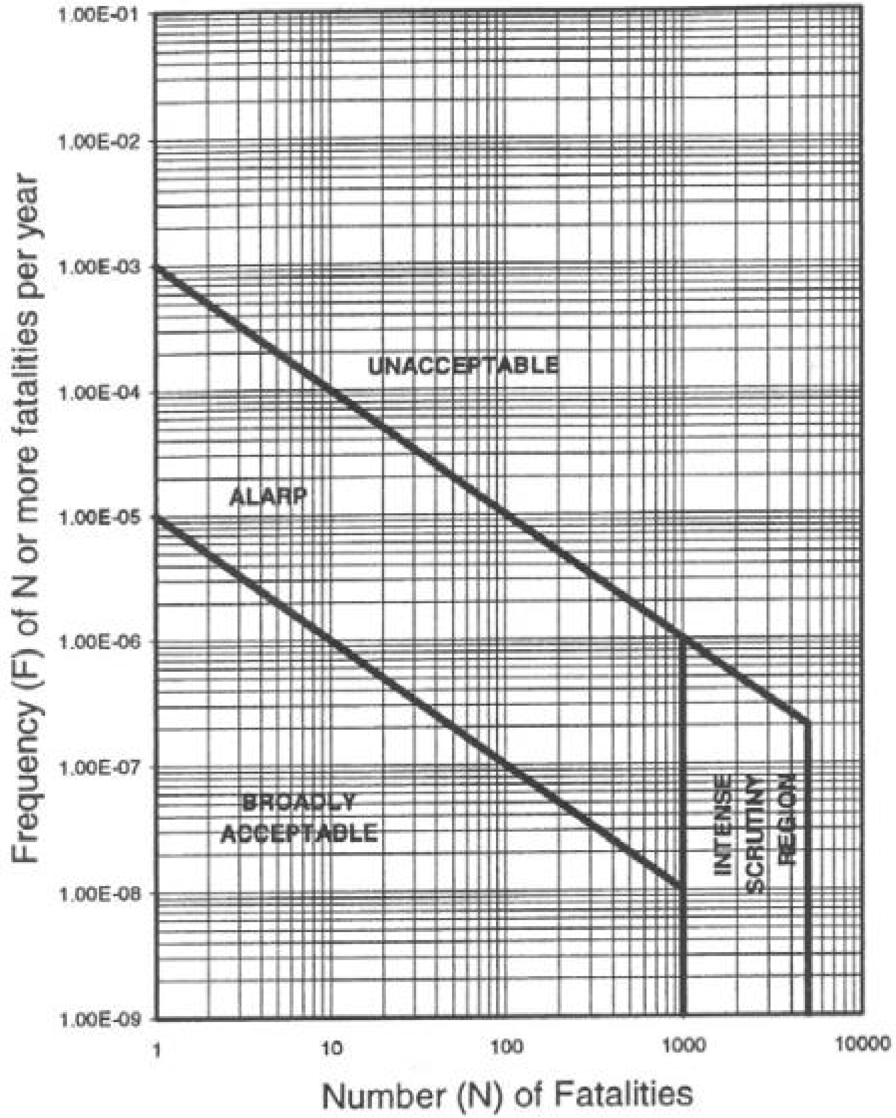
Risk assessment

F – N curves: Curves relating the probability per year of causing N or more fatalities (F) to N. Such curves maybe used to express societal risk criteria and to describe the safety levels of particular facilities.

Acceptable risk: A risk which everyone impacted is prepared to **accept**. Action to further reduce such risk is usually not required unless reasonably practicable measures are available **at low** cost in terms of money, time and effort.

Tolerable risk: A risk with in a range that society **can live with** so as to secure certain net benefits. It is a range of risk regarded as non-negligible and needing to be kept under review and reduced further if possible.

ALARP (As Low As Reasonably Practicable): Principle which states that risks, lower than the limit of tolerability, are tolerable **only if risk reduction is impracticable** or if its cost is grossly in disproportion (depending on the level of risk) to the improvement gained.



