Massive Open Online Course
Resilience, Sustainability & Digitalisation in Critical Infrastructure

Lecture 2 Vulnerability and risk assessment for climate change

Lecture Notes

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Introduction

A Massive Open Online Course (MOOC) is a free, open, online course designed to offer a taste of higher education to learners from across the world. The University of Birmingham is delivering new MOOCs in partnership with FutureLearn. Delivered by world-class academics from the University of Birmingham and other partners of the HORIZON Recharged project (GA no. 101086413), the course enable learners worldwide to sample high-quality academic content via an interactive web-based platform from leading global universities, increasing access to higher education for a whole new cohort of learners.
The course is developed by senior academic staff and their content is reviewed regularly, taking into account student feedback.

This MOOC brings together world experts, including general audiences, aiming to provide training with life-long updates and professional development opportunities for general and specialised audiences. The MOOC contains all the necessary components of a university taught module, e.g. prerequisites, content and aims, learning outcomes, attributes for sustainable professional development (cognitive, analytical, transferable skills, professional and practical skills), expected hours of study, assessment patterns, units of assessment and reading list, warm-up sessions, with relevant podcasts and videos, lecture notes and recorded lectures, some of which will be tailored for general audiences. This open course will be available on futurelearn.com and on the project website.

These lecture notes are accompanying the seven lectures of the MOOC. Following is the MOOC description, which contains the outcomes, the aims per week and the learning activities. The latter include a combination of material acquisitions and discussions, investigations and production, practical examples and analysis of case studies, and a set of collaboration and discussion forum.

Outcomes

Lecture 2-Week 2
The aim of this week is to introduce the concepts of vulnerability and risk for critical infrastructure subjected to climate hazards. This includes the classification and characterisation of natural hazards, identification of hazard exacerbations due to climate change, and the definition of fragility and vulnerability models for critical infrastructure. Week 2 will also present applications for representative transport and energy assets and systems which may also suffer from ageing and other natural and human induced stressors.

- 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.

Lecture 2. Vulnerability and risk assessment for climate change

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.

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Activity 1. Natural Hazards and climate projections

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.

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Classification and characterisation of hazards

geohazards	climatic	environmental & weather	biohazards	cyber	anthropogenic	conflicts
(e.g. earthquakes, landslides, volcanic eruptions)	(e.g. extreme temperatures, hurricanes, wildfires)	(e.g. floods, rainfall, snowfall)	(e.g. bacteria, GMOs)	(e.g. malware, data breaches, generative AI)	(e.g. pollution, accidents, contamination)	(e.g. wars, political, ethnic/religious)

➡ **threat-agnosticity !**

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The different types of hazards are categorised into the following groups:
Geohazards: Includes natural events like earthquakes, landslides, and volcanic eruptions.
Climatic Hazards: Covers extreme weather conditions such as hurricanes, wildfires, and extreme temperatures. **Environmental Hazards**: Encompasses floods, heavy rainfall, and snowfall.
Biohazards: Refers to biological threats like bacteria, viruses, and genetically modified organisms (GMOs). **Cyber Hazards**: Involves digital threats such as malware, data breaches, and issues related to

generative AI. **Anthropogenic Hazards**: Includes human-caused risks like pollution, accidents, and contamination. **Conflicts**: Pertains to wars, political conflicts, and ethnic or religious tensions.
The concept of "**threat-agnosticity"** refers to an approach that can be applied universally across various types of threats. It emphasizes designing critical infrastructure to be resilient against all possible hazards, regardless of their specific nature. By adopting a threat-agnostic approach, organizations and governments can enhance their ability to protect against and respond to a wide array of potential hazards, ensuring greater overall security and resilience.

A **natural hazard** is defined as a natural phenomenon that might have a negative effect on humans or the built/natural environment. Examples include earthquakes, tsunamis, volcanic eruptions, landslides, floods, droughts, and heavy rainfall. **Cascading/Multiple hazards** are natural hazards that can be correlated, meaning one event can trigger another. Examples include a tsunami triggered by an earthquake and a landslide or flood caused by heavy rain.

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**

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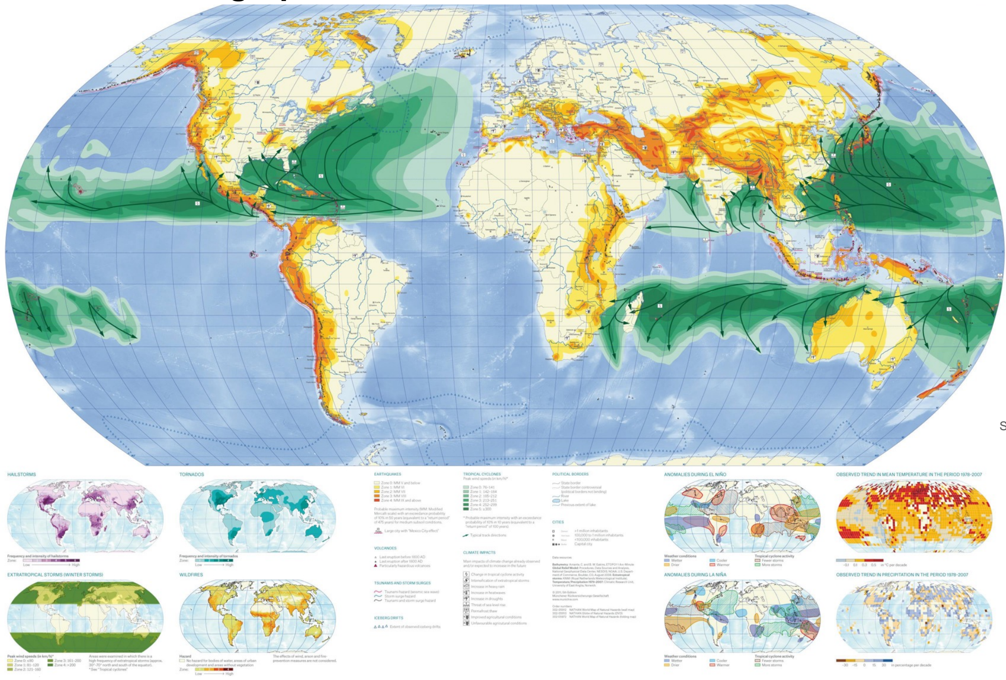
Natural hazards include the following main categories:

- 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

Natural hazards: Geographical distribution



Source : MUNICH RE NATHAN
World Map of Natural Hazards

The world map of natural hazards shows the geographical distribution of main hazards[1]. The exposure levels shown on the maps and the experience from major natural catastrophes form the basis for risk assessment and support risk rating calculation.

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

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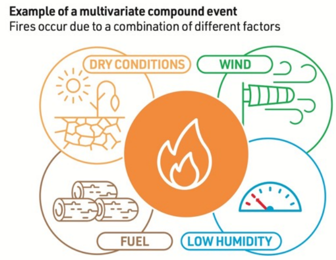
[1] https://catalogue.unccd.int/Map_NATHAN%20-%20World%20map%20of%20natural%20hazards.pdf

The classification of climate related hazards according to the EU taxonomy considers chronic and acute hazards. The hazards are classified to temperature-, wind-, water- and solid mass related hazards. The list of climate-related hazards in this table is non-exhaustive, and constitutes only an indicative list of most widespread hazards that are to be taken into account as a minimum in the climate risk and vulnerability assessment (EU Taxonomy Regulation[2]).

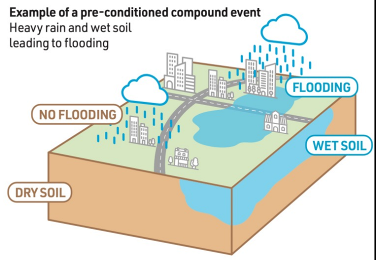
Compound hazards

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.



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[2] https://ec.europa.eu/sustainable-finance-taxonomy/faq

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.

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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. Two examples of compound hazards are given. More details on the categorisation of compound events can be found at the NCA report[3].

[3] https://nca2023.globalchange.gov/chapter/focus-on-1/

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.


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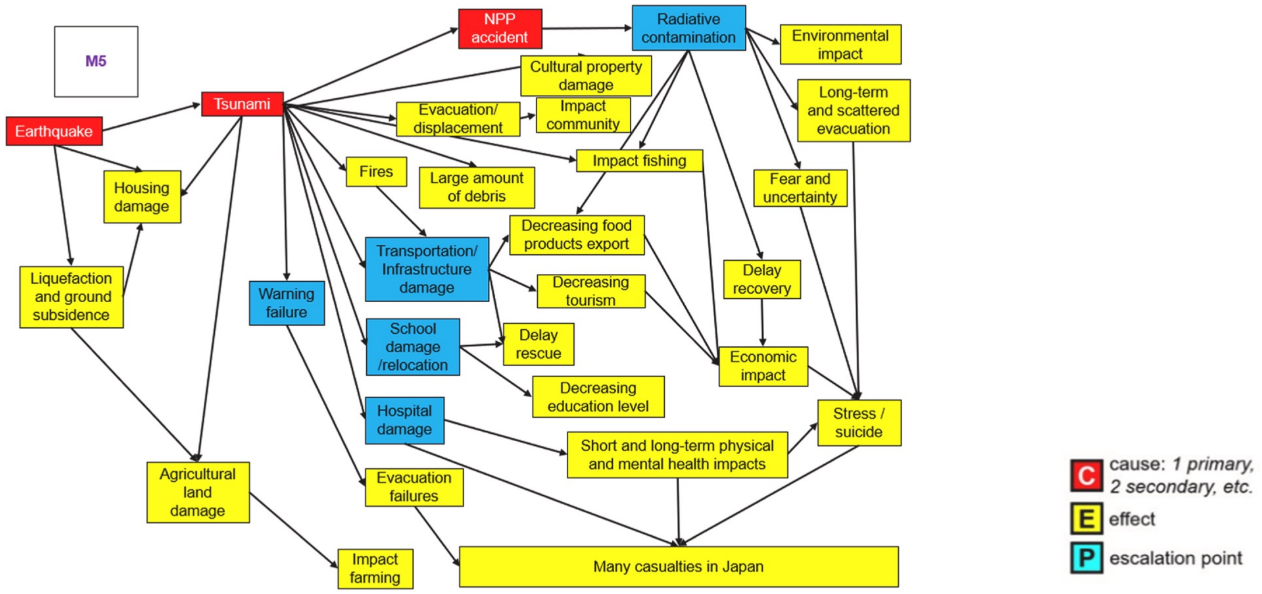
Cascading events are sequences of events where one event triggers another, leading to a chain reaction. These events are characterised by two main features: triggering relationships and sequential dependency. Triggering relationships occur when an initial event sets off a series of subsequent events, with each event in the sequence exacerbating the situation. For example, a natural disaster like an earthquake can trigger a tsunami, which in turn can cause flooding and further destruction.

Sequential dependency means that 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. For instance, a drought can create dry conditions that make wildfires more likely. Once a wildfire starts, it can spread rapidly, causing extensive damage and potentially triggering other crises such as air pollution and health issues.

Cascading events - example



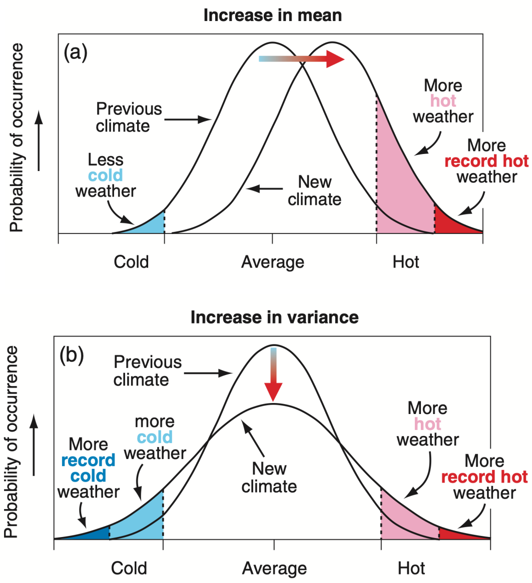
Cascading impacts of the 2011 Great East Japan Earthquake and Tsunami (Suppasri et al., 2021)

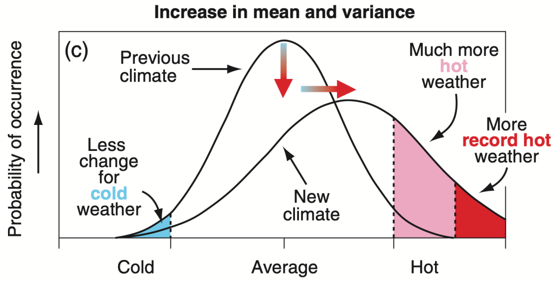
Cascading events refer to a sequence of events where one event triggers another, leading to a chain reaction. These events are characterized by triggering relationships and sequential dependency. Triggering relationships occur when an initial event sets off a series of subsequent events, each exacerbating the situation. Sequential dependency means that the occurrence of one event depends on the occurrence of a preceding event, often leading to a domino effect where the impact grows as the sequence progresses.

An example of cascading events is the 2011 Great East Japan Earthquake and Tsunami (Suppasri et al., 2021). The primary cause of this disaster was the earthquake and tsunami. This initial event led to several secondary effects, including housing damage, the release of hazardous substances, liquefaction and ground subsidence, and agricultural damage. These secondary effects further triggered tertiary impacts such as a decrease in the tourism industry, delays in reconstruction work, fear and uncertainty among the population, a decrease in food product exports, and a decline in education levels. Additionally, there were significant short and long-term physical and mental health impacts, including increased stress and suicide rates. The overall economic impact was substantial, and there were many casualties in Japan.

The flowchart illustrating these cascading events highlights the progression from the primary cause through various secondary effects to tertiary impacts. It includes annotations for the National Contingency Plan (NCP), National Disaster Preparedness (NDP), cultural property displacement, and import food shortages, emphasizing specific areas affected by the cascading events. This example underscores the importance of understanding and preparing for cascading effects in disaster management.

