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

Massive Open Online Course:

Resilience, Sustainability & Digitalisation in Critical Infrastructure

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Lecture 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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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 extreme stressors that are caused by climate projections

ACTIVITY 1: Proactive and reactive adaptation measures

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

Types of proactive and reactive adaptation measures

Adaptation strategies - Bridges

R =	$P(H)$ ·	$P(E \mid H)$ ·	$P(D \mid E \cap H)$ ·	$C(D)$
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

Types of proactive and reactive adaptation measures

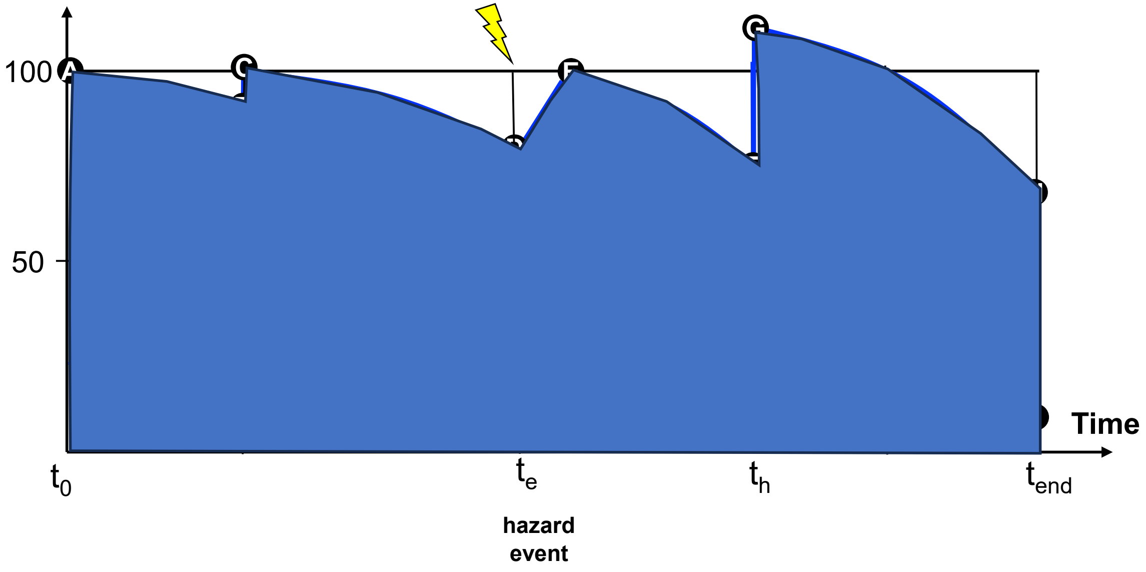
Adaptation strategies - Bridges

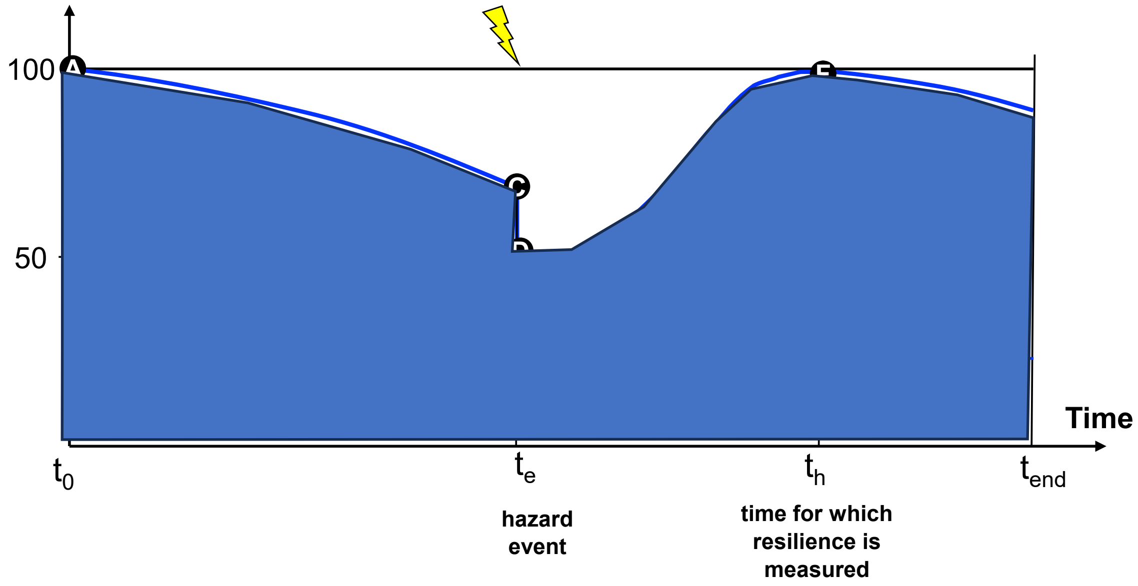
Climate hazard	Adaptation
Floods	Relocation or flood-proofing (Mehrotra et al., 2011; Meyer & Weigel, 2011); Flood control seawalls, dikes, and levees (Stewart & Deng, 2015); Elevation of bridges, strengthening and heightening of existing levees, increase in real-time monitoring of flood levels, restriction 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)

Source: Nasr et al., 2020

Making the case for proactive climate adaptation

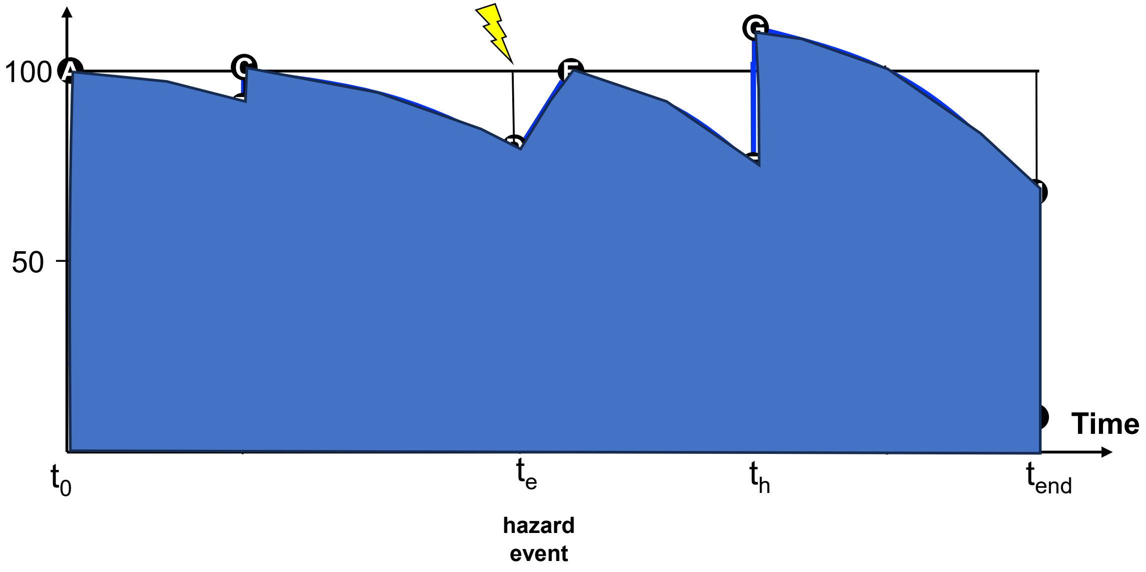
Proactive (ex-ante) vs. reactive (ex-post) and comparisons strategies

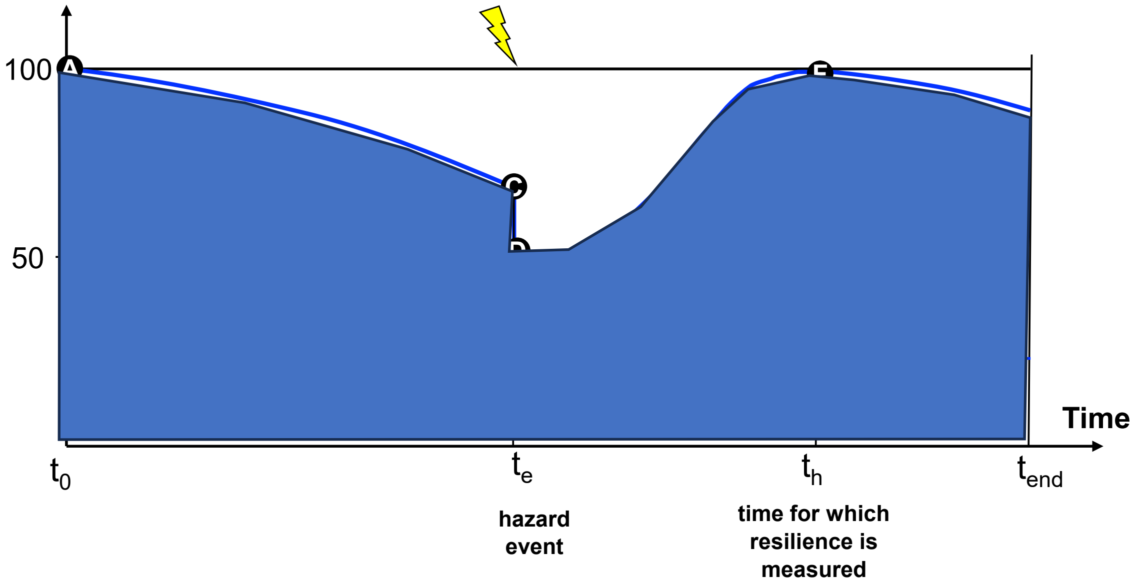




Making the case for proactive climate adaptation

Proactive (ex-ante) vs. reactive (ex-post) and comparisons strategies





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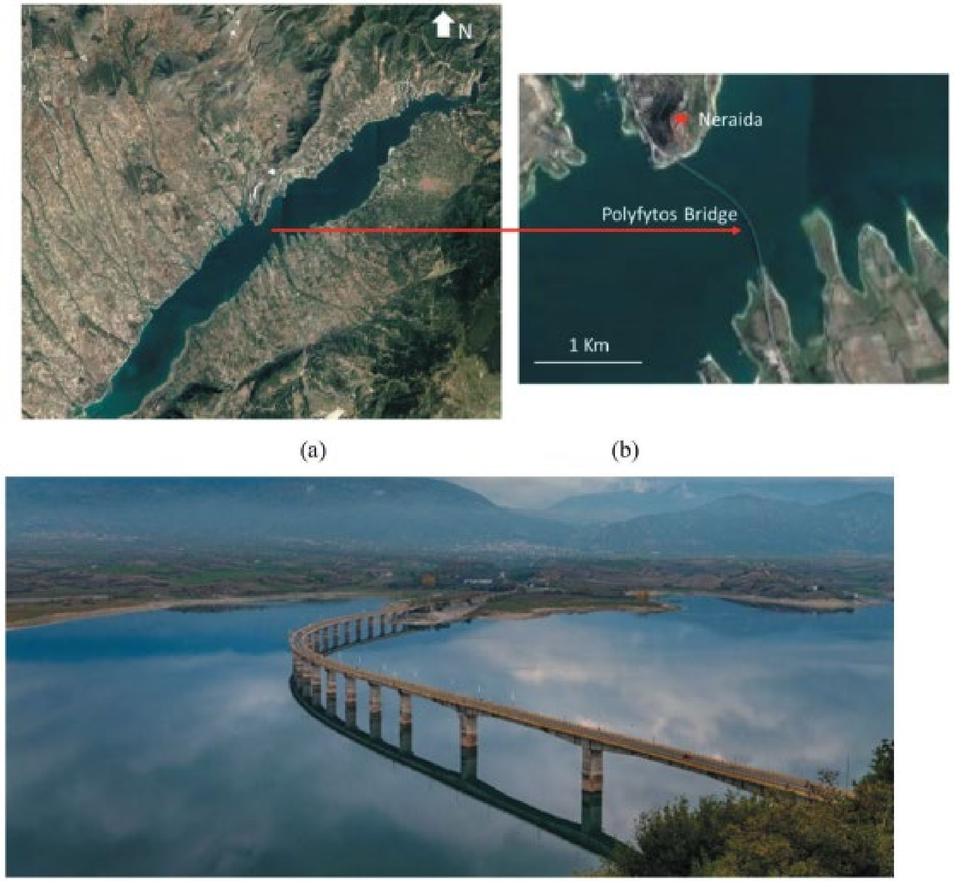
Example of proactive adaptation on a real bridge

