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

Lecture 7 Proactive and reactive adaptation strategies, nature-based solutions, and stress-testing

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 7-Week 7

The aim of this week is to introduce adaptation strategies for climate change projections in critical infrastructure sector. Through a combination of theoretical knowledge and practical applications, students will learn how to stress-test infrastructure systems, implement proactive and reactive adaptation measures, and evaluate the impact of these actions on greenhouse gas emissions for different climate scenarios. This week will delve into innovative strategies such as Nature Based Solutions, providing students with tools to enhance infrastructure's capacity to withstand shocks and adapt to changing environments. Focusing on transport assets, students will engage in real-world comparisons, ensuring they can make informed decisions for creating robust and sustainable infrastructure systems in the face of complex challenges.

- Resilience and sustainability stress-testing and GHG emissions
- Reactive and Proactive adaptation measures
- Nature Based Solutions
- Application on transport assets and comparisons of adaptation measures for different climate projections

Lecture 7. Proactive and reactive adaptation strategies, nature-based solutions, and stress-testing

Lecture 7
Massive Open Online Course
Resilience, Sustainability & Digitalisation in Critical Infrastructure

Proactive and reactive adaptation strategies, nature-based solutions, and stress-testing

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This is the last lecture of the MOOC. Here, the concepts of proactive and reactive adaptation are introduced from the prism of adaptation of critical infrastructure. Currently there are different climate models available in the international literature that provide projections for future infrastructure development and assessment. For example, there are over 50 global models that predict future climate change, however, their uncertainties are usually so severe that they can hardly be modelled as random variables. For this reason, climate projections are likely to be used at regional or national level assessments, eg country level rather than at system of assets level, which is the scope of this MOOC. The requirement for assessing infrastructure under increasing and unprecedented stressors in the face of increasing demand due to climate change is covered in the lecture by stress testing techniques.

Lecture 7 Outcomes

- Proactive and reactive adaptation measures
- Resilience and sustainability stress-testing
- Nature Based Solutions
- Application on transport assets and comparisons of adaptation measures for different climate projections

The main outcomes of this lecture are:

- Resilience and sustainability stress-testing
- Reactive and Proactive adaptation measures
- Nature Based Solutions
- Application on transport assets and comparisons of adaptation measures for different climate projections

Activity 1. Proactive and reactive adaptation measures

ACTIVITY 1: Proactive and reactive adaptation measures

- Types of proactive and reactive adaptation measures
- Making the case for proactive climate adaptation
- Examples

In Activity 1, the types of proactive and reactive adaptation measures are discussed, with a focus on transport infrastructure assets, e.g., bridges. This part demonstrates the importance of proactively adapting infrastructure for avoiding losses in the future and damage in infrastructure that can lead to cascading events, which can magnify losses in complex socio-economical systems.

The main reason that proactive adaptation is not common relates mainly to decision makers and operators' decision, who work under tight budgets (usually a percentage of the country's GDP). Having a limited allocation of funding for building new and maintaining or refurbishing existing infrastructure in a country leads to slow investment to existing infrastructure. The literature needs strong case studies to incentivise more investment in proactive adaptation of critical infrastructure.

Proactive adaptation of critical infrastructure involves anticipating potential challenges and making adjustments or improvements before damage occurs due to a climate hazard occurrence. Reactive adaptation instead occurs in response, i.e. after hazardous events or failures after they have happened. Proactive adaptation is generally considered better than reactive adaptation for several reasons.

The reasons are briefly discussed here from the prism of risk reduction, resilience, cost efficiency and disruption, sustainability output, and regulatory compliance and avoidance of penalties.

Proactive adaptation of critical infrastructure leads to more effective risk reduction and increased resilience, because by anticipating risks and vulnerabilities, we can better plan preparation to deal with the risk and therefore safeguarding more efficiently against hazards, threats and stressors. Proactive adaption also leads quick recovery, because preparation will allow for having in place materials, resources and people allocated to timely reduce downtime and maintain continuity of services.

Cost efficiency is another benefit of proactive restoration. By assessing the costs over the lifespan of infrastructure repaired and made more robust throughout its life leads to lower lifecycle cost (LCC). While proactive adaptation may involve upfront costs, it is typically less expensive than responding to emergencies-as the latter is done under the pressures of time, reputation costs and at an emergency state. Reacting to crises often requires costly emergency repairs, replacements, or temporary solutions that are less efficient. Such emergency reactive actions are not always led by technically objective decisions, and in some cases might be the result of "firefighting" action, e.g. when a bridge has been damages, a temporary expensive temporary bridge might be used, while additional costs in design and construction might incur due to the urgency of the project and the time limitations.

Also, sometimes the failure of an assets and the corresponding costs might not be linearly correlated, instead it can lead to exponential costs. For example, the recent failure of the Francis Scott Key Bridge across the Patapsco River in the Baltimore metropolitan area led to costs that relate to the traffic disruption of the road network. The costs because increasingly non-linear when the Port of Baltimore shipping channel closed for 11 weeks, leading to loss of jobs, and shipping companies terminating their container contracts to a diversion port.

In regard to sustainability, proactive adaptation involves considering future trends, such as climate change, technological advancements, and population growth. This approach helps ensure that infrastructure remains effective and relevant over time, reducing the need for frequent, reactive changes which impact negatively on sustainability.

Last, in regard to policy, proactive adaptation ensures that infrastructure stays in line with evolving regulatory standards and requirements, and helps operators avoiding fines or penalties associated with non-compliance that might arise from a reactive approach.

Types of proactive and reactive adaptation measures

Adaptation strategies - Bridges

R =	$P(H)$ ·	$P(E\|H)$ ·	$P(D\|E \cap H)$ ·	$C(D)$
Description	Hazard: The probability of a climatic hazard (e.g. increased storm activity)	Exposure: The probability of an adverse impact on the bridge as a result of the hazard (e.g. increased storm surge heights)	Vulnerability: The probability of a damage resulting from the increased hazard and exposure	Consequences: The consequences of such a damage
Possible risk management measures	Reduction of GHG emissions (by e.g., introducing more strict regulations, reducing VMT through land use and urban planning strategies, etc.)	Regional adaptation measures, e.g.: • Storm surge barriers • Improved land use planning (e.g. relocation)	Local adaptation measures, e.g.: • Increase bridge elevation • Insert holes in the bridge superstructure • Improve span continuity • Use tie-down, restrainers, or anchorage bars	Adaptation measures for reducing cascading effects: • Increase robustness • Increase network redundancy • Improved emergency planning and disaster preparedness • Improved understanding of the interdependencies between different infrastructure
	Climate change mitigation	Climate change adaptation		

source: Nasr et al., 2020

In the slide above proactive and reactive adaptation measures for bridges in the context of climate change are described. It is divided into five columns labelled with different probabilities and consequences, each of which corresponds to a specific aspect of risk management. For all the steps of risk assessment the table provides mitigation measures i.e.,:

1. **P(H) - Hazard**:
    - **Description**: This represents the probability of a climatic hazard, such as increased storm activity.
    - **Possible risk management measures**: These include climate change mitigation strategies like reducing greenhouse gas (GHG) emissions by introducing more strict regulations, reducing vehicle miles travelled (VMT) through land use and urban planning strategies, and more.
    -
2. **P(E|H) - Exposure**:
    - **Description**: This indicates the probability of an adverse impact on the bridge as a result of the hazard, such as increased storm surge heights.
    - **Possible risk management measures**: This involves regional adaptation measures like implementing storm surge barriers and improving land use planning (e.g., relocation).
    -
3. **P(D|E∩H) - Vulnerability**:
    - **Description**: This represents the probability of damage occurring due to the increased hazard and exposure.
    - **Possible risk management measures**: These are local adaptation measures, including increasing bridge elevation, inserting holes in the bridge superstructure, improving span continuity, and using tie-downs, restrainers, or anchorage bars.
    -
4. **C(D) - Consequences**:
    - **Description**: This concerns the consequences of such damage.
    - **Possible risk management measures**: Adaptation measures to reduce cascading effects include increasing robustness, increasing network redundancy, improving

emergency planning and disaster preparedness, and enhancing the understanding of interdependencies between different infrastructure systems.

At the bottom of the diagram, there is a progression from "Climate change mitigation" to "Climate change adaptation" along the horizontal axis. This suggests a continuum from reducing the likelihood of climate change impacts (mitigation) to managing the risks and impacts once they occur (adaptation).

Types of proactive and reactive adaptation measures

Adaptation strategies - Bridges

Climate hazard	Adaptation
Floods	Relocation or flood -proofing (Mehrotra et al., 2011; Meyer & Weigel, 2011); Flood control seawalls, dikes, and levees (Stewart & Deng, 2015); Elevation of bridges, strengthening and heightening of existing levees, increase in real -time monitoring of flood levels, restriction of most vulnerable coastal areas from further development, increase insurance rates to help restrict development (NRC, 2008); Channel alteration and stabilization, diversion and storage of floodwaters (e.g., Dunne, 1988); Regulate the flow of water through dams (Batchabani, Sormain, & Fuamba, 2016)
Storms	Elevate critical infrastructures, insert holes, tie -down, restrainers, anchorage bars, etc., concrete shear tabs etc., connect adjacent spans, cladding (e.g., toe nails, hurricane straps, etc.) (Mondoro et al., 2018); Strengthened connections, improved span continuity, modified bridge shape, increased elevation (Cleary, Webb, Douglass, Buhring, & Steward, 2018); Relocation and restriction of development in vulnerable regions (Meyer & Weigel, 2011; NRC, 2008); Strengthening and heightening existing storm surge barriers and building new ones (NRC, 2008)
Wildfires	Vulnerability assessments incorporated into infrastructure location decisions, use of fire -resistant materials and landscaping (Meyer & Weigel, 2011); Installing monitoring systems, installing on site firefighting equipment, implementing structural fire design for bridges, fire proofing main structural elements (Naser & Kodur, 2015); Vegetation management strategies (i.e. control operating situation around the structure by regularly removing vegetation in the vicinity of bridges) (NRC, 2008; Wright, Lattimer, Woodworth, Nahid, & Sotelino, 2013); Bigger expansion gaps, passive fire protection, active fire suppression (e.g. wet pipe water systems, dry pipe water systems, total flooding agents, foam deluge systems) (Wright et al., 2013)

ReCharged UNIVERSITY OF BIRMINGHAM Source: Nasr et al., 2020

On this slide, examples of proactive and reactive adaptation measures are provided for bridges. The use of the measures as proactive adaptation actions does not exclude these measures from being used as reactive measures too. Here are the measures that are proposed:

For floods:

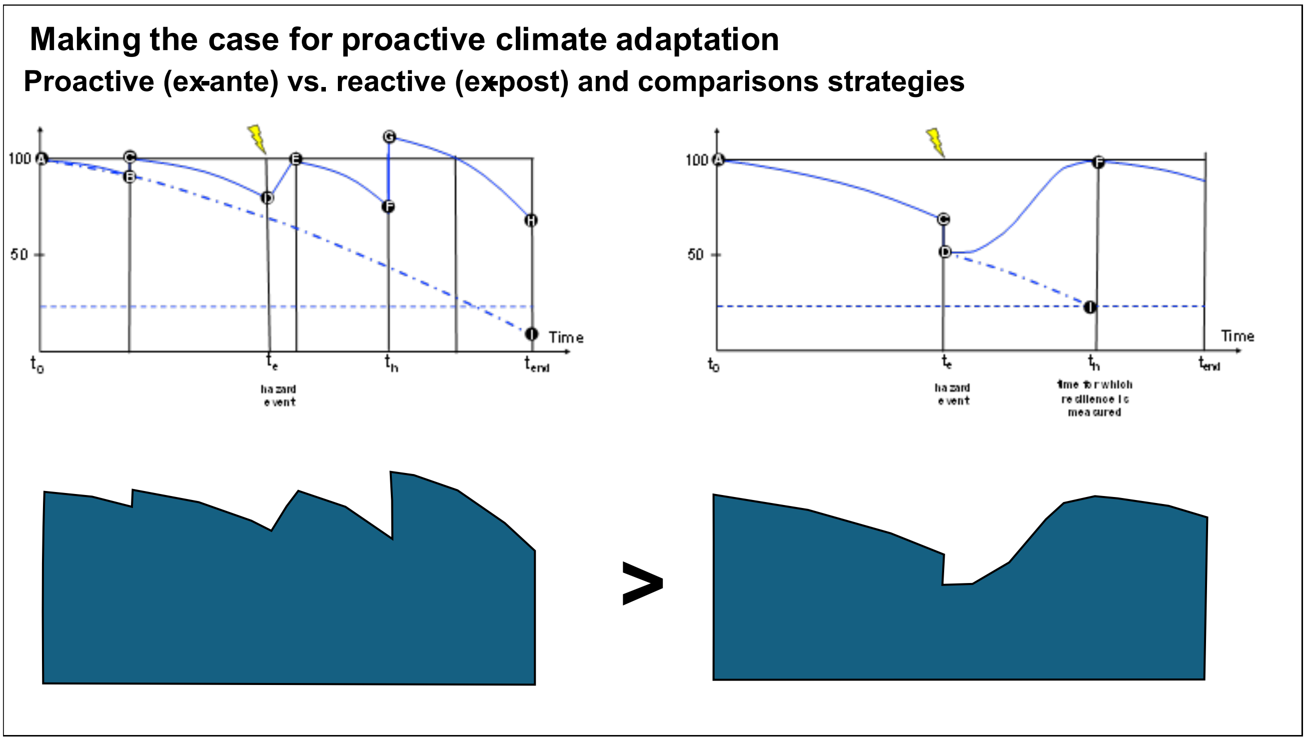
Relocation of the asset i.e. to an area where risk is lower or flood-proofing (Mehrotra et al., 2011; Meyer & Weigel, 2011) – mainly reactive (R) measure
Flood control seawalls, dikes, and levees (Stewart & Deng, 2015) – both proactive (P) and reactive (R)
Elevation of bridges (P and R), strengthening and heightening of existing levees (R), increase in real-time monitoring of flood levels (R), restriction of most vulnerable coastal areas from further development (P), increase insurance rates to help restrict development (P) (NRC, 2008);
Channel alteration and stabilization (R), diversion and storage of floodwaters (P and R) (e.g., Dunne, 1988);
Regulate the flow of water through dams (P and R) (Batchabani, Sormain, & Fuamba, 2016)

For storms:

Elevate critical infrastructures, insert holes, tie-down, restrainers, anchorage bars, etc., concrete shear tabs etc., connect adjacent spans, cladding (e.g., toe nails, hurricane straps, etc.) (Mondoro et al., 2018) (P and R);
Strengthened connections (R), improved span continuity (P and R), modified bridge shape (P and R), increased elevation (P and R) (Cleary, Webb, Douglass, Buhring, & Steward, 2018);
Relocation and restriction of development in vulnerable regions (P) (Meyer & Weigel, 2011; NRC, 2008);