Climate exacerbations and stress-testing





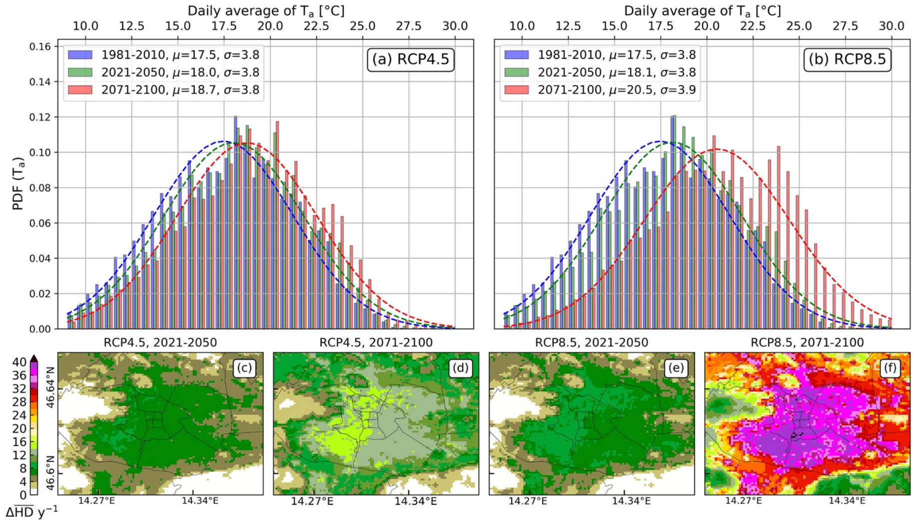
Schematics showing the effect on extreme temperatures when (a) the mean temperature increases, (b) the variance increases, (c) when both the mean and variance increase for a normal distribution of temperature *(IPCC, 2001)*

The figure illustrates how changes in climate conditions affect extreme temperatures through three different scenarios.

Increase in Mean Temperature: The first graph shows that when the average temperature increases, the entire temperature distribution shifts to the right. This means there is a higher likelihood of experiencing hot weather and new record hot temperatures, while the chances of cold weather decrease. **Increase in Temperature Variance**: The second graph depicts an increase in temperature variance, where the distribution becomes wider and flatter. This results in a broader range of temperatures, leading to more occurrences of both record cold and record hot weather compared to the previous climate average. **Increase in Both Mean and Variance**: The third graph combines the effects of the first two scenarios. The distribution shifts to the right and becomes wider, indicating a significant increase in hot weather and a higher frequency of new record hot temperatures.

Overall, even small changes in average temperature or variability can lead to notable differences in climate extremes, emphasising the impact of climate change on weather patterns.

Climate projections

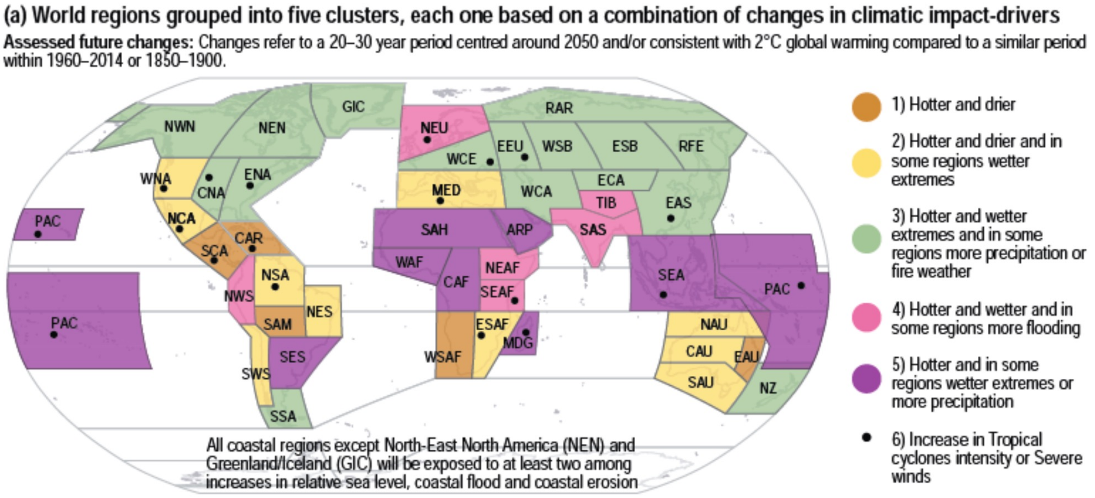


Future climate projections shown as a probability density function (PDF) of the air temperature (Ta) taken from the bias-corrected EURO-CORDEX data set for Representative Concentration Pathways (RCP) of (a) RCP4.5 and (b) RCP8.5 for the extended summer season (MJJAS) *(Oswald et al. 2020)*

The figure shows an example by Oswald et al. (2020) on how different levels of greenhouse gas emissions (RCP4.5 and RCP8.5) can lead to varying degrees of temperature increases over time. The top graphs display the daily average temperatures for different time periods (2001-2010, 2021-2030, 2071-2080). The RCP4.5 scenario shows a moderate increase in temperatures, while the RCP8.5 scenario shows a more significant rise. The maps at the bottom illustrate the spatial distribution of temperature changes for the periods 2021-2050 and 2071-2100. The maps under RCP8.5 indicate more pronounced warming compared to RCP4.5.

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). Panels (a) and (b) provide histograms and a Gaussian normal distribution for the time periods 1981–2010 (blue), 2021–2050 (green) and 2071–2100 (red) with the average value (μ) and standard deviation (σ), respectively. The difference in the average number of hot days per year compared to 1981–2010 is shown for each time period for RCP4.5 in panels (c) and (d) and for RCP8.5 in panels (e) and (f). *For interpretation of the references to colour in this figure legend, the reader is referred to Oswald et al. (2020).*

Climate exacerbations



IPCC (2021)

This map from the IPCC (Arias et al., 2021) report illustrates how different regions of the world are expected to experience changes in climatic impact-drivers (CIDs) due to global warming, particularly at 2°C above pre-industrial levels:

- **Hotter and Drier**: Regions like the Mediterranean and parts of North America are expected to become hotter and drier.
- **Hotter and Drier with Some Regions Wetter**: Some areas, such as parts of Europe and North America, will experience a mix of hotter and drier conditions along with wetter extremes.
- **Hotter with More Flooding**: Certain regions, including parts of Asia, will face hotter conditions with increased flooding.
- **Hotter and Wetter**: Areas like Southeast Asia will become hotter and wetter.
- **Regions at Risk of Storms and Flooding**: Some regions, particularly coastal areas, will be at higher risk of storms and flooding.
- **Increase in Tropical Cyclones**: Southeast Asia is expected to see an increase in tropical cyclones.

Climate exacerbations

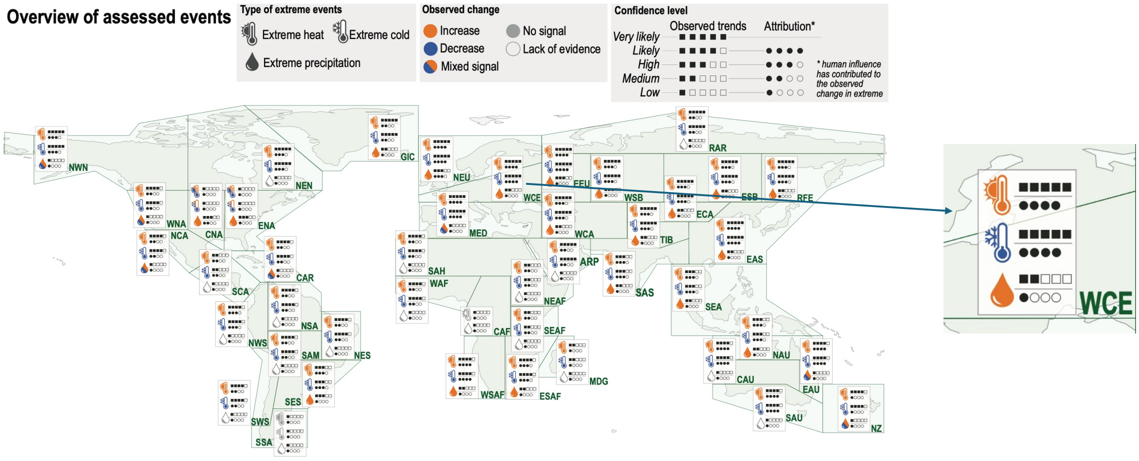
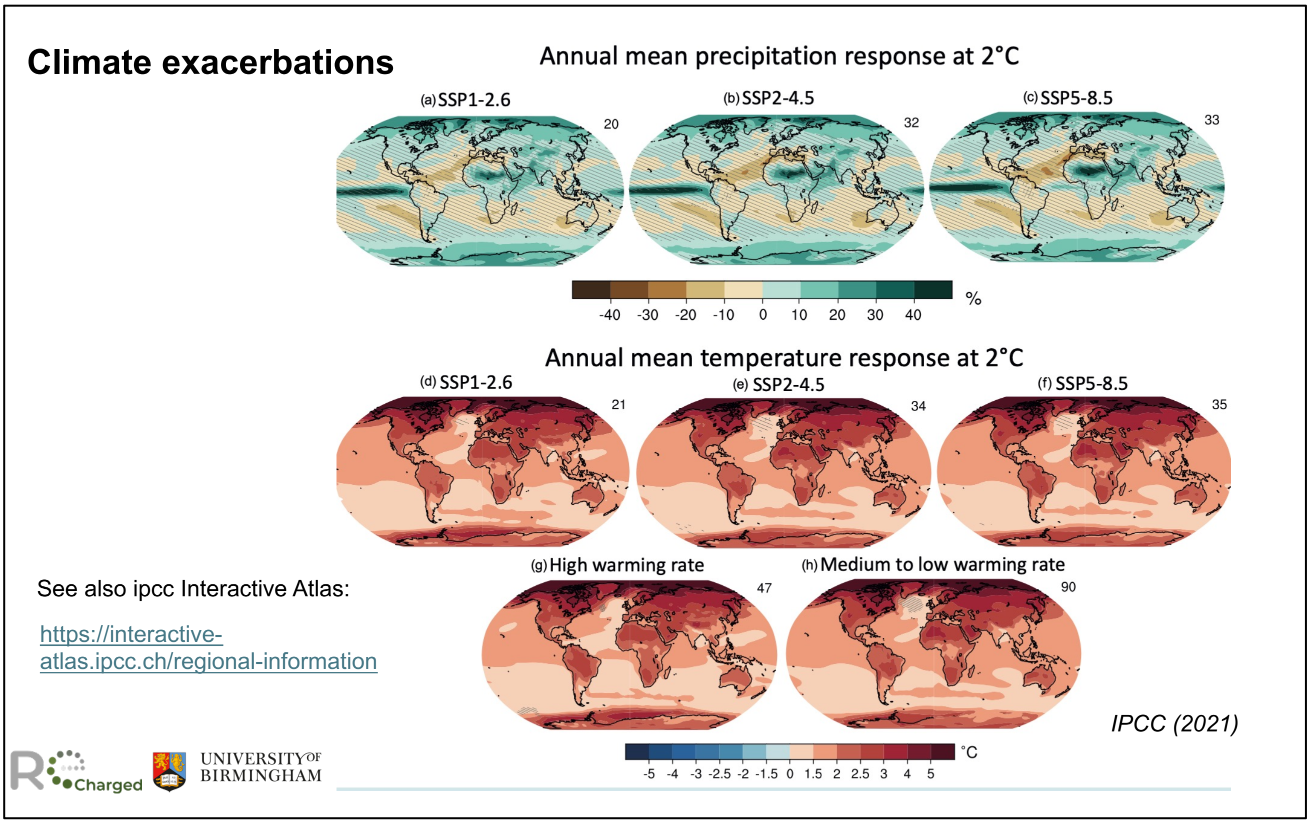


Figure 11.4 | Overview of observed changes for cold, hot, and wet extremes and their potential human contribution. Shown are the direction of change and the confidence in: 1) the observed changes in cold and hot as well as wet extremes across the world; and 2) whether human-induced climate change contributed 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)

This Figure summarizes assessments of observed changes in temperature extremes, in heavy precipitation and in droughts, and their attribution in a map form (IPCC report, Seneviratne et al., 2021). The figure categorizes different types of climate-related events, such as extreme heat, extreme cold, extreme precipitation, river floods, wildfires, and heatwaves. Each event type is represented by a specific icon and colour. The map shows the geographical distribution of these events. Different regions are marked with icons indicating the type of event observed or projected in that area. The text boxes connected to the icons provide brief descriptions of the changes in these events due to climate change. They also indicate the confidence levels associated with these changes, ranging from low to very high.



The **IPCC WGI Interactive Atlas** is a powerful tool developed by the Intergovernmental Panel on Climate Change (IPCC) to support their Sixth Assessment Report (AR6)[4]. Users can perform spatial and temporal analyses of observed and projected climate change data. It provides various data visualizations and summary statistics, making it easier to understand complex climate data. The atlas includes a regional component that allows users to explore climate data from both global and regional databases. The tool offers regional synthesis for climatic impact-drivers, which are factors that can affect climate impacts.

[4] https://interactive-atlas.ipcc.ch/?trk=public_post_comment-text

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 **loss** 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?