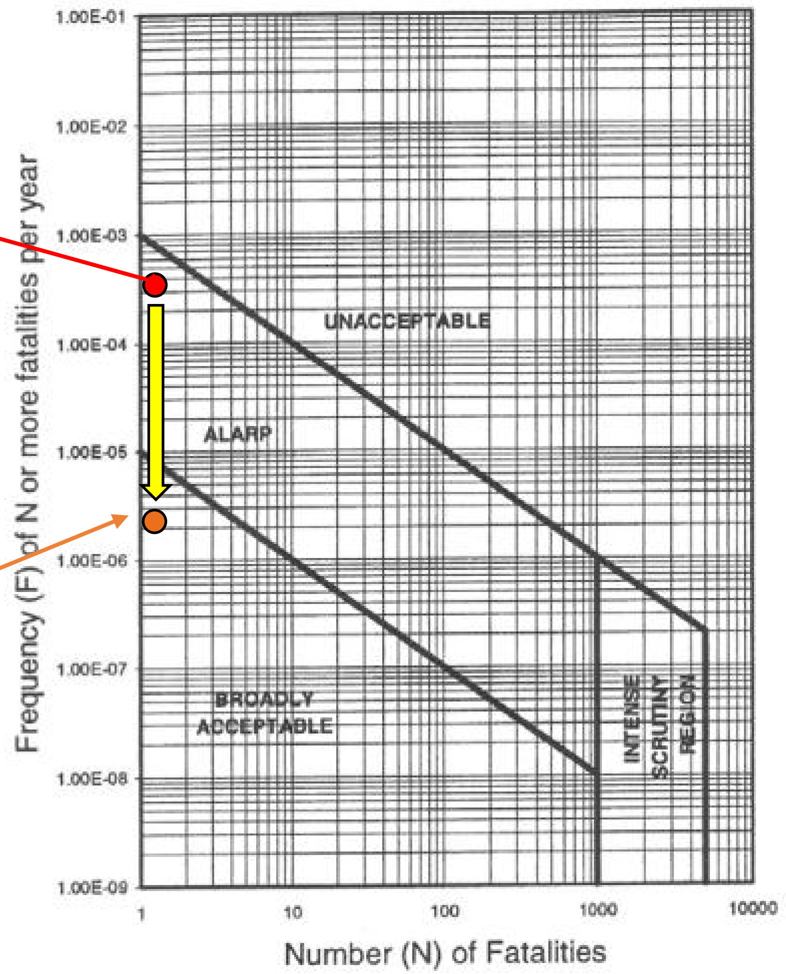
Risk assessment

A highway slope exposed to rockfalls

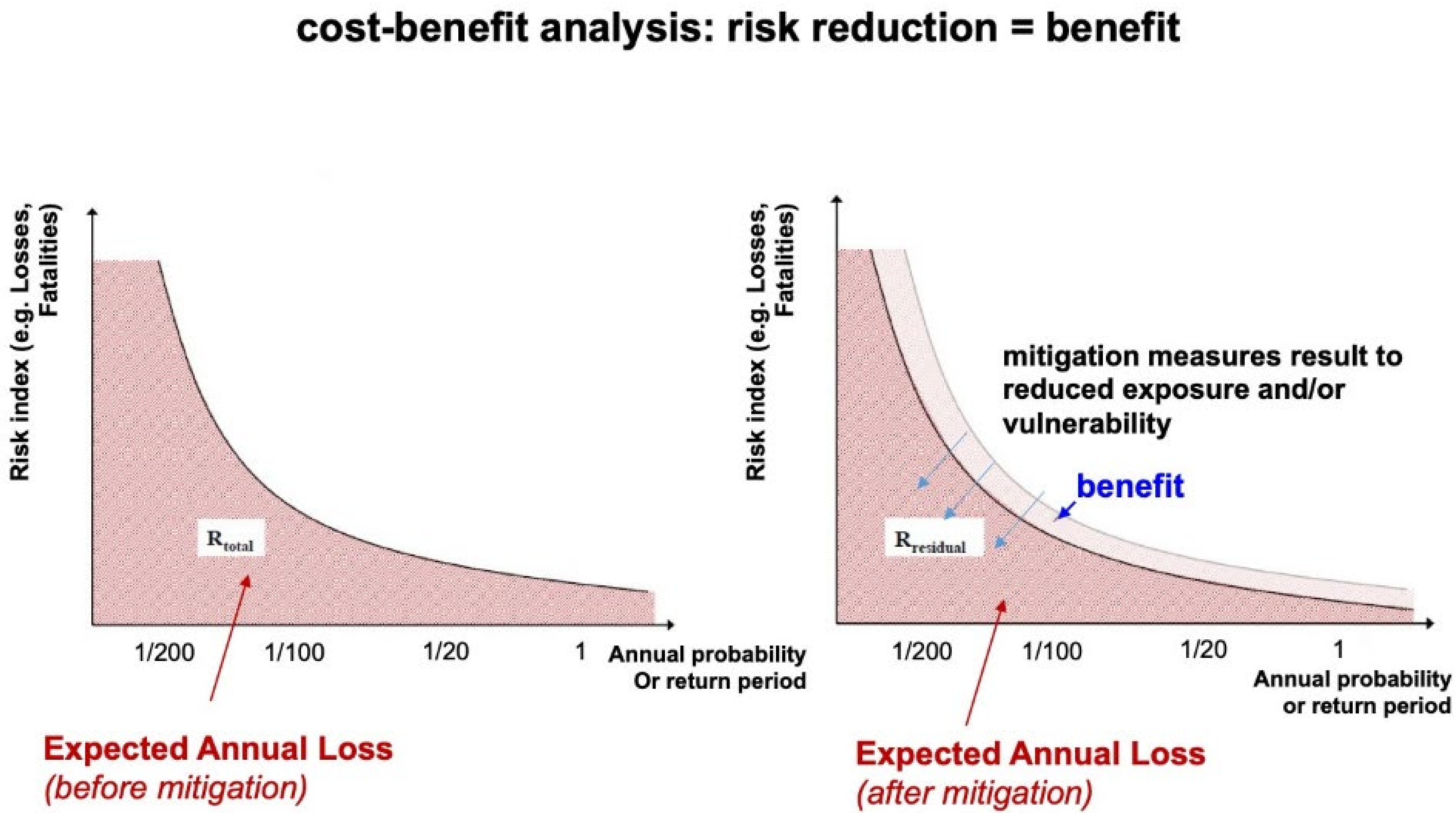
Protection barriers during rockfall event