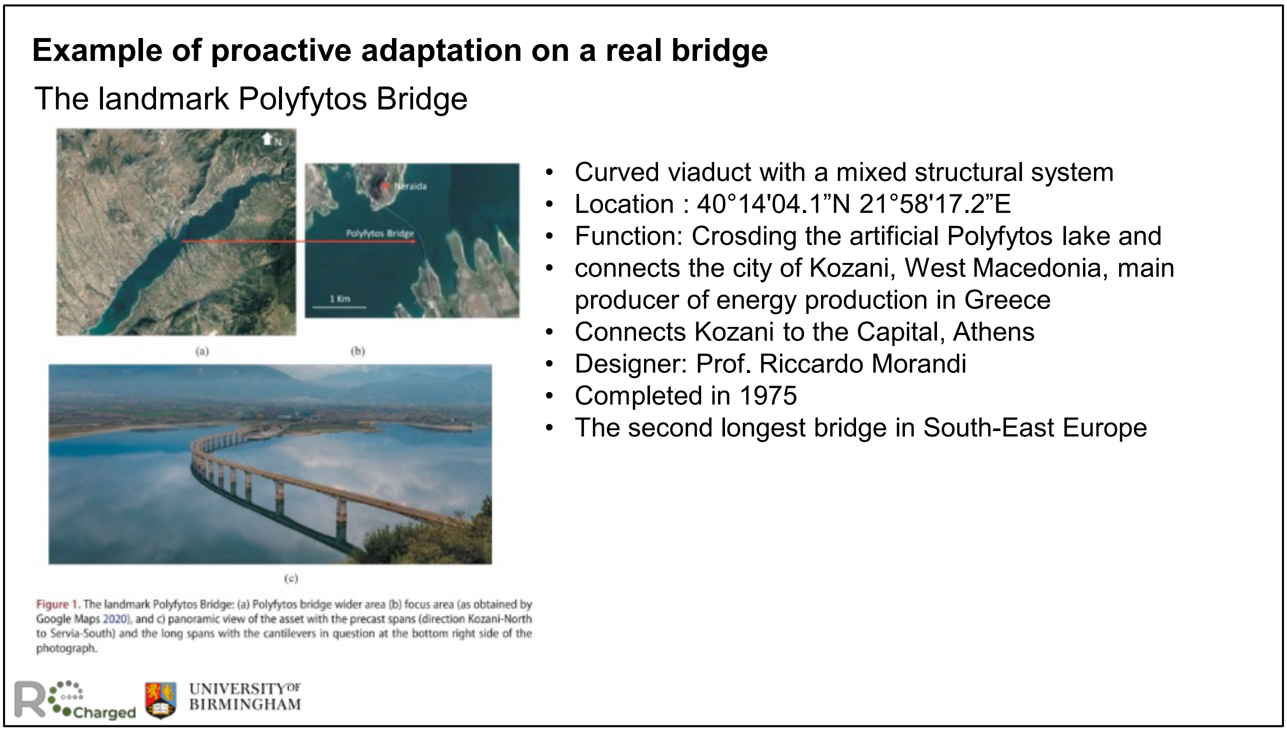
Strengthening and heightening existing storm surge barriers and building new ones (NRC, 2008) (R)

For wildfires:
Vulnerability assessments incorporated into infrastructure location decisions, use of fire-resistant materials and landscaping (Meyer & Weigel, 2011); (P)
Installing monitoring systems, installing on site firefighting equipment, implementing structural fire design for bridges, fire proofing main structural elements (Naser & Kodur, 2015); (P)
Vegetation management strategies (i.e. control operating situation around the structure by regularly removing vegetation in the vicinity of bridges) (NRC, 2008; Wright, Lattimer, Woodworth, Nahid, & Sotelino, 2013); (P)
Bigger expansion gaps, passive fire protection, active fire suppression (e.g. wet pipe water systems, dry pipe water systems, total flooding agents, foam deluge systems) (Wright et al., 2013) (P and R).



The figures in this slide illustrate the resilience curves of the transport asset or system of interest throughout their lifetime. Two cases are shown here: The figure on the left shows the resilience of systems which are strengthened with proactive measures. These measures are applied on the asset or the system of interest in a preventive way, i.e., before the occurrence of the hazard.
The figure on the right shows the resilience of the asset or system when adaptation measures are applied in a corrective (reactive) way i.e., after the hazard occurrence. The area under the resilience curves is a metric of resilience, also known as R, resilience index. By comparing the areas of the two figures it is extracted that the ex-ante adaptation and preventive maintenance leads to higher resilience, i.e., greater areas under the curve, in comparison to reactive measures, which corresponds to an unmaintained asset which will responds poorly during hazard occurrences leading to a longer recovery time. It is noted that in transport assets, the resilience is typically measured for the time window between the hazard event occurrence (t_e) and time t_h, which could be the time when the recovery is completed.

For the operators to decide the application of proactive or reactive measures, requires that the resilience of alternative adaptation scenarios have been assessed and the losses are estimated. Based on these estimates the operators are then able to make the case for proactive adaptation of their infrastructure, to minimise risks and potential uncontrollable damage and cascading events, which cause excessive damage and loss.

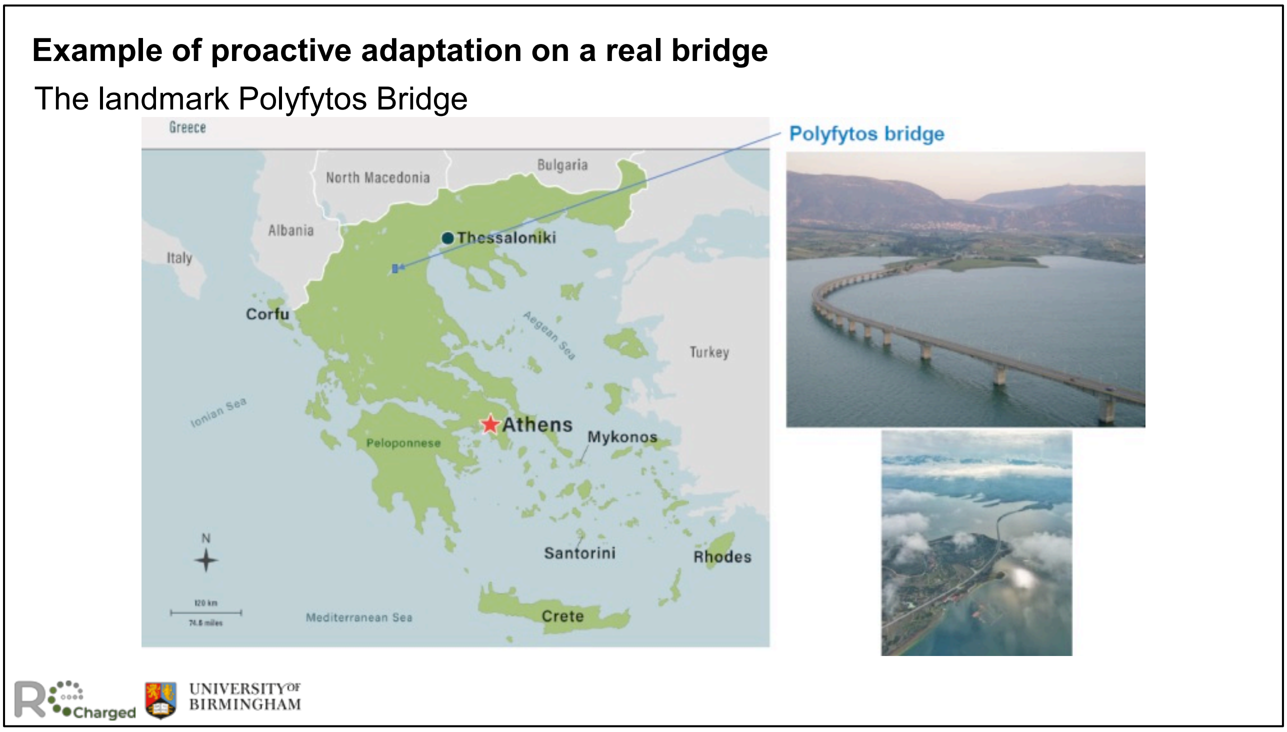


In what follows is an example of proactive adaptation measures that are designed for the landmark **Polyfytos Bridge** in Greece, which is a curved in plane and with a complex and mixed structural system. The bridge is curved in plane, along the first 24 out of the total 29 spans and has a total length of 1371 m. The first 25 spans from south to north are simply supported on the piers consisting of three precast prestressed I-beams and cast in situ slabs, while expansion joints are placed at every pier. The remaining four spans, which are the longest and located over the tallest piers, shown in Figure 1c, are constructed by balanced cantilevers, a popular and challenging method. The 30-m long cantilevers, extending from the piers and support 40-m long simply-supported precast beams. The long spans vary from 70 m to 100 m.

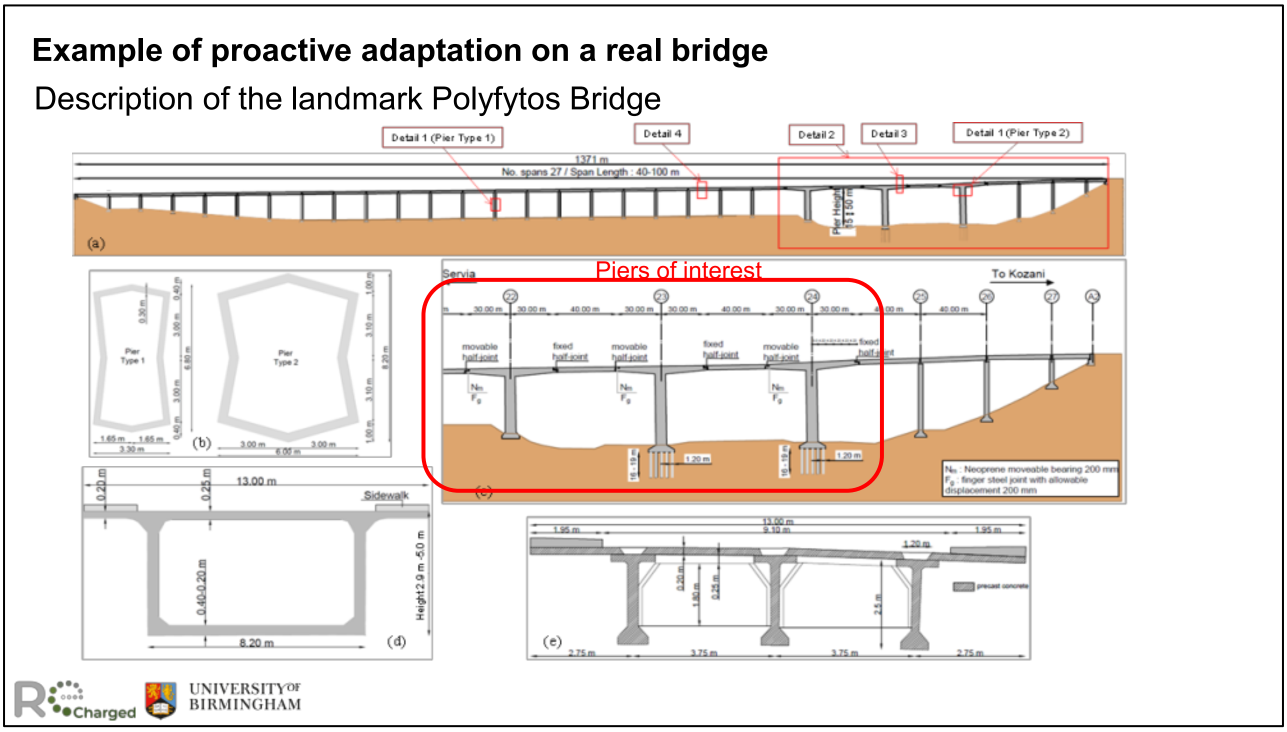
Two satellite images (marked as (a) and (b)) showing the bridge location and its surroundings are shown at the top and a larger image (marked as (c)) shows a side view of the Polyfytos Bridge spanning across the lake.

Further information and context for the Polyfytos bridge:

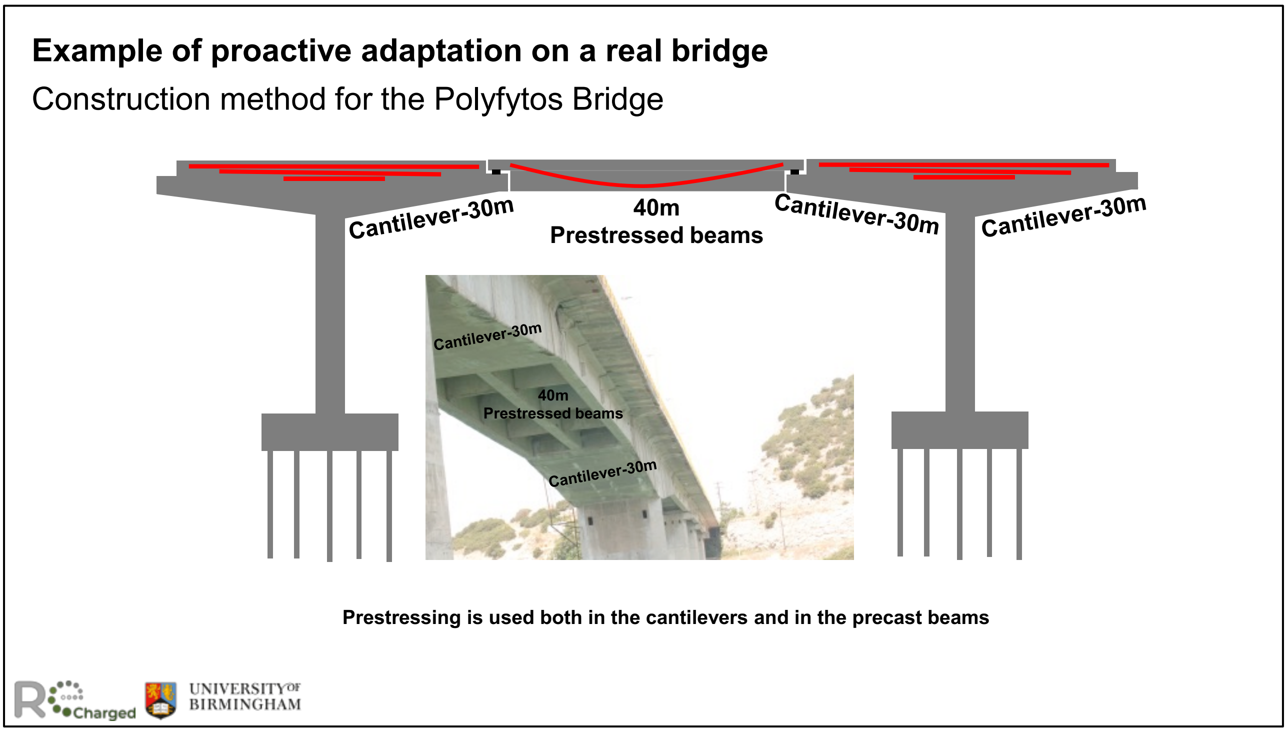
- **Location:** 40°14'04.1"N 21°68'17.2"E
- **Function:** Crosses the artificial Polyfytos Lake and connects the city of Kozani, West Macedonia, which is a major producer of energy in Greece.
- **Connects** Kozani to the capital, Athens
- **Designer:** Prof. Riccardo Morandi, who also designed the infamous Polcevera Viaduct (Ponte Morandi - English: Morandi Bridge) in Padova Italy that collapsed in 2018 as a result of corrosion
- Completed in **1975**, thus its almost 50 years old
- It's the **second longest bridge in South-East Europe**