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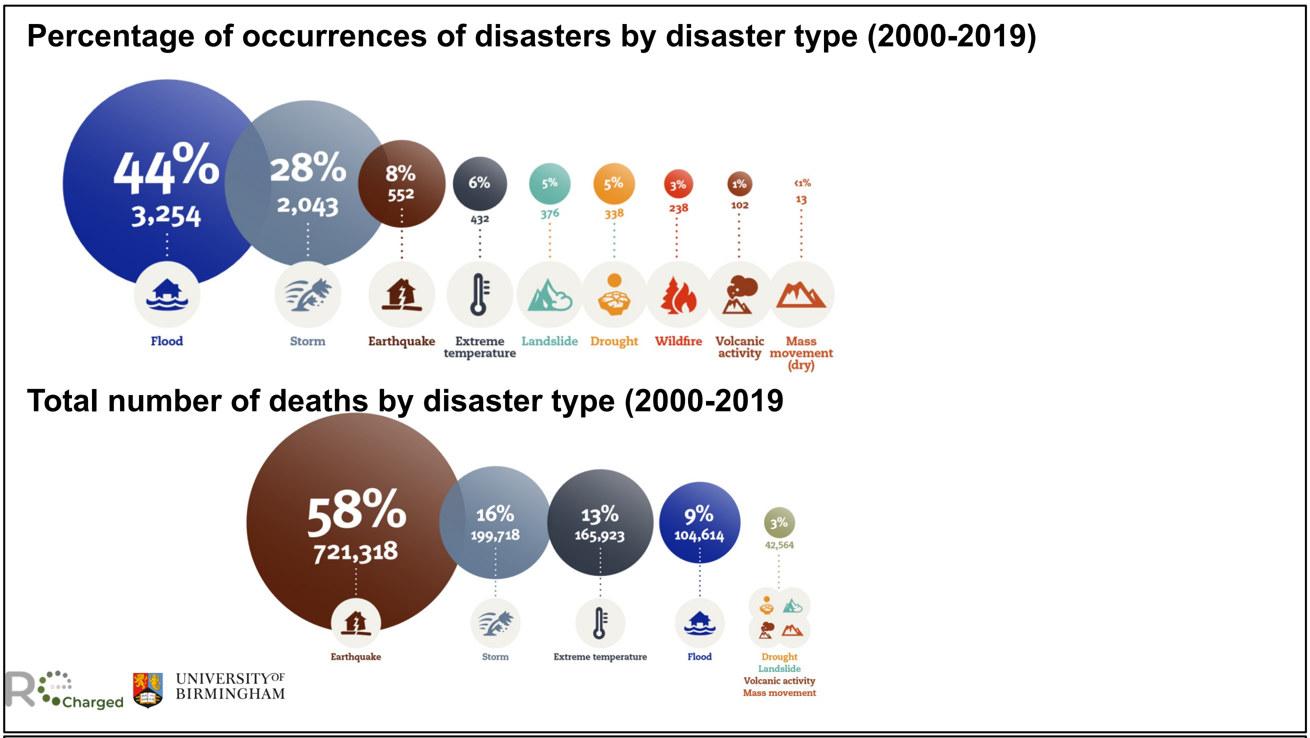
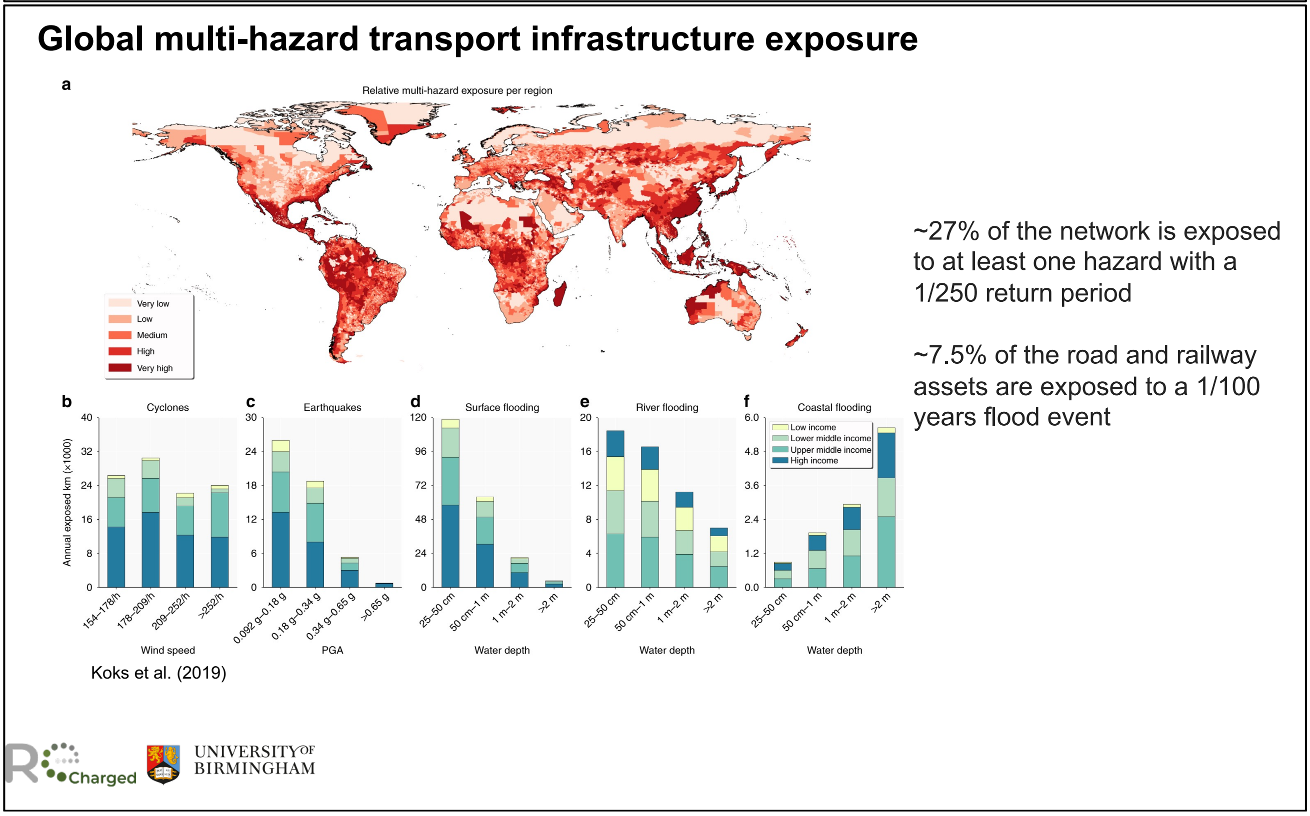
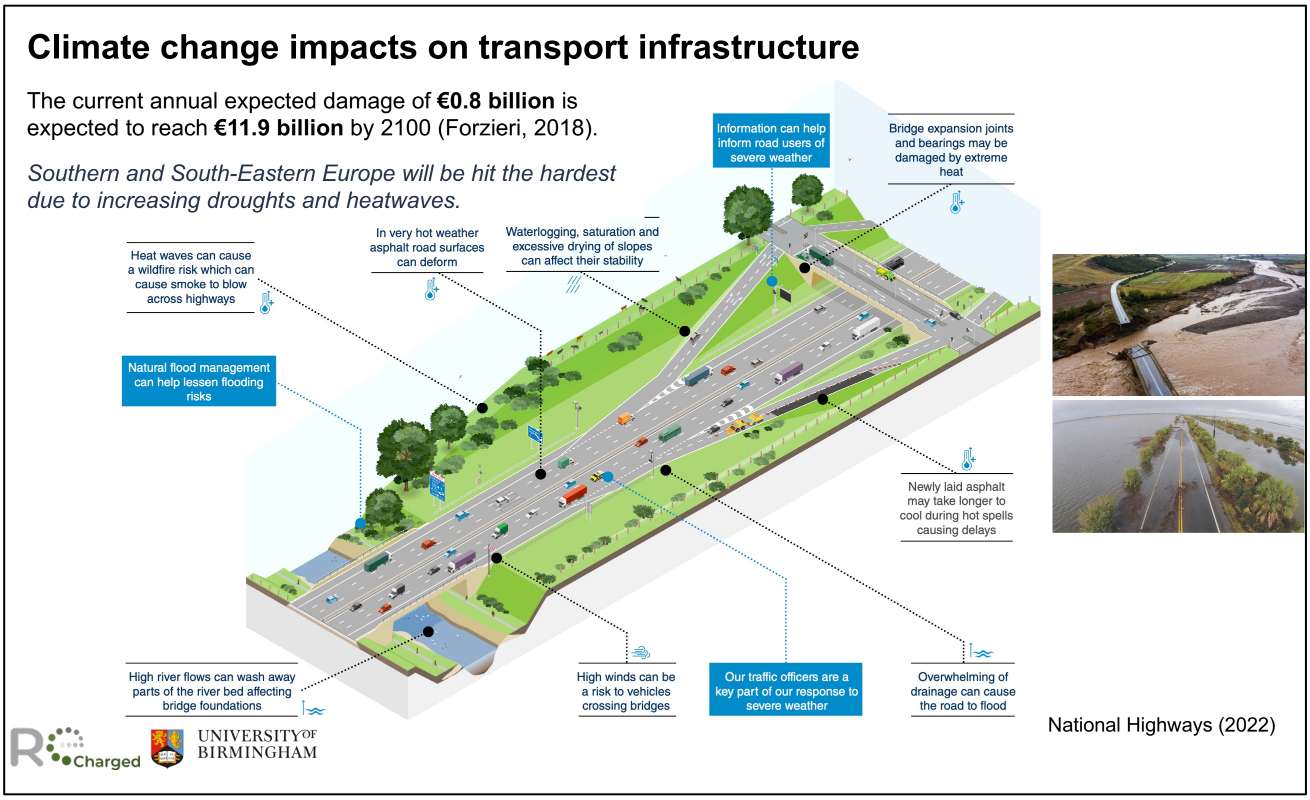
Natural hazards can impact the built environment and affect people, activities, and both built and natural environments. For instance, a flash flood in an uninhabited area is considered a non-catastrophic hazard. Natural disasters can cause loss of life, property damage, and economic impacts, with the severity depending on the resilience of society and infrastructure, and their ability to recover quickly. The robustness, preparedness, and resourcefulness of infrastructure, services, and society play crucial roles in recovery. Factors that may aggravate losses due to natural hazards, include among others, the lack of preparedness, weak designs of infrastructure, or insufficient resources.





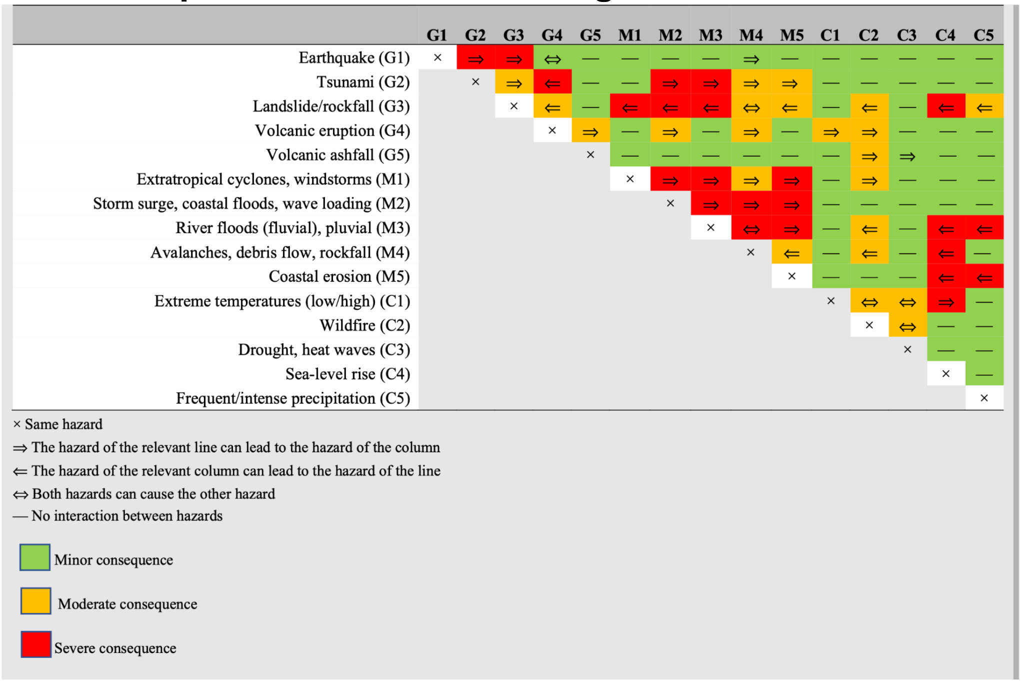
Transport networks worldwide are vulnerable to various natural hazards (Koks et al., 2019). The world map highlights areas in red where transport networks are exposed to multiple hazards, noting that approximately 27% of the network is exposed to at least one hazard with a 1/250 return period, and 7.5% of road and railway assets are exposed to a 1/100 years flood event. Below the map, bar graphs show the percentage of transport assets at risk for different types of hazards: cyclones, earthquakes, surface flooding, river flooding, and coastal flooding, illustrating the varying levels of risk for each type of infrastructure. The inclusion of both a global map and specific hazard data helps convey the widespread nature of these risks and the need for comprehensive, multi-hazard approaches to infrastructure protection.



Impacts of climate change on highways include increased rainfall leading to flooding, high temperatures causing road surfaces to soften, and extreme weather events damaging bridge structures[5]. Key risks include the following: Overwhelming of drainage causing the road to flood; High river flows washing away river beds surrounding the support structures for bridges; Waterlogging and saturation of slopes and earthworks affecting their stability; Excessive water soaking into the layers of a road.
The expected annual expense due to these impacts will be £1.19 billion by 2100 (Forzieri et al., 2018). Southern and South-Eastern Europe will be hit the hardest due to increasing droughts and heatwaves.

[5] https://nationalhighways.co.uk/media/3xmfhsbp/gfd22_043-climate-change-and-the-srn-v18.pdf

Impact of interdependent hazards on bridges and road networks



Mitoulis et al., 2022

The matrix chart illustrates the impact of interdependent hazards on bridges and road networks (Mitoulis et al., 2022). The chart is divided into two main sections: the types of hazards listed on the vertical axis (such as Earthquake, Landslide, Tsunami, etc.) and the same hazards repeated on the horizontal axis. Each cell in the matrix represents the interaction between two different types of hazards, with colour coding indicating the severity of the consequences. The diagonal cells from top left to bottom right are marked with an 'X,' signifying that a hazard does not interact with itself.

This chart visually summarizes how different natural disasters can affect infrastructure in an interconnected way. It highlights potential compound risks that engineers and planners need to consider when designing and maintaining bridges and road networks. Understanding these interactions is crucial for developing resilient infrastructure that can withstand multiple, simultaneous hazards. The color-coded severity levels provide a clear and immediate understanding of which hazard combinations pose the greatest risks, emphasizing the need for comprehensive risk assessment and mitigation strategies.