Risk without mitigation measures

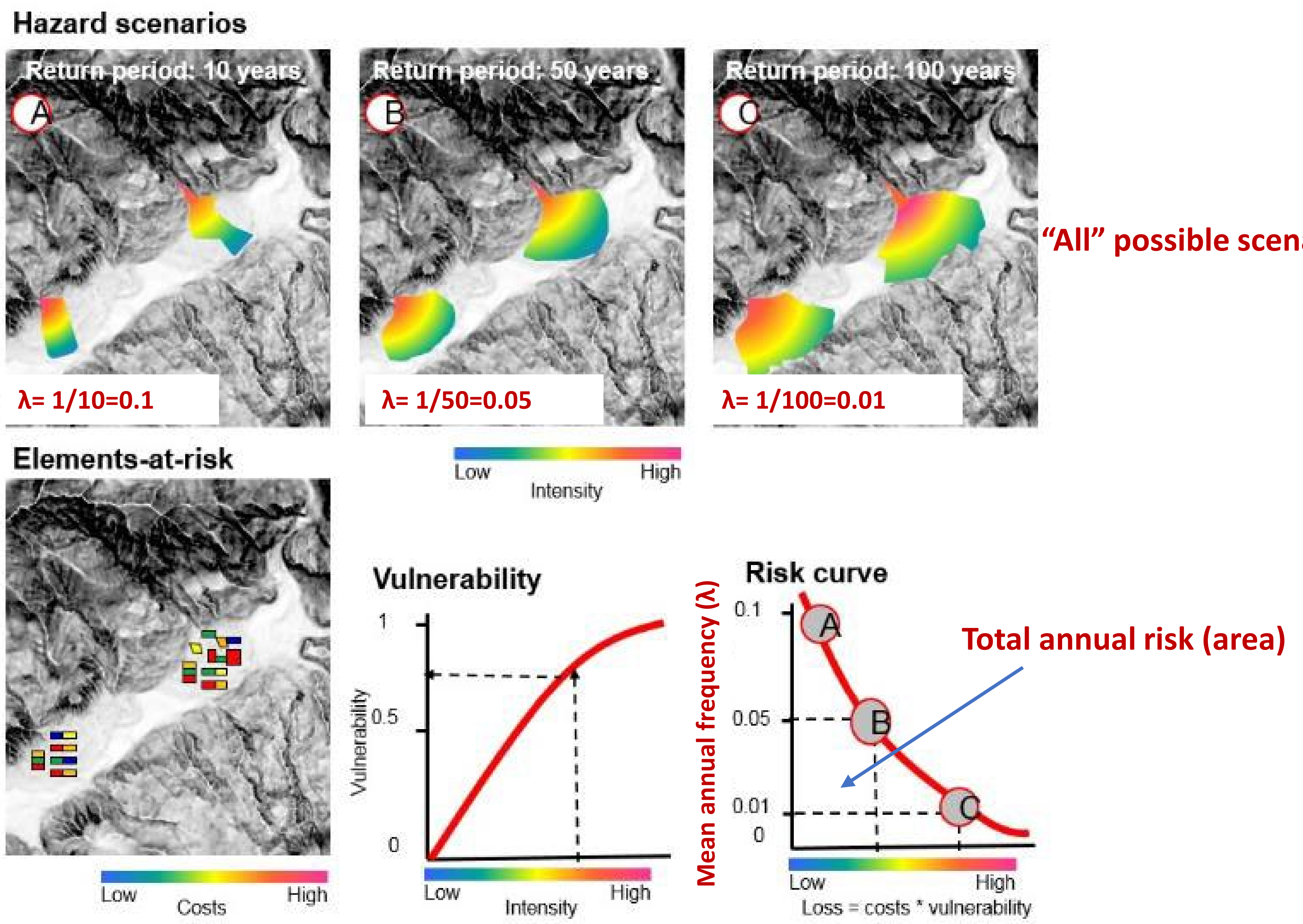
Risk after taking mitigation measures



Risk reduction (example for flood)