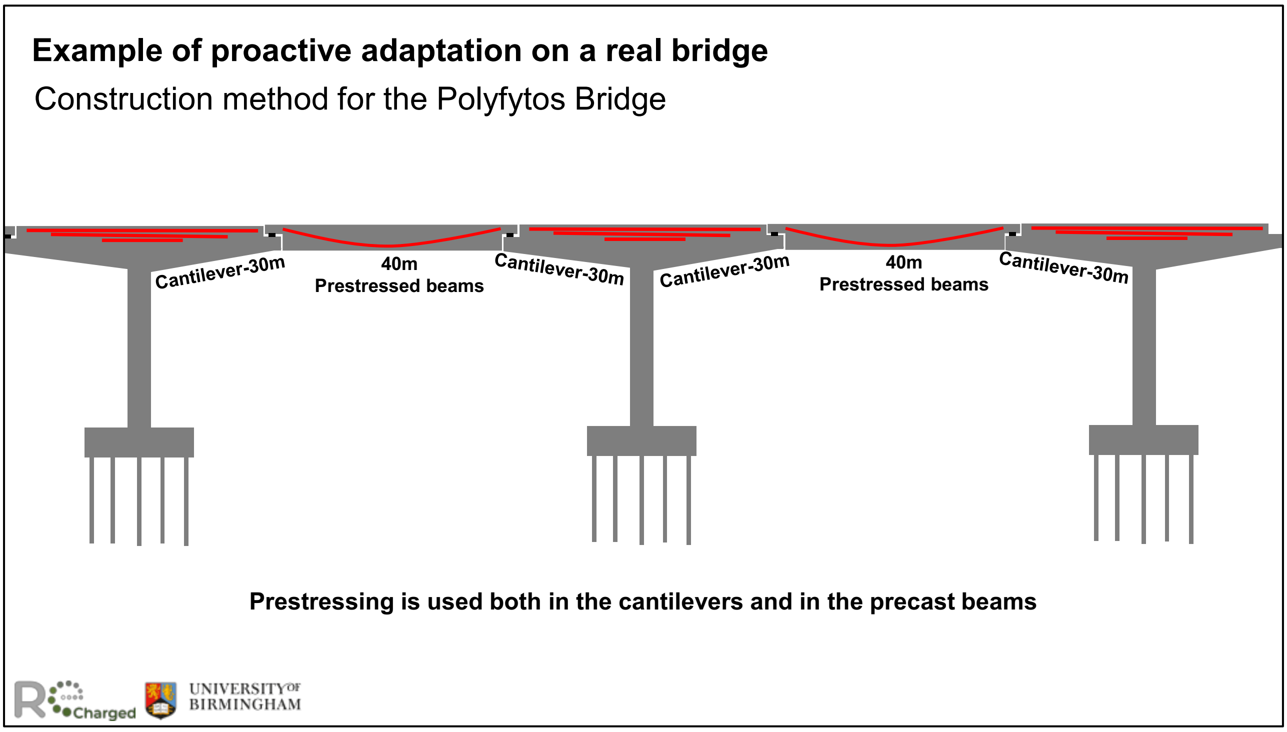


More figures and maps are showing the bridge location and its surroundings. Also, the top image shows a wide-angle view of the Polyfytos Bridge curving over the lake and the bottom image shows an aerial view of the bridge, with the lake and surrounding area visible.



This slide shows the elevation and cross sections of the box girder deck at supports and the precast segments of the superstructure and cross sections of the piers supporting the box girder and the precast deck with I-beams of the landmark ‘Polyfytos’ Bridge of Kozani, Greece. a) Longitudinal section of the bridge b) Detail 1, pier cross-sections c) Detail 2, northern part of the bridge with the cantilevers, d) Detail 3, box girder deck at support, e) Detail 4, I-beams cross section

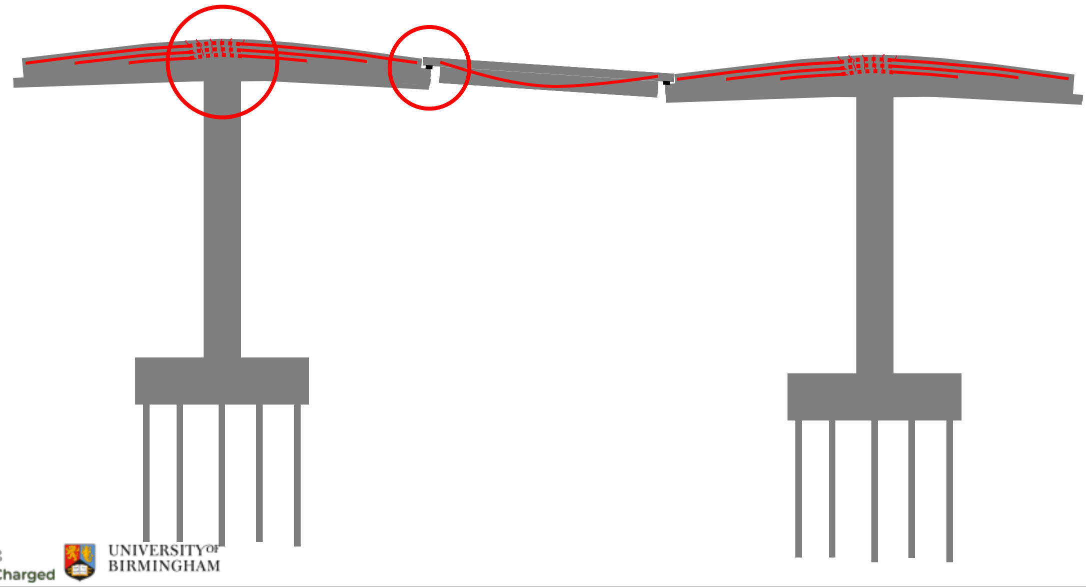




These slides show, in a simplistic way, the design of the balanced cantilevers of the bridge, which extent 30 metres on both sides of the pier, as well as the central prestressed beams, which are precast components sat, through bearings, on the cantilever of the bridge. This illustration also shows with red lines the prestressed tendons, which are used for the cantilever part and for the prestressed beams of the bridge. The prestressing steel within the balanced cantilevers usually comprises straight tendons, which are anchored at the ends of the cantilever, whereas the prestressed beams the prestressing steel tendon profile usually has a parabolic shape, following the bending moment diagram. The large bridge spans reach lengths up to 100 metres.

Example of proactive adaptation on a real bridge

Deterioration of the Polyfytos Bridge



Example of proactive adaptation on a real bridge

Pathology – deformation of the cantilevers

The bridge deck is drawn in the slide above to show the two potential challenges the bridge is faced:

- The visible deformations of the deck, which are also shown on the real bridge (down a photograph showing the deformed bridge) and
- The potential deterioration of tendons with emphasis above the piers where the wider and potential most harmful cracks are developing.

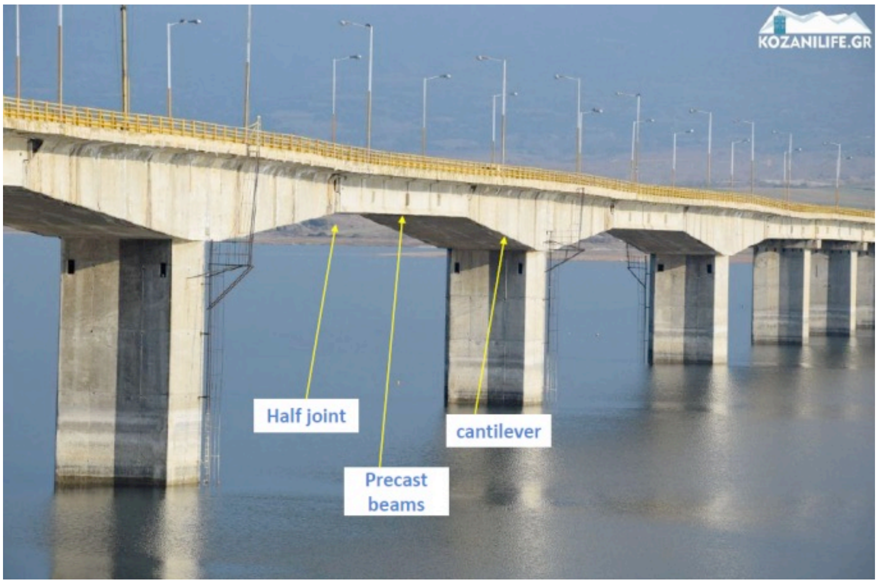
-

Red Circles: There are two red circles emphasising areas of interest or concern on the bridge structure. These circles indicate critical points of structural deterioration including areas of excessive tendon loss and half-joint which are known to deteriorate faster than other structural components due to them being exposed to water ingress, dirt, structural deformations etc.

Bottom: real photograph of the Polyfytos Bridge surface illustrating the pathology and deformation of the cantilevers. The image shows visible structural deformations along the bridge surface.

Example of proactive adaptation on a real bridge

Pathology – deformation of the cantilevers



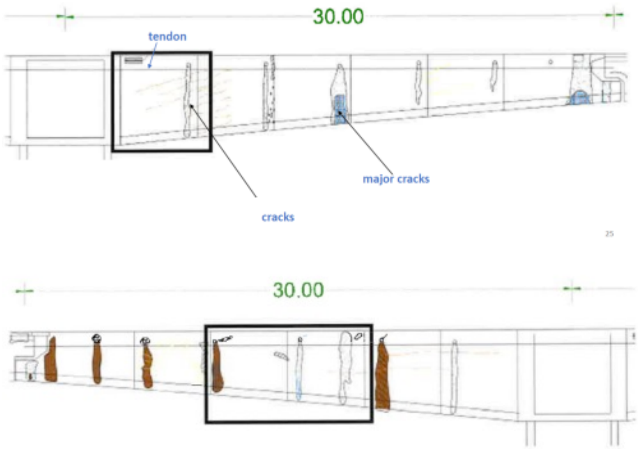
The slide shows a photograph of the bridge, highlighting specific structural components. It illustrates and explains elements of the bridge design and potential areas of concern. Here's a detailed description and analysis:

Components Labelled:

- **Half Joint:**
  - This refers to the location where two sections of the bridge deck meet, allowing for some relative movement between sections. It is often a point of structural vulnerability, particularly to issues like water ingress and structural wear.
- **Cantilever:**
  - This label points to the section of the bridge deck that extends beyond the support provided by the piers, indicating that part of the structure's cantilevers.
- **Precast Beams:**
  - Part of the bridge's deck structure comprises precast concrete beams. These beams are manufactured off-site and then transported to the bridge location for assembly, providing a rapid construction solution with consistent quality.

Example of proactive adaptation on a real bridge

Pathology – Extensive structural damage, cracking and half-joint deterioration



Further damage and deterioration of the bridge was identified during an inspection in 2021 where extensive concrete spalling, and tendon corrosion, as well as severe deterioration of the half-joints was established. The deterioration and defects were mainly attributed to the poor drainage of the bridge deck and the deficient protection of tendons and their anchorages and this was the main reasons for proposing the immediate replacement of the drainage of the bridge and the inspection of the tendons and anchorage areas.

It is generally very challenging, if not impossible, to fully assess the remainder strength of the bridge at this condition. However, considering the large deflections of the bridge (of the order of 300mm) it is reasonable to assume that the deck and prestressing have both deteriorated substantially, therefore it is reasonable to plan adaptation measures, assuming that the deck is not reliable to take large traffic loads. In the slides following this presentation examples of adaptation measures are described.

Example of proactive adaptation on a real bridge

Adaptation scenarios: Scenario #0: Keep as is with light local interventions

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Intervention on the most critical half joint

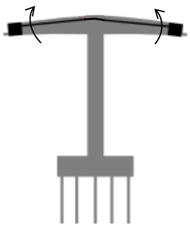
This slide illustrates the case of scenario #0 which corresponds to the case where no interventions are applied on the bridge, or minor/light adaptation measures, and local strengthening measures and interventions are utilised. Such measures are aiming at reducing the risk of obvious and imminent damage, e.g., the extensive cracking of the seating area of the precast beams at the position of the half-joint in this case. Such measures of bracing and cables restrainers are very typical in bridge strengthening, e.g., the use of an external components with prestressed rods, cables and bearing plates tailored to the local needs, are expected to be completed within a few days.