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

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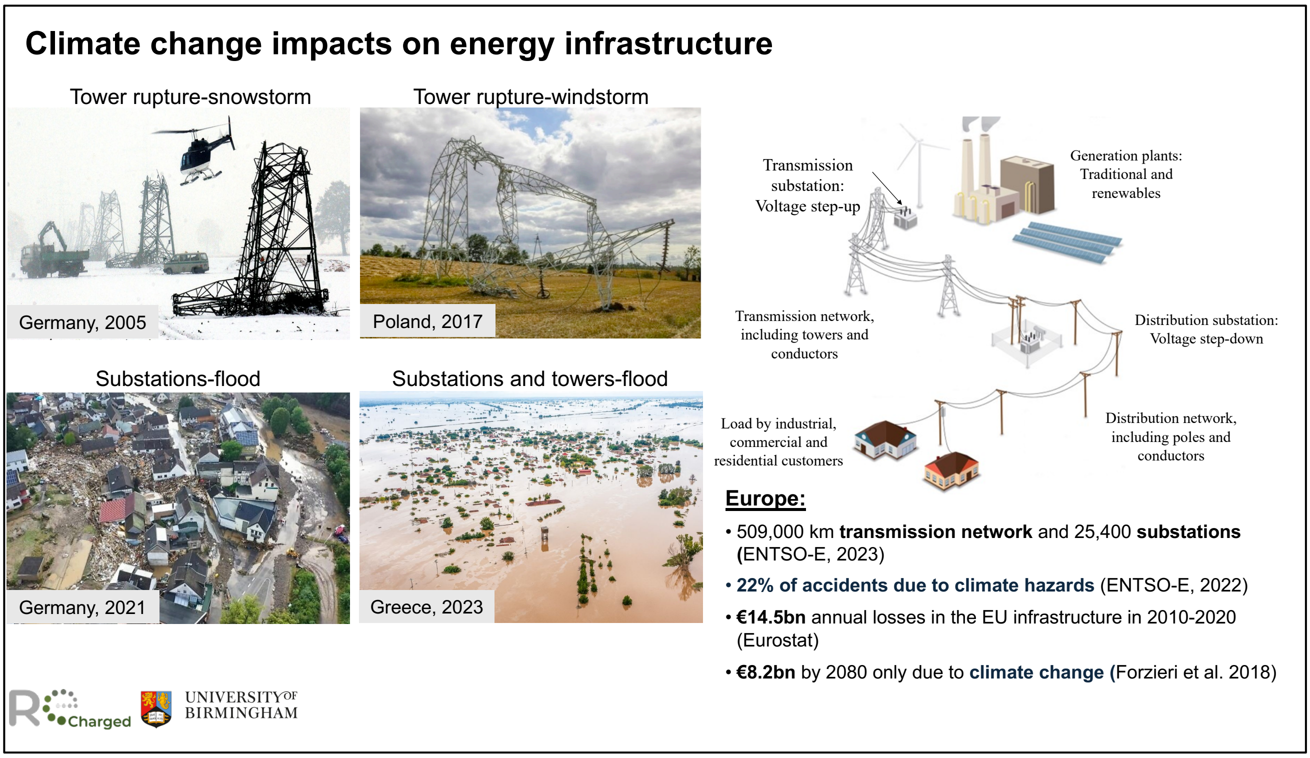
This table assesses the vulnerability of various types of power plants and infrastructure to natural disasters such as earthquakes, cyclones, floods, tsunamis, wildfires, drought, and extreme heat[6]. It categorises thermal plants, hydropower plants, nuclear plants, solar (PV), wind, T&D lines (transmission and distribution), and substations, rating their vulnerability from 'Very low' to 'Very high.' The table highlights that thermal and nuclear plants, as well as substations, are particularly vulnerable to multiple hazards, while solar and wind installations generally have lower vulnerability. These vulnerabilities are due to factors like lack of disaster risk management capacities, ageing and poorly maintained assets, and poorly designed networks without adequate redundancy. This underscores the importance of enhancing the resilience of power infrastructure to ensure reliable energy supply in the face of increasing natural disasters.

[6] https://documents1.worldbank.org/curated/en/200771560790885170/pdf/Stronger-Power-Improving-Power-Sector-Resilience-to-Natural-Hazards.pdf



Common impacts on energy infrastructure include tower ruptures from snowstorms and windstorms, and flooded substations and towers. According to recent reports: 500,000 km of transmission network and >25000 substations are at risk, 22% of accidents occurred due to climate hazards (ENTSO-E, 2020), and €14 billion in annual losses to EU electricity infrastructure for 2011-2020 (Eurostat). The losses due to climate change are projected to increase to €8.2 billion by 2080 (Forzieri et al., 2018). This underscores the urgent need for resilient energy infrastructure to withstand the increasing frequency and severity of climate-related events.

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

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Activity 2. Fragility and vulnerability

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).

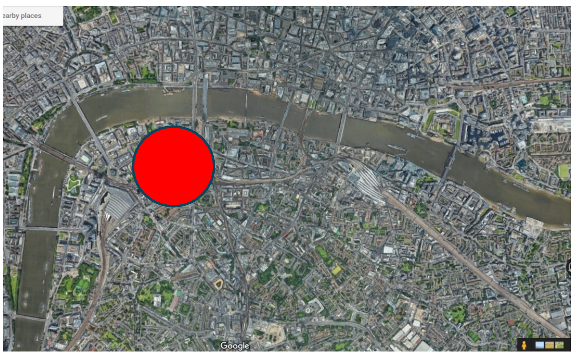
Terminology

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

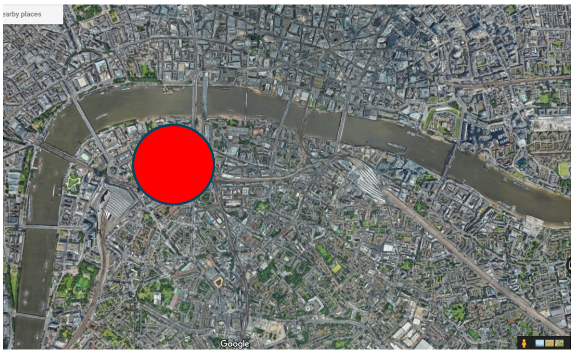
Terminology

Exposure

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

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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.

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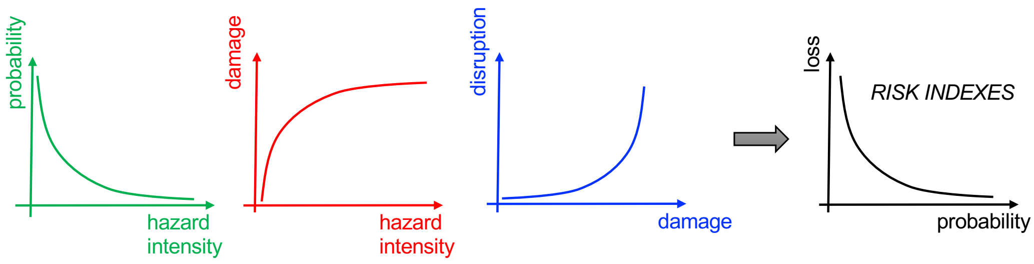
According to IPCC AR6, **exposure** is "The presence of [...] assets in places and settings that could be adversely affected", while **vulnerability** is defined as the propensity or predisposition to be adversely affected. Vulnerability encompasses a variety of concepts and elements including sensitivity or susceptibility to harm and lack of capacity to cope and adapt.

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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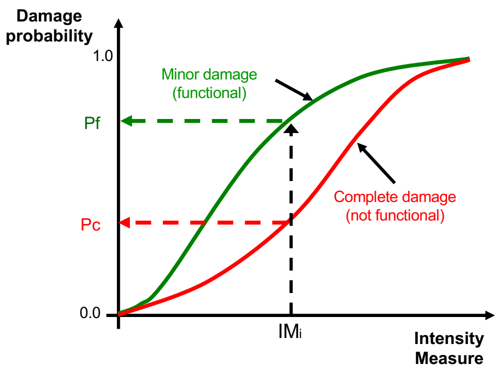
Fragility functions

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

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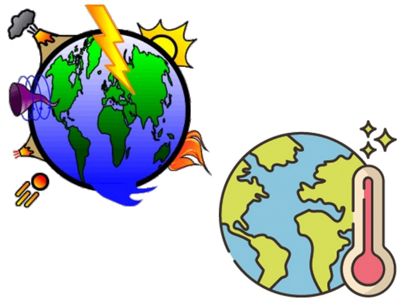
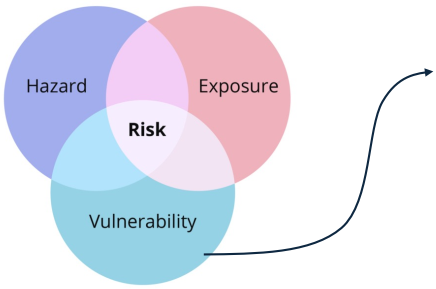
The need for climate aware fragility models

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.

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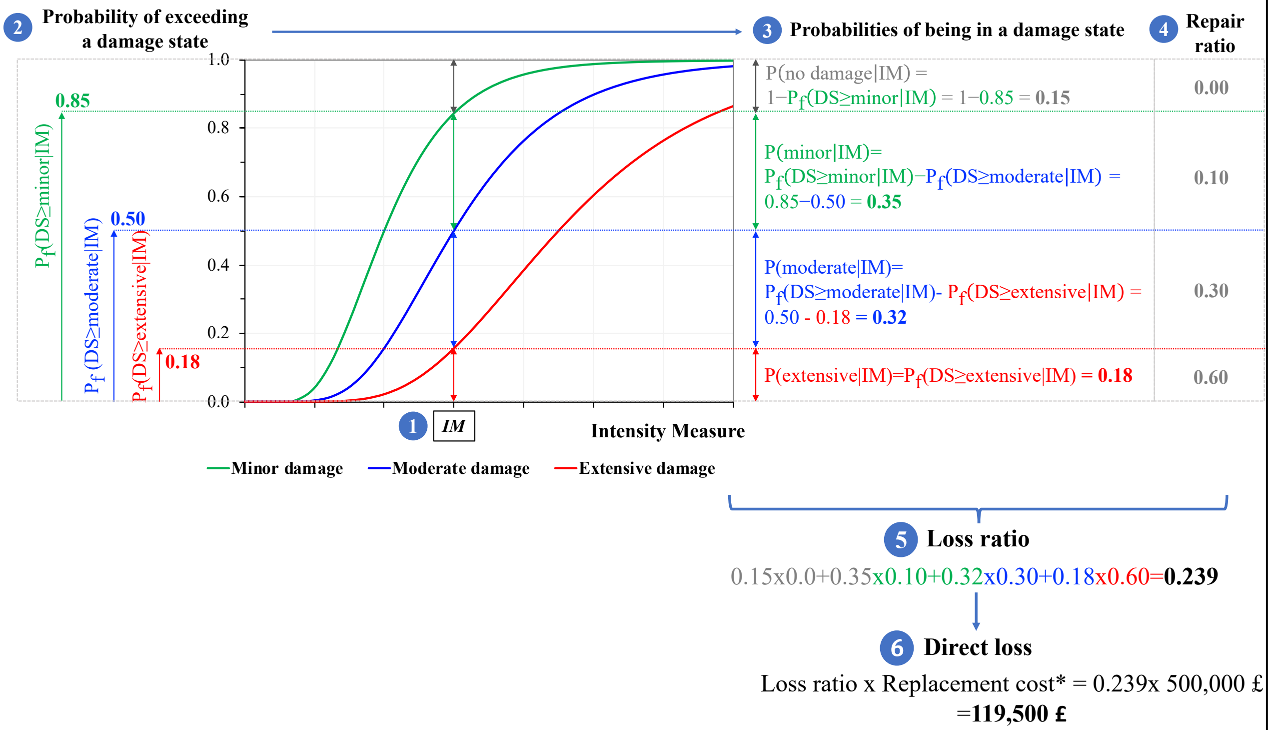
Fragility functions



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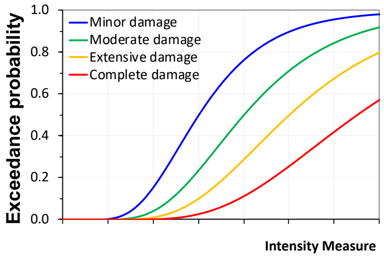
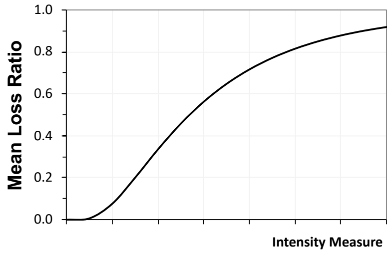
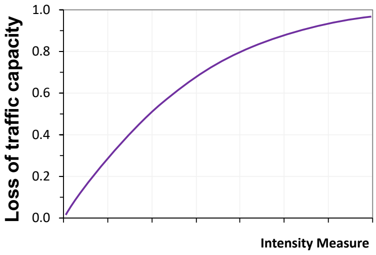
Fragility and vulnerability functions



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.