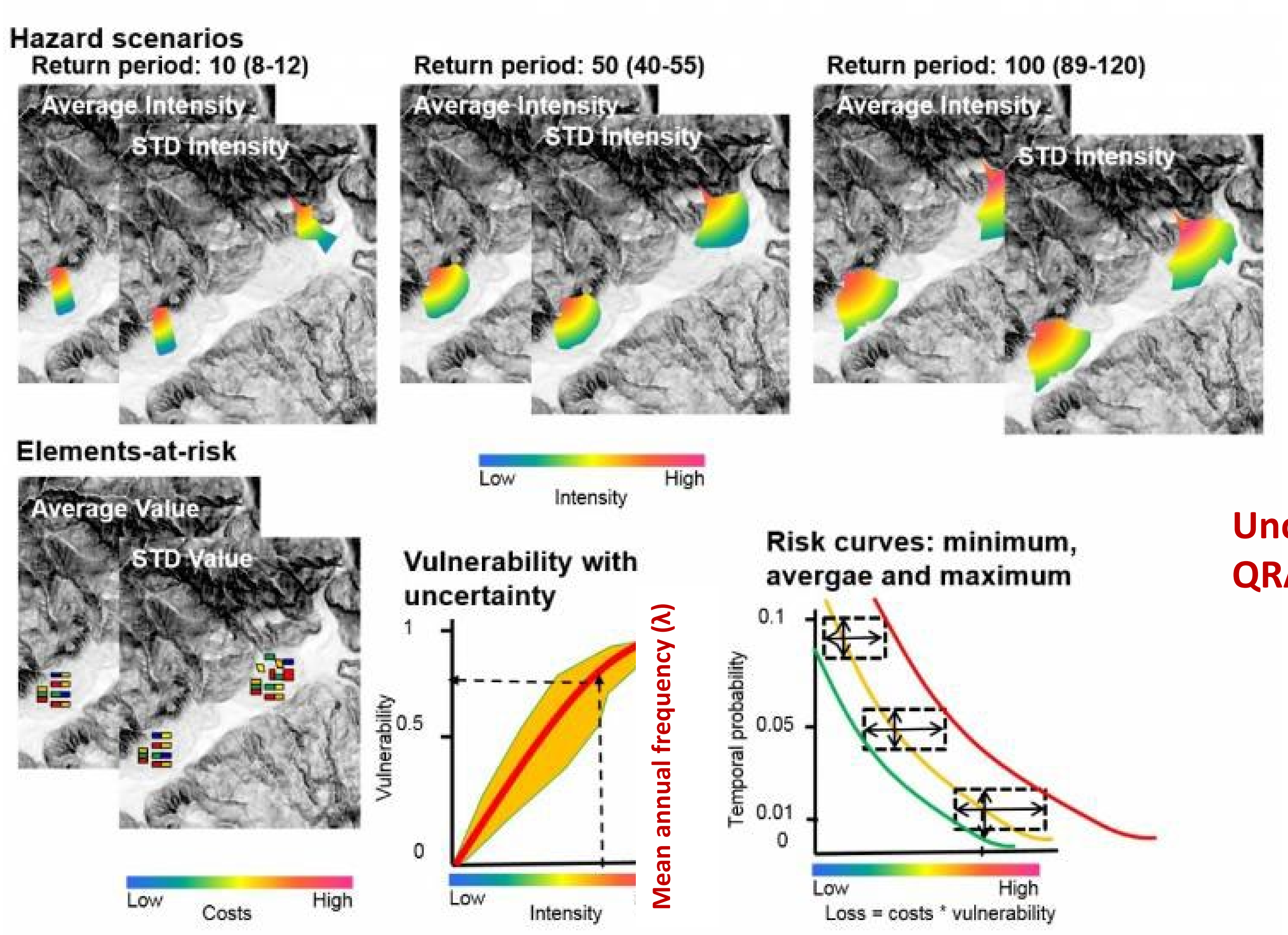


Risk assessment – QRA for all possible scenarios in a given exposure time



"All" possible scenarios

Risk assessment – QRA for all possible scenarios in a given exposure time DT



Uncertainty in QRA

by C.J. van Westen,
http://www.charim.net/methodology/55

Risk analysis approaches

Scale of Analysis	Scale	Possible objectives
International, Global	< 1 : 1 million	Prioritization of countries/regions; Early warning
Small: provincial to national scale	< 1:100,000	Prioritization of regions; Analysis of triggering events; Implementation of national programs
		Strategic environmental assessment; Insurance
Medium: municipality to provincial level	1:100000 to 1:25000	Analysing the effect of changes; Analysis of triggering events; Regional development plans
Local: community to municipality	1:25000 to 1:5000	Land use zoning; Analysing the effect of changes; Environmental Impact Assessments; Design of risk reduction measures
Site-specific	1:5000 or larger	Design of risk reduction measures; Early warning systems; detailed land use zoning