Example of proactive adaptation on a real bridge

Adaptation scenarios:

Scenario #1: demolition of the deck and reconstruction as originally, with prestressed concrete beams

Scenario #2: Keep cantilevers as is and installation of new external prestressing cables. Restoration of half-joints. Replacement of prestressed concrete beams with steel beams and continuity slab



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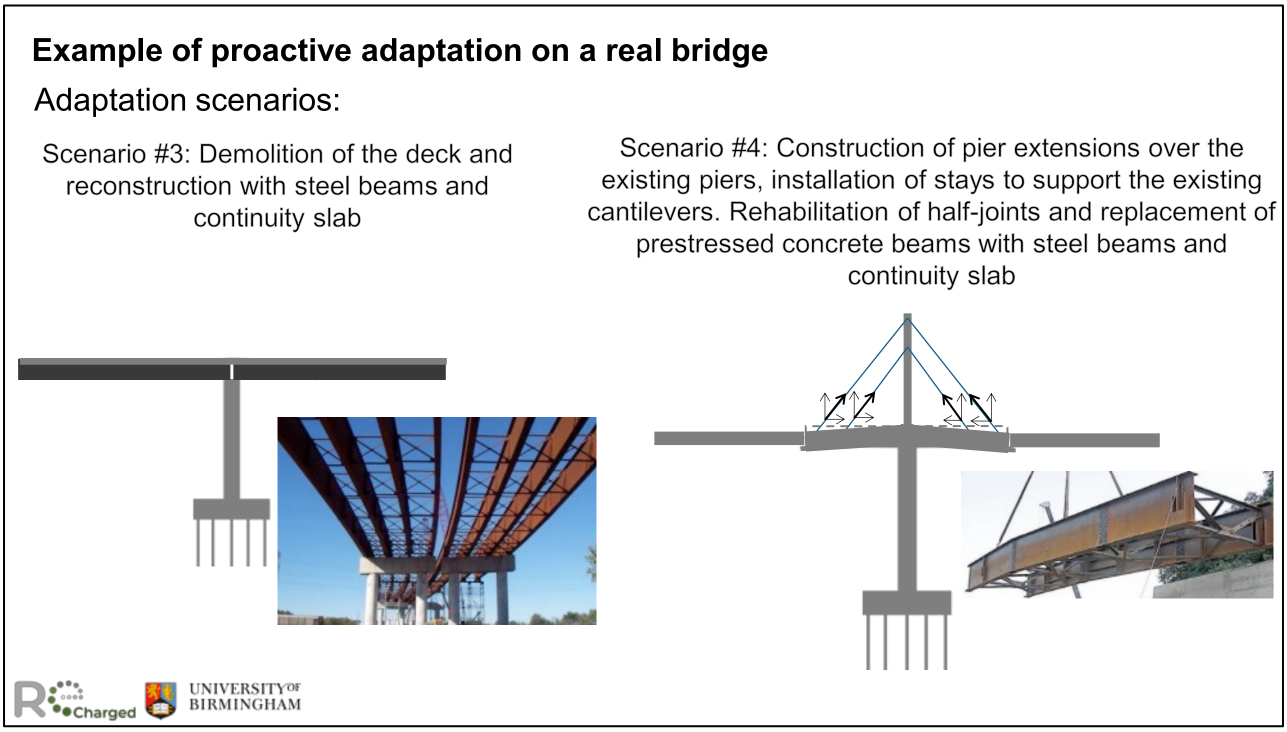

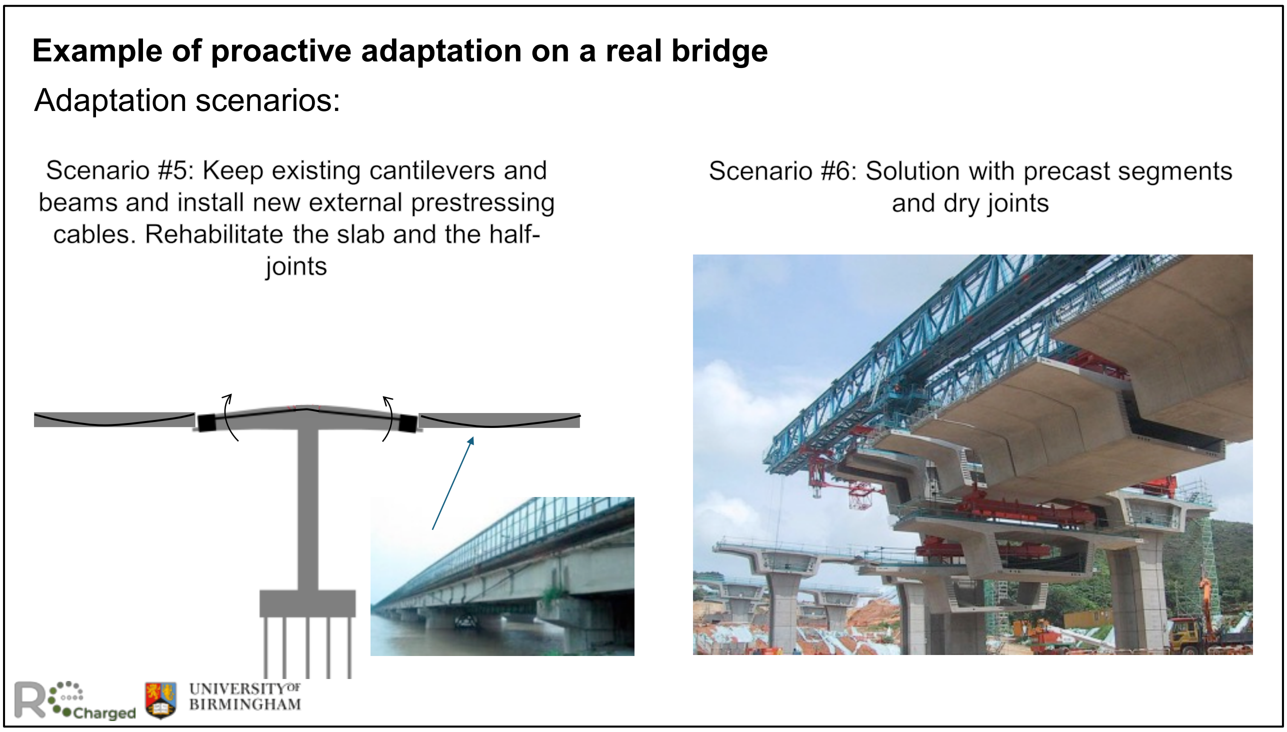

This slide describes another two scenarios, #1 and #2 which are considered to be more invasive and hence more time-consuming interventions.

Scenario #1 involves the demolition of the deck and reconstruction as originally designed, with prestressed concrete beams.

Scenario #2 involves the preservation of the cantilevers as is and the installation of a new external prestressing system with cables. This method also involves the restoration of half-joints, the replacement of prestressed concrete beams with steel beams and the use of a continuity slab which connects all precast members into an integral deck.

Scenario #3 requires the demolition of the deck and its reconstruction with steel beams with a concrete continuity slab, thus delivering a fast reconstruction based on a composite solution, potentially much faster than cast-in-place solutions.

Scenario #4: Construction of pier extensions over the existing piers (column on column) and installation of cables to suspend the existing cantilevers. This scenario also involves the rehabilitation of half-joints and the replacement of prestressed concrete beams with steel beams and the use of a concrete continuity slab.

Scenario #5: This scenario involves maintaining the existing cantilevers and beams and install new external prestressing cables. This also includes rehabilitating the slab and the half-joints.

Scenario #6: Solution with precast segments and dry joints.

All scenarios were developed after interviewing bridge engineers and consultants to understand the availability of materials and prefabrications option in the area.

Activity 2. Nature Based Solutions

ACTIVITY 2: Nature Based Solutions
• Types of Nature based Solutions (NbS) • Examples • Application

This section describes Nature based Solutions (NbS), which are solutions that reduce the environmental impact and the negative consequences of structures on nature and biodiversity. In what follows, the types of NbS in the infrastructure sector are given along with examples and applications.

Nature based Solutions (NbS) and types

Nature-based solutions are actions to protect, sustainably manage, or restore natural ecosystems, that address societal challenges such as climate change, human health, food and water security, and disaster risk reduction effectively and adaptively, simultaneously providing human well-being and biodiversity benefits.

For example, a common problem is the **flooding** in coastal areas that occurs as a result of storm surges and coastal erosion. This challenge, traditionally tackled with manmade **(grey) infrastructure** such as sea walls or dikes, coastal flooding, can also be addressed by actions that take advantage of ecosystem services such as tree planting. **Planting trees** that thrive in coastal areas – known as mangroves -- reduces the impact of storms on human lives and economic assets, and provides a habitat for fish, birds and other plants supporting biodiversity.

Source: https://www.worldbank.org

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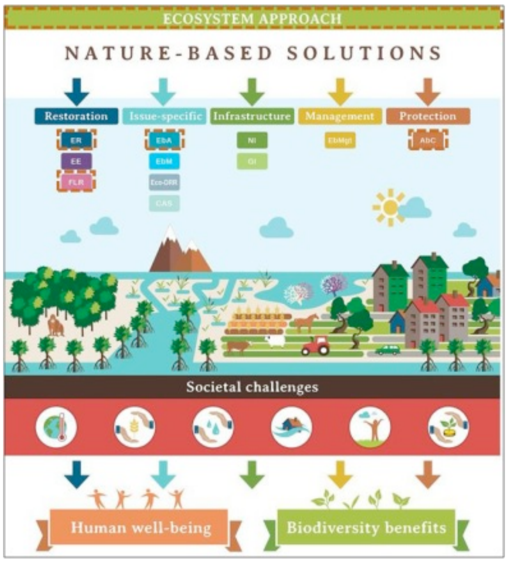
The image on the right hand side of this slide is a conceptual illustration of various nature-based solutions aimed at addressing environmental challenges and promoting sustainable development. The illustration is divided into different sections, each representing a specific strategy or approach:

1. **Climate Smart Forestry**: Depicted in the mountainous region, this concept involves managing forests in a way that maximises their ability to absorb carbon dioxide, thus helping to mitigate climate change while also preserving biodiversity and supporting local communities.
2. **River Restoration**: Shown along the river, this approach focuses on returning rivers and their ecosystems to a more natural state, improving water quality, restoring habitats, and reducing the risk of floods and the negative impacts on biodiversity.
3. **Climate Smart Agriculture**: Illustrated with a tractor in the fields, this involves farming practices that increase productivity and resilience while reducing greenhouse gas emissions, conserving water, and enhancing soil health.
4. **Wetland Restoration**: Located near the lower parts of the river, this strategy restores wetlands to improve water filtration, provide habitat for wildlife, promotes biodiversity, and act as natural buffers against floods.

5. **Peatland Restoration**: Shown adjacent to the agricultural fields, peatland restoration involves rewetting drained peatlands to prevent carbon emissions, improve biodiversity, and restore water regulation functions.
6. **Green Cities**: Depicted as a cluster of buildings surrounded by greenery, this concept refers to urban planning that incorporates green spaces, sustainable infrastructure, and energy-efficient buildings to reduce environmental impacts and enhance the quality of life.
7. **Coastal Flood Protection**: Found in the lower right of the image, this strategy uses natural barriers like mangroves and wetlands to protect coastal areas from storm surges and flooding, reducing the need for engineered solutions.

Source: https://www.worldbank.org

Nature based Solutions (NbS) and types



Five categories of ecosystem-based approaches

Ecological Restoration (ER);
Ecological Engineering (EE);
Forest Landscape Restoration (FLR);

Ecosystem-based Adaptation (EbA);
Ecosystem-based Mitigation (EbM);
Climate Adaptation Services (CAS);
Ecosystem-based Disaster Risk Reduction (Eco-DRR);

Natural Infrastructure (NI);
Green Infrastructure (GI);

Ecosystem-based Management (EbMgt);

Area-based Conservation (AbC).

Societal challenges: climate change, food security, water security, disaster risk, human health, and social and economic development.

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The image provided is a detailed illustration of **Nature-Based Solutions (NBS)** within an **Ecosystem Approach**. It visually connects various strategies for ecological and environmental management, highlighting how these strategies can address societal challenges while contributing to both human well-being and biodiversity benefits:
Top Section: Ecosystem Approach
Title: Nature-Based Solutions
The image is segmented into five primary categories of nature-based solutions, each represented by a different coloured arrow pointing downward:
Restoration (Blue)
Issue-specific (Light Blue)
Infrastructure (Green)
Management (Yellow)
Protection (Orange)
Each category corresponds to specific approaches and strategies aimed at achieving sustainable and ecologically sound solutions. Let's look at each category in detail:

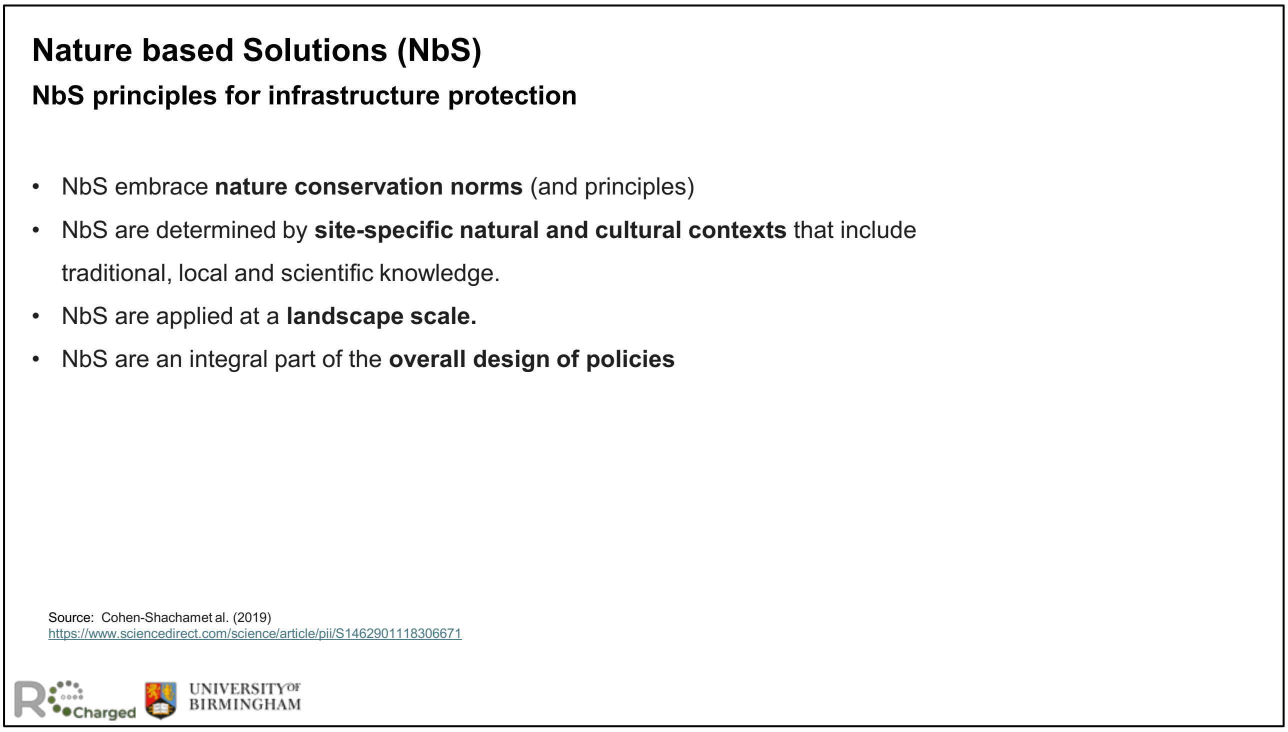
Nature-Based Solutions Categories

Restoration (Blue Arrow)
ER: **Ecological Restoration**
Involves restoring ecosystems to their original state, focusing on rebuilding native habitats and biodiversity.
EE: **Ecological Engineering**
Uses engineering principles to design sustainable ecosystems that integrate human needs with natural systems.
FLR: **Forest Landscape Restoration**
Focuses on restoring forest landscapes to maintain ecological functions and provide socio-economic benefits.
Issue-Specific (Light Blue Arrow)
EbA: **Ecosystem-based Adaptation**
Utilises biodiversity and ecosystem services to help people adapt to climate change effects.
EbM: **Ecosystem-based Management**
An integrated approach that considers the entire ecosystem, including humans, to achieve sustainable management.
Eco-DRR: **Ecosystem-based Disaster Risk Reduction**
Employs ecosystem services to reduce disaster risks and enhance resilience against natural hazards.
CAS: **Climate Adaptation Services**
Provides services to assist in adapting to climate change impacts, focusing on resilience building.
Infrastructure (Green Arrow)
NI: **Natural Infrastructure**
Natural infrastructure, also referred to as green infrastructure, uses existing natural areas (and engineered solutions that mimic natural processes) to minimize flooding, erosion, and runoff. Involves using natural elements (like wetlands and forests) to provide infrastructure services.
GI: **Green Infrastructure**
Green infrastructure or blue-green infrastructure refers to a network that provides the "ingredients" for solving urban and climatic challenges by building with nature. Integrates green spaces and networks into urban planning to improve environmental quality and human health.
Management (Yellow Arrow)
EbMgt: **Ecosystem-based Management**
Focuses on managing ecosystems holistically to maintain biodiversity and ecosystem services.
Protection (Orange Arrow)
AbC: **Area-based Conservation**
Encompasses the designation and management of protected areas to conserve natural habitats and biodiversity.