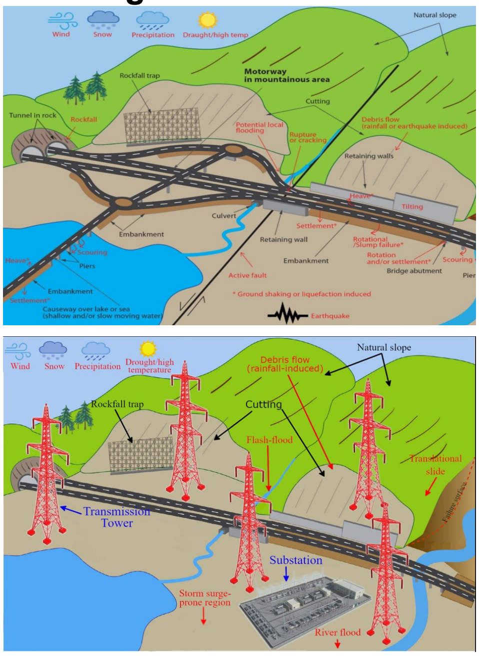
Correlation of damage and functionality

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

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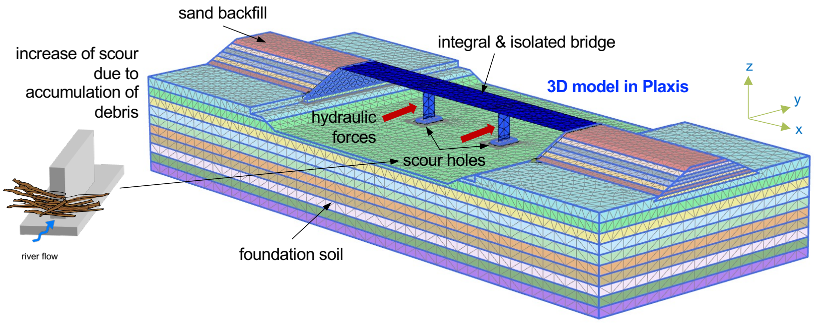
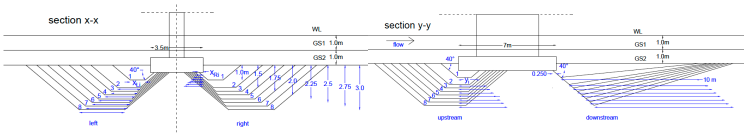
Fragility models based on detailed numerical modelling - Bridges



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)

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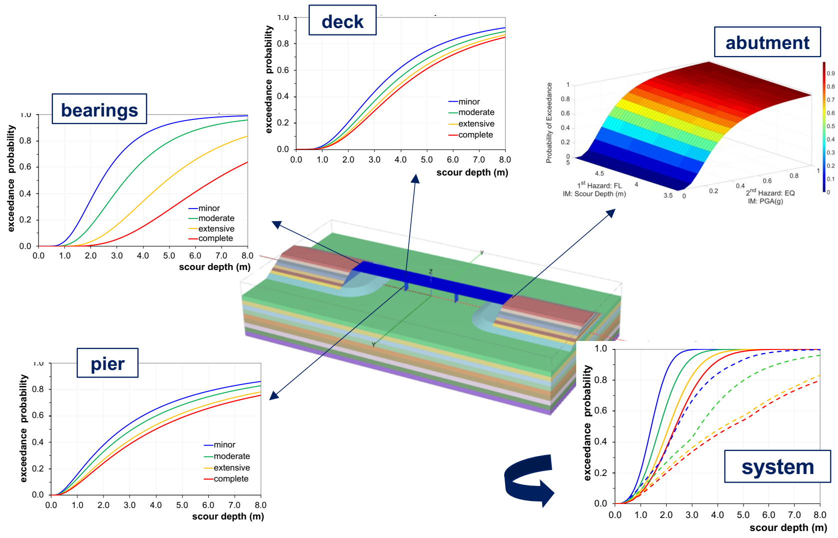
Fragility models based on detailed numerical modelling – Bridge specific



System of Assets:
bridge-embankments-foundation soil
Hazards: flood/scour, hydraulic forces
IM: scour depth (m)

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

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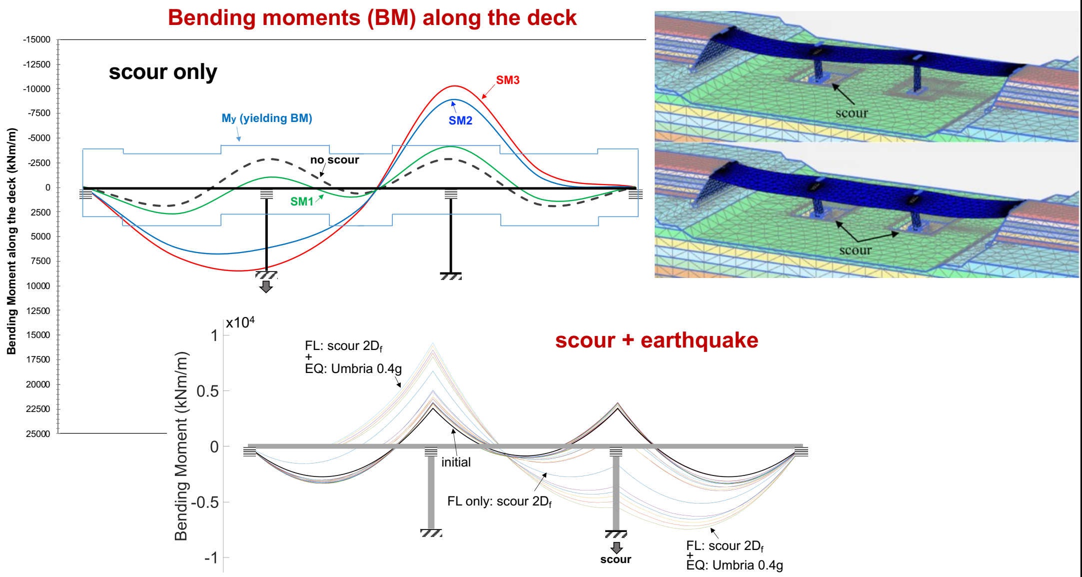
Fragility functions for transport assets under multiple hazards



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

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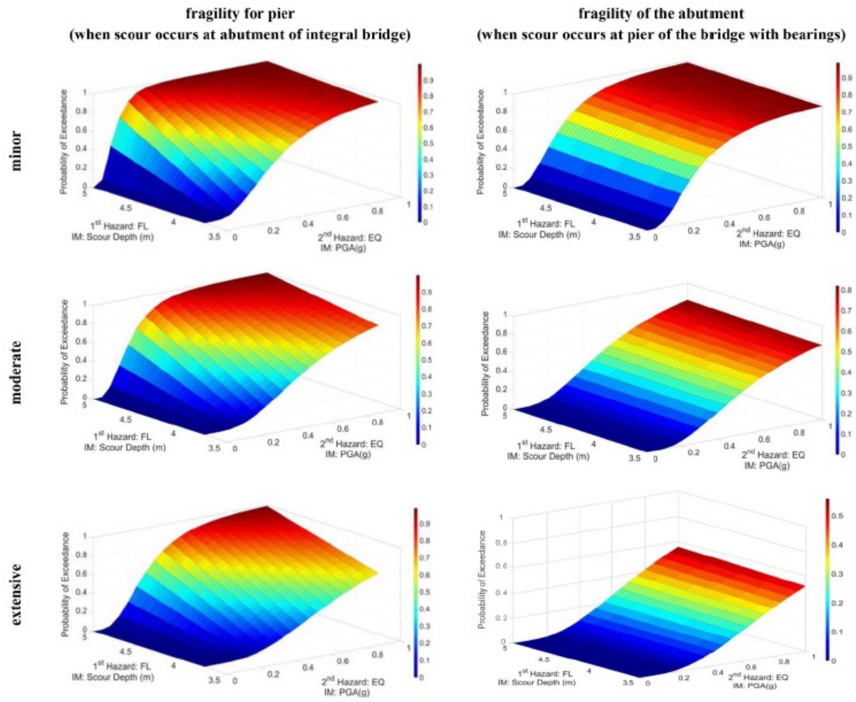
Fragility functions for transport assets under multiple hazards



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

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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?

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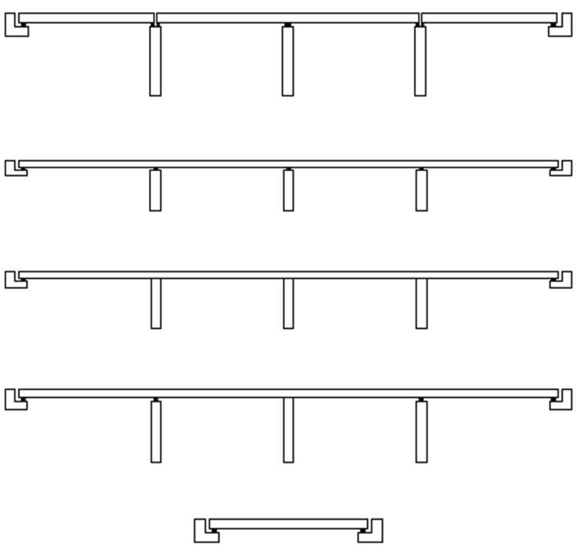
common bridge typologies



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

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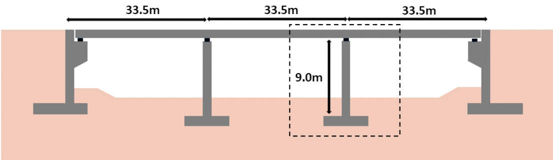
Flood fragility models based on simplified numerical modelling – portfolio of bridges

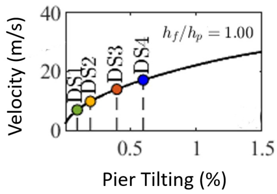
Unified **quantitative** bridge flood fragility framework

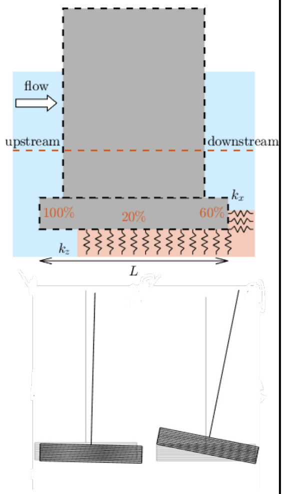
- ❑ Suitable for flood fragility assessments with:
- ✓ Specific bridge assets
- ✓ Bridge portfolios

- ❑ 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





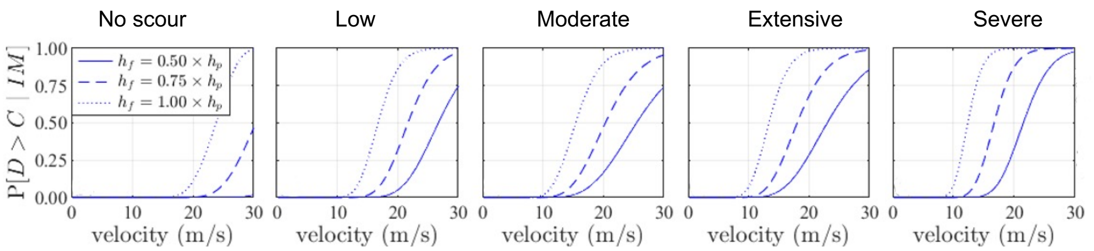


Kazantzi et al. (2024)

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

Bridge flood fragilities for different Damage States and:

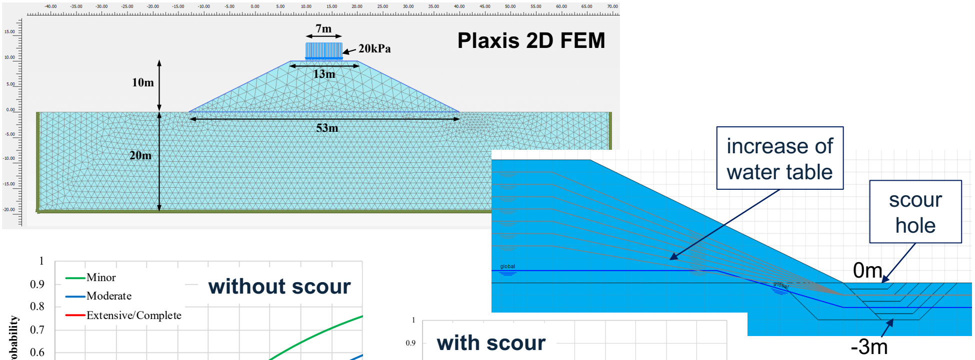
- ❑ Various scour severity scenarios (No scour, Low, Moderate, Extensive, Severe)
- ❑ Three inundation depths that with water velocity define a vector flood IM

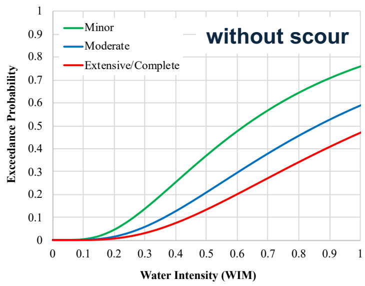


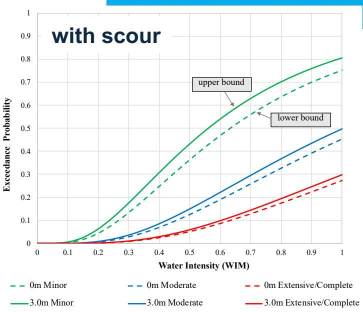
Kazantzi et al. (2024)

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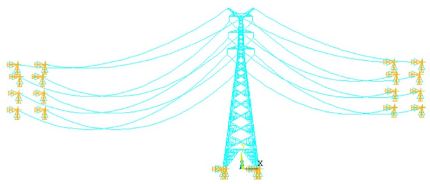
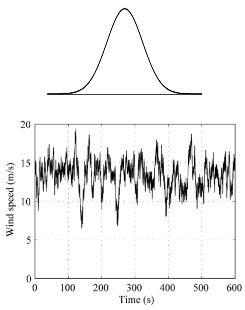
Fragility models based on numerical modelling: transmission tower-line systems under combined wind and rain loads



FEM of the transmission tower-line system

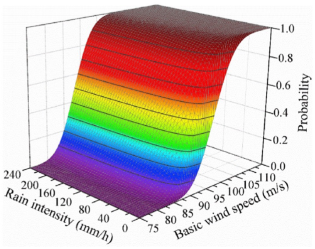
Uncertain variables (material, geometrical properties of steel members): Elastic modulus, Poisson's ratio, Yield strength, Damping ratio, Drag coefficient, Web thickness, Width

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

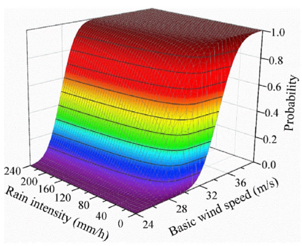


IMs: wind speed (m/s), rain intensity (mm/h)

Fragility surfaces for Collapse (buckling point)



Wind attack angle θ=0°



Wind attack angle θ=67.5°

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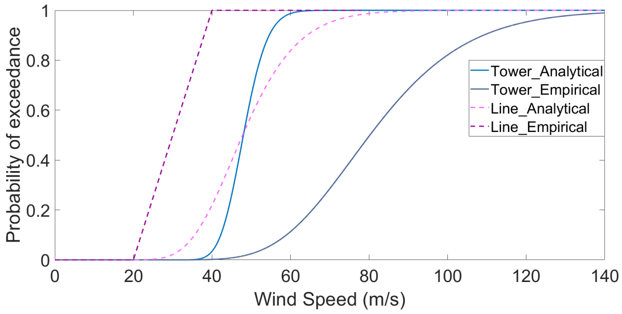
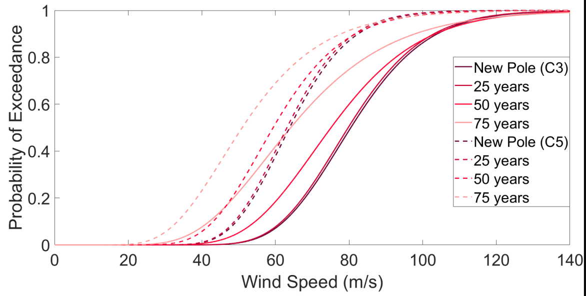
Source: Fu et al. (2020) Journal of Wind Engineering & Industrial Aerodynamics