The landmark Polyfytos Bridge



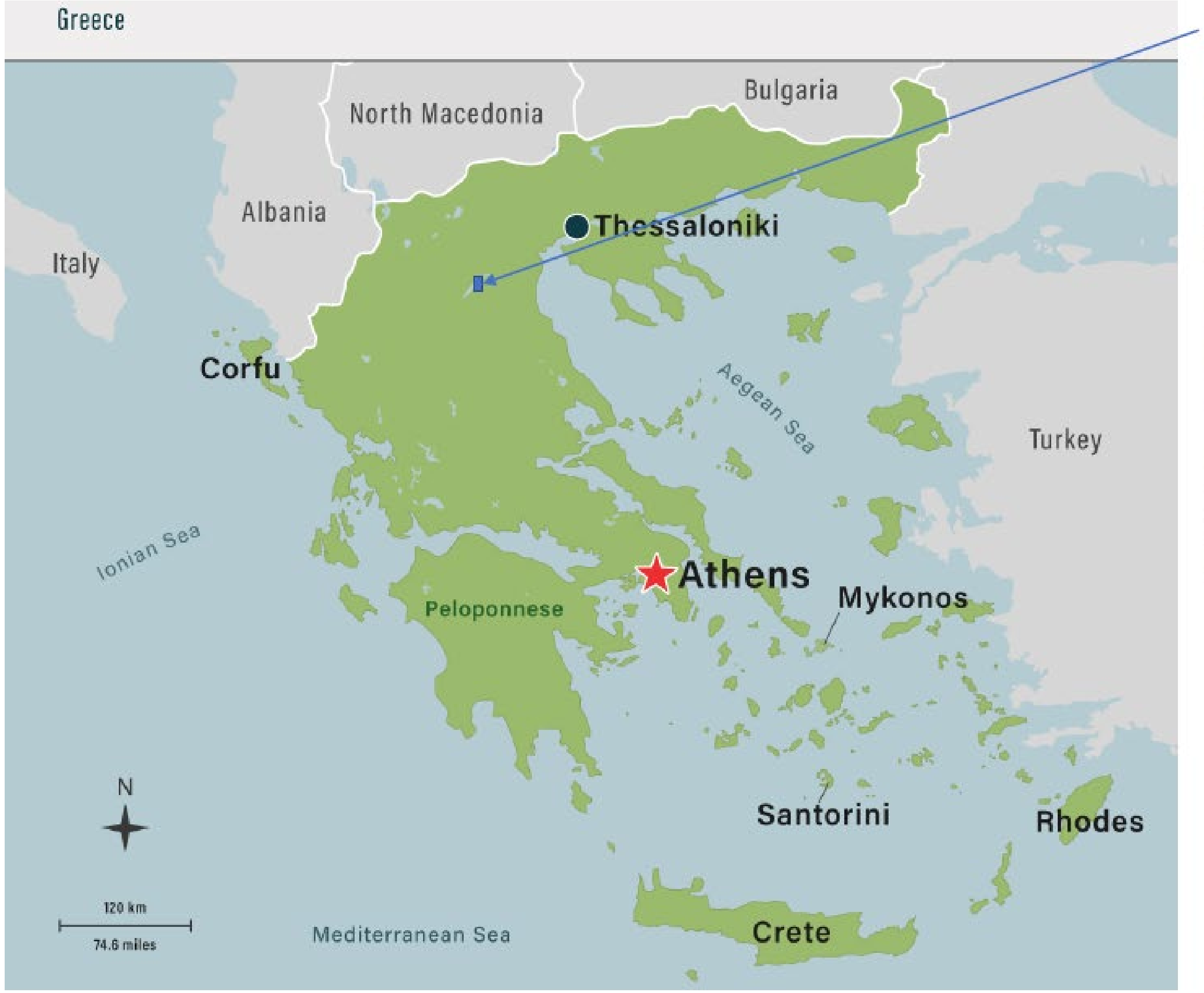
(a) (b) (c)

Figure 1. The landmark Polyfytos Bridge: (a) Polyfytos bridge wider area (b) focus area (as obtained by Google Maps 2020), and c) panoramic view of the asset with the precast spans (direction Kozani-North to Servia-South) and the long spans with the cantilevers in question at the bottom right side of the photograph.

- Curved viaduct with a mixed structural system
- Location : 40°14’04.1”N 21°58’17.2”E
- Function: Crosding the artificial Polyfytos lake and
- connects the city of Kozani, West Macedonia, main producer of energy production in Greece
- Connects Kozani to the Capital, Athens
- Designer: Prof. Riccardo Morandi
- Completed in 1975
- The second longest bridge in South-East Europe

Example of proactive adaptation on a real bridge

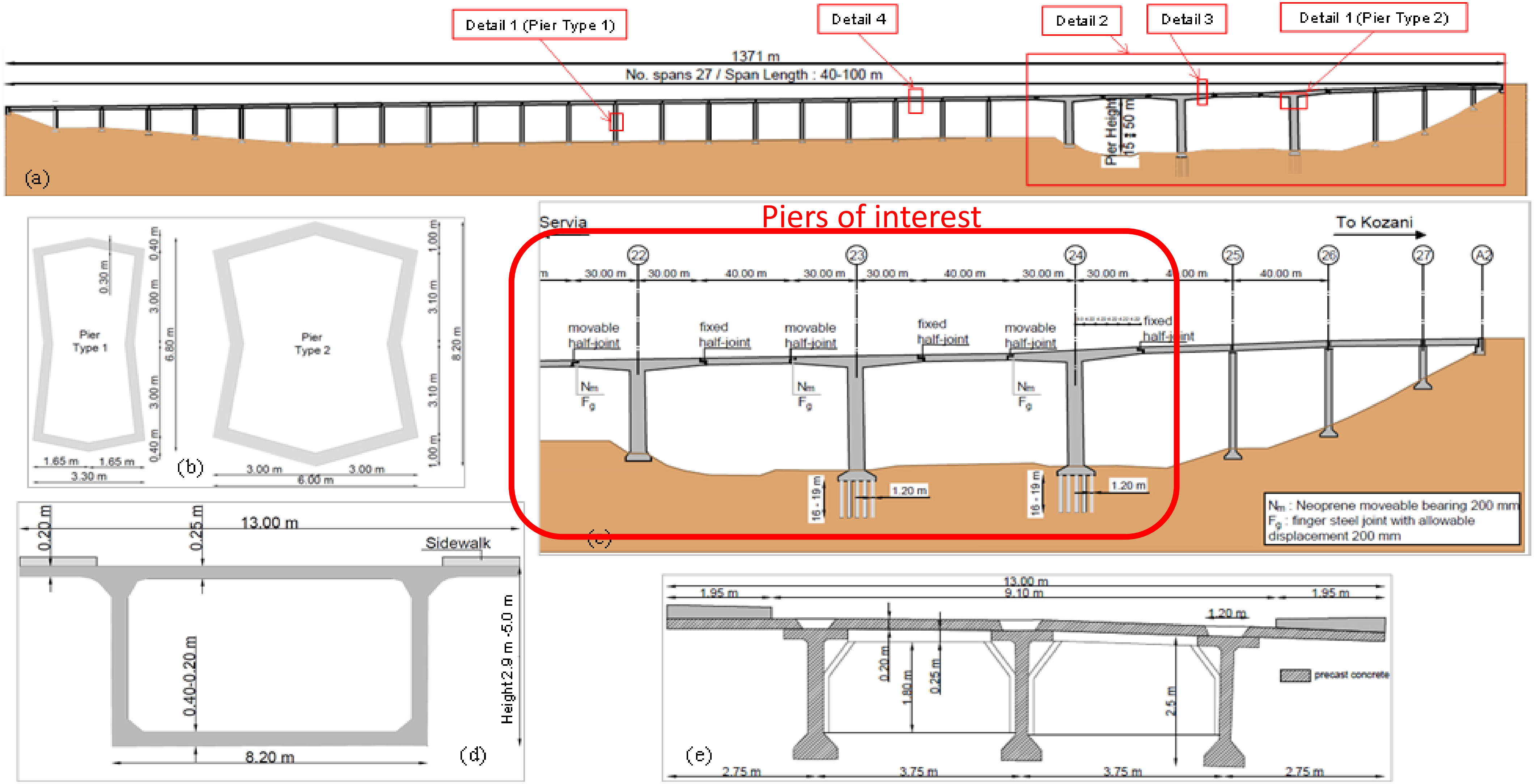
The landmark Polyfytos Bridge



Polyfytos bridge

Example of proactive adaptation on a real bridge

Description of the landmark Polyfytos Bridge



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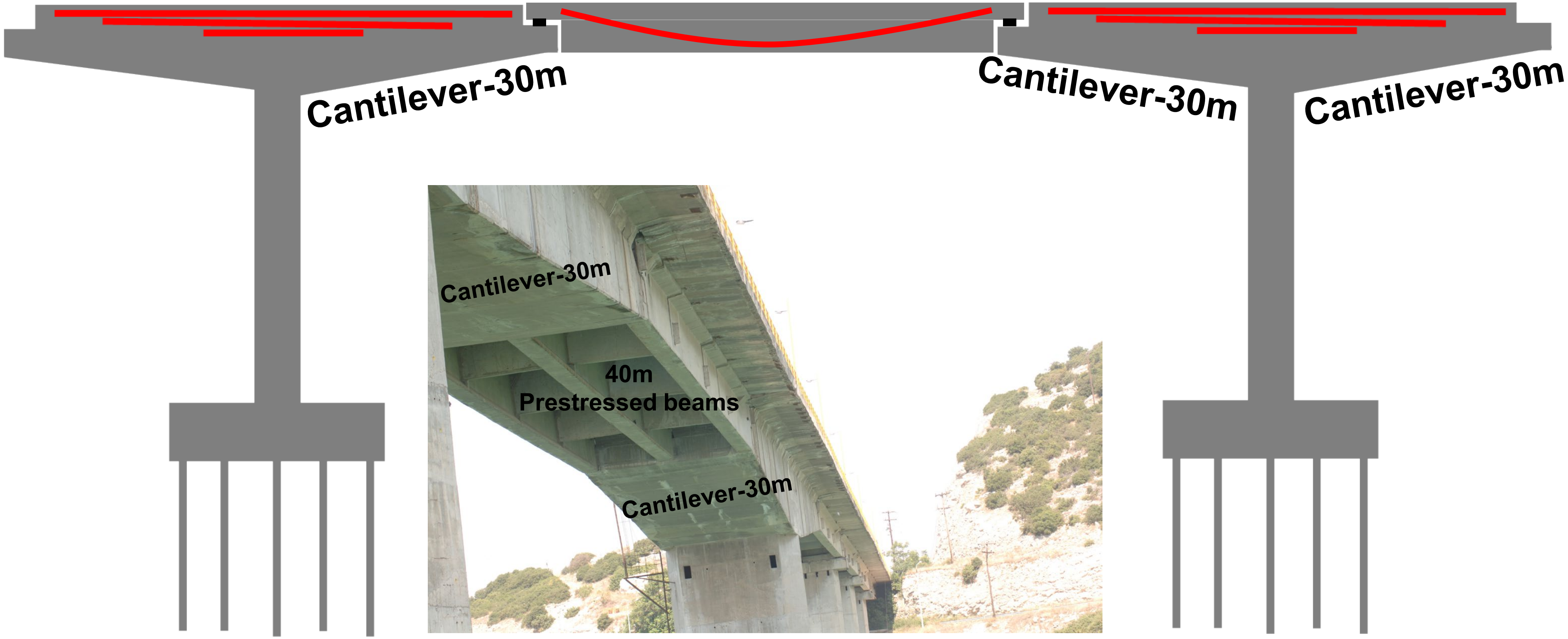
Example of proactive adaptation on a real bridge

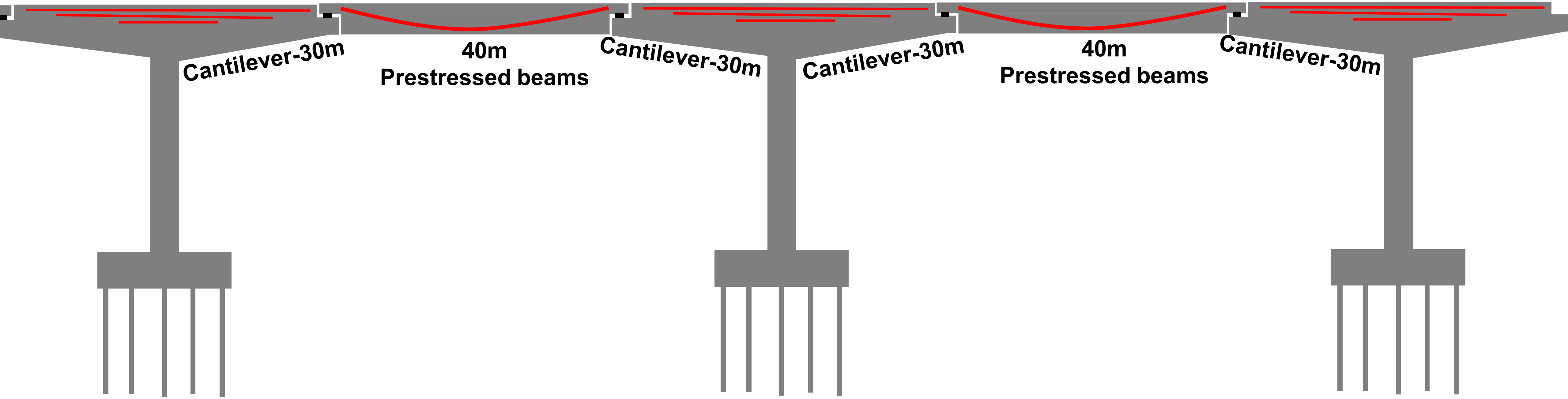
Construction method for the Polyfytos Bridge