Middle Section: Visual Representation
Illustration includes:
Natural Elements
Agriculture
Urban Areas
Infrastructure
Biodiversity
Societal Challenges (Dark Red Banner)
This section highlights the societal challenges that Nature-Based Solutions aim to address. It uses icons to represent various global challenges:
Climate Change
Food Security
Water Management
Disaster Risk Reduction

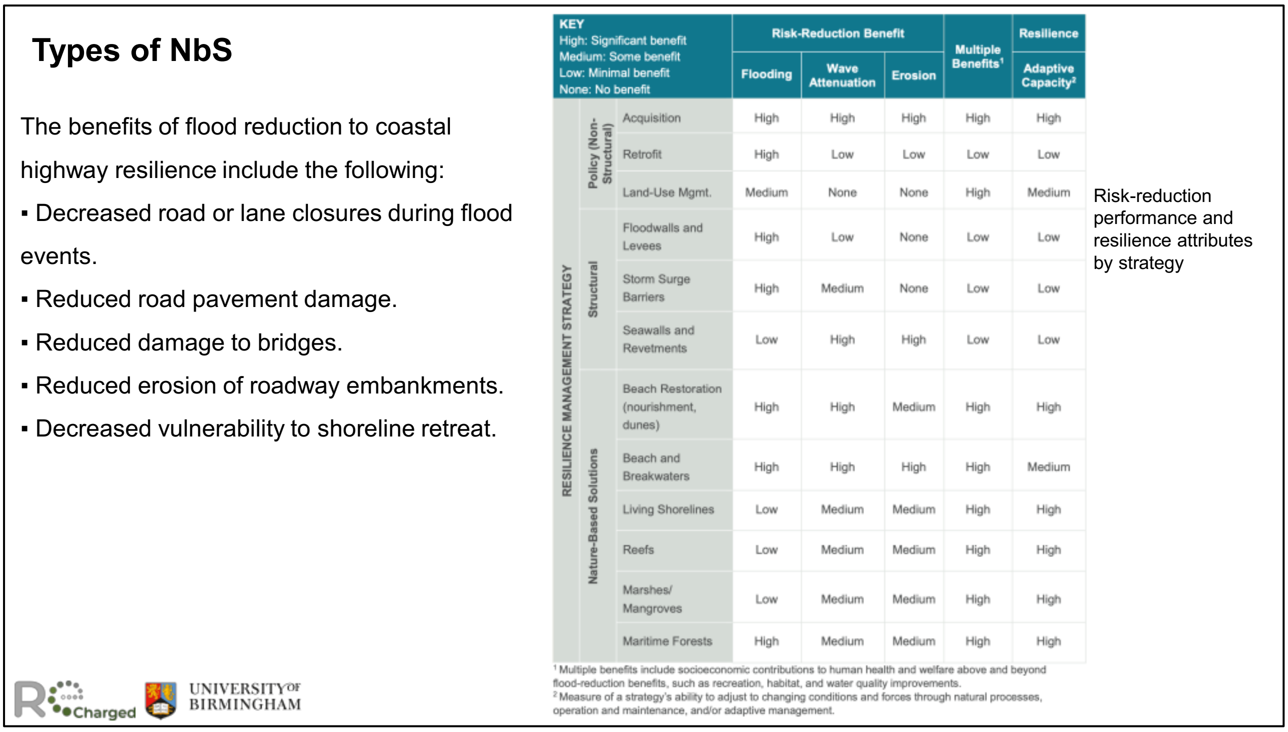
Health and Well-being
Environmental Sustainability
These challenges are interconnected with nature-based strategies to provide comprehensive solutions.

Benefits
The bottom section of the image divides the benefits of nature-based solutions into two main areas:
Human Well-being (Left, Orange Banner)
Biodiversity Benefits (Right, Green Banner)



Hence, the main NbS principles for infrastructure protection are:

NbS embrace nature conservation norms (and principles)
NbS are determined by site-specific natural and cultural contexts that include traditional, local and scientific knowledge.
NbS are applied at a landscape scale.
NbS are an integral part of the overall design of policies



KEY: High: Significant benefit; Medium: Some benefit; Low: Minimal benefit; None: No benefit			Risk-Reduction Benefit			Multiple Benefits[1]	Resilience
			Flooding	Wave Attenuation	Erosion		Adaptive Capacity[2]
RESILIENCE MANAGEMENT STRATEGY	Policy (Non-Structural)	Acquisition	High	High	High	High	High
		Retrofit	High	Low	Low	Low	Low
		Land-Use Mgmt.	Medium	None	None	High	Medium
	Structural	Floodwalls and Levees	High	Low	None	Low	Low
		Storm Surge Barriers	High	Medium	None	Low	Low
		Seawalls and Revetments	Low	High	High	Low	Low
	Nature-Based Solutions	Beach Restoration (nourishment, dunes)	High	High	Medium	High	High
		Beach and Breakwaters	High	High	High	High	Medium
		Living Shorelines	Low	Medium	Medium	High	High
		Reefs	Low	Medium	Medium	High	High
		Marshes/ Mangroves	Low	Medium	Medium	High	High
		Maritime Forests	High	Medium	Medium	High	High

[1] Multiple benefits include socioeconomic contributions to human health and welfare above and beyond flood-reduction benefits, such as recreation, habitat, and water quality improvements.
[2] Measure of a strategy's ability to adjust to changing conditions and forces through natural processes, operation and maintenance, and/or adaptive management.

This slide shows the benefits of applying different types of NbS and the risk-reduction performance and resilience attributes by strategy, with a focus on flood reduction to coastal highway resilience. The main benefits include:

Decreased road or lane closures during flood events: This implies improved traffic flow and reduced disruption during adverse weather conditions, contributing to economic stability and public safety.

Reduced road pavement damage: Highlights the protective aspect of NbS, where natural elements can help minimise the degradation of road surfaces caused by water exposure.

Reduced damage to bridges: Indicates the role of NbS in protecting vital infrastructure by mitigating the impact of high water levels and associated forces.

Reduced erosion of roadway embankments: Underlines the erosion control capabilities of NbS, preserving the integrity of embankments and preventing costly repairs.

Decreased vulnerability to shoreline retreat: Emphasises the protective barrier that nature-based solutions can provide against coastal erosion, safeguarding both natural habitats and human developments.

Based on the table on the right side of the slide:

A compelling argument for integrating Nature-Based Solutions into coastal resilience planning, advocating for strategies that offer environmental, social, and economic benefits is offered. By aligning with nature, these solutions aim to create sustainable and adaptive coastal environments, reducing the risk of damage to critical infrastructure while supporting biodiversity and community well-being:

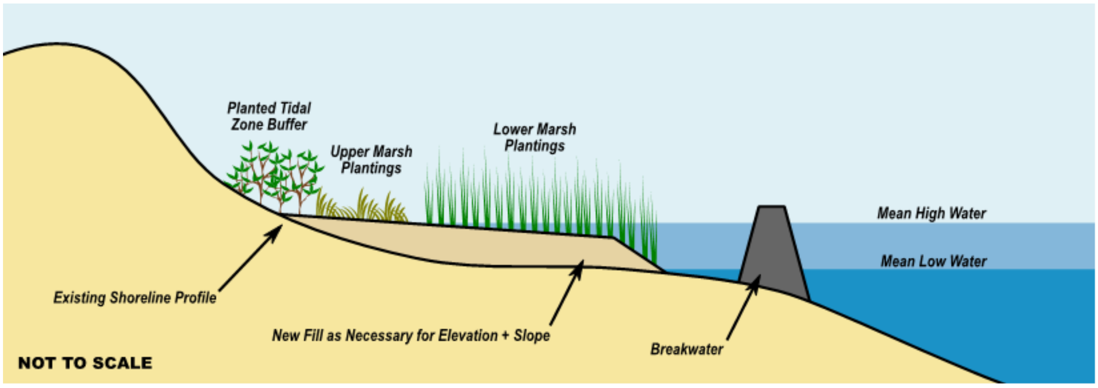
Nature-Based Solutions (NbS): These strategies generally show strong performance in multiple benefit areas, emphasising biodiversity and ecological health while offering protection against flooding and erosion. They also score high on adaptive capacity, reflecting their ability to adjust to changing environmental conditions.

Structural Solutions: These offer targeted high protection in specific areas, such as floodwalls for flood reduction and seawalls for wave attenuation. However, they often lack in providing multiple benefits and adaptive capacity, potentially making them less sustainable in the long term.

Key Takeaways:
Nature-Based vs. Structural Solutions: The table illustrates the comparative advantages of NbS over traditional structural solutions, highlighting the former's ecological benefits and adaptability, though sometimes at the cost of immediate and intense protection provided by structural approaches.
Holistic Approach: Emphasising the synergy between various solutions, combining structural measures with NbS may provide a balanced strategy for managing coastal resilience effectively.

Nature based Solutions (NbS)

Example: Coastal protection - a constructed marsh with breakwaters



Source:
Webb et al. (2019) 'NATURE-BASED SOLUTIONS FOR COASTAL HIGHWAY RESILIENCE: AN IMPLEMENTATION GUIDE'
https://www.fhwa.dot.gov/environment/sustainability/resilience/ongoing_and_current_research/green_infrastructure/implementation_guide/fhwahep19042.pdf

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The construction of a marsh, including fill and plantings but without structural elements, in the intertidal zone of a shoreline. Native marsh plants are appropriate for the site conditions (e.g., tide range, salinity, wave energy) along with sediment, if necessary, to build a platform of gradual slope at an appropriate elevation for the marsh to sustain itself.

The illustration depicts the following elements:

- **Existing Shoreline Profile:** The original contour of the shoreline before any interventions.
- **Planted Tidal Zone Buffer:** An area where tidal plants are introduced to provide a buffer zone.
- **Upper Marsh Plantings:** Vegetation planted at a higher elevation in the marsh area.
- **Lower Marsh Plantings:** Vegetation planted at a lower elevation, closer to the waterline.
- **New Fill as Necessary for Elevation + Slope:** Additional material added to adjust the elevation and slope of the marsh.
- **Breakwater:** Protects the shoreline from the force of waves.
- **Mean High Water and Mean Low Water:** Indicators of the average high and low water levels.

Nature based Solutions (NbS)

Example: green bridge

Source: https://www.manchestereveningnews.co.uk/news/greater-manchester-news/stunning-green-bridge-designed-help-14169472

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The second slide shows a green bridge. Green structures like this enable the survival of biodiversity. Such structures could be green bridges & tunnels. Green bridges (also known as landscape bridges or wildlife overpasses) allow birds, mammals and insects to keep moving despite a railway or road being in their path, e.g., underpass in the slide above.

Nature based Solutions (NbS)

Example: Urban green roofs

Benefits:

- Reduced and delayed stormwater runoff
- Enhanced groundwater
- Storm water pollutant reductions
- Fewer sewer overflow events
- Increased carbon sequestration
- Urban heat island (UHI) mitigation and lower energy demands
- Improved air quality
- Additional wildlife habitats and recreational space
- Better human health
- Higher land values

Source: https://blog.urbanscape-architecture.com/why-does-urban-green-infrastructure-matter

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Implementing green infrastructure in urban areas can bring about a multitude of benefits, addressing environmental, economic, and social challenges. Below is a detailed exploration of each benefit listed, highlighting how green infrastructure contributes to urban sustainability and resilience.

1. Reduced and Delayed Stormwater Runoff

Description: Green infrastructure manages rain where it falls, reducing the volume and speed of stormwater runoff by allowing water to infiltrate into the ground or be absorbed by vegetation. This mimics natural hydrological processes, effectively reducing pressure on urban drainage systems.

Benefits:

- **Decreased Flood Risk:** By absorbing excess rainwater, green infrastructure reduces the likelihood of urban flooding during heavy rainfall events.
- **Erosion Control:** Reduced runoff minimizes soil erosion and the destabilization of stream banks and urban landscapes.
- **Infrastructure Longevity:** By decreasing the volume of water entering stormwater systems, the lifespan of urban infrastructure is extended, reducing maintenance costs and the need for expensive upgrades.

Examples:

- **Rain Gardens:** Depressed areas in the landscape that collect runoff and allow it to infiltrate.
- **Permeable Pavements:** Surfaces designed to allow water to percolate through, reducing surface runoff.

2. Enhanced Groundwater Recharge

Description: By promoting infiltration, green infrastructure enhances the natural replenishment of groundwater aquifers, which are crucial sources of water for many communities.

Benefits:

- **Water Security:** Recharging aquifers can help sustain water supplies during dry periods and droughts.
- **Environmental Protection:** Maintaining healthy groundwater levels supports ecosystems that depend on consistent water availability.

Examples:

- **Bioswales:** Landscape elements that channel stormwater runoff into vegetated areas, facilitating infiltration.
- **Green Roofs:** Roofs covered with vegetation that capture rainwater, reducing runoff and promoting infiltration.

3. Storm Water Pollutant Reductions

Description: Green infrastructure can filter pollutants from stormwater before they reach water bodies, improving water quality.
Benefits:

Pollutant Removal: Vegetation and soil in green infrastructure systems can trap sediments, nutrients (like nitrogen and phosphorus), heavy metals, and other contaminants.
Ecosystem Health: Cleaner waterways support healthier aquatic ecosystems and biodiversity.
Examples:
Constructed Wetlands: Engineered wetlands designed to treat stormwater by natural processes involving vegetation and soil interactions.
Riparian Buffers: Vegetated areas along waterways that filter runoff and provide habitat for wildlife.

4. Fewer Sewer Overflow Events

Description: Green infrastructure reduces the volume of stormwater entering combined sewer systems, thereby decreasing the frequency and severity of sewer overflows.
Benefits:
Public Health Protection: Fewer overflows reduce the risk of exposure to untreated sewage, which can carry pathogens harmful to human health.
Water Quality Improvement: Reducing sewer overflows leads to cleaner rivers and streams, benefiting both aquatic life and recreational activities.
Examples:
Retention Basins: Structures designed to hold stormwater temporarily, allowing controlled release into sewer systems.
Detention Ponds: Similar to retention basins but often dry, except during periods of stormwater accumulation.

5. Increased Carbon Sequestration

Description: Green infrastructure can capture and store atmospheric carbon dioxide, a major greenhouse gas, thereby contributing to climate change mitigation.

Benefits:

- **Climate Regulation:** By sequestering carbon, green spaces help moderate the effects of climate change.
- **Air Quality Enhancement:** Increased vegetation not only captures CO2 but also filters pollutants from the air, contributing to healthier urban environments.