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)

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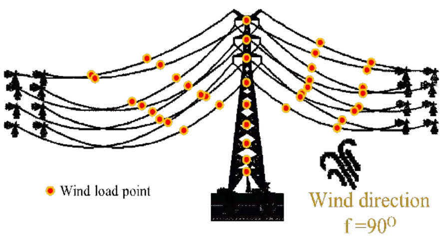
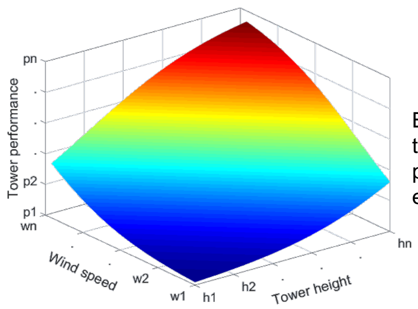
Climate aware fragility modelling

Advanced numerical model

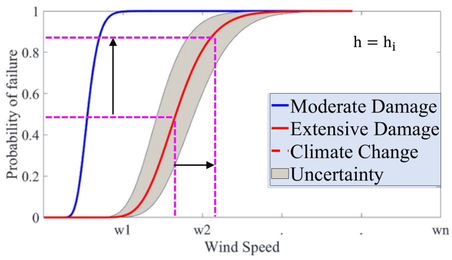




Fragility modelling

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

Parameterised fragility functions



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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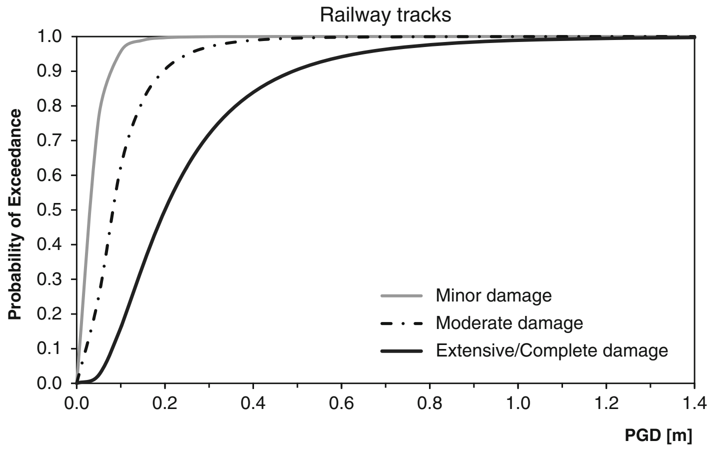
Empirical fragility curves for rail tracks (ground deformation)



Argyroudis & Kaynia (2014)

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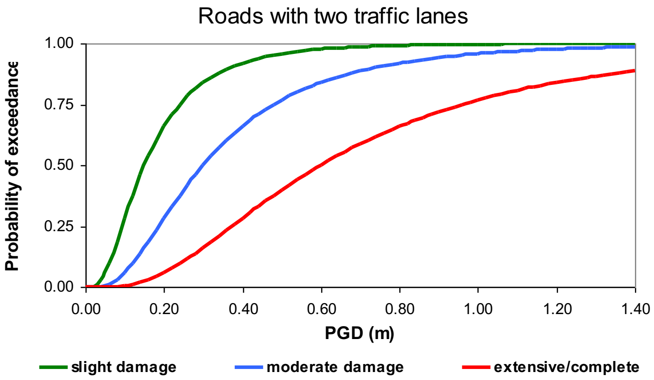
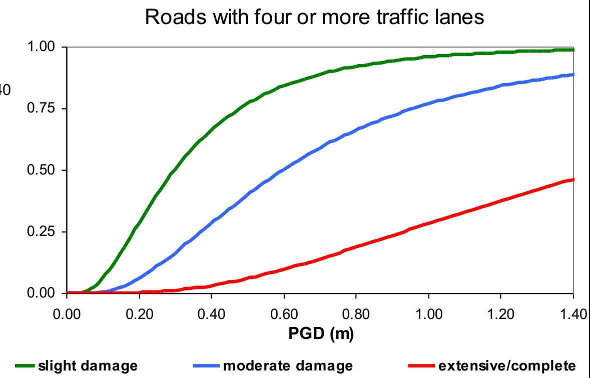
Empirical fragility curves for road pavements (ground deformation)





Argyroudis & Kaynia (2014)

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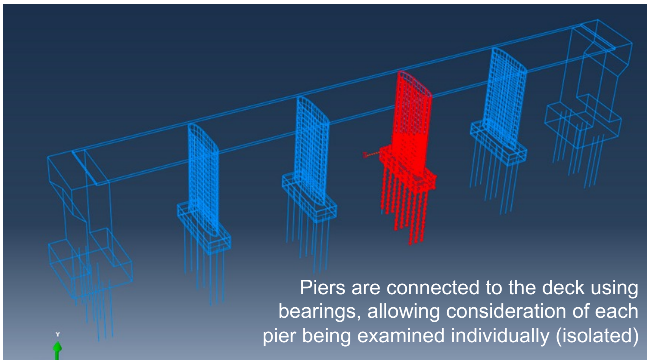
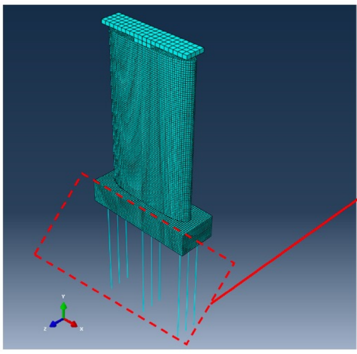
Numerical fragility curves for case specific bridges

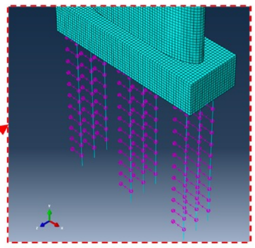


Finite element model of a bridge (ABAQUS) exposed to flood (scour)

Kim et al. (2017)

Pier model



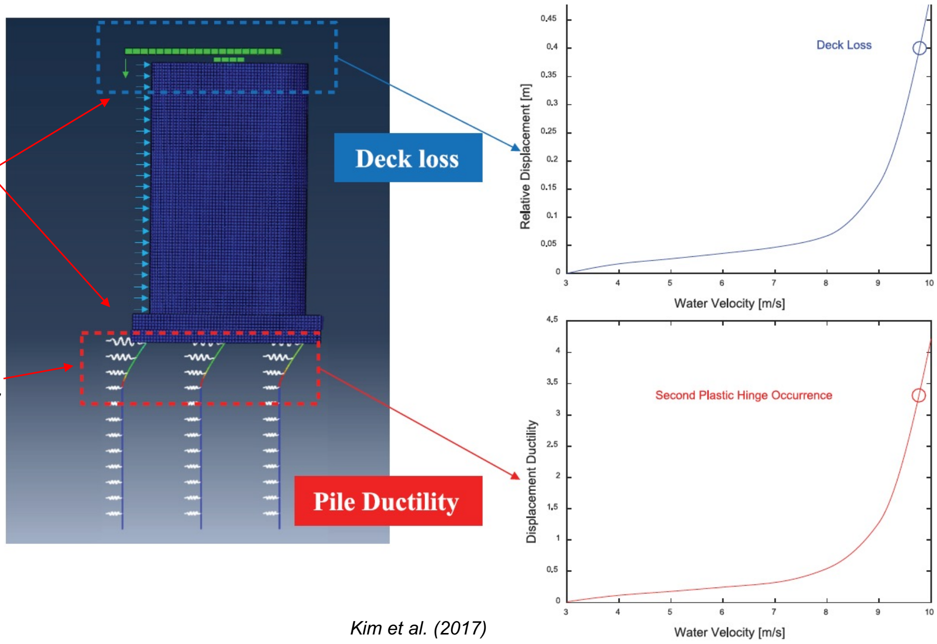


Scour holes around pile foundations are simulated with removal of springs

Numerical fragility curves for case specific bridges

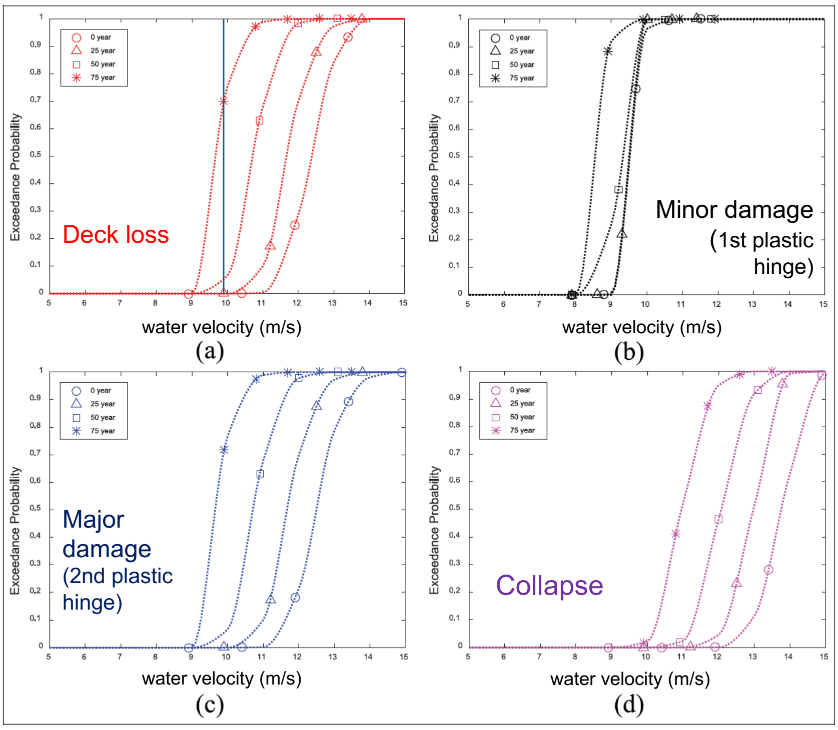
Water pressure on pier

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)

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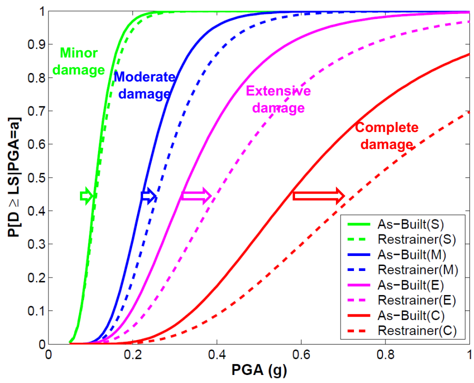
Fragility curves to facilitate decision making

Retrofitting of bridges
(steel girders on bearings)



Padgett (2005)

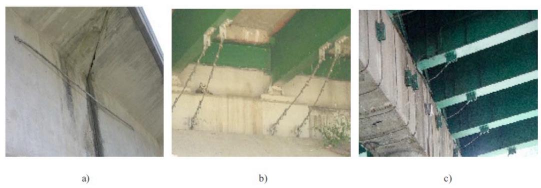


Fig. 9. Restrainer cables (a) in Kentucky connecting two adjacent girders; (b) in Tennessee (SR59 over I-40) connecting girders to the abutment; and (c) in Illinois attached to girders and wrapped around bent beam

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

How useful is that? Can we justify investments?

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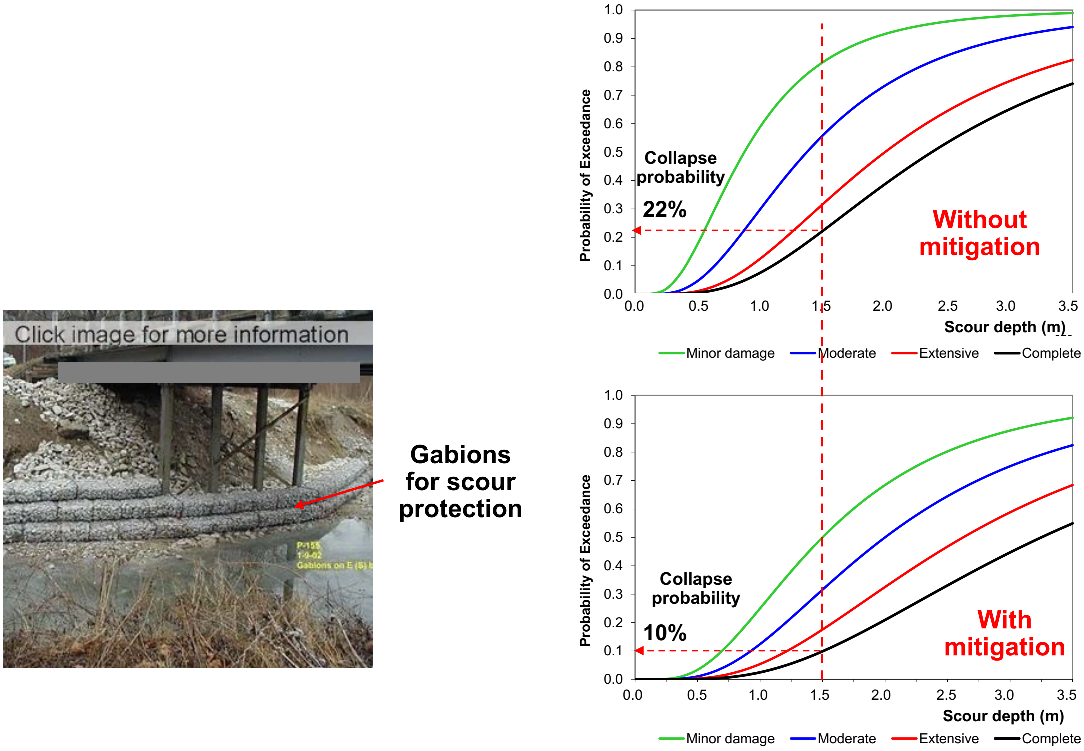
Fragility curves to facilitate decision making