Prestressing is used both in the cantilevers and in the precast beams

Example of proactive adaptation on a real bridge

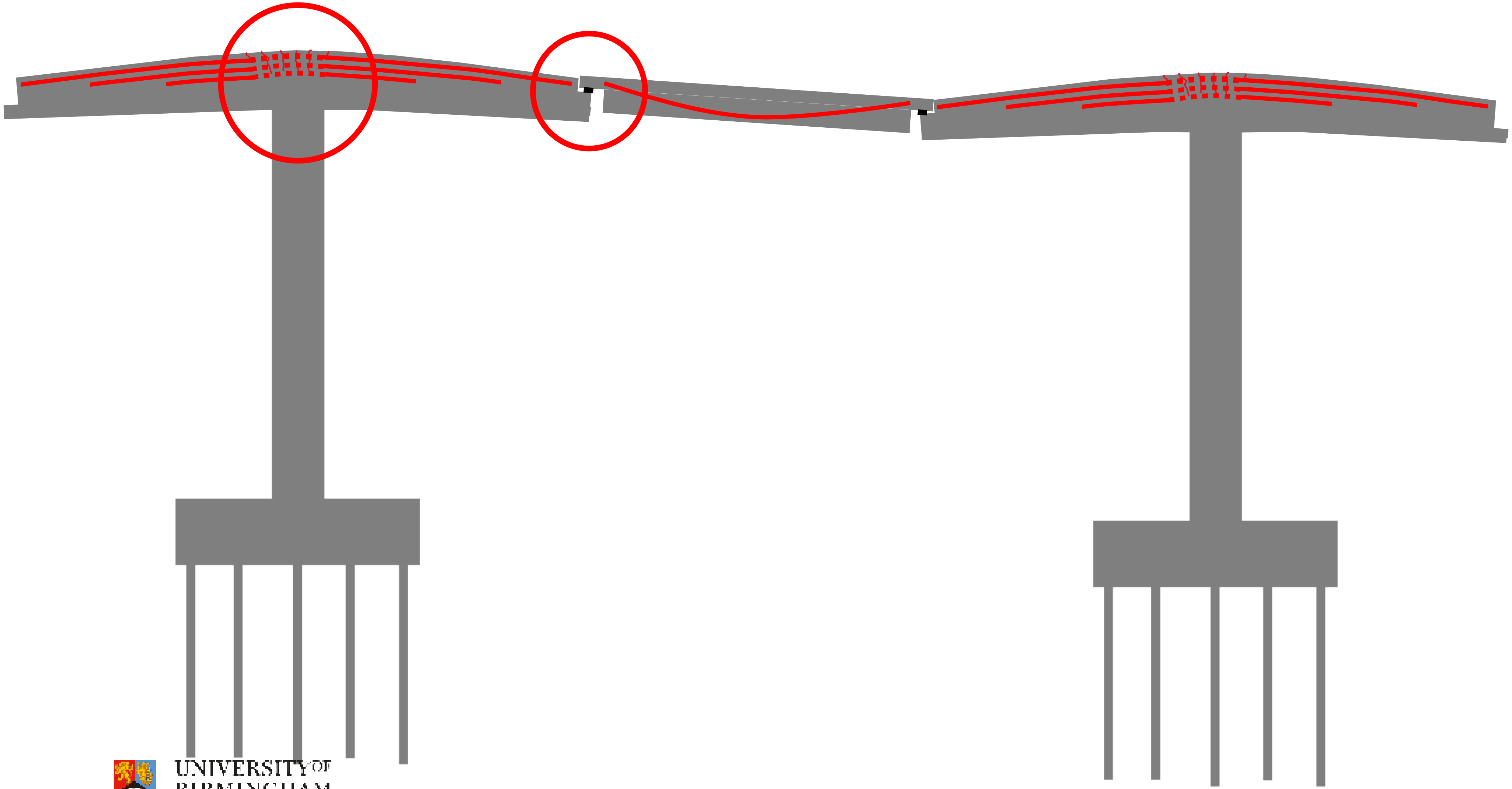
Construction method for the Polyfytos Bridge



Prestressing is used both in the cantilevers and in the precast beams

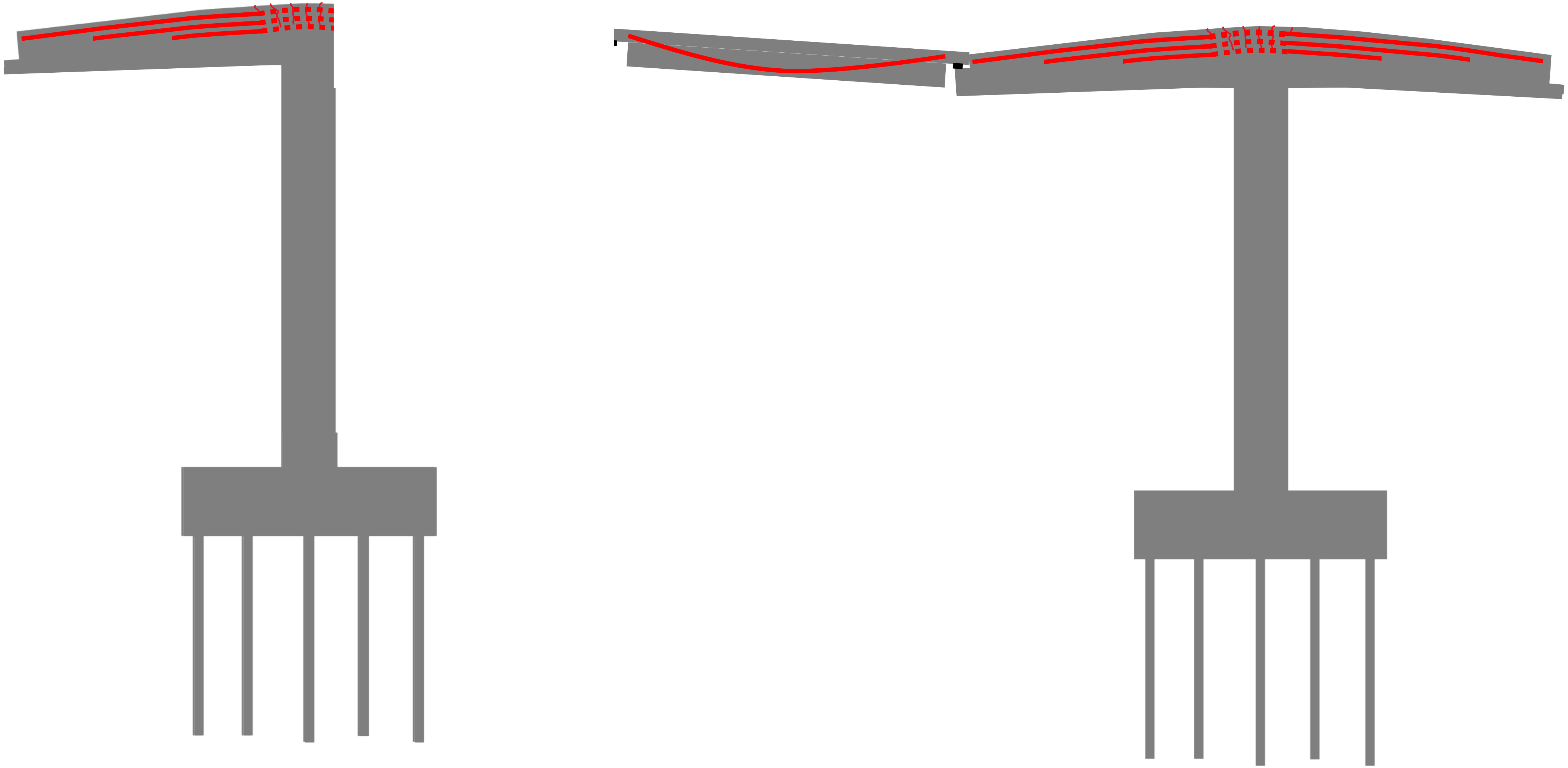
Example of proactive adaptation on a real bridge

Deterioration of the Polyfytos Bridge



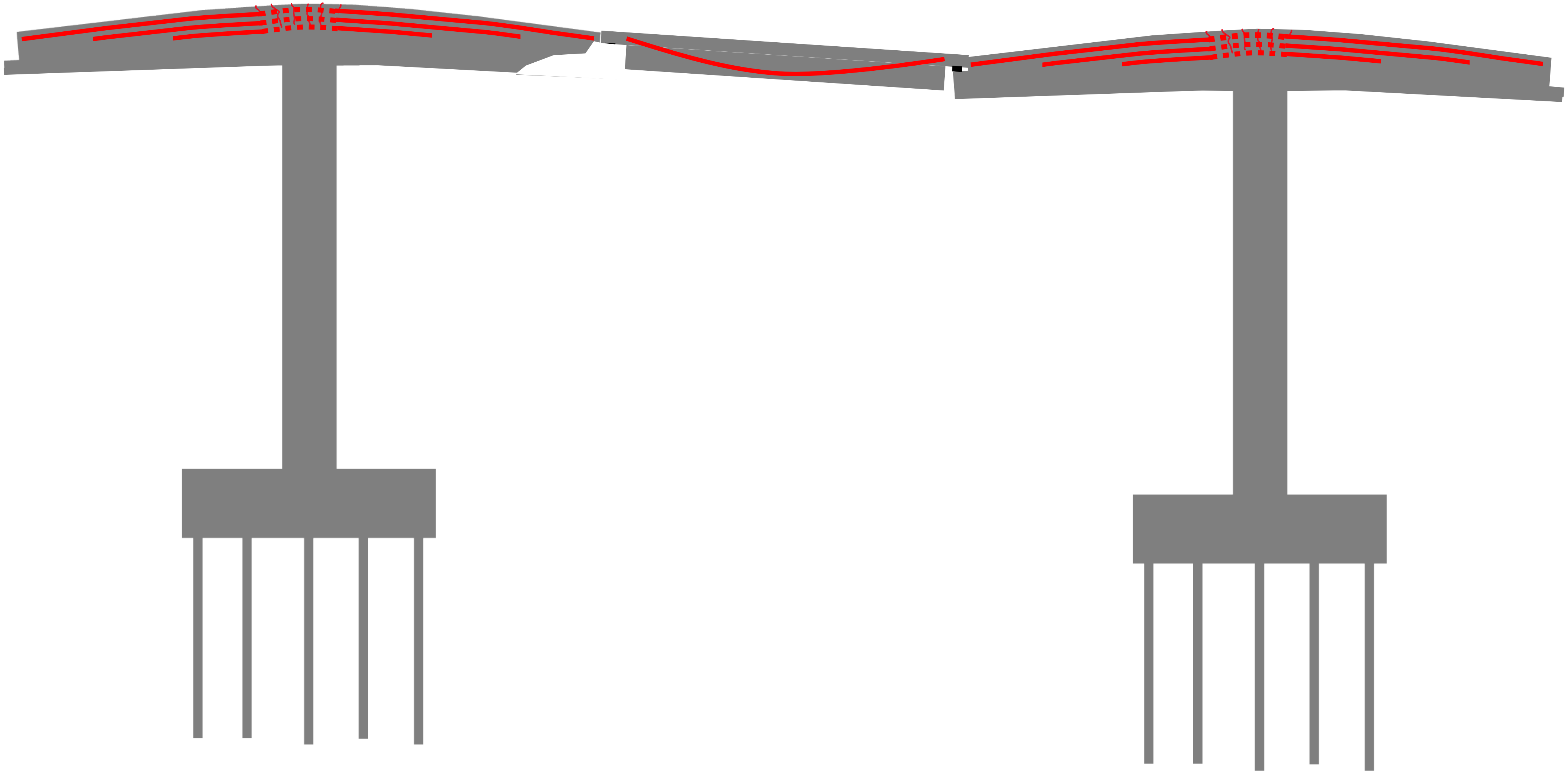
Example of proactive adaptation on a real bridge

Potential failure mechanisms



Example of proactive adaptation on a real bridge

Potential failure mechanisms



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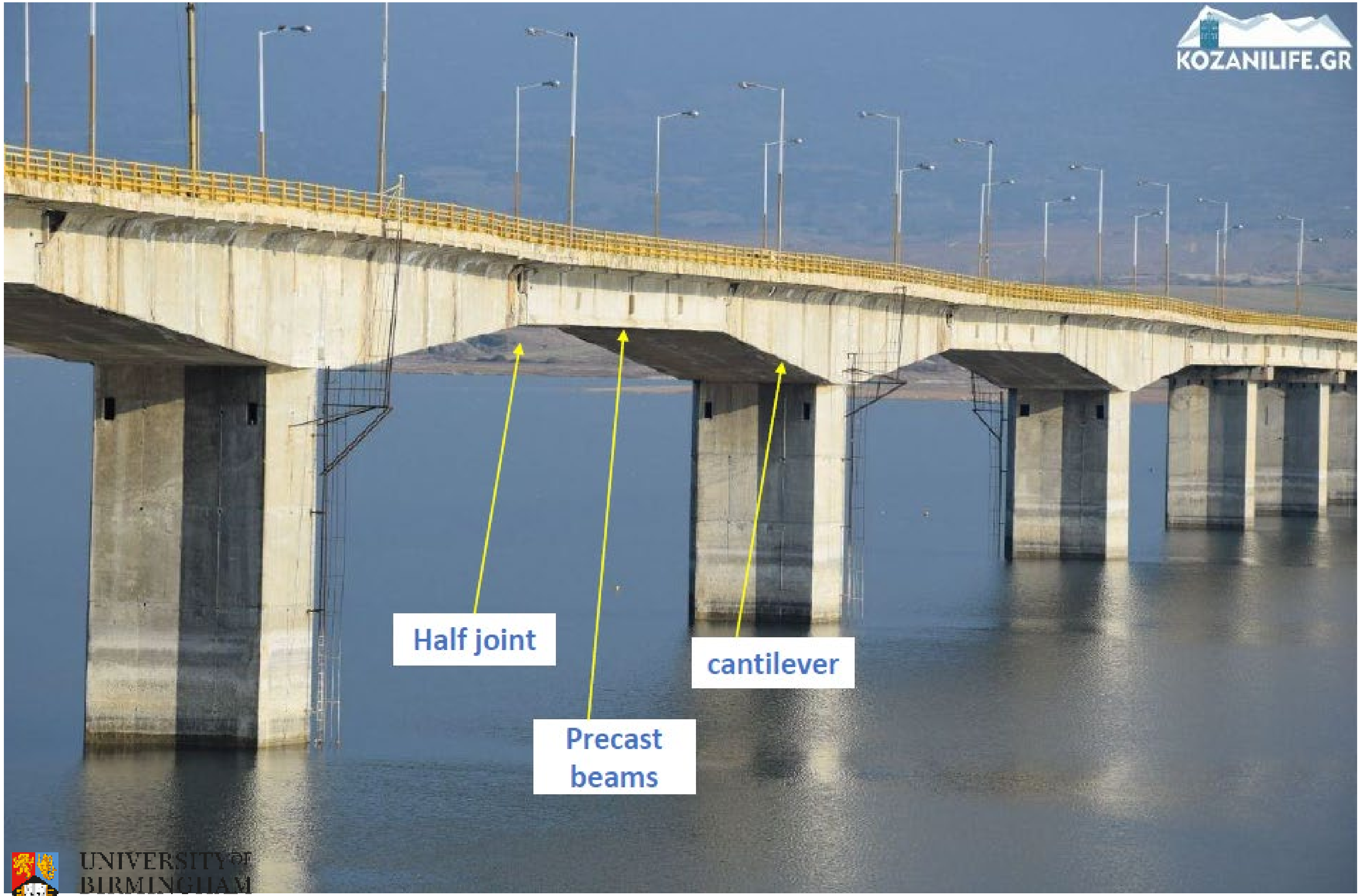
Example of proactive adaptation on a real bridge