Simplified/Qualitative

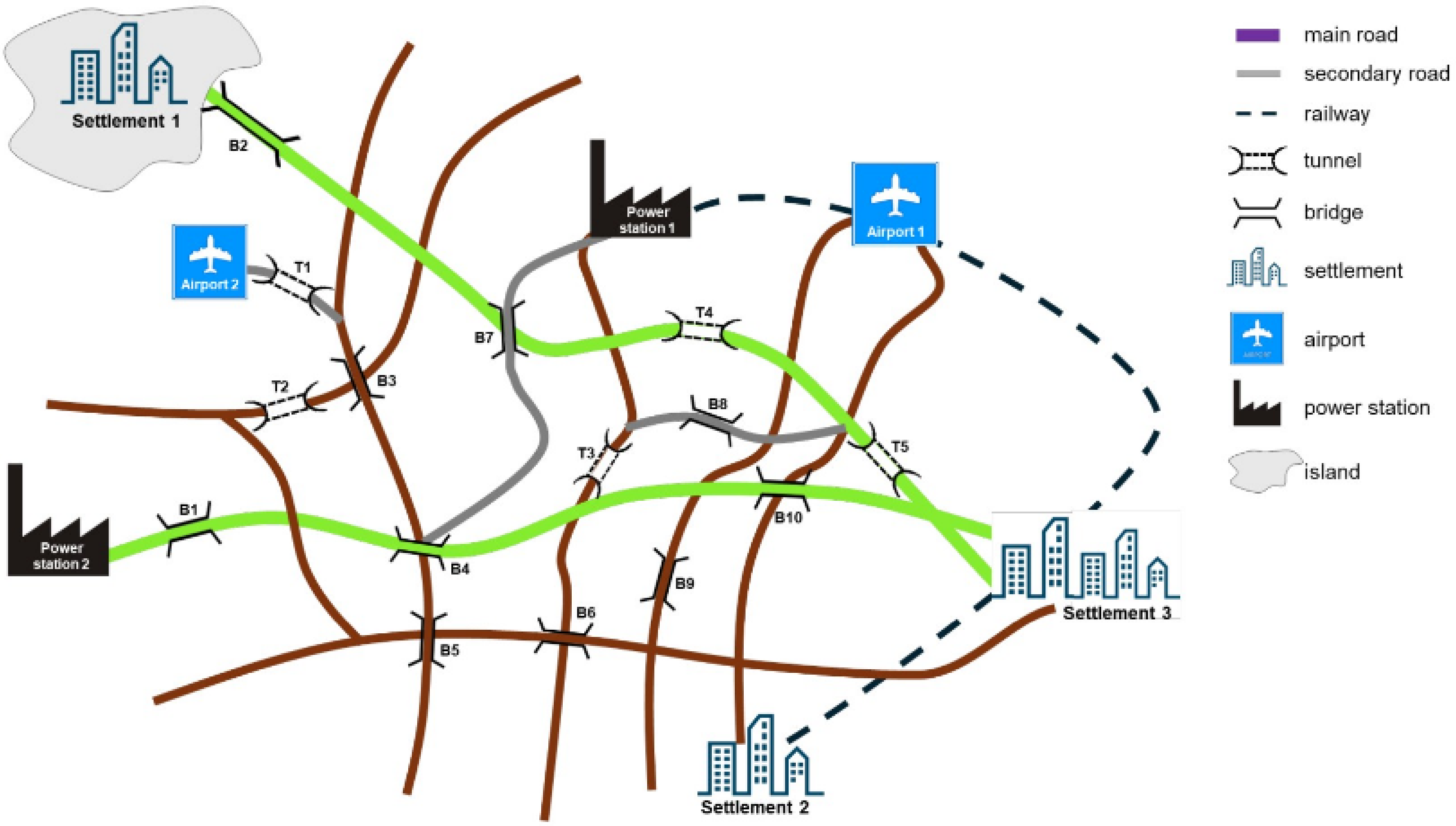
↓

Advanced/Quantitative

Risk analysis – example for portfolio of bridges

Elements at risk – Inventory

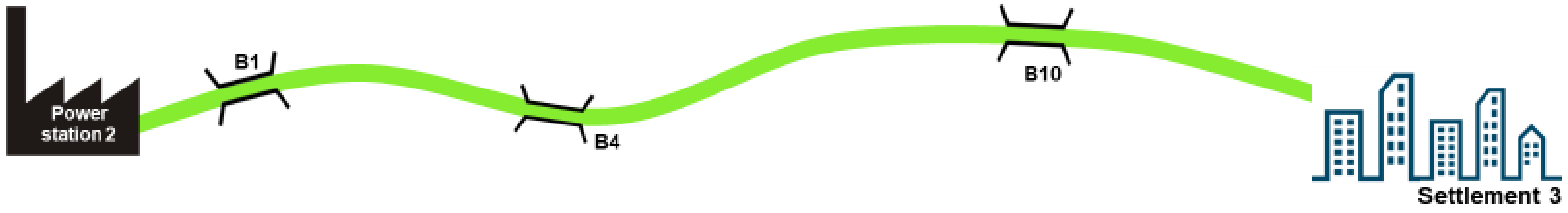
Location of assets, type of road, geometry, materials… (OpenStreetMaps, GoogleMaps)



Risk analysis – example for portfolio of bridges

Elements at risk – Inventory

Location of assets, type of road, geometry, materials, river characteristics etc (OpenStreetMaps, GoogleMaps)



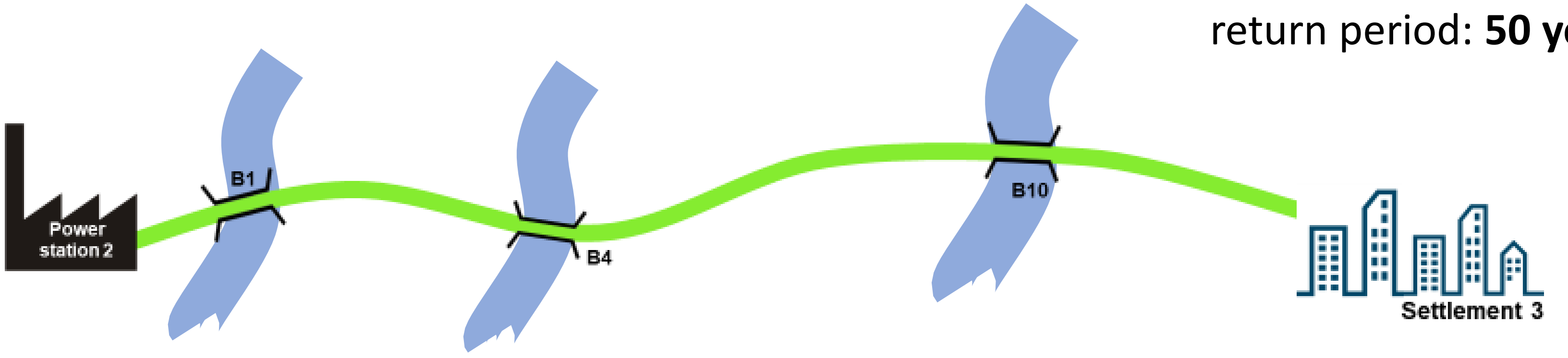
bridge	type	length [m]	width [m]	area [m^2]
B1	II	100	15	1500