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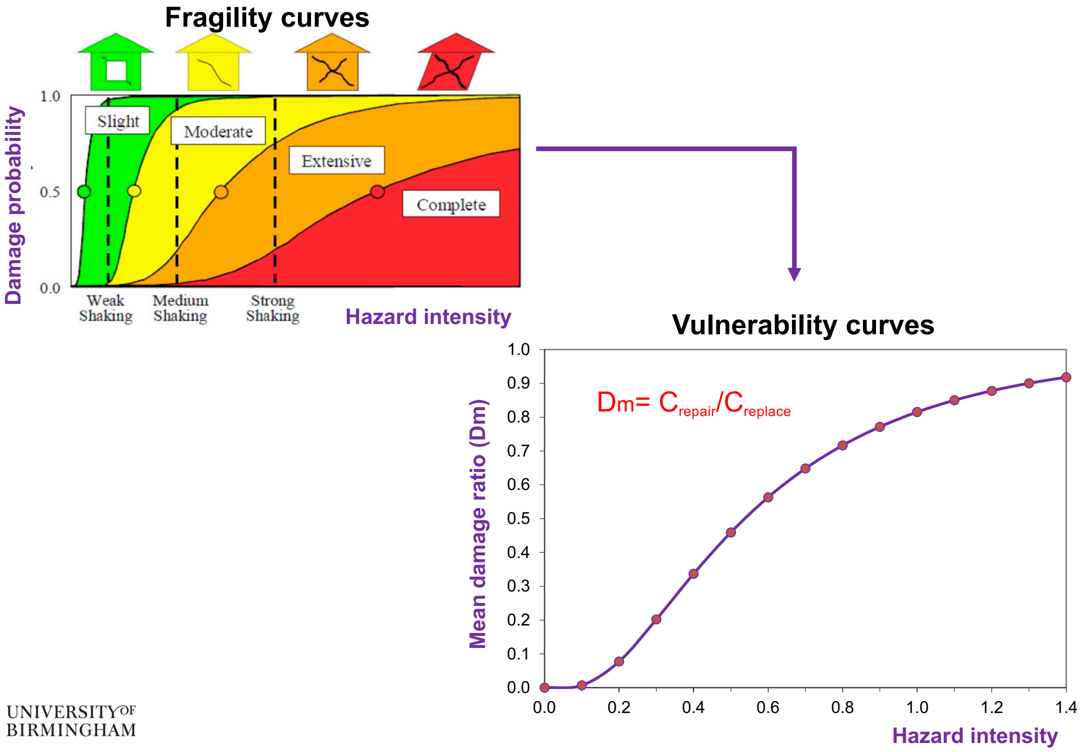
Vulnerability as a measure of robustness



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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 $

Lifeline	Selected for Evaluation (X) "Special" (S)	Overall Vulnerability	Flood Sub-hazard Vulnerability			Criticality	Dollar Loss and Outage Time
			Inundation	Scour/ Erosion	Debris Impact/ Hydraulic Pressure		
Power							
Generation Plants	S	High	High	None	None	Low	High
Substations	X	High	High	None	None	Low	Medium
Transmission/Distribution (above)		Low	None	Medium	Low	Low	Low
Distribution (below)		Low	Low	None	None	Low	Medium
Access Vaults		Low	High	Low	Low	Low	Low

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. Additional damage to cabling and incidental damage to transformers and switchgear.
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	
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

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For unprotected facilities, the damage and recovery time will increase to a maximum as the water depth increases to a defined level (assumed to be one-half a story height (i.e. damage is 100% when flood level is 4 feet above the floor level).

For protected facilities, there will be no damage until the protection elevation is exceeded (dike overtops). At this point the entire facility would be expected to flood. This same approach may also be used for facilities with below-grade components. For example, for a wet-well/dry-well sewage pump station, there would be no damage until the water elevation rose above the ground floor slab elevation. Once that elevation was exceeded, the dry well and the electrical components located in the dry well would be submerged. The user will be required to input this information as part of the site data.

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**

high-voltage substation/unprotected

equipment height=0.5m

HAZUS MH FLOOD TECHNICAL MANUAL

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Electric power system: typology & vulnerability (flood)

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

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

high-voltage substation/protected
protection wall: 1.0m
equipment height 0.5m

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

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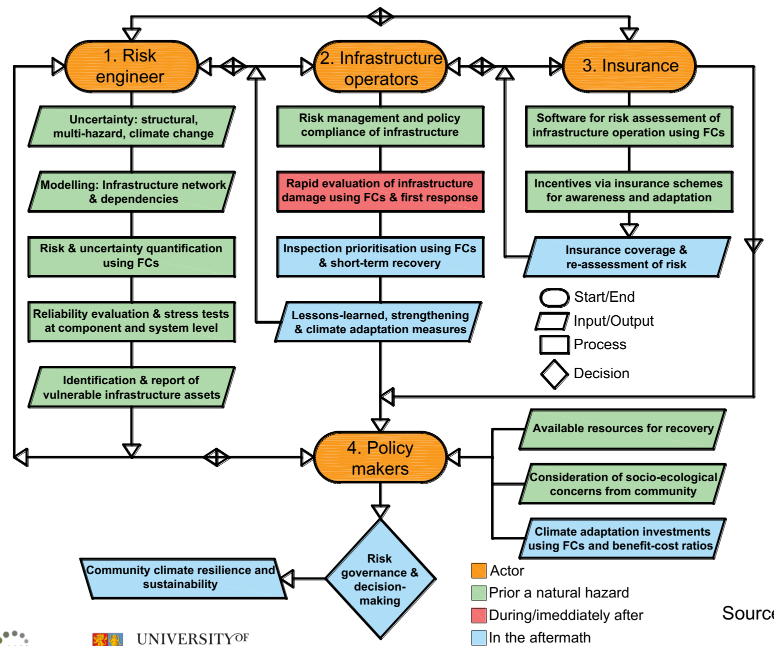
Fragility assessments empower decision-making



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 et al. (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.

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Activity 3. Risk analysis

ACTIVITY 3: Risk analysis

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

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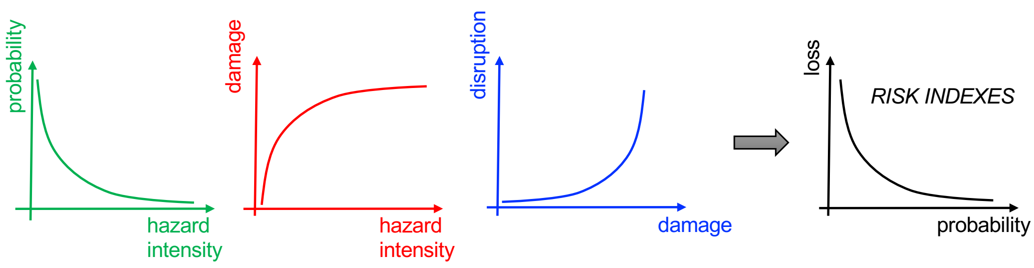
Quantitative Risk Analysis (QRA)

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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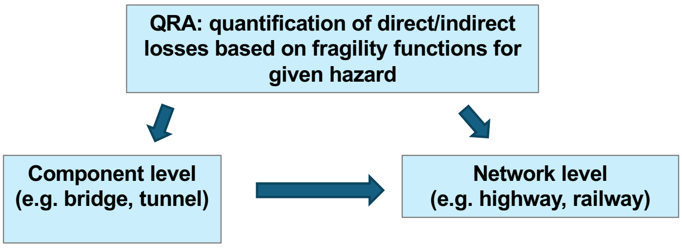
Benefits of QRA

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



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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

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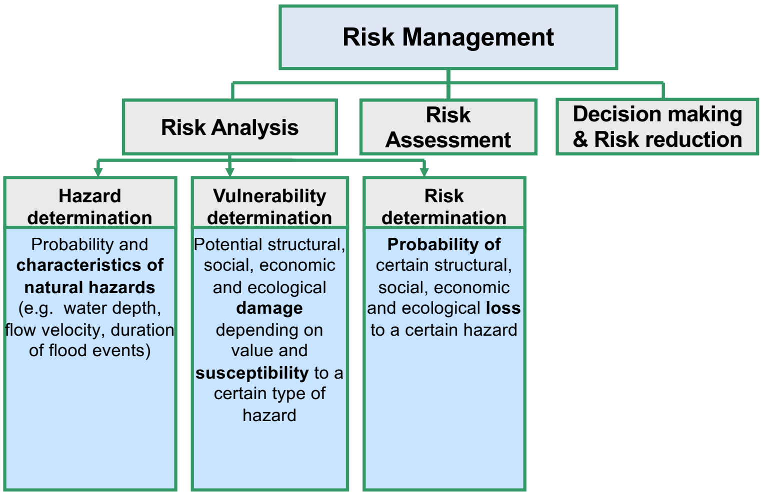
Risk-based decision-making framework



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

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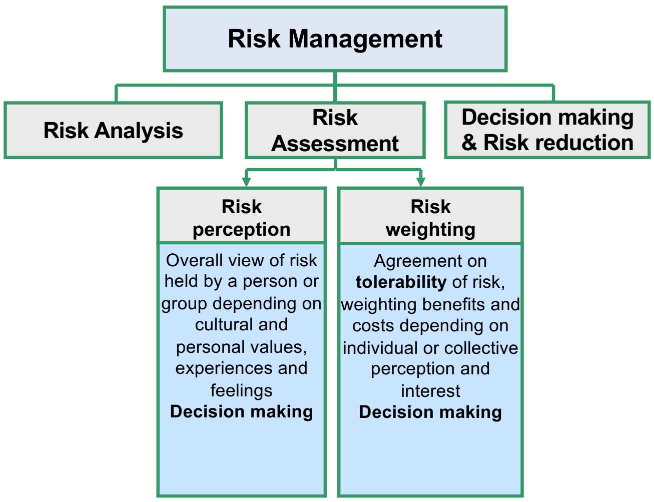
Risk-based decision-making framework



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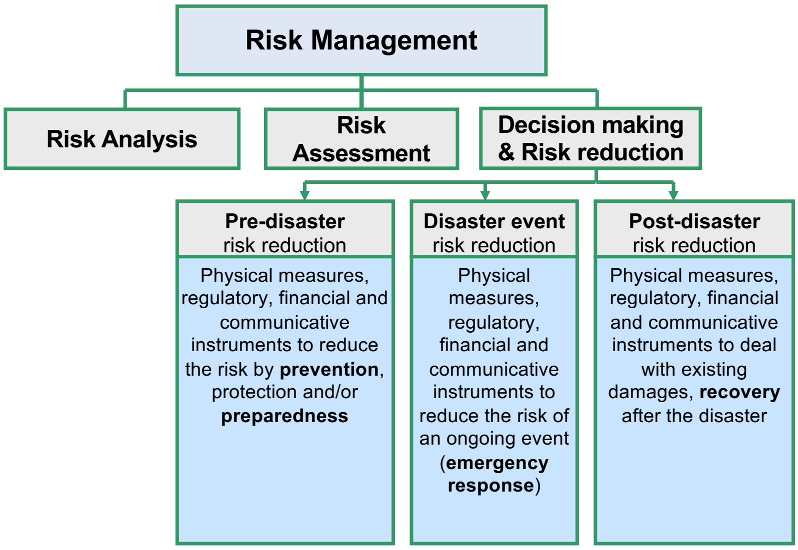
Risk-based decision-making framework



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

the importance of quick recovery → resilience

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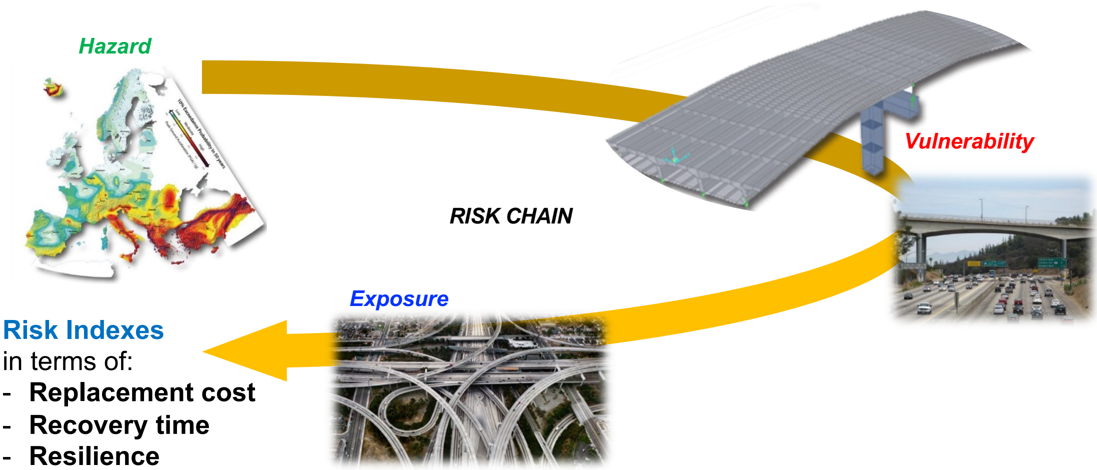
Risk analysis for portfolios of bridges and transportation networks

The ***RISK CHAIN*** should be followed:



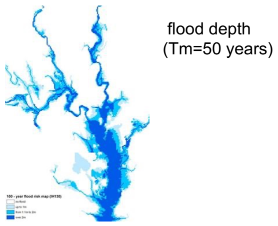
Risk Indexes
in terms of:
- **Replacement cost**
- **Recovery time**
- **Resilience**
- **Business interruption**
- **Injuries and fatalities**
- **…**

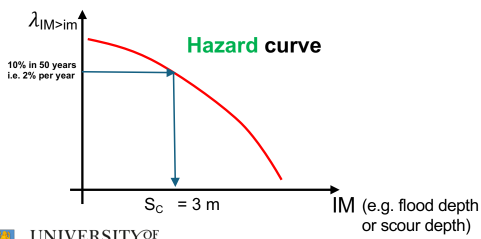
Risk assessment – QRA for a single scenario

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

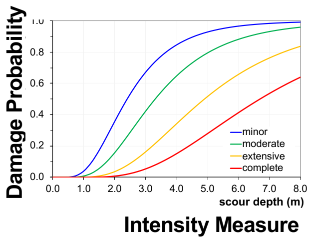
Risk (R_{single}) = Hazard x Vulnerability x Exposure

from hazard maps or site specific hazard analysis





from fragility/vulnerability functions for each asset



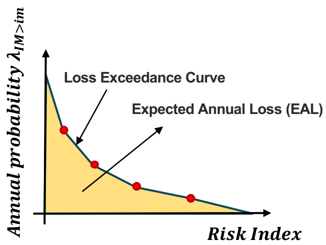
from inventory (number of assets, monetary costs etc)