Examples:

- **Urban Forests:** Trees planted in urban areas that absorb CO2 and other pollutants while providing shade and aesthetic benefits.
- **Green Walls and Roofs:** Vertical and horizontal green spaces that capture CO2 and provide insulation to buildings.

6. Urban Heat Island (UHI) Mitigation and Lower Energy Demands

Description: Urban areas often experience higher temperatures than their rural surroundings due to human activities and infrastructure, a phenomenon known as the Urban Heat Island (UHI) effect. Green infrastructure can help mitigate UHI by providing shade and promoting evapotranspiration.

Benefits:

- **Temperature Regulation:** Vegetated areas can cool urban environments, reducing the need for air conditioning and associated energy use.
- **Energy Savings:** Cooler urban temperatures translate to lower energy consumption for cooling, reducing costs and greenhouse gas emissions.

Examples:

- **Street Trees:** Trees planted along streets that provide shade and cooling through transpiration.
- **Vegetated Roofs:** Roofs covered with plants that insulate buildings and reduce rooftop temperatures.

7. Improved Air Quality

Description: Green infrastructure enhances air quality by removing pollutants from the atmosphere, including particulate matter and gaseous pollutants such as nitrogen oxides and sulfur dioxide.

Benefits:

- **Healthier Populations:** Cleaner air reduces respiratory problems and other health issues, contributing to better overall public health.
- **Biodiversity Support:** Improved air quality benefits both humans and urban wildlife, supporting diverse ecosystems.

Examples:

- **Green Belts:** Large green areas surrounding urban areas that filter air and provide recreational spaces.
- **Living Walls:** Vertical gardens that clean air and improve aesthetics in dense urban environments.

8. Additional Wildlife Habitats and Recreational Space

Description: Green infrastructure provides essential habitats for wildlife in urban areas and offers recreational opportunities for residents.

Benefits:

- **Biodiversity Conservation:** Urban green spaces support a wide range of species, promoting biodiversity in otherwise built-up areas.
- **Community Well-being:** Access to green spaces enhances mental and physical health, providing areas for relaxation, exercise, and social interaction.

Examples:

- **Parks and Greenways:** Large areas dedicated to recreation and wildlife habitat, connecting urban communities with nature.
- **Rooftop Gardens:** Urban agriculture and gardens on rooftops that support pollinators and provide community gardening opportunities.

9. Better Human Health

Description: Exposure to green spaces has been linked to various health benefits, both physical and mental, contributing to overall well-being.

Benefits:

- **Reduced Stress:** Nature exposure helps alleviate stress, anxiety, and depression, improving mental health.
- **Physical Activity:** Accessible green spaces encourage outdoor activities, promoting physical fitness and reducing the risk of chronic diseases.

Examples:

- **Community Gardens:** Shared gardens that foster community engagement, healthy eating, and physical activity.
- **Nature Trails:** Pathways through green spaces that encourage walking, running, and cycling.

10. Higher Land Values

Description: Properties near green infrastructure often see increased value due to the aesthetic and environmental benefits they provide.

Benefits:

- **Economic Growth:** Increased property values can boost local economies, attracting businesses and residents.
- **Community Investment:** Higher land values can lead to increased funding for community projects and infrastructure improvements.

Examples:

- **Waterfront Developments:** Projects near green spaces or restored waterways that attract investment and enhance community appeal.
- **Eco-Friendly Neighborhoods:** Developments designed with sustainability in mind that command premium prices due to their environmental benefits.

Activity 3. Resilience and sustainability stress-testing

ACTIVITY 3: Resilience and sustainability stress-testing

- Risk assessment and stress testing
- Challenges of stress testing
- Methodology to rank stress tests
- Case study: Road network in Switzerland subject to flooding

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Risk assessment

- **Three main tasks**
  - Identifying input factors, e.g., hazard intensity, asset exposure and vulnerability
  - Defining risk measures, e.g., [average] costs of restoration
  - Implementing a risk model, which connects input factors to risk measure
- **Probabilistic Risk Analysis (PRA) - using scenario development (simulation)**
  - Modelling uncertainties, e.g., using random variables, and probabilistic models
  - Generating a host of random scenarios (realizations of the system)
  - Quantifying risk measure using probability distribution of outputs

***Unconditioned** probabilistic analysis:*
<u>All possible realizations of the system</u>
- *All potentially occurring events*
- *All possible ranges of assets behaviour*
- *…*

→

Limitation
- *Identifying and explicitly assessing risks under **stressed** situations*

*[part(s) of the system is worse than its expected realizations, due to **Stressor**]*

Risk assessment, traditionally, has three main tasks:
The state-of-the-art in risk assessment is probabilistic risk assessment using scenario development by simulation
For that, first one needs to model the uncertainties, for example, using random variables and probabilistic models
Then, generate a host of random scenarios, which each of basically represent a realization of the system
And lastly, quantifying the risk measure based on the probability distributions of the outputs.

This common approach in risk assessment is basically "unconditioned", which means that we did not impose any condition on any part of the system and because of that, here all possible realizations of the system are considered, lile all potentially occurring events, and all possible ranges of asset behavior, etc.
This approach is limited, however, in identifying and explicitly assessing the risks under stress situations. Stressed situations occur when one part of the system, because of a stressor, is worse that its expected realizations.

Stress testing for Transport Systems

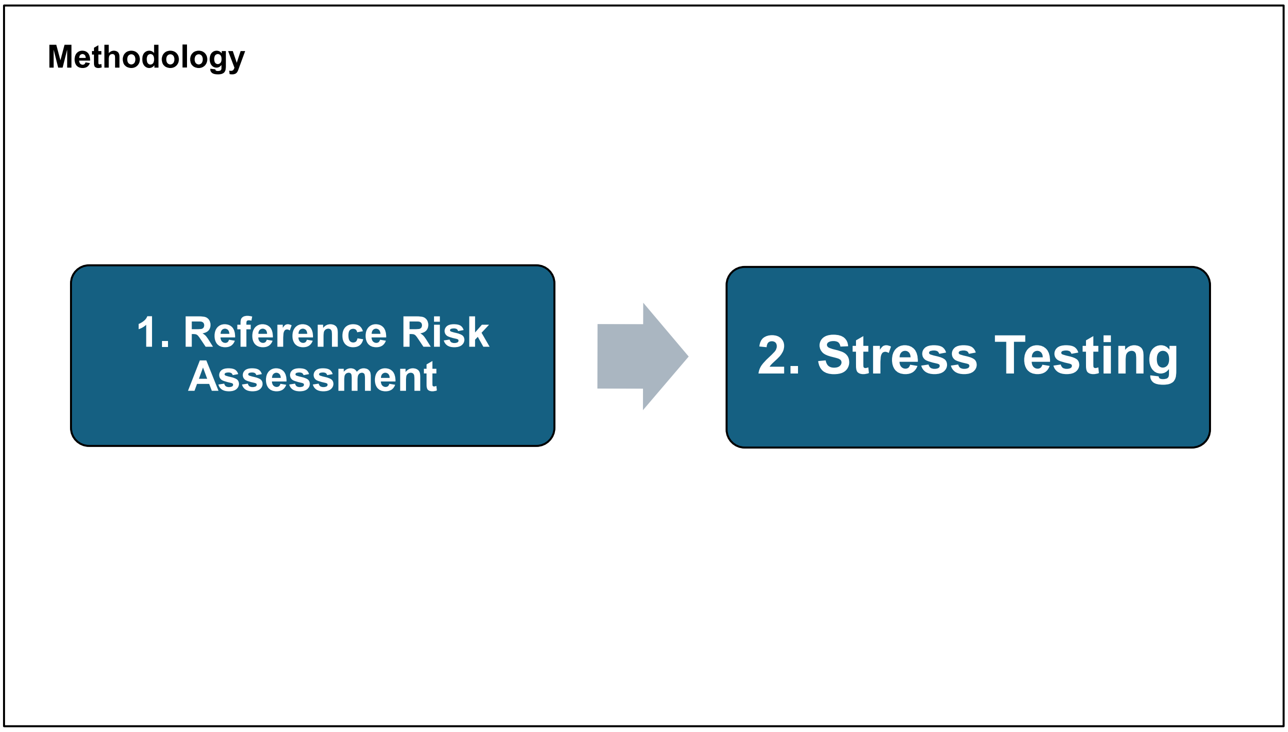
- Definition: (Agreed by the Group of Experts at UNECE)

> *"A stress test is a set of one or more **hypothetical scenarios** designed to help determine if a transport system can continue to provide an acceptable level of service when subjected to one or more potentially disruptive events"*

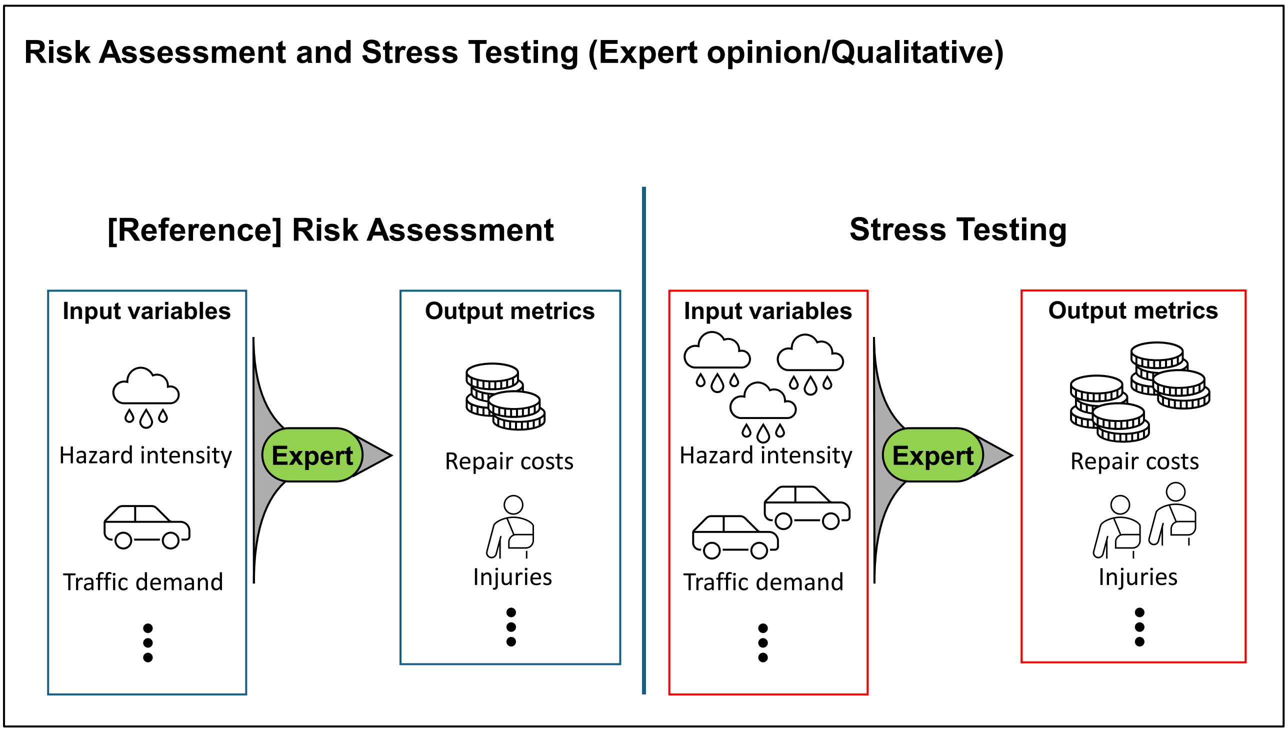
- *Hypothetical scenarios*

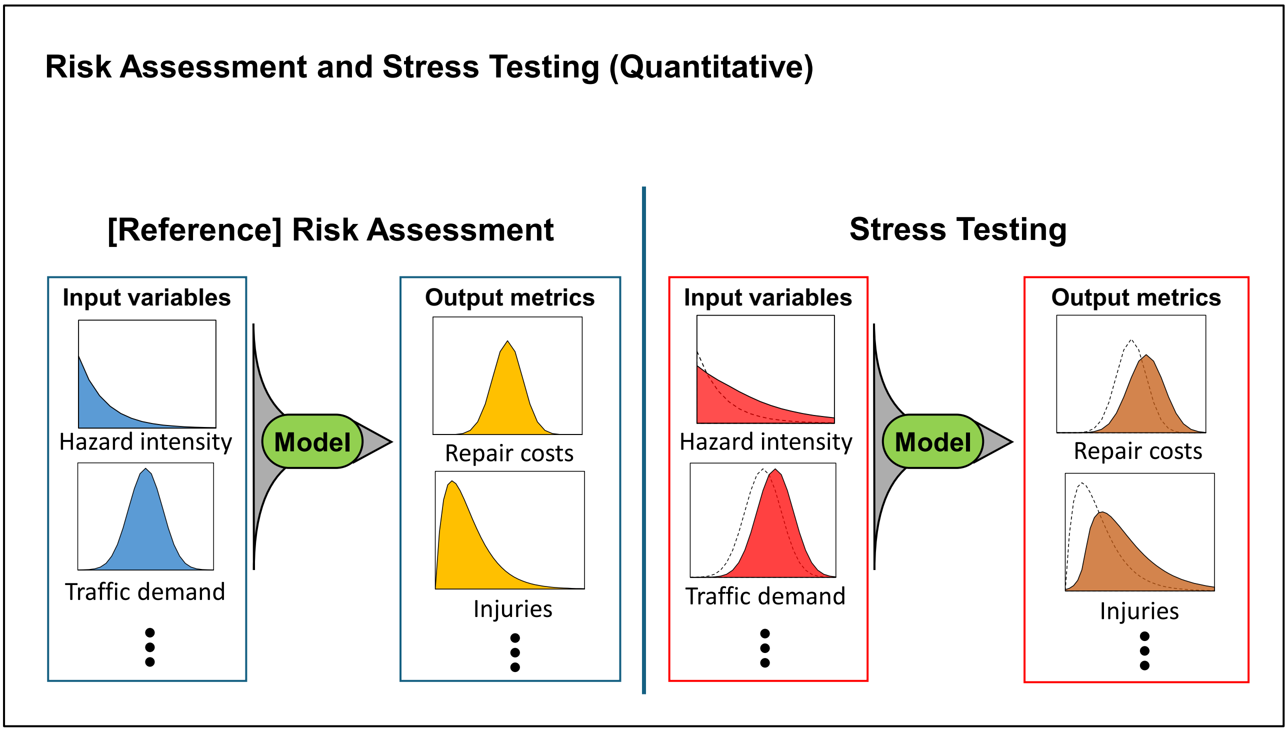
> *"situations where at least one uncertainty in the system, because of a stressor, is having significantly **more unfavorable values than expected**"*

Keeping these stressors in mind, stress test is defined as a set of one or more hypothetical scenarios designed to help determine if a transport system can continue to provide an acceptable level of service when subjected to one or more potentially disruptive events"
These hypothetical scenarios basically represent situations where at least one variable in the system, because of a stressor, is having significantly more unfavorable values than expected
In that sense, stress testing is not sth apart from risk assessment. It is essential a complementary approach to risk assessment.