Pathology – deformation of the cantilevers

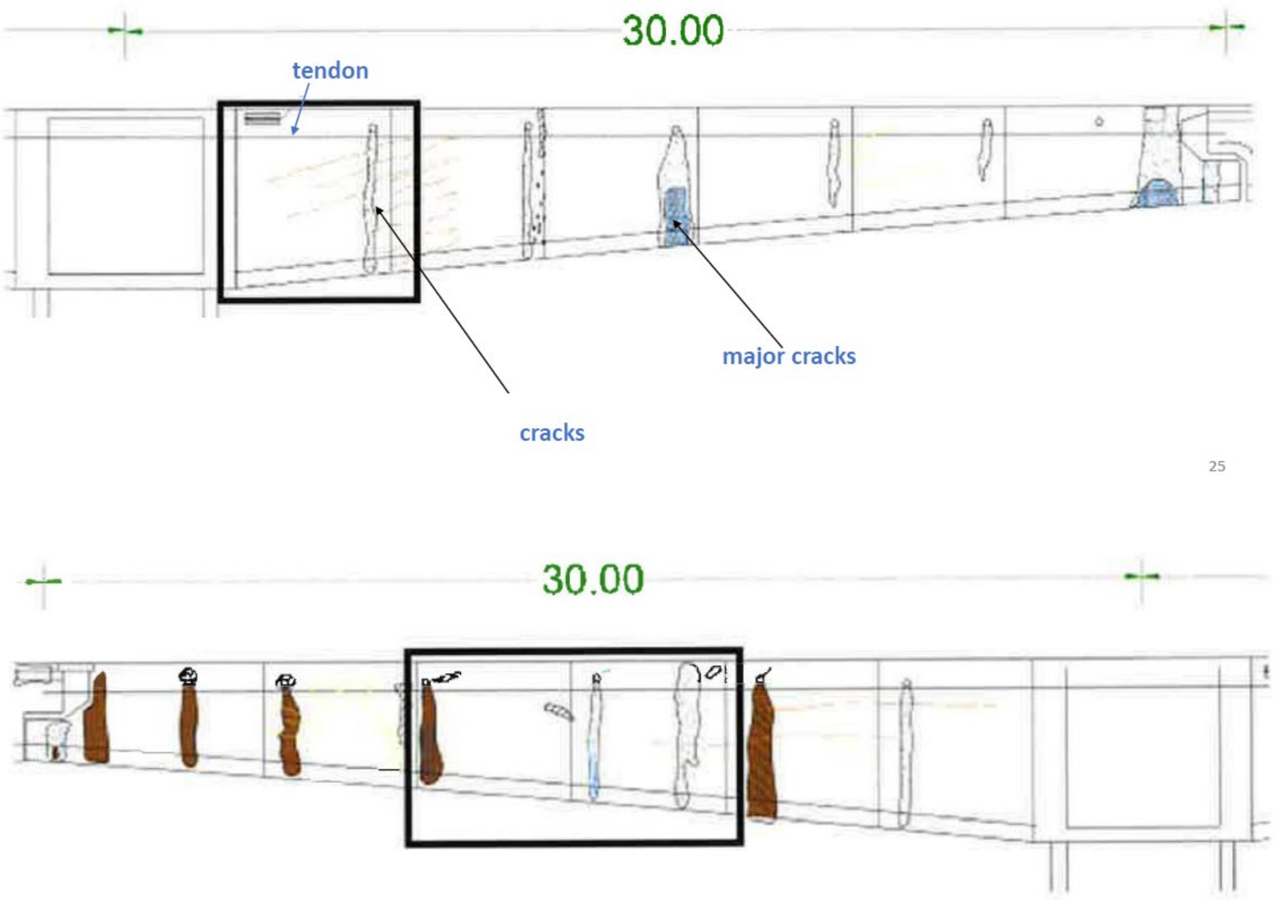
Example of proactive adaptation on a real bridge

Pathology – deformation of the cantilevers



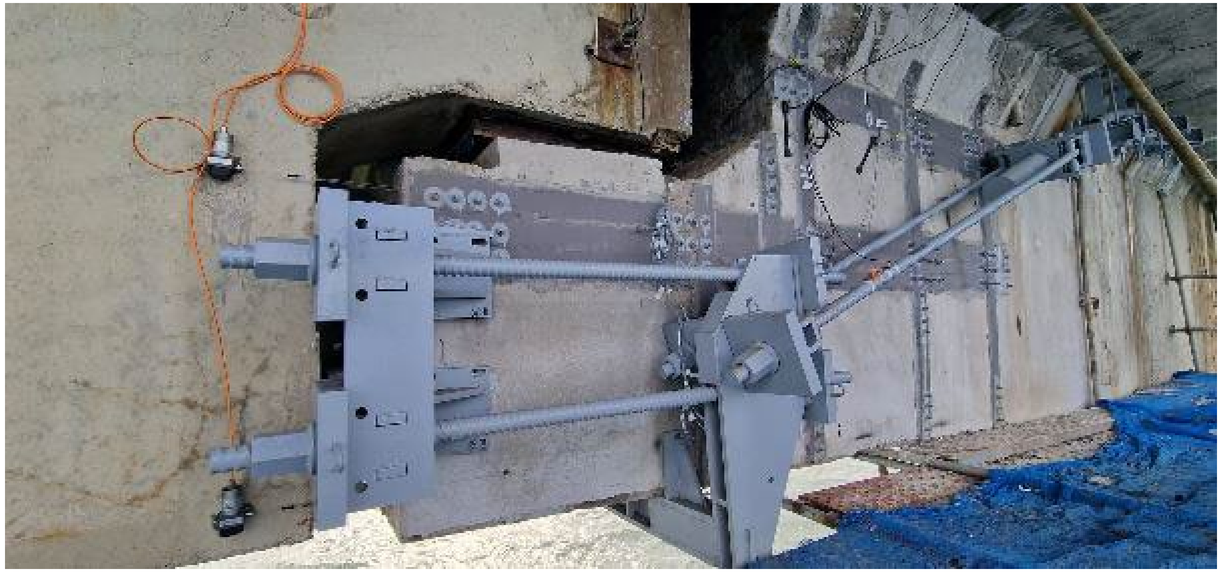
Example of proactive adaptation on a real bridge

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



Example of proactive adaptation on a real bridge

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



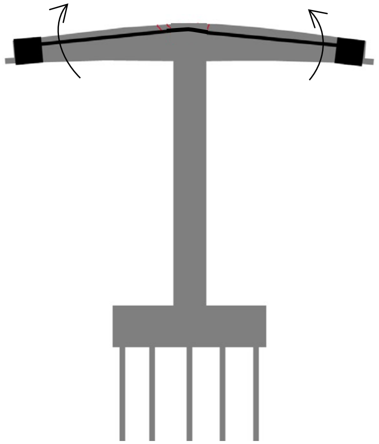
Intervention on the most critical half joint

Example of proactive adaptation on a real bridge

Adaptation scenarios:

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

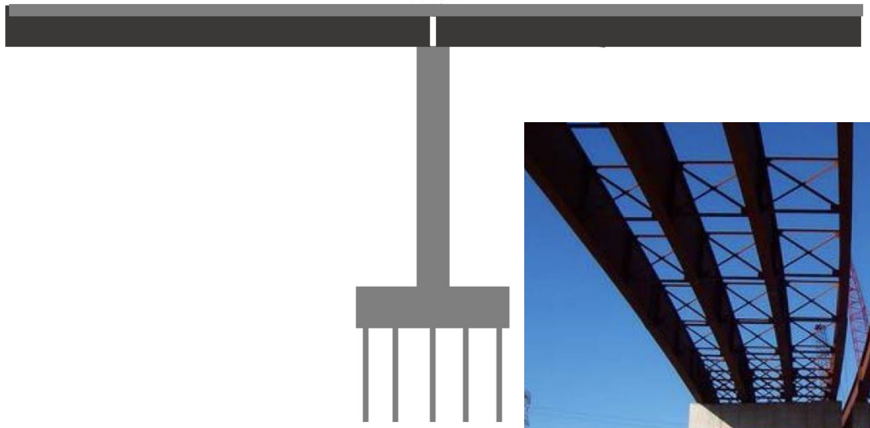
Scenario #2: Keep cantilevers as is and installation of new external prestressing cables. Restoration of half-joints. Replacement of prestressed concrete beams with steel beams and continuity slab



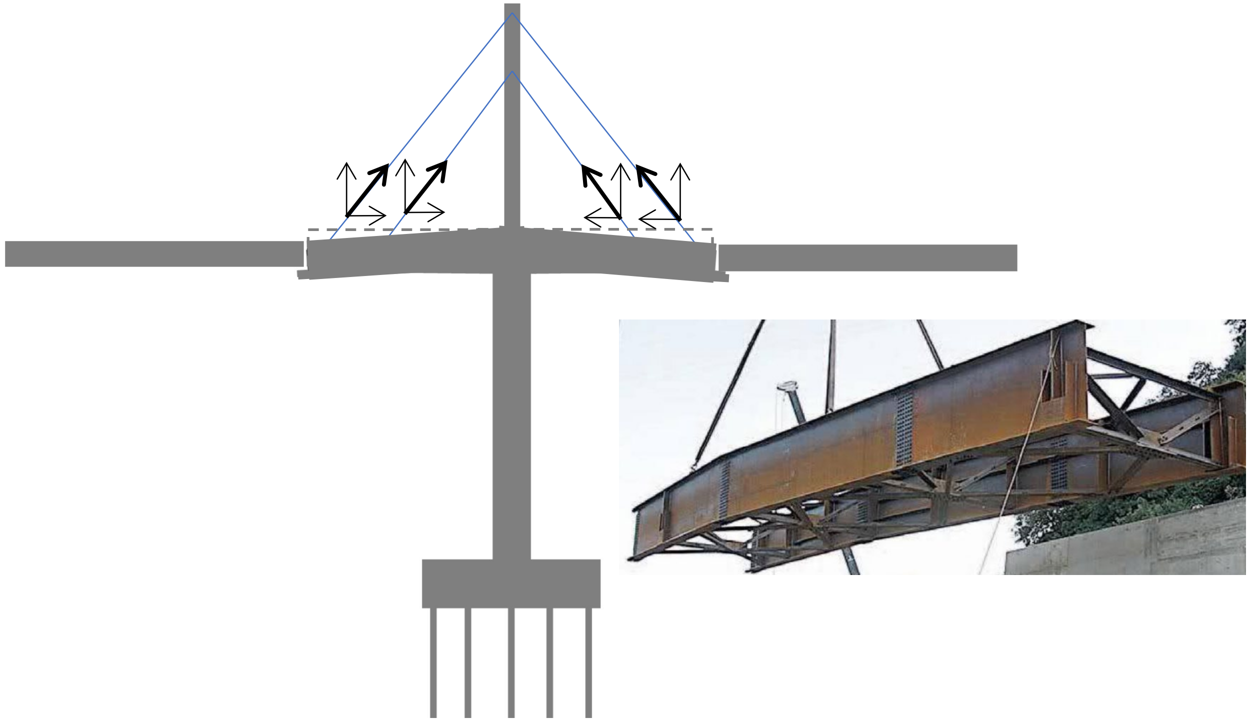
Example of proactive adaptation on a real bridge

Adaptation scenarios:

Scenario #3: Demolition of the deck and reconstruction with steel beams and continuity slab



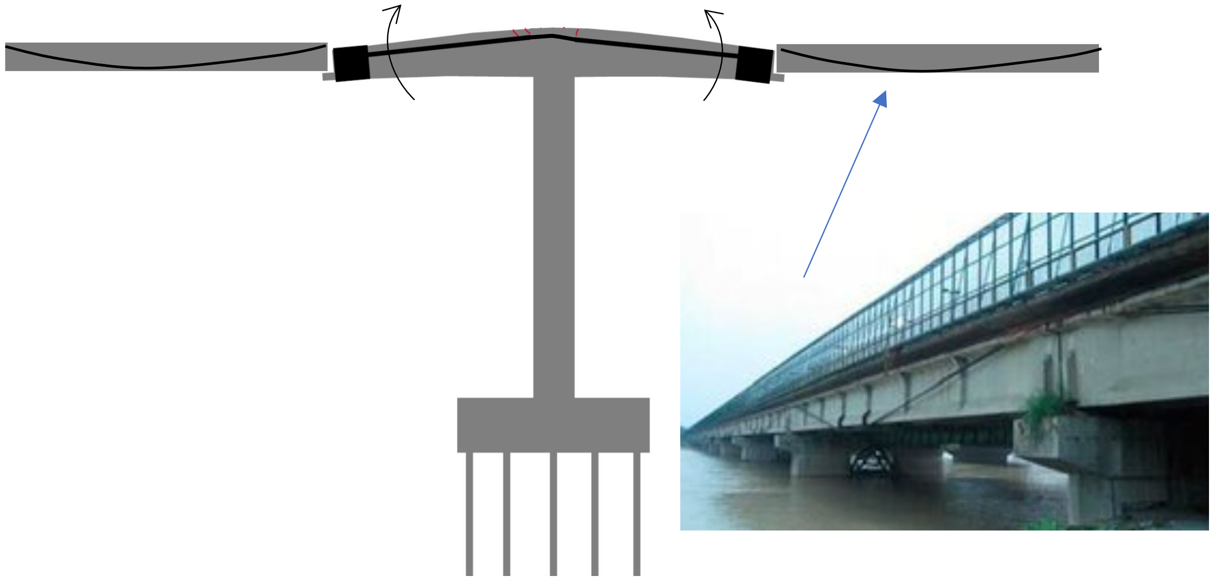
Scenario #4: Construction of pier extensions over the existing piers, installation of stays to support the existing cantilevers. Rehabilitation of half-joints and replacement of prestressed concrete beams with steel beams and continuity slab