B4	I	120	15	1800
B10	II	150	15	2250

type I: concrete, integral connection, shallow foundation
type II: concrete, with bearings, shallow foundation

Risk analysis – example for portfolio of bridges

Flood hazard – intensity measures (based on flood maps or site-specific analysis)

return period: **50 years**



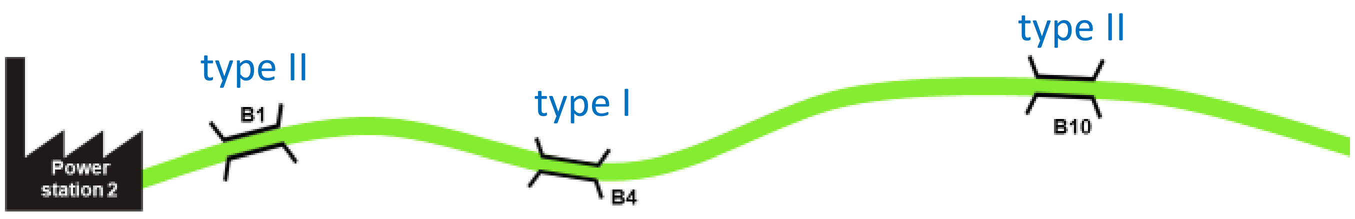
return period:	2 years	10 years	50 years
bridge	water discharge [m³/s]		
B1	400	600	800
B4	500	700	900
B10	600	800	1000
	scour depth [m]		
B1	2.3	2.5	2.8
B4	2.5	3.0	3.3
B10	2.7	3.2	3.8

using closed form solutions for scour depth, e.g.