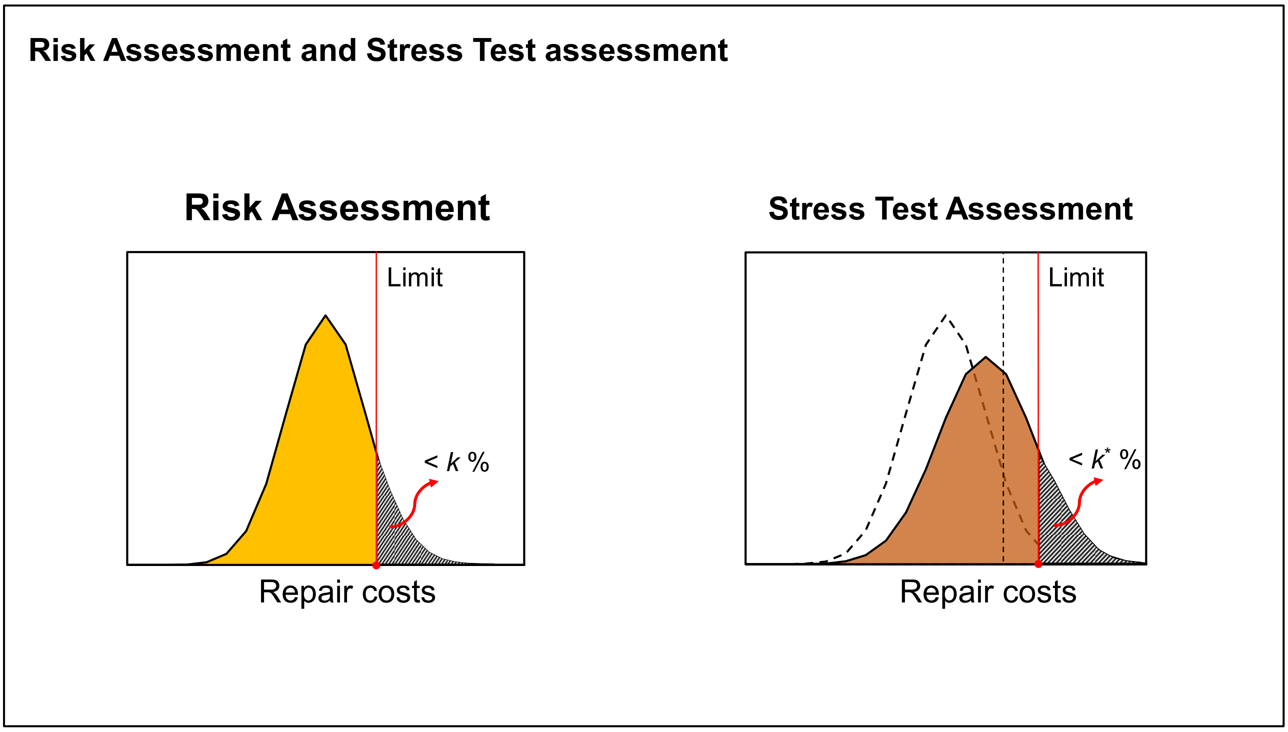


The methodology that we have in place is twofold:
The first part is called probabilistic risk assessment, which is essentially evaluating the risks under baseline situation.
And the next part is stress testing, which is evaluating the risks under the effect of stress tests.



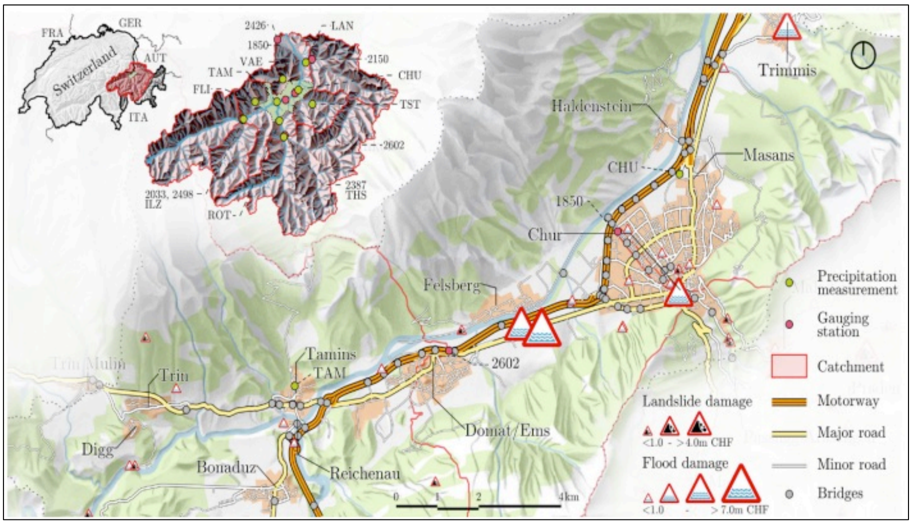


To conduct prob. Risk assessment, the analysis starts with identifying and defining input parameters, for example hazard intensity, asset performance, traffic demand and so on. Each input parameter basically has a random distribution, it could be either a quantitative continuous distribution or qualitative discrete, e.g., low, medium and high intensity hazards.
[]
These parameters are then fed into a model. []
The model then produces some outputs, for example, direct costs, or travel time. Since the input is probabilistic, the output measures also have probability distribution.
The model we developed in this study is a simulation-based model, which I explain more later. However, it could be a model based on expert's opinions. So basically, experts determine how much direct costs we would incur if we have high intensity hazard, low asset performance, and medium traffic, []
The last step is then using the outputs measures to assess the risks. I will discuss this in a bit.
The important note about prob risk assessment is that we use the entire range of possibilities for input parameters, in other words, we do not impose any condition on our input parameters. So, we can have hazard with various all levels of intensities, from low to high, and similarly for other parameters.



In this presentation, my main focus is on how we defined and conducted stress tests and not necessarily whether the stress tests passed or failed.
However, I would like to make a quick note on how risk assessment and stress test assessment can be done.
So, here we see the pdf of one of the output measures, which is direct costs, under baseline situation and under the effect of a stress test.
One way to assess the risks is to set a threshold or limit and observe whether the probability of exceeding that limit is small enough.
To assess stress test, basically a same procedure can be followed. That is we need to define a limit and then check whether the probability of exceeding that limit is acceptable or not.
I emphasize again that this is one way to assess risks and stress tests among many others. The simplest way that some might use for example is setting a limit for the average value of the output measures.

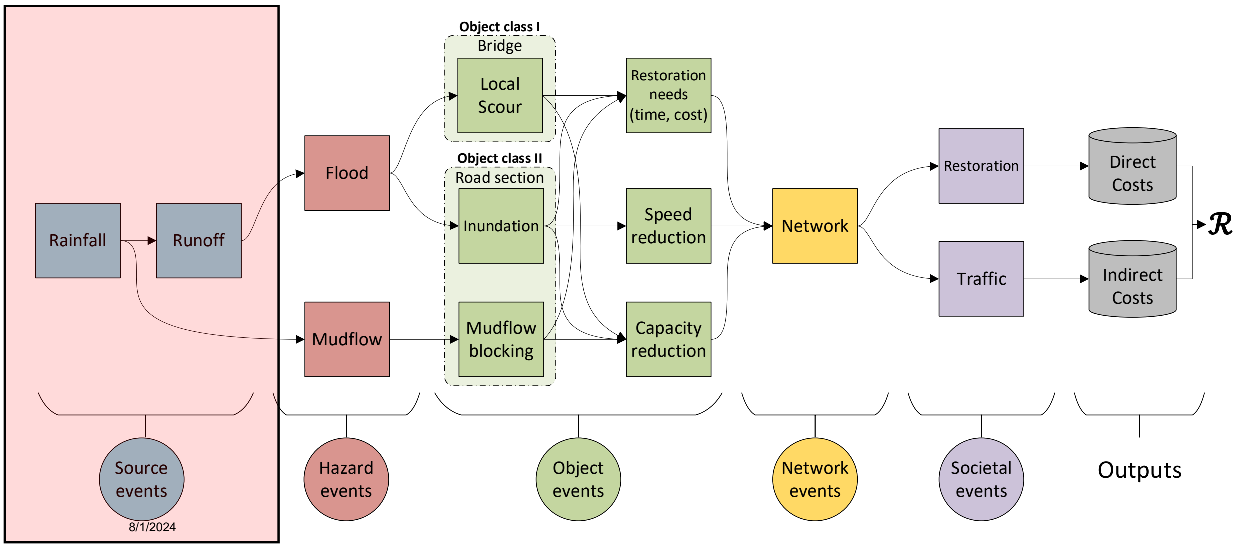
Case Study: Region of Chur, Switzerland



Roads/Bridges	
National	51 km (31%)
Other roads	554 km (39%)
Bridges	121 (20%)
River bridge	18

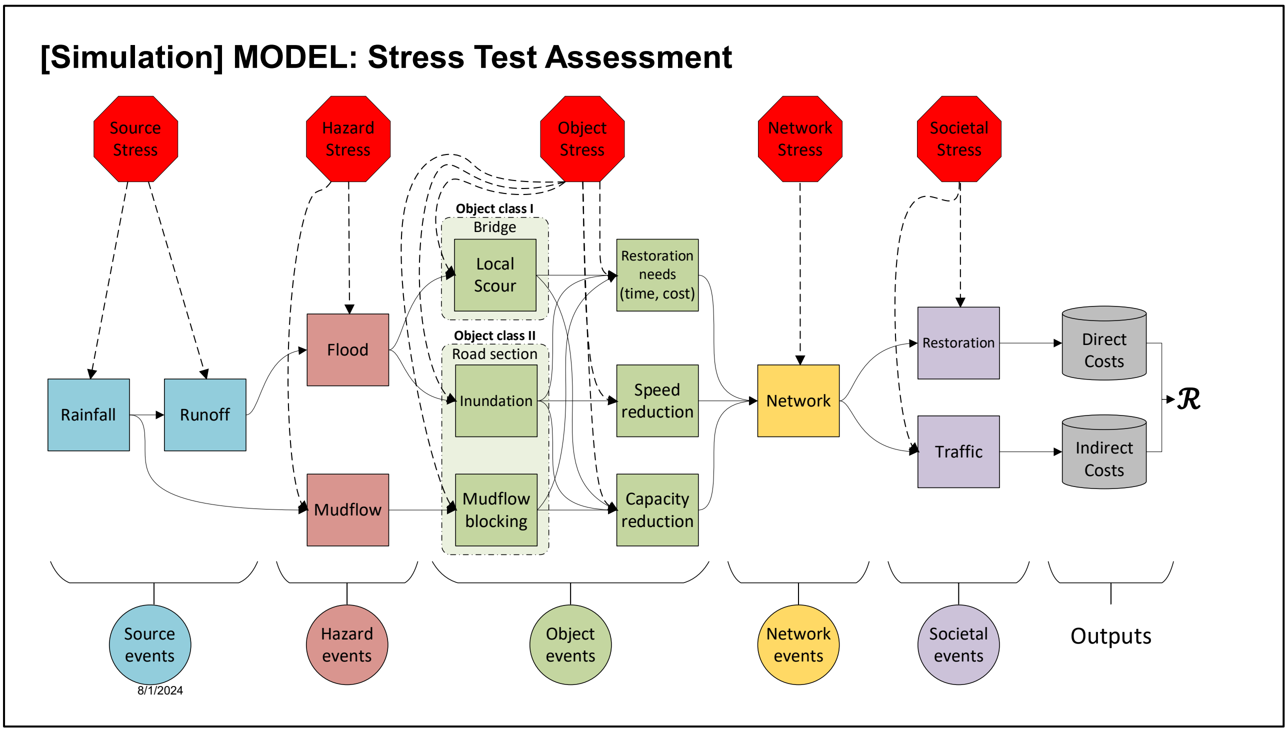
This picture shows the area of study as well as the road network.
The investigated network consists of 605km of roadways, including 51km of national highways, and 121 bridges, including 18 river bridges that are susceptible to scouring.

[Simulation] MODEL: Reference Risk Assessment



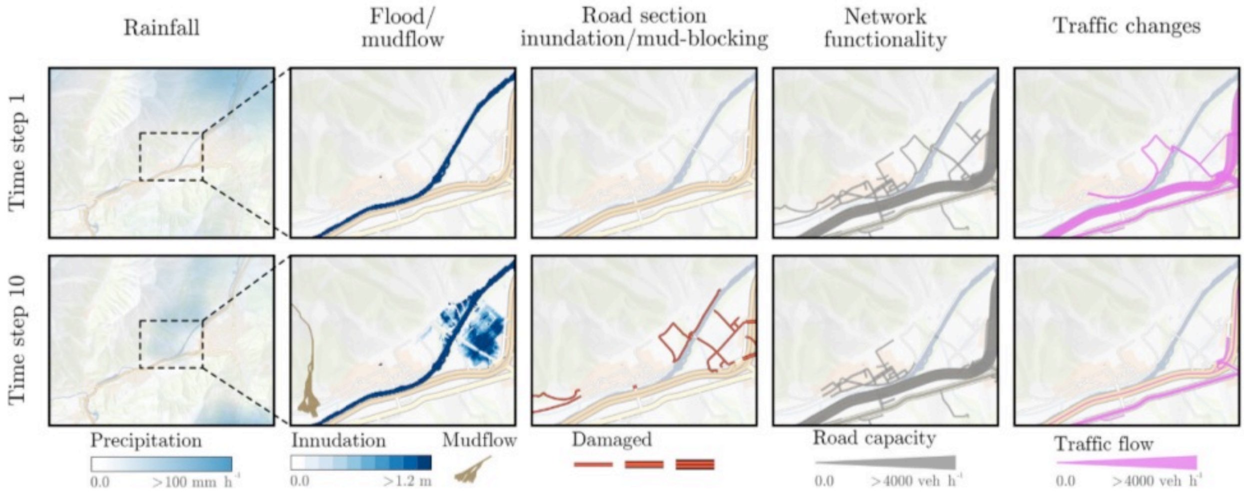
This picture shows a schematic overview of the model. It is composed of 5 types of events/models that each represent a part of the entire system. It starts with simulating source events, here rainfall and runoff. Then it models how the consequent hazards are formed and evolved over time and space, including flooding and landslides. Object events then capture the impact of those hazard on functionality of individual objects, here roads and bridges, and then network events model the collective performance

of individual objects as a network. Next, the societal impacts are estimated using restoration activities as well as the traffic flow within the network. Lastly, the associate direct and indirect costs of societal events are quantified. Here, direct costs include cost of restoration activities, like repair of road pavement or mudflow removal, and indirect costs include costs due to loss of service, such as increased travel time and loss of connectivity.
To assess the risks of the network, multiple stochastic scenarios of the considered events using the probability distribution of the input parameters are generated which then provides us with probability distribution of costs, based on which we can assess risks.