Example of proactive adaptation on a real bridge

Adaptation scenarios:

Scenario #5: Keep existing cantilevers and beams and install new external prestressing cables. Rehabilitate the slab and the half-joints



Scenario #6: Solution with precast segments and dry joints

ACTIVITY 2: Nature Based Solutions

- Types of Nature based Solutions (NbS)
- Examples
- Application

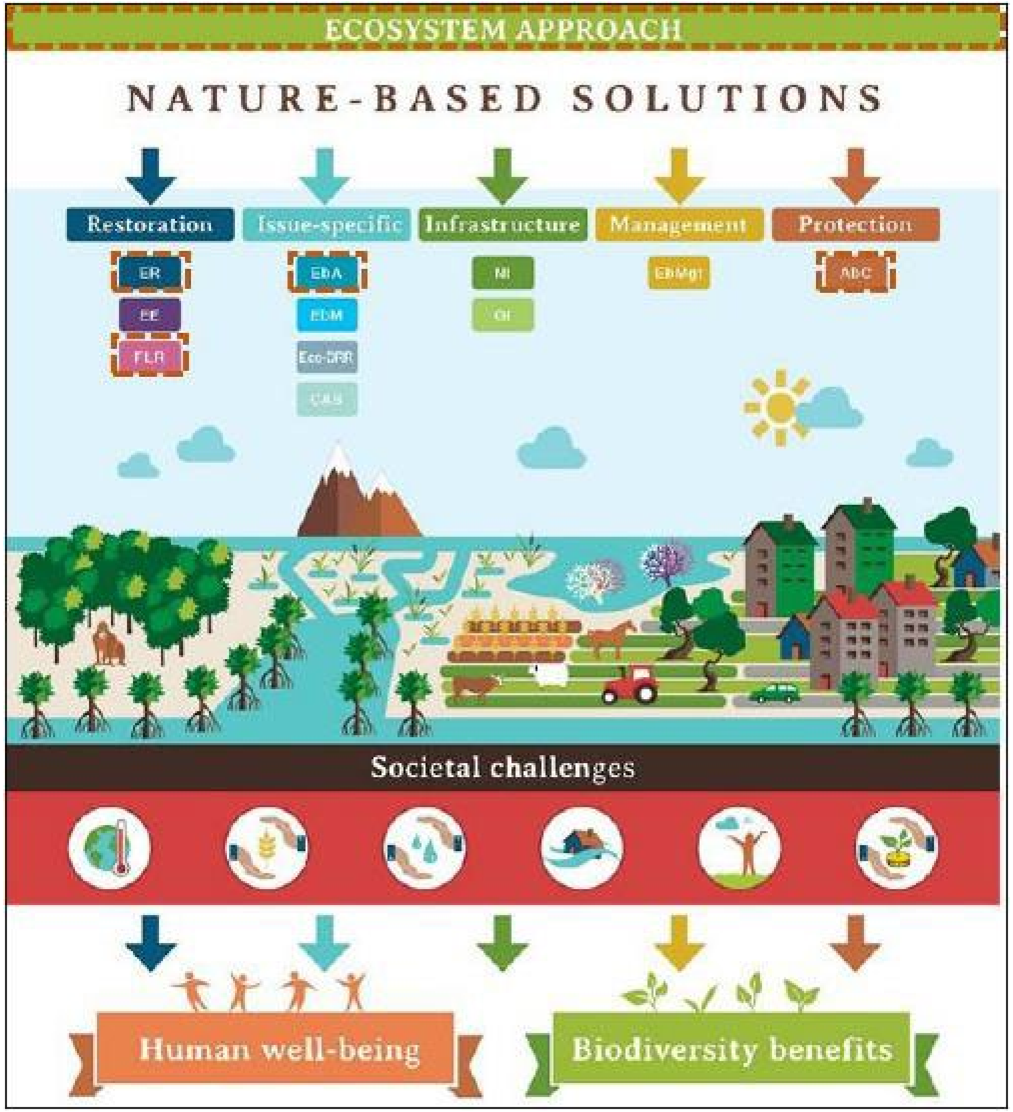
Nature based Solutions (NbS) and types

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

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.

Source: Cohen-Shachamet al. (2019)
https://www.sciencedirect.com/science/article/pii/S1462901118306671

Nature based Solutions (NbS)

NbS principles for infrastructure protection

- 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**

Source: Cohen-Shachamet al. (2019)
https://www.sciencedirect.com/science/article/pii/S1462901118306671

Types of NbS

The benefits of flood reduction to coastal highway resilience include the following:

- Decreased road or lane closures during flood events.
- Reduced road pavement damage.
- Reduced damage to bridges.
- Reduced erosion of roadway embankments.
- Decreased vulnerability to shoreline retreat.

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

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.

Risk-reduction performance and resilience attributes by strategy

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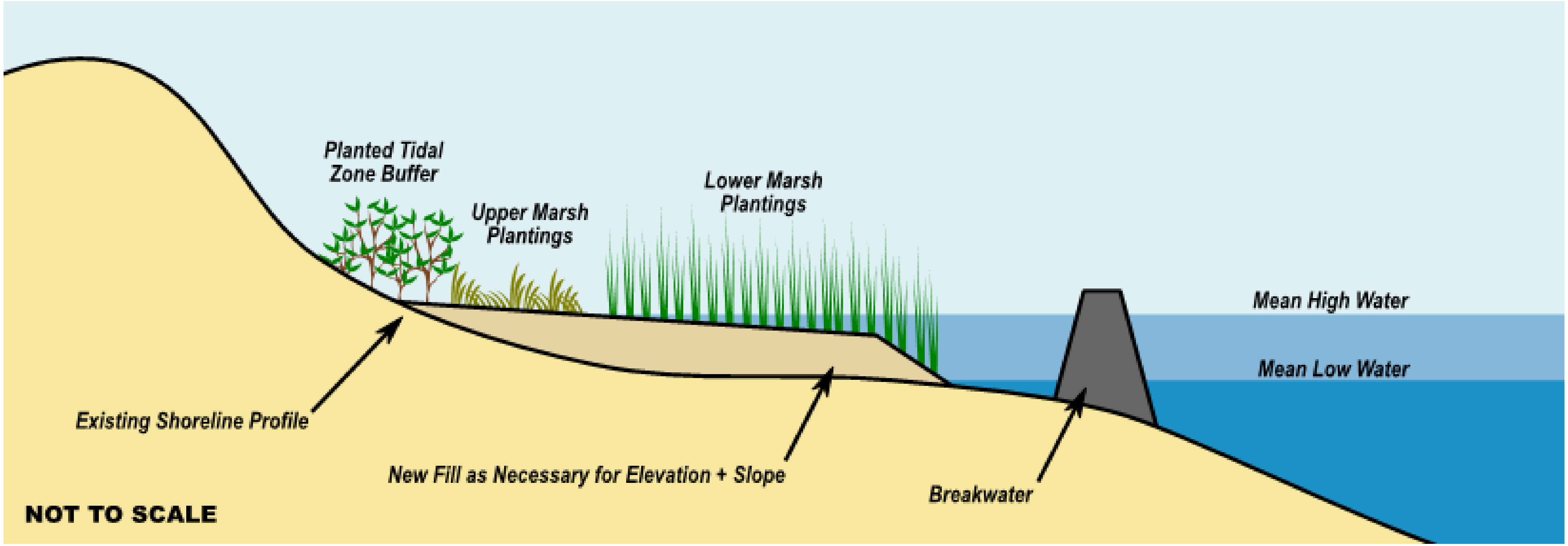
Nature based Solutions (NbS)

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

Nature based Solutions (NbS)

Example: green bridge

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

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

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

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**]*

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****"*

Methodology

1. Reference Risk Assessment

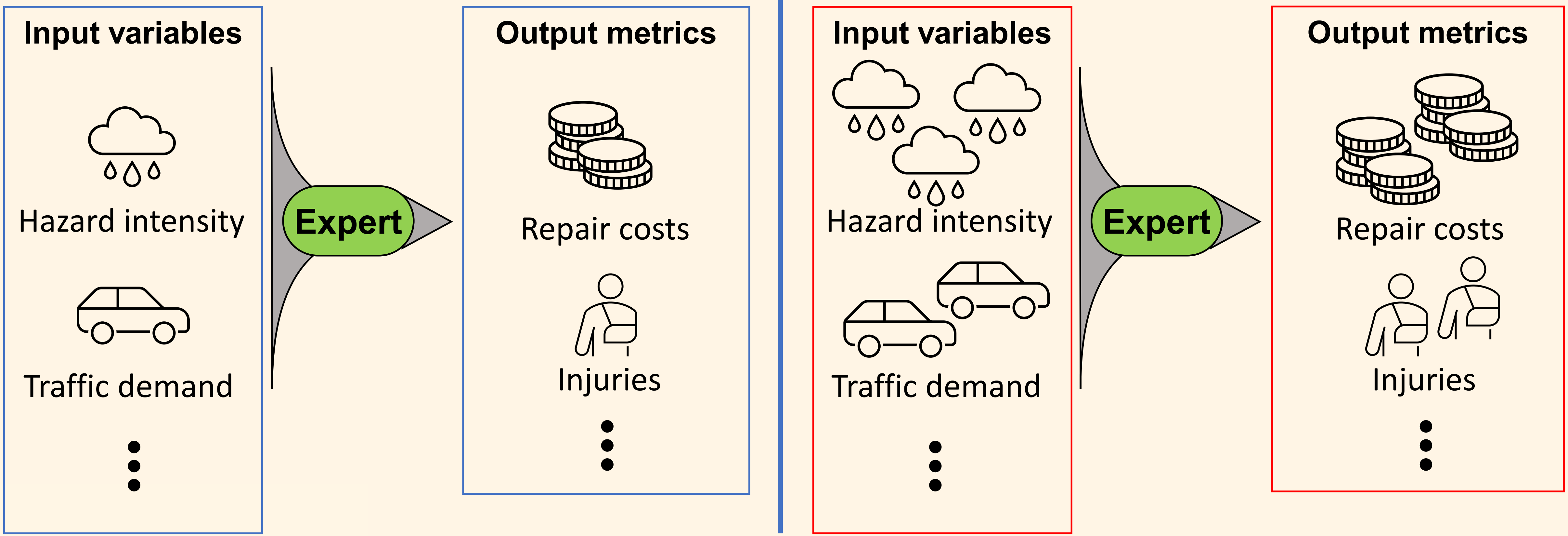
→

2. Stress Testing

Risk Assessment and Stress Testing (Expert opinion/Qualitative)