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

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

$\Sigma (R_{Single}) = \Sigma$ (**Hazard** x **Vulnerability** x **Exposure**) = ∫ (**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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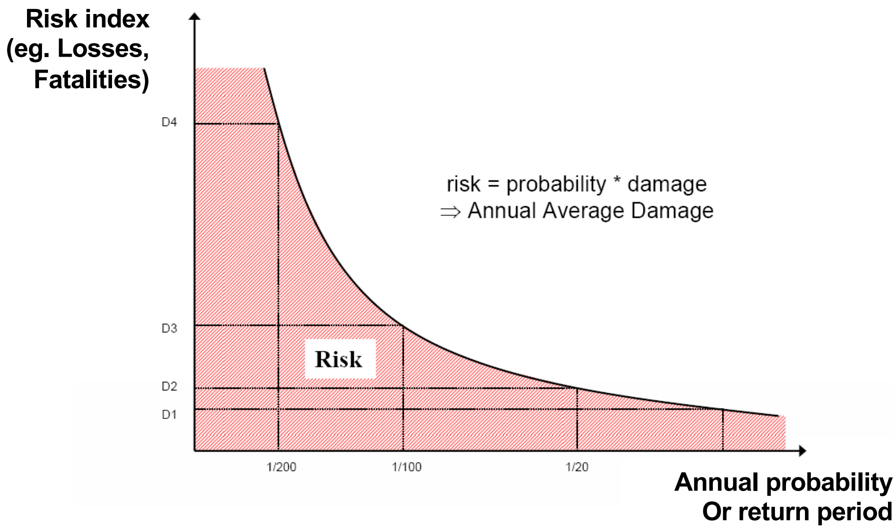
Risk curve

Risk calculation



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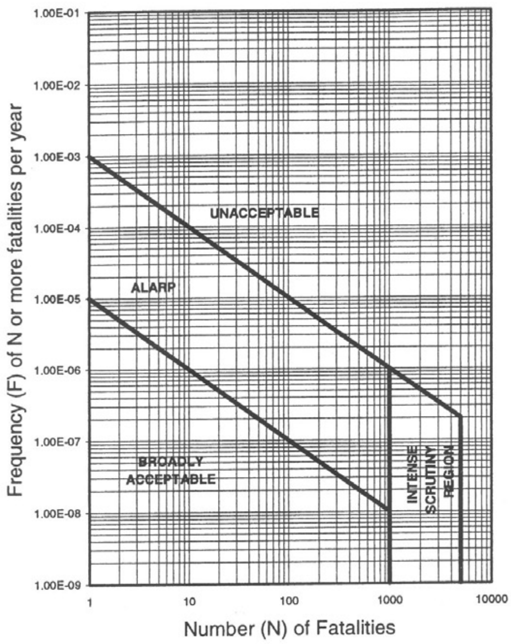
Risk assessment

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.



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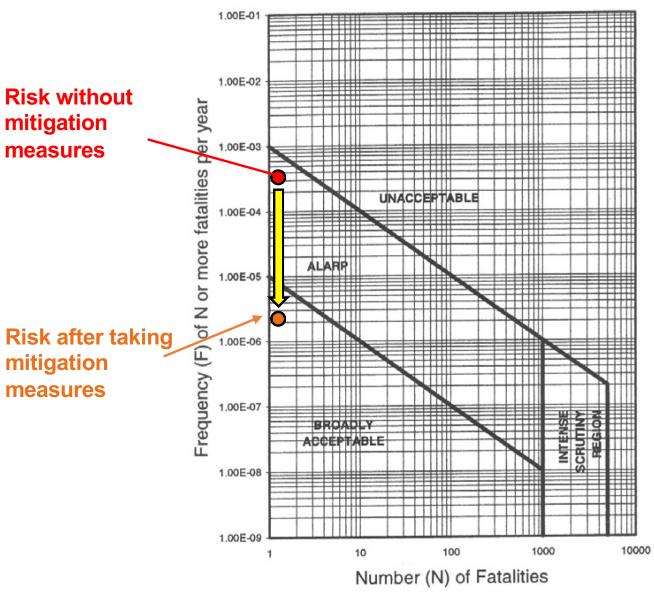
Risk assessment

A highway slope exposed to rockfalls

Protection barriers during rockfall



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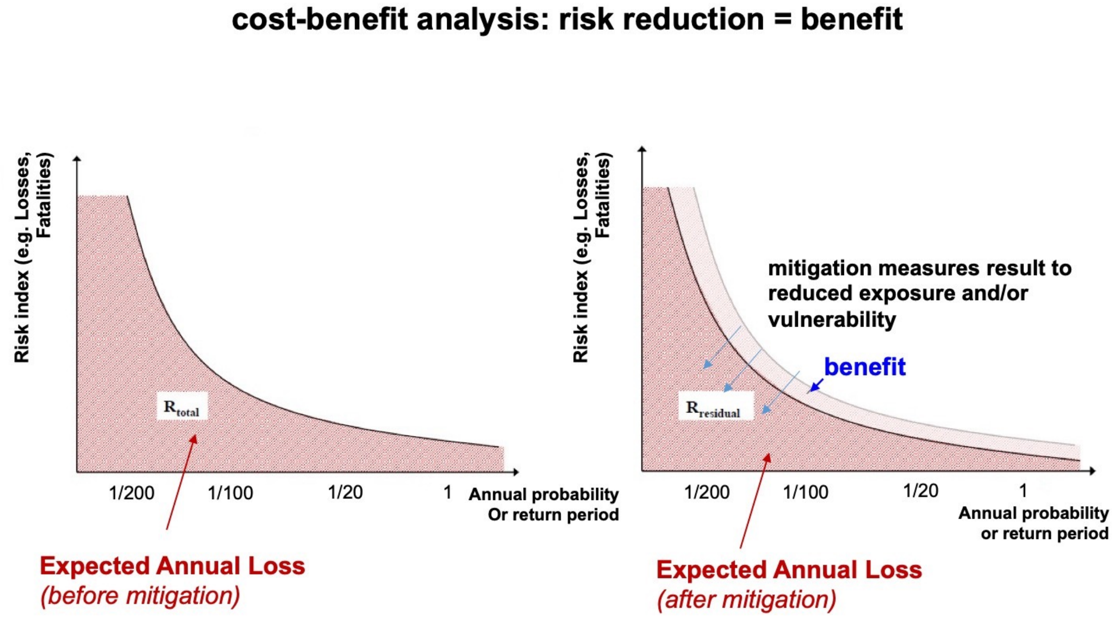
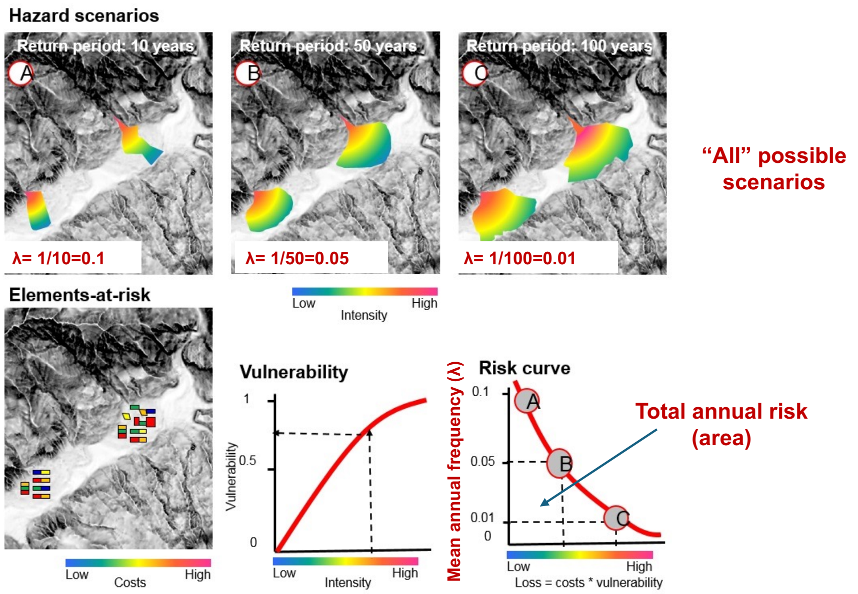
Risk reduction (example for flood)

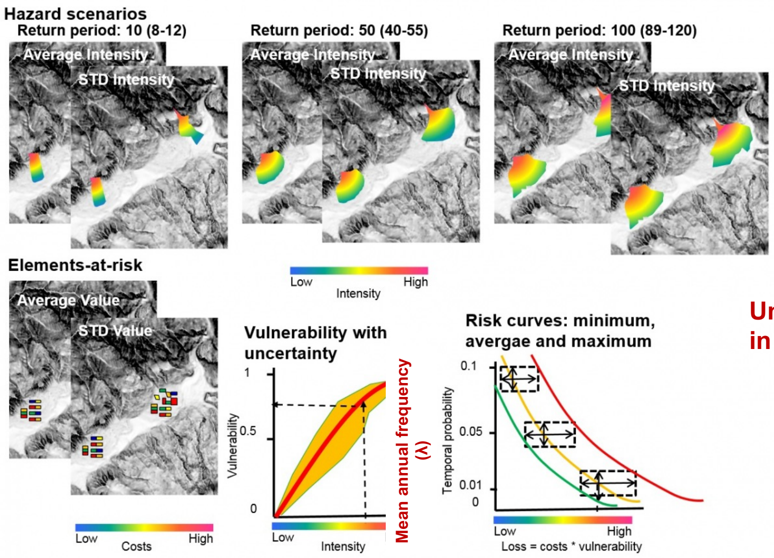


Risk assessment – QRA for all possible scenarios in a given exposure time



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

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

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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

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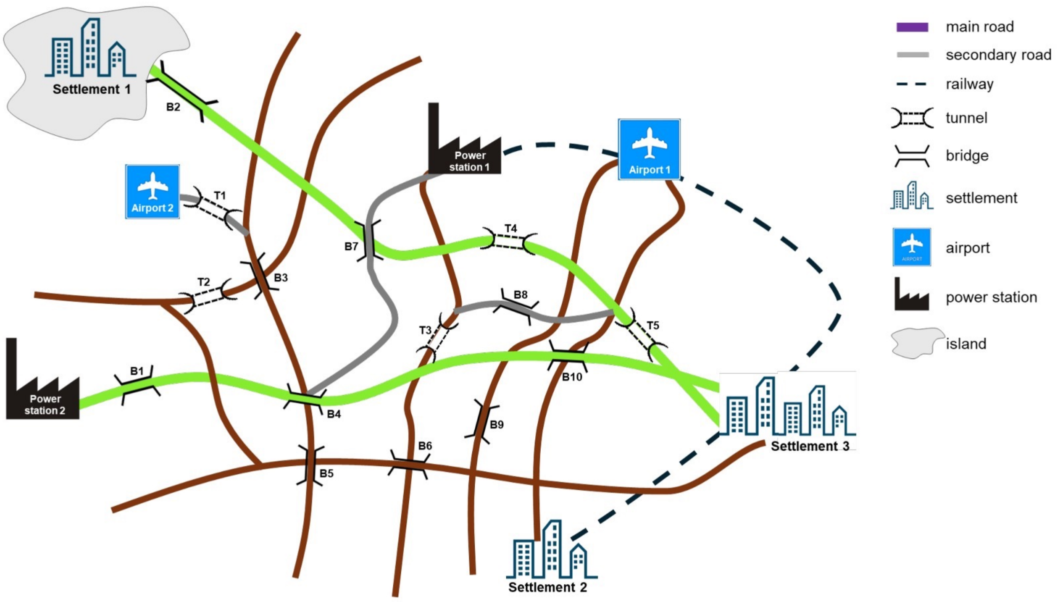
Risk analysis – example for portfolio of bridges

Elements at risk – Inventory

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



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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 [m²]
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

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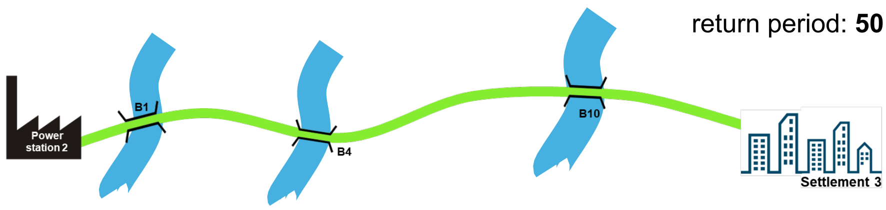
Risk analysis – example for portfolio of bridges

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.

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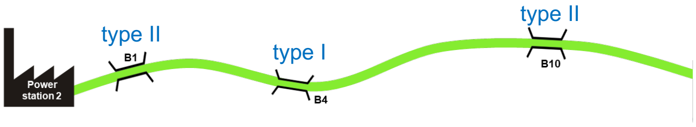
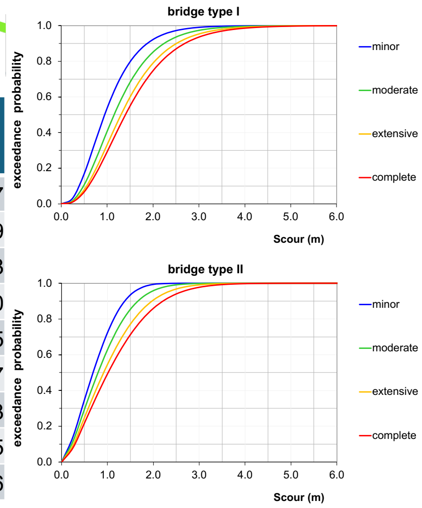
Risk analysis – example for portfolio of bridges

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



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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

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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 €/m²

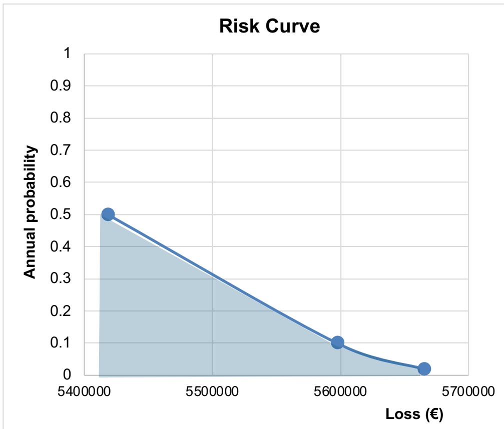
see Mitoulis et al. 2021
https://doi.org/10.1016/j.engstruct.2021.112180

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:

- Discussion about standards, design guidelines and policies on risk-based design and assessment of critical infrastructure

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