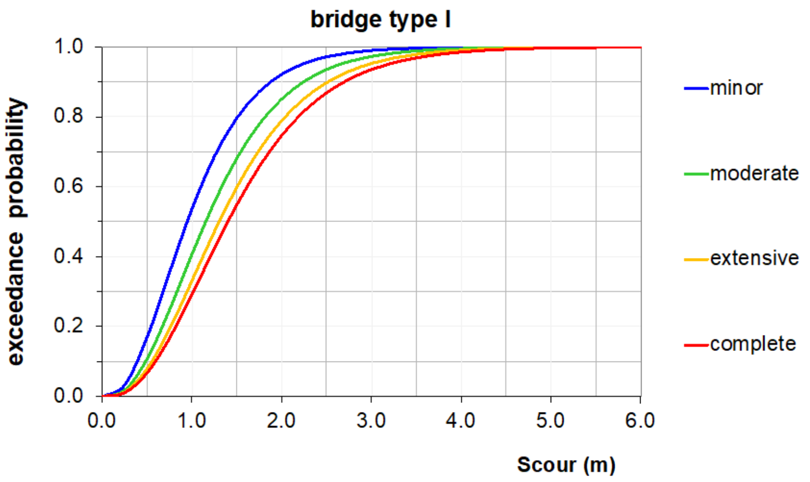
Arneson L.A., Zevenbergen L.W., Lagasse P.F., Clopper P.E. Evaluating scour at bridges. Hydraulic Engineering Circular (HEC) No. 18, Publication No. FHWA-HIF-12-003, Washington, DC, 2012.

Risk analysis – example for portfolio of bridges

Fragility analysis – probability of exceeding a damage state for a given hazard intensity (scour depth)

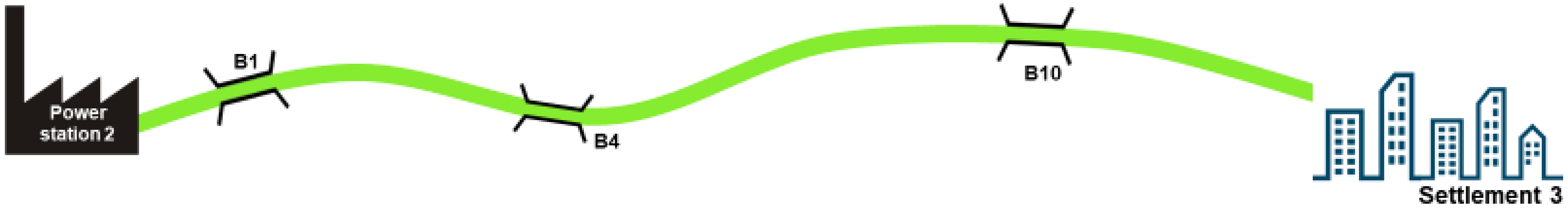


bridge	return period [years]	scour depth [m]	P (≥minor)	P (≥moderate)	P (≥extensive)	P (≥complete)
B1	2	2.3	0.998	0.980	0.944	0.907
B4	2	2.5	0.972	0.936	0.898	0.869
B10	2	2.7	1.000	0.996	0.982	0.963
B1	10	2.5	1.000	0.991	0.968	0.940
B4	10	3.0	0.990	0.973	0.953	0.935
B10	10	3.2	1.000	0.999	0.995	0.987
B1	50	2.8	1.000	0.996	0.982	0.963
B4	50	3.3	0.994	0.983	0.968	0.955
B10	50	3.8	1.000	1.000	0.999	0.996



Risk analysis – example for portfolio of bridges

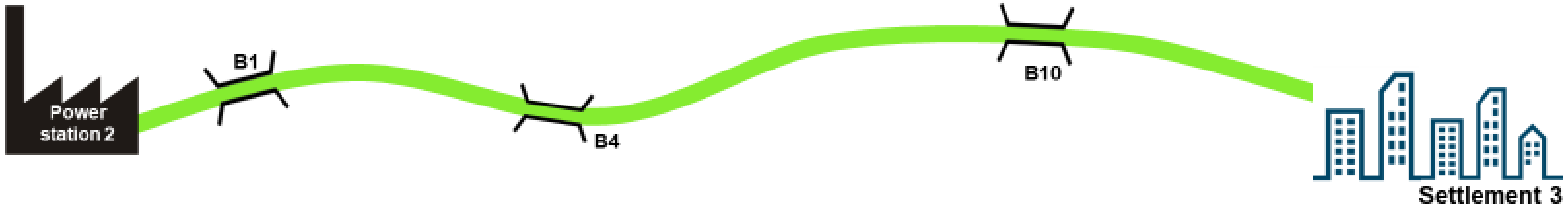
Fragility analysis – probability of being in a damage state for a given hazard intensity (scour depth)



bridge	return period [years]	scour depth [m]	P (no damage)	P (minor)	P (moderate)	P (extensive)	P (complete)
B1	2	2.3	0.002	0.018	0.036	0.037	0.907
B4	2	2.5	0.028	0.036	0.038	0.029	0.869
B10	2	2.7	0.000	0.004	0.014	0.020	0.963
B1	10	2.5	0.000	0.008	0.023	0.028	0.940
B4	10	3.0	0.010	0.017	0.020	0.017	0.935
B10	10	3.2	0.000	0.001	0.004	0.009	0.987
B1	50	2.8	0.000	0.004	0.014	0.020	0.963
B4	50	3.3	0.006	0.011	0.015	0.013	0.955
B10	50	3.8	0.000	0.000	0.001	0.003	0.996