[Reference] Risk Assessment

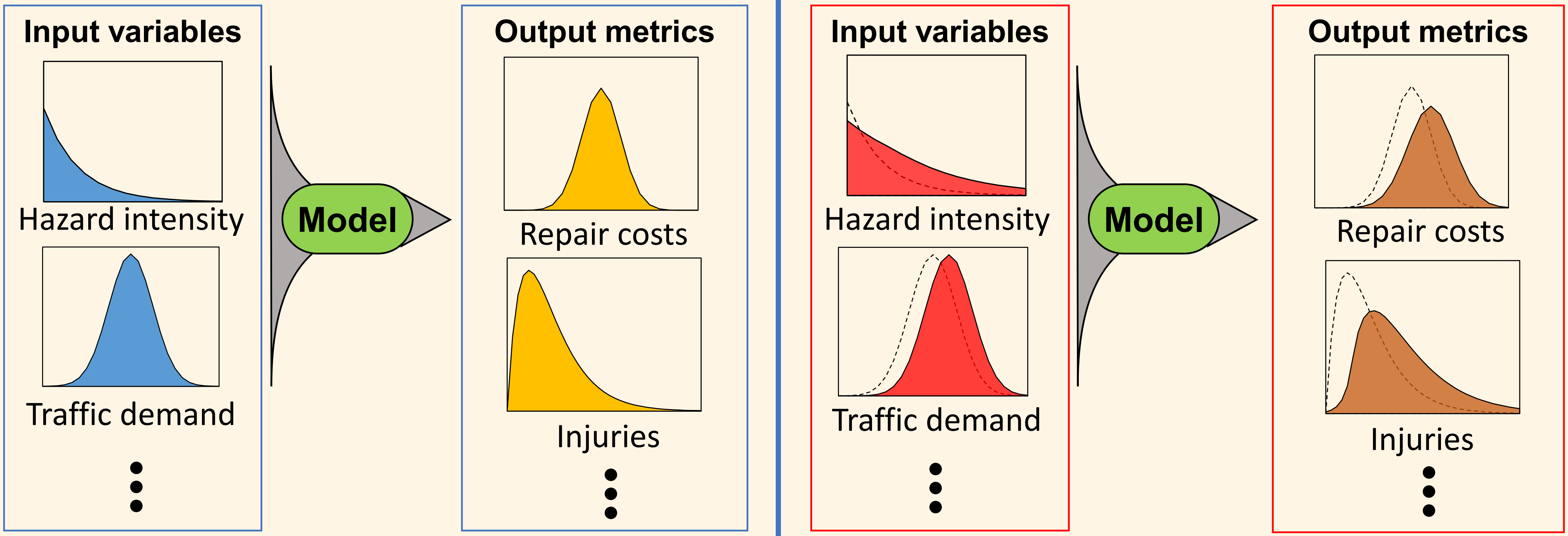
Stress Testing



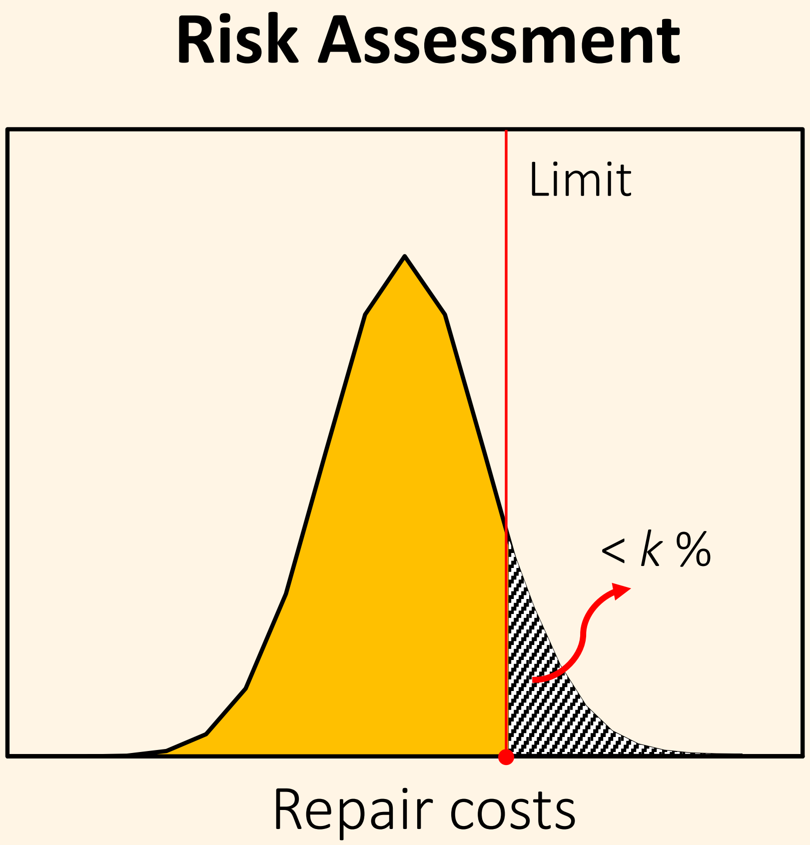
Risk Assessment and Stress Testing (Quantitative)