Each stress test is composed of one or multiple stressors, each imposing a condition on a model in the underlying PRA part.
Conducting a stress test starts with conditioning the appropriate models as defined per its stressors, Therefore, in accordance with the PRA part, and as shown in Figure 1, there are five types of stressors, i.e., five types of models can be modified in stress tests, source stress, hazard stress, object stress, network stress, societal stress. I will give examples on each of these stressors in a bit.
As I pointed out earlier, to conduct stress tests, we impose the conditions on the model, run the model, in our case simulations, and then we assess the stress test based on the probability distribution of output measures.

Simulation MODEL: Sample output



One last slide on the model, this picture shows a sample output of the model for one random scenario. It essentially shows a spatio-temporal representation of the considered events starting from spatial patterns of rainfall over time, then inundation maps and landslides. It then shows the damages to the roads and bridges and then their functionality in the network. And lastly, it shows the evolution of traffic flow within the network over time.

Stress test: Example stressors

Source
- ❑ Increase in the average intensity of rainfall events due to Climate change
- ❑ Occurrence of only <u>low-probability high-intensity events</u>

Hazard
- ❑ Change in the land use which can lead to more extreme runoff and flooding
- ❑ River morphology (change in shape and direction of river channels over time)
- ❑ Consecutive rainfall ➔ wet land ➔ lower absorption capacity of water ➔ more runoff ➔ more flood
- ❑ Decreased soil cohesion (due climate change) ➔ more landslides

Object
- ❑ Poor performance of infrastructure assets against hazards
- ❑ Lack of serviceability of certain [critical] links

Network
- ❑ Lack of serviceability/connectivity of part of the network

Societal
- ❑ Increase in travel demand to certain locations immediately after the hazard event
- ❑ Increase in the average travel demand in the future
- ❑ Reduction in the post-hazard restoration capacity

Lack of serviceability
x% more paved (urbanized) areas (lower absorption capacity of water)

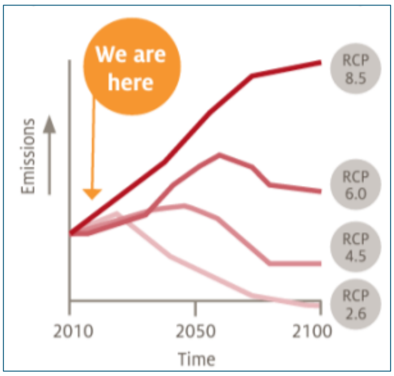
y (due to falling trees)

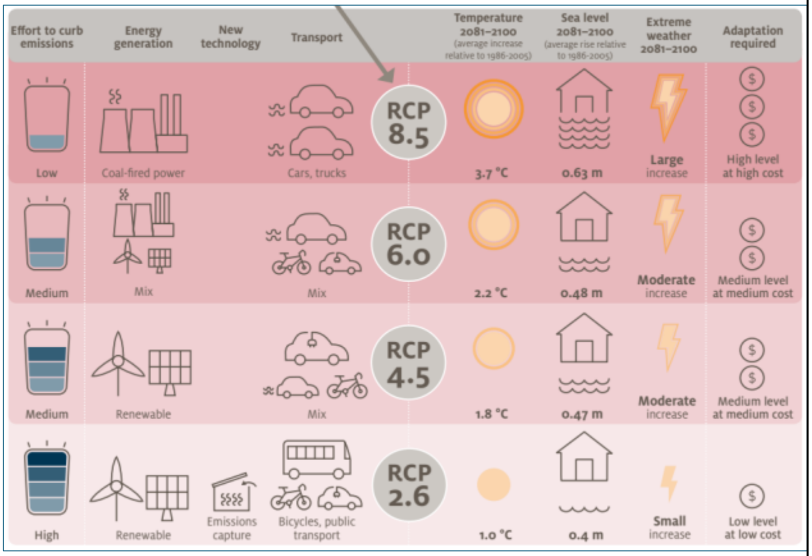
Climate change stress test

Representative Concentration Pathways (RCP Scenarios)

RCP Scenarios:

Future projections of greenhouse gas concentration and the resulting impact on climate indicators





Source: coastadapt.com.au/infographics

The first type of stress test we investigated was climate change. Before getting into details of that, I need to talk a bit about an essential aspect of climate science: RCP scenarios.

RCP, or Representative Concentration Pathways, are a set of scenarios used to project future greenhouse gas concentrations and resulting climate change.

There are four main RCP scenarios: RCP2.6, RCP4.5, RCP6, and RCP8.5.

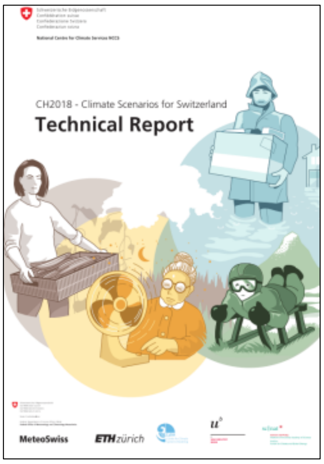
The RCPs were used in the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) in 2014 as a basis for the report's findings.

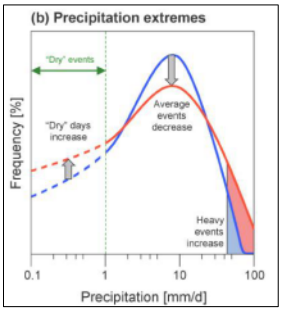
RCP2.6 represents a world with ambitious emission reductions, like by extensive use of renewable energy or public transport, resulting in limited warming to under 2 degrees Celsius

RCP4.5 and RCP6 represent scenarios with moderate emission reductions, leading to a projected temperature increase of 2 to 3 degrees Celsius. RCP8.5 shows a future with continued high emissions, potentially leading to a temperature rise exceeding 4 degrees Celsius by the end of the century.

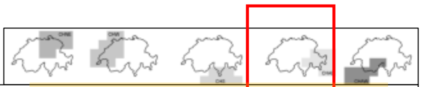
Climate change stress test

Increase in the intensity of extreme rainfall events due to climate change





Parameter	Rainfall intensity
Scenarios	RCP 2.6: +6% RCP 4.5: +14% RCP 8.5: +18%

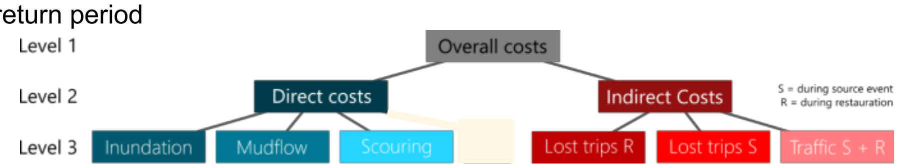


RCP 8.5					
	100-year return levels of one-day precipitation events (Summer) (%)				
2035	+10 (-13 to +31)	+7 (-14 to +19)	+5 (-11 to +16)	+7 (-2 to +15)	+3 (-9 to +22)
2060	+19 (-4 to +43)	+12 (+3 to +26)	+9 (-14 to +39)	+13 (-10 to +27)	+10 (-9 to +29)
2085	+20 (-6 to +42)	+12 (+2 to +38)	+11 (-24 to +38)	+18 (-9 to +41)	+17 (-5 to +27)
	100-year return levels of one-day precipitation events (Winter) (%)				
2035	+8 (-11 to +31)	+16 (-5 to +27)	+6 (-6 to +27)	+7 (-6 to +27)	+10 (+1 to +20)
2060	+5 (-4 to +28)	+7 (-11 to +28)	+12 (-2 to +28)	+12 (-9 to +34)	+8 (-5 to +29)
2085	+19 (-2 to +59)	+22 (-2 to +46)	+16 (-0 to +50)	+18 (-1 to +50)	+18 (+5 to +41)

We conducted three types of stress tests
The first type, I call it climate change stress test
Which is basically the increase in the intensity of extreme rainfall events due to climate change
There are climate change scenarios for countries around the world; Switzerland also has such scenarios for the next 80 years almost.
One of the interesting figures from their report on climate change scenarios is this one, which shows the intensity vs frequency of precipitation events. The blue line is the current situation, and the red line is with the effect of climate change. The interesting observation here is that climate change decreases the frequency of average precipitation events, however it increases the frequency of extreme events.
This is exactly what I showed earlier on how the probability distribution of parameters change due to a stress.
This table here shows the essentially the effect of climate change in extreme rainfall. In particular, it shows the increase in the intensity of 100yr return level one day prec event in summer and in winter for three time periods of 2035, 2060, and 2085.
In our case study, which is located in this area, we considered the longest time period, that is 2085, and
In summary, we have 6% increase in the intensity of extreme rainfall events under RCP2.6, 14% under RCP4.5, and 18% under RCP8.5.

Conducting stress tests

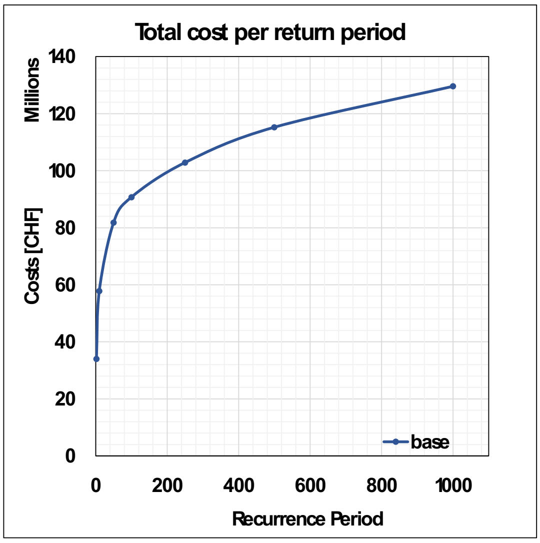
- **3 stress tests + 1 Reference**
  - 3 climate change stress tests
- **For each stress test, 700 random scenarios were generated**
  - 7 Return periods (years): 2, 5, 10, 25, 50, 100, 250, 500, 1000
  - 100 scenarios for each return period
- **Output measures**
  - Direct and indirect costs



  - **Annualized costs ($\mathcal{R}$) = expected annual costs considering all potential hazard events**

We considered three types of stress test and in total, we conducted 8 stress tests plus obviously the baseline situation
The stress tests are three climate change, three increase in the demand, and 2 reduction in the capacity.

Reference

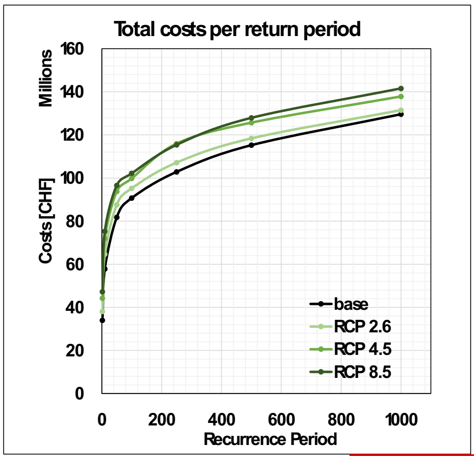


	Annualized cost (Mio. CHF)		
	Level 1	Level 2	Level 3
Overall costs	22.45		
Direct costs		7.25	
Inundation			6.24
Mudflow			0.76
Scouring			0.25
Indirect costs		15.2	
Traffic S+R			0.41
Lost trips S			2.04
Lost trips R			12.75

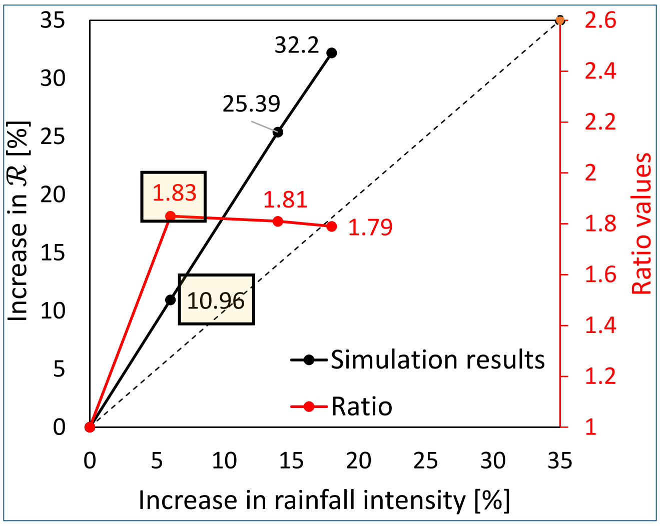
The first result that I would like to show is the baseline situation.
This figure shows the average total costs per return period. For example, for a 500 yr flood event we and average loss of 115million francs.
This table sow

Results: Climate change stress tests

Parameter	Rainfall intensity
Scenarios	RCP 2.6: +6%
	RCP 4.5: +14%
	RCP 8.5: +18%



	Recurrence Period							Annualized Costs	Percentage increase
Scenario	2	10	50	100	250	500	1000	$\mathcal{R}$ [Mio CHF]	
Base	34	58	82	91	103	115	130	22.45	-
RCP 2.6	38	65	88	95	107	118	131	24.91	10.96 %
RCP 4.5	44	72	94	100	116	126	138	28.15	25.39 %
RCP 8.5	47	75	97	102	115	128	142	29.68	32.2 %



Results: Climate change stress tests

Parameter	Rainfall intensity
Scenarios	RCP 2.6: +6%
	RCP 4.5: +14%
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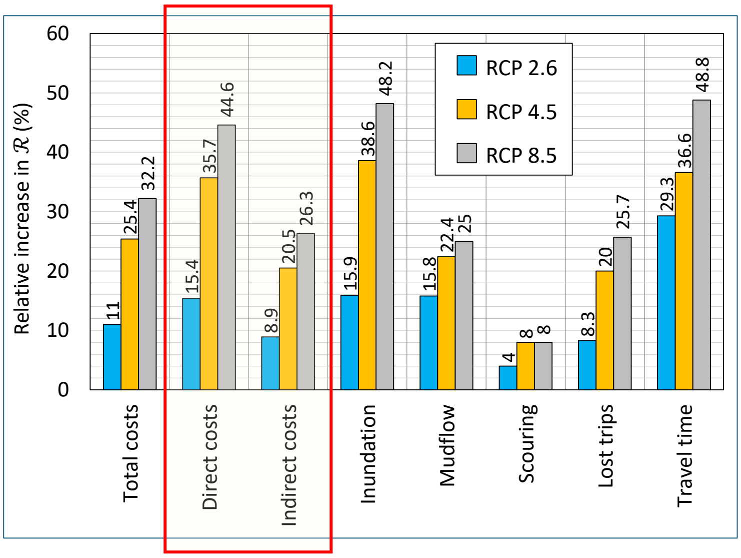

Next Steps

- Setting thresholds and passing requirements for conducted stress tests
- If failed, plan for [risk reducing] interventions to achieve satisfactory results for stress tests
- Find the relevant and appropriate stress tests to ensure the resilience of the system
- Develop a guideline on how to conduct stress test on transport infrastructure