Risk analysis – example for portfolio of bridges

loss assessment – for given cost ratio (repair cost/replacement cost)



bridge	return period [years]	scour depth [m]	loss ratio	area [m²]	loss (€) = loss ratio * area [m²] * 2,000 [€/m²]	total loss for each scenario [€]
B1	2	2.3	0.486	1500	1458671	
B4	2	2.5	0.466	1800	1676238	
B10	2	2.7	0.507	2250	2283432	**5,418,342**
B1	10	2.5	0.499	1500	1497375	
B4	10	3.0	0.494	1800	1779083	
B10	10	3.2	0.516	2250	2320904	**5,597,362**
B1	50	2.8	0.507	1500	1522288	
B4	50	3.3	0.502	1800	1808600	
B10	50	3.8	0.519	2250	2334091	**5,664,979**

Mean cost ratio:

Minor damage: 0.05
Moderate damage: 0.125
Extensive damage: 0.25
Complete damage: 0.52

Construction cost: 2,000 €/m^2

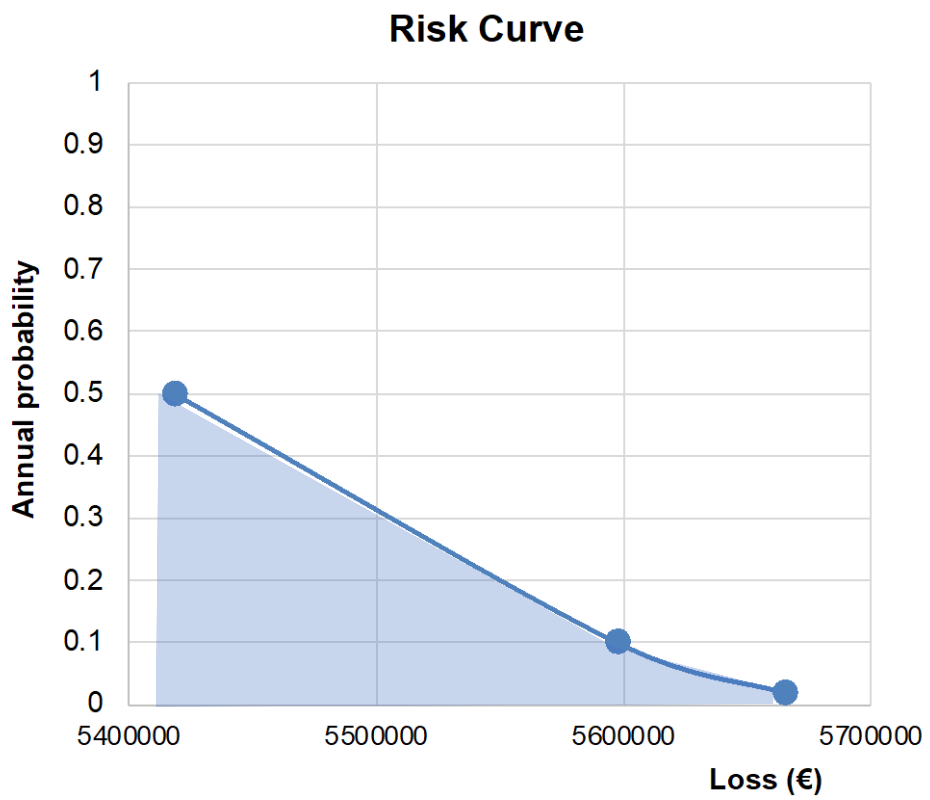
see Mitoulis et al. 2021 https://doi.org/10.1016/j.engstruct.2021.112180

Risk analysis – example for portfolio of bridges

risk curve

For each scenario we need to know:
the probability of occurrence and the corresponding expected loss

bridge	return period [years]	annual probability	total loss [€]
B1, B4, B10	2	0.5	5,418,342
B1, B4, B10	10	0.1	5,597,362
B1, B4, B10	50	0.02	5,664,979



the risk curve can be used to calculated the Average Annual Losses (AAL) by calculating the area under the curve.

Standards, design guidelines and policies

Discussion:

- A discussion about standards, design guidelines and policies.