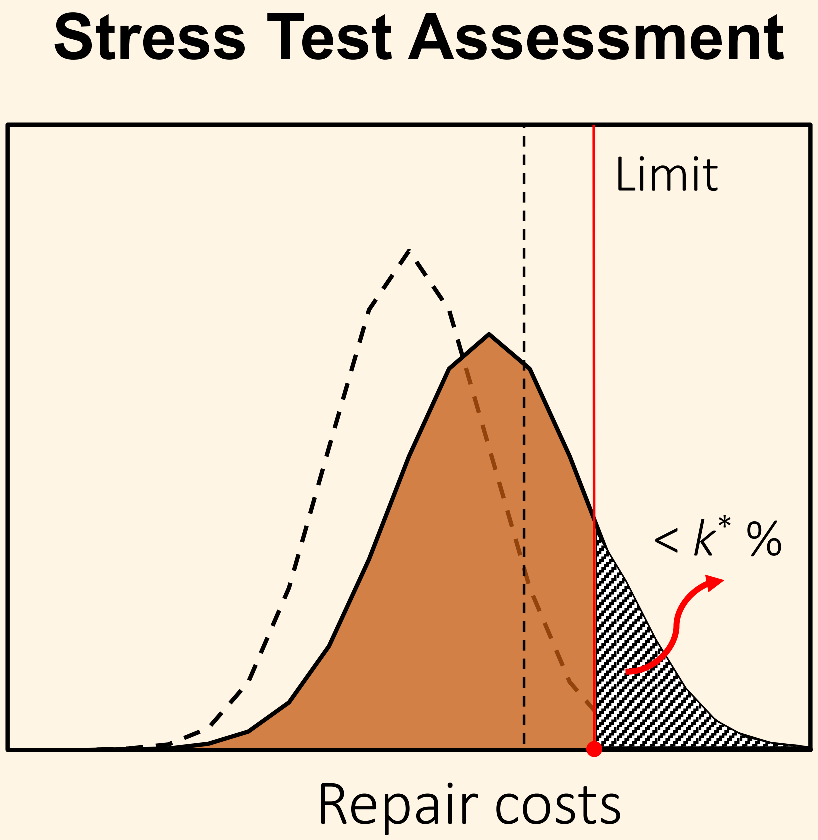
[Reference] Risk Assessment

Stress Testing

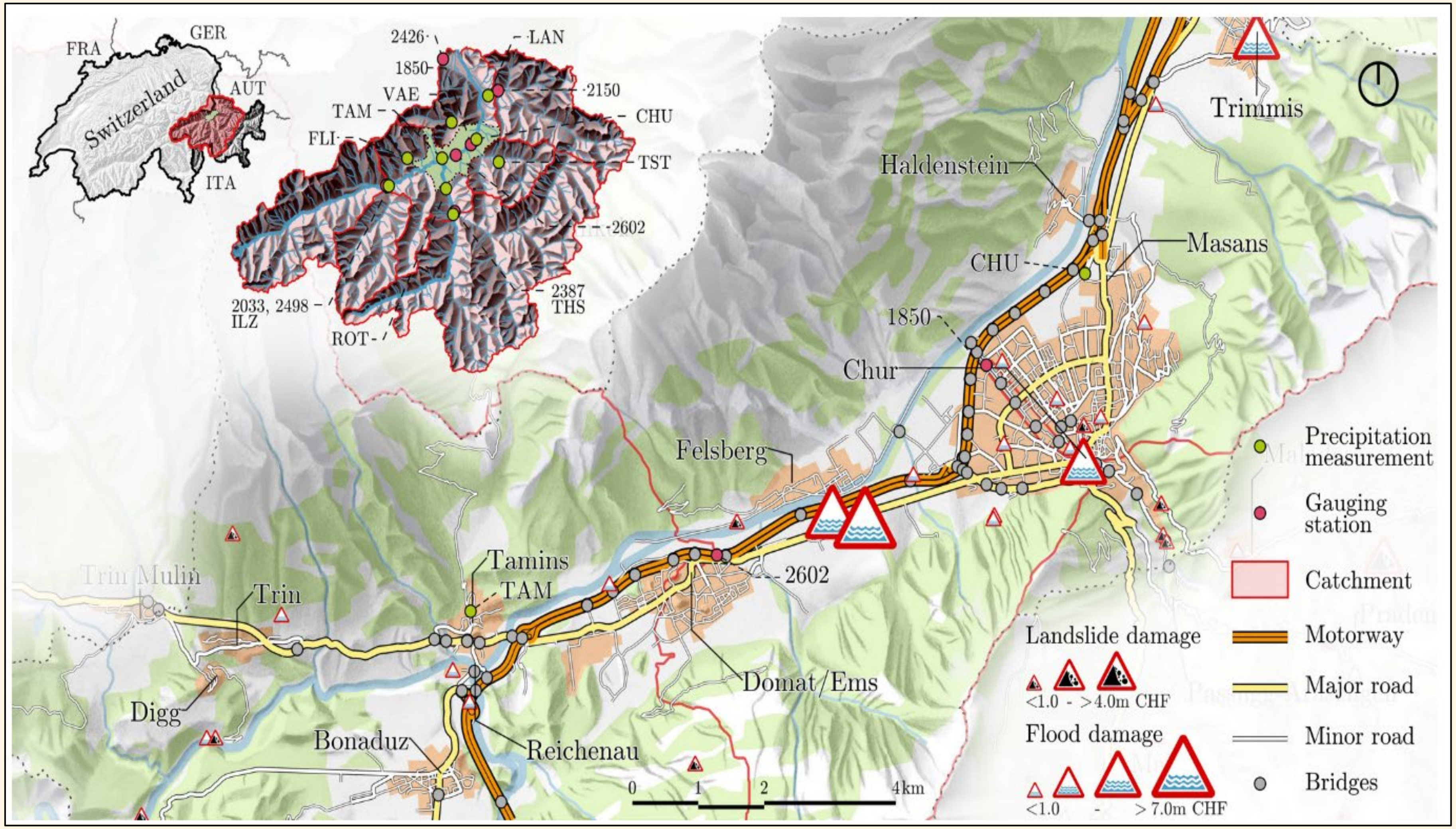


Risk Assessment and Stress Test assessment



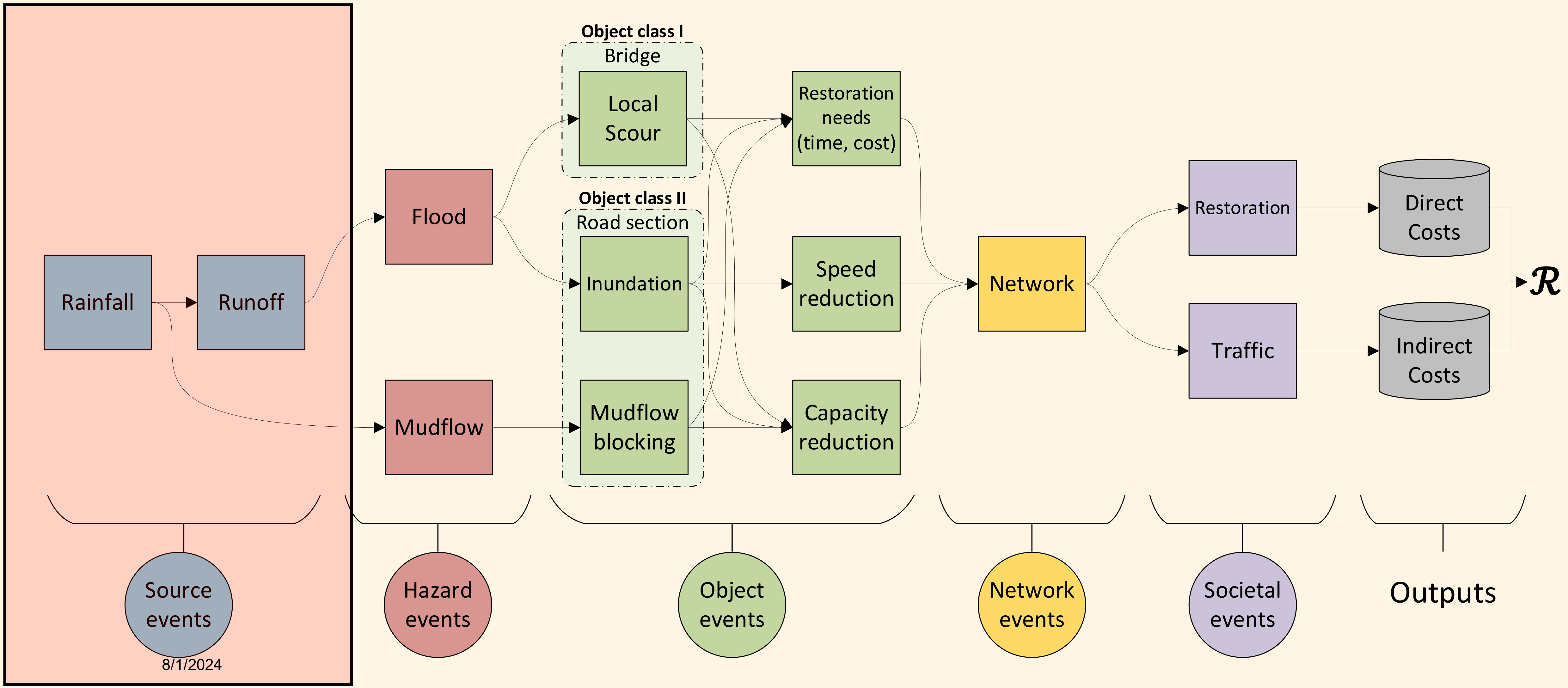


Case Study: Region of Chur, Switzerland

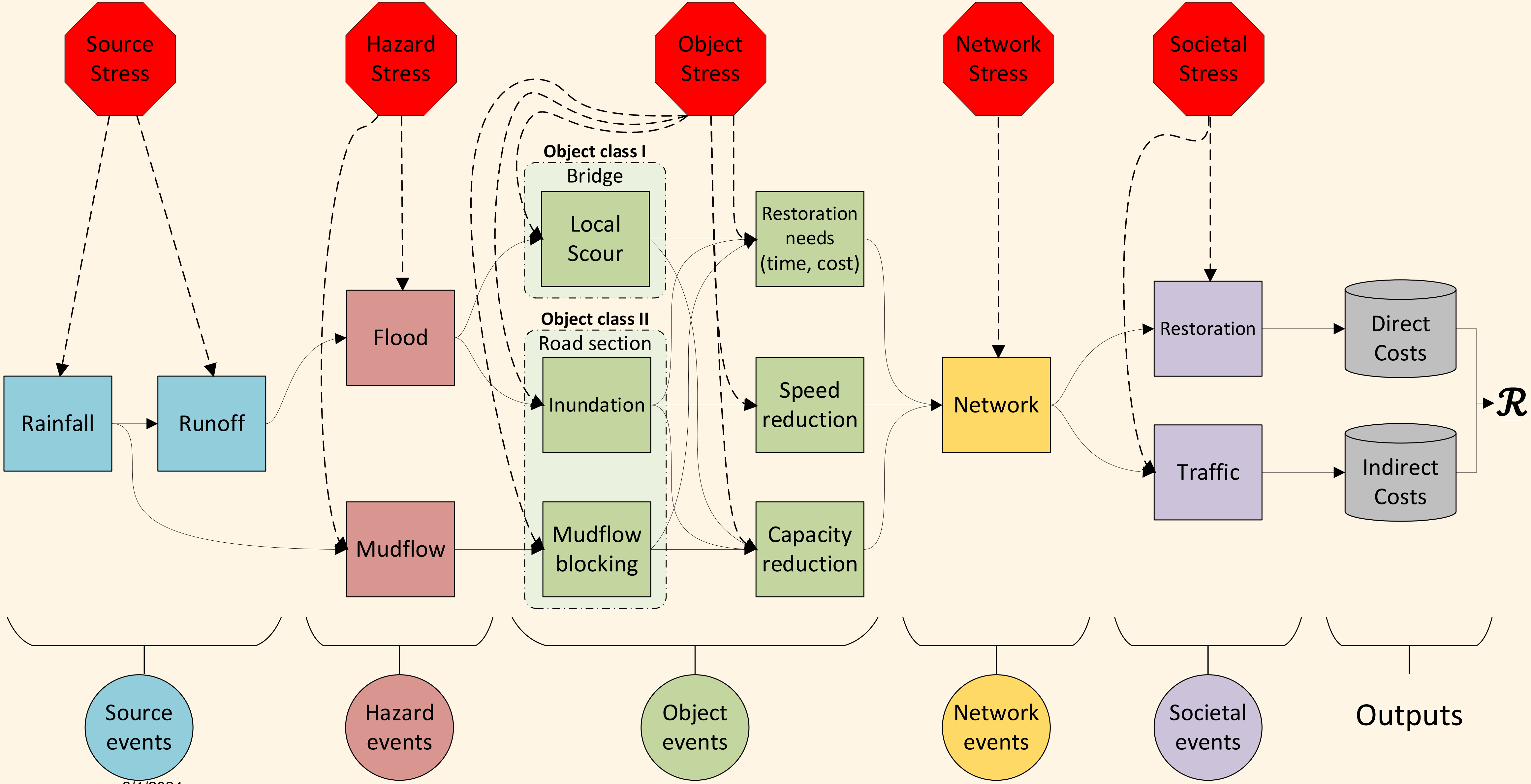


Roads/Bridges	
National	51 km (31%)
Other roads	554 km (39%)
Bridges	121 (20%)
River bridge	18

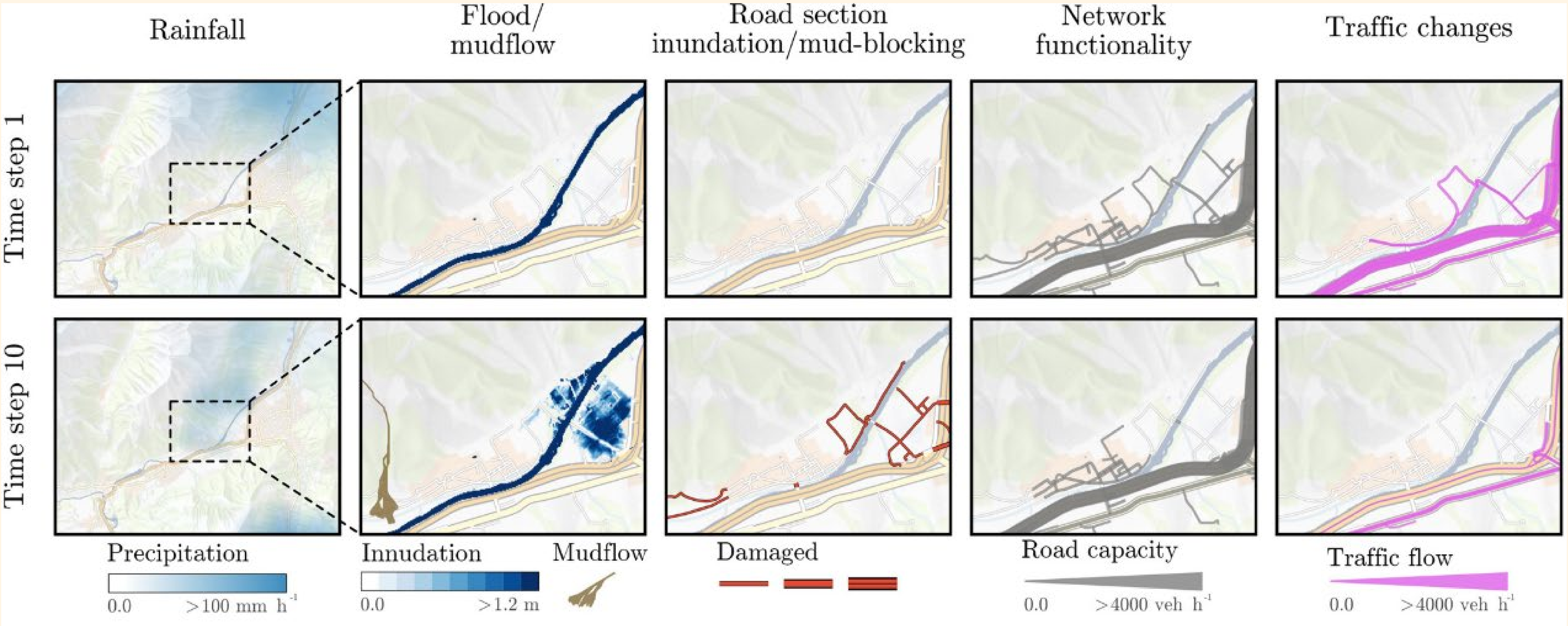
[Simulation] MODEL: Reference Risk Assessment



[Simulation] MODEL: Stress Test Assessment



Simulation MODEL: Sample output



Stress test: Example stressors

Source

- ❑ Increase in the average intensity of rainfall events due to Climate change
- ❑ Occurrence of only low-probability high-intensity events

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

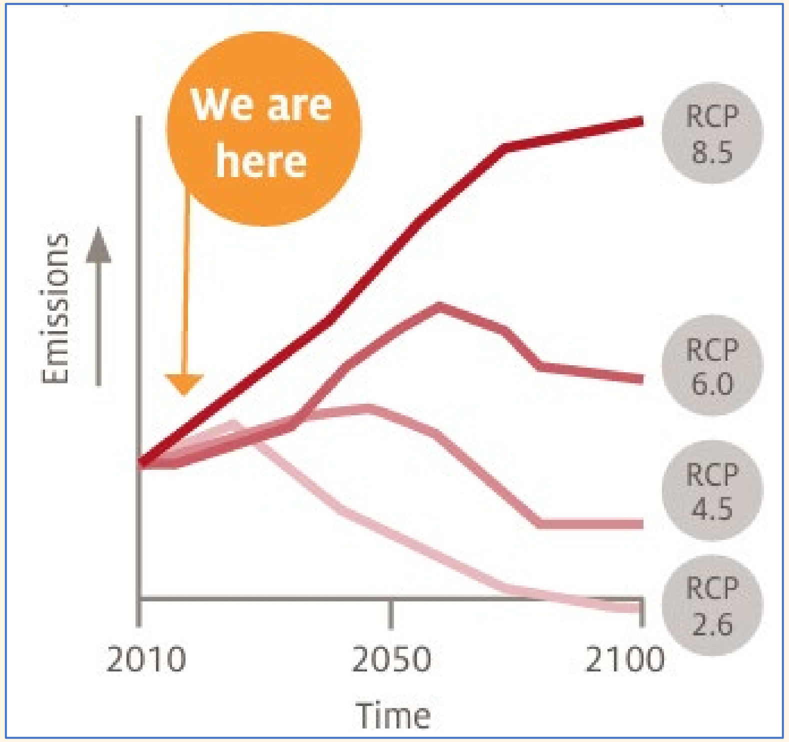
- ❑ Increase in travel demand to certain locations immediately after the hazard event
- ❑ Increase in the average travel demand in the future
- ❑ Reduction in the post-hazard restoration capacity

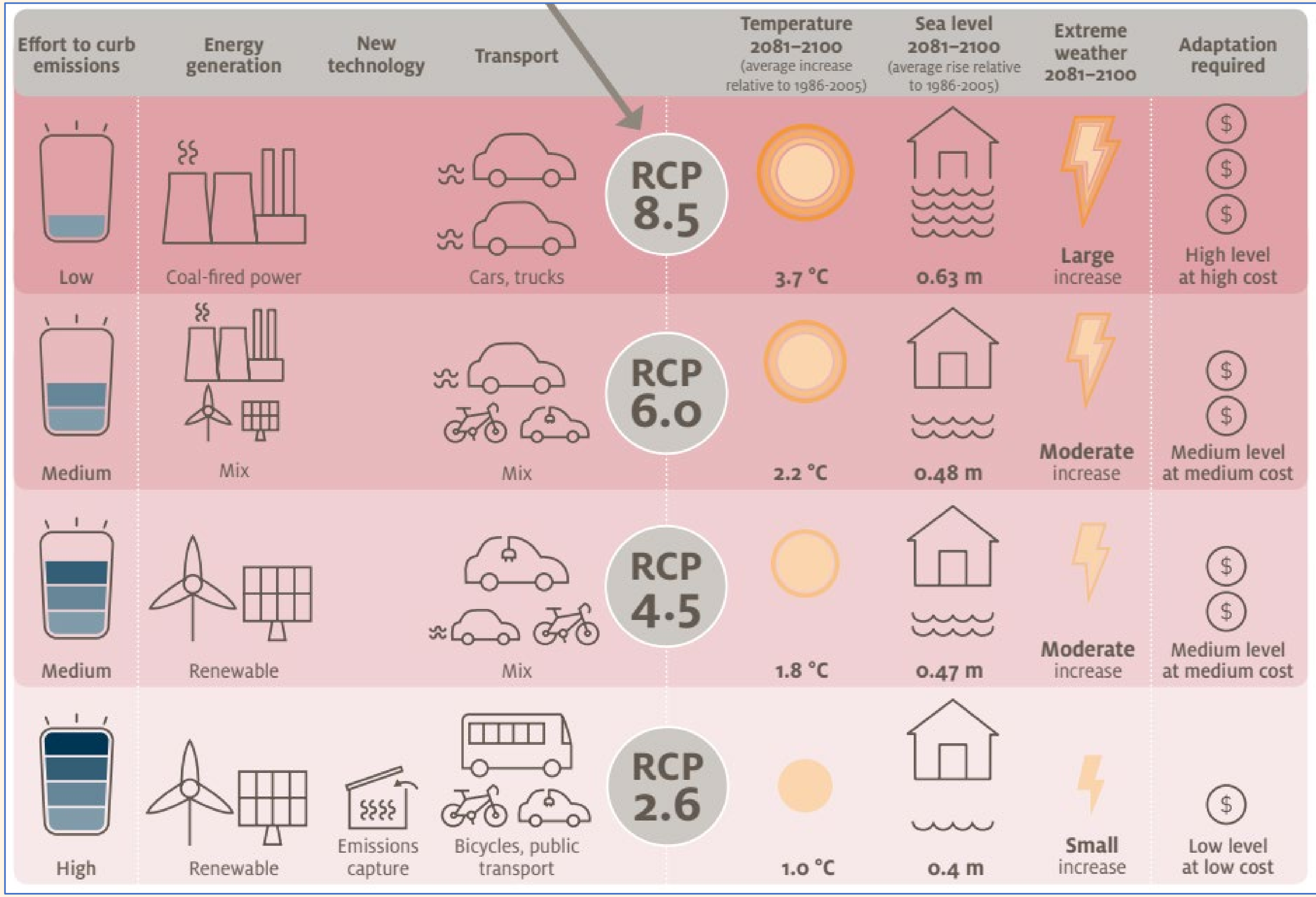
Climate change stress test

Representative Concentration Pathways (RCP Scenarios)

RCP Scenarios:

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

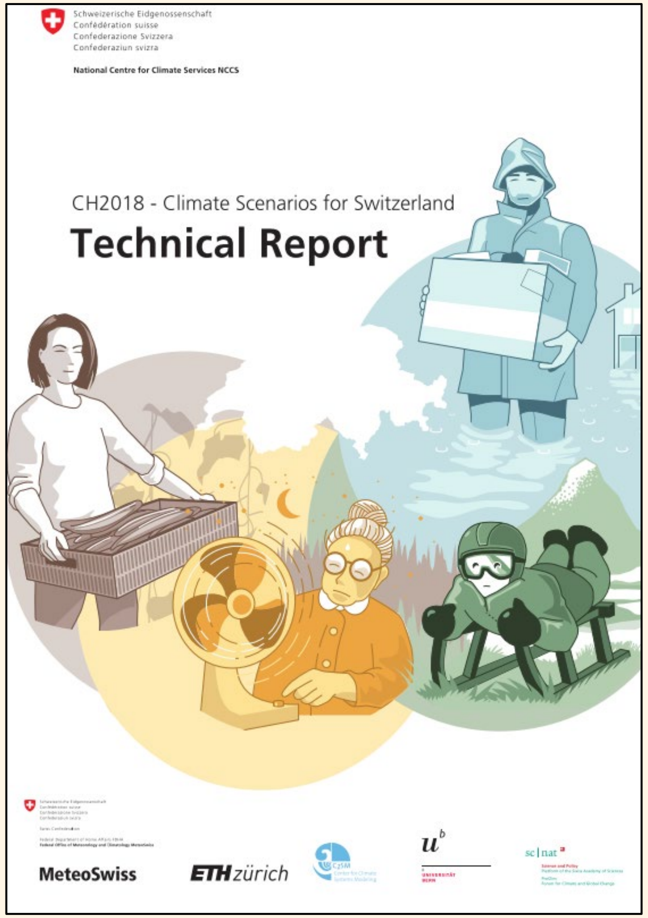


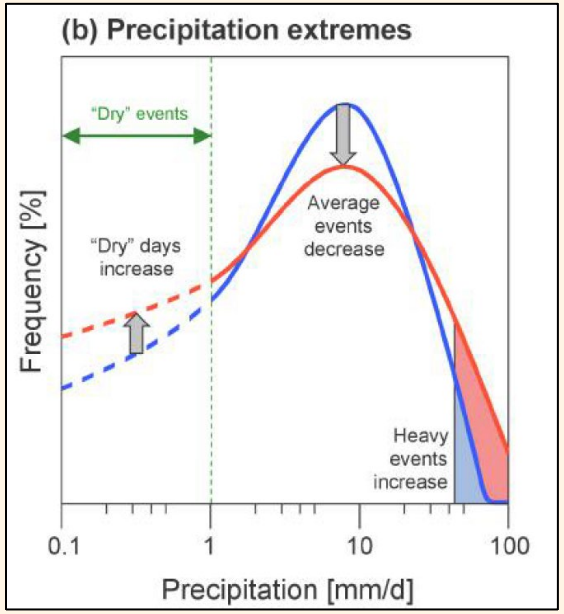


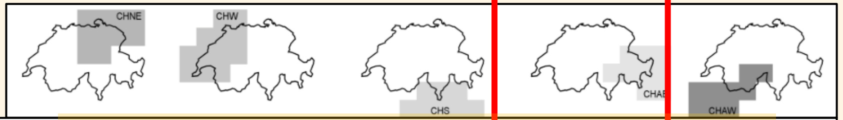
Source: coastadapt.com.au/infographics

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%



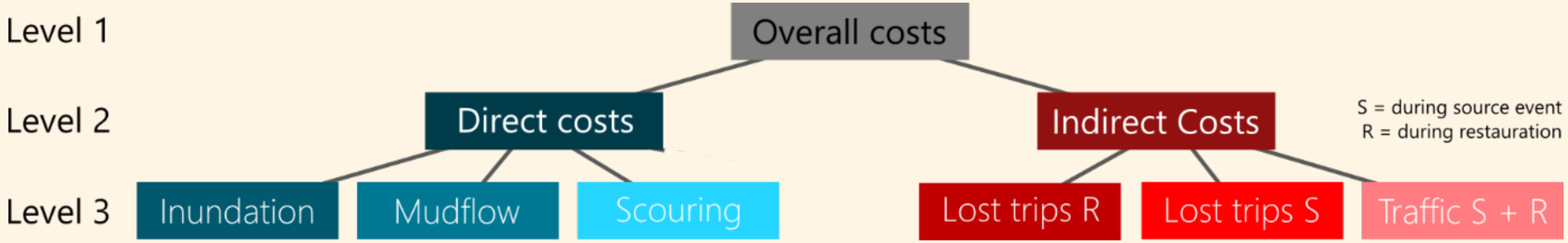




RCP 8.5					
	100-year return levels of one-day precipitation events (Summer) (%)				
2035	+10 (-13 to +31)	+7 (-14 to +19)	+5 (-11 to +16)	+7 (-2 to +15)	+3 (-9 to +22)
2060	+19 (-4 to +43)	+12 (+3 to +26)	+9 (-14 to +39)	+13 (-10 to +27)	+10 (-9 to +29)
2085	+20 (-6 to +42)	+12 (+2 to +38)	+11 (-24 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)

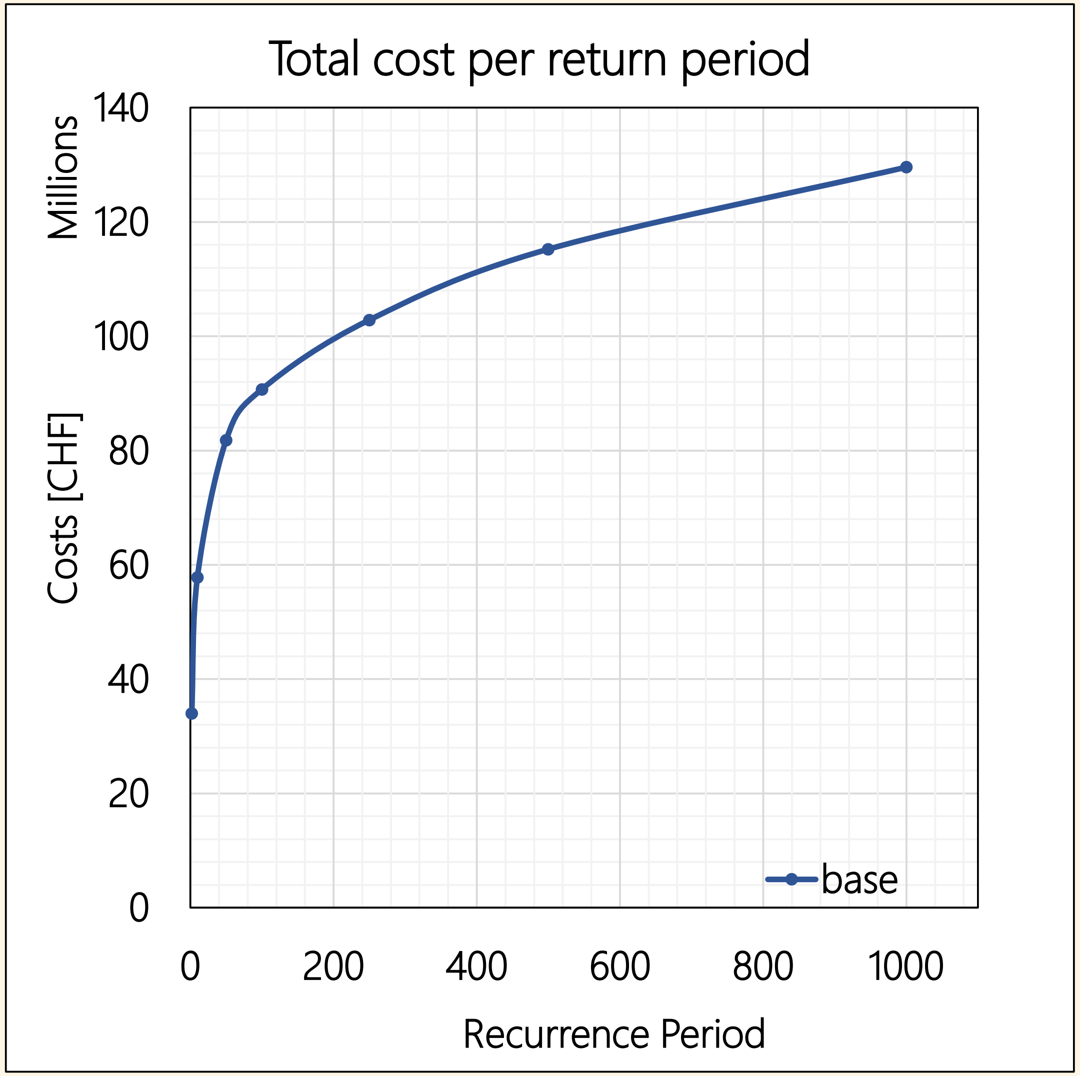
Conducting stress tests

- **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**

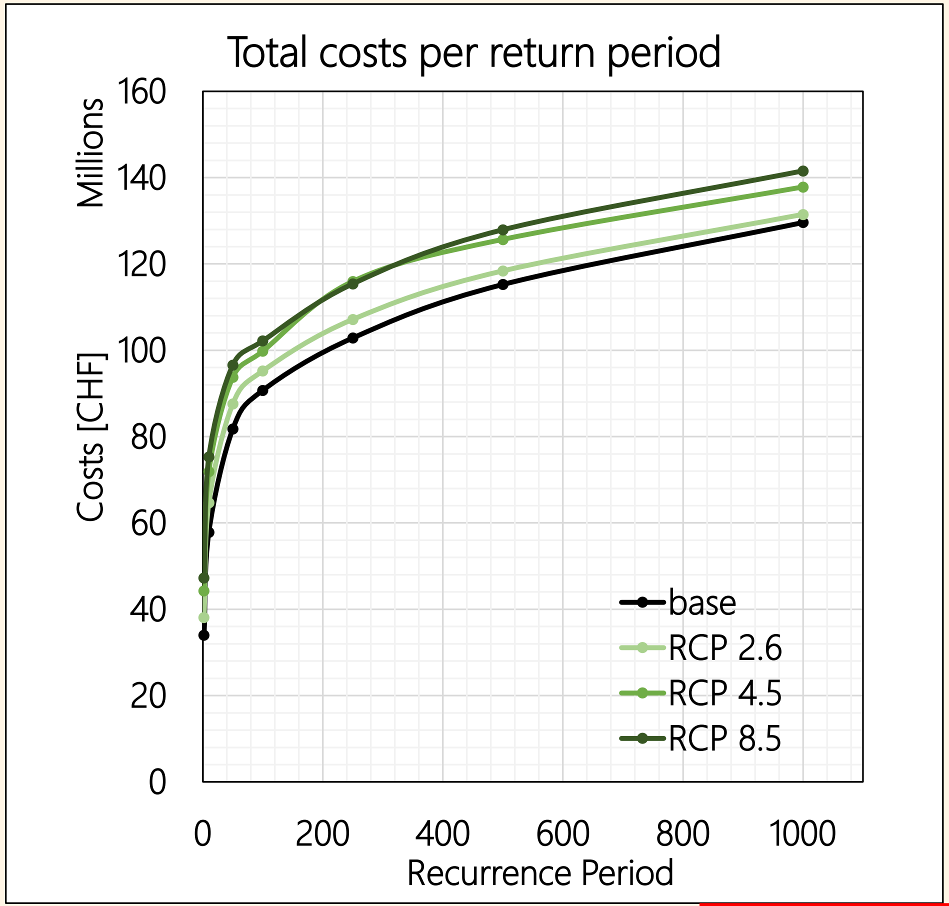
Reference

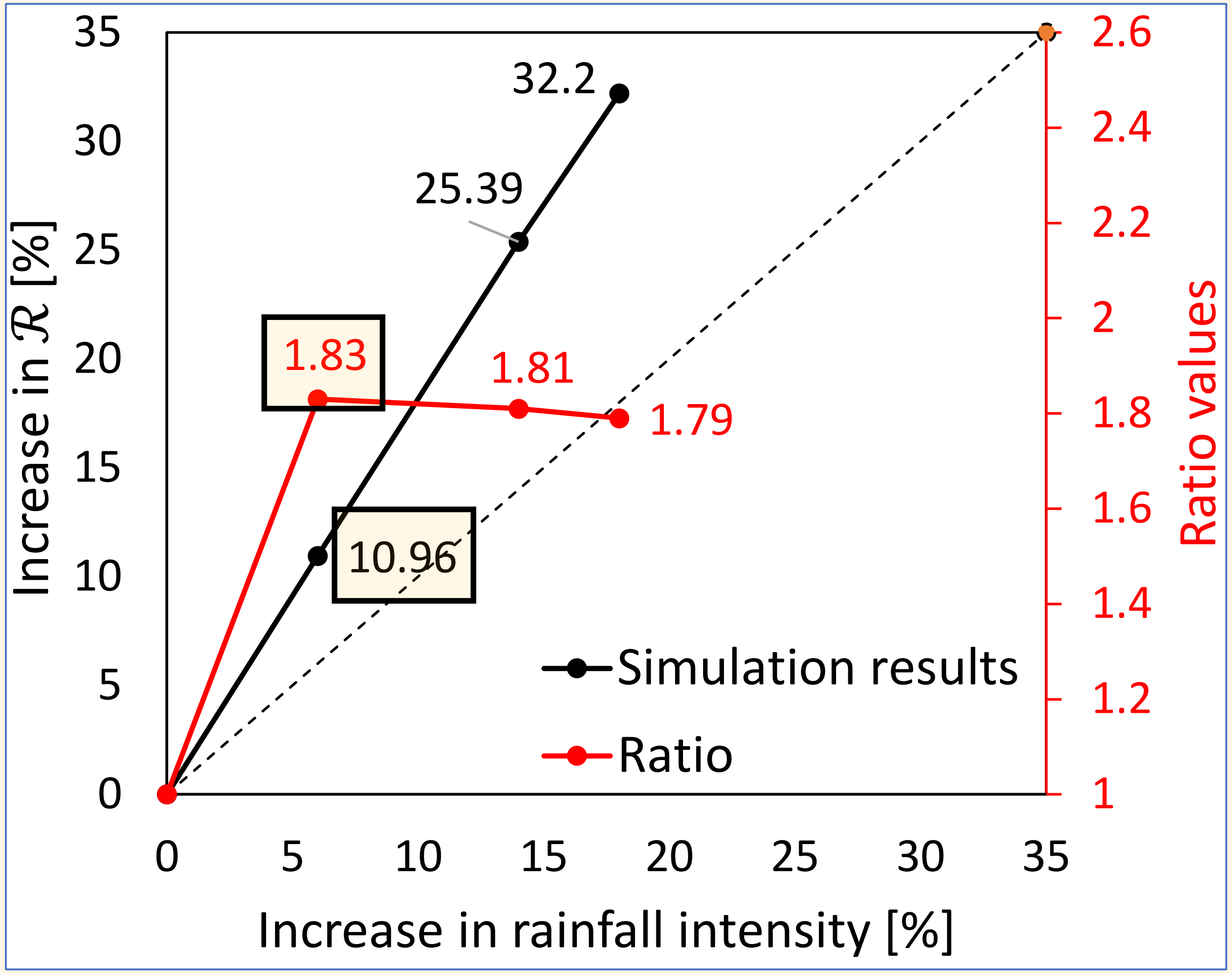


	Annualized cost (Mio. CHF)		
	Level 1	Level 2	Level 3
Overall costs	22.45		
Direct costs		7.25	
Inundation			6.24
Mudflow			0.76
Scouring			0.25
Indirect costs		15.2	
Traffic S+R			0.41
Lost trips S			2.04
Lost trips R			12.75

Results: Climate change stress tests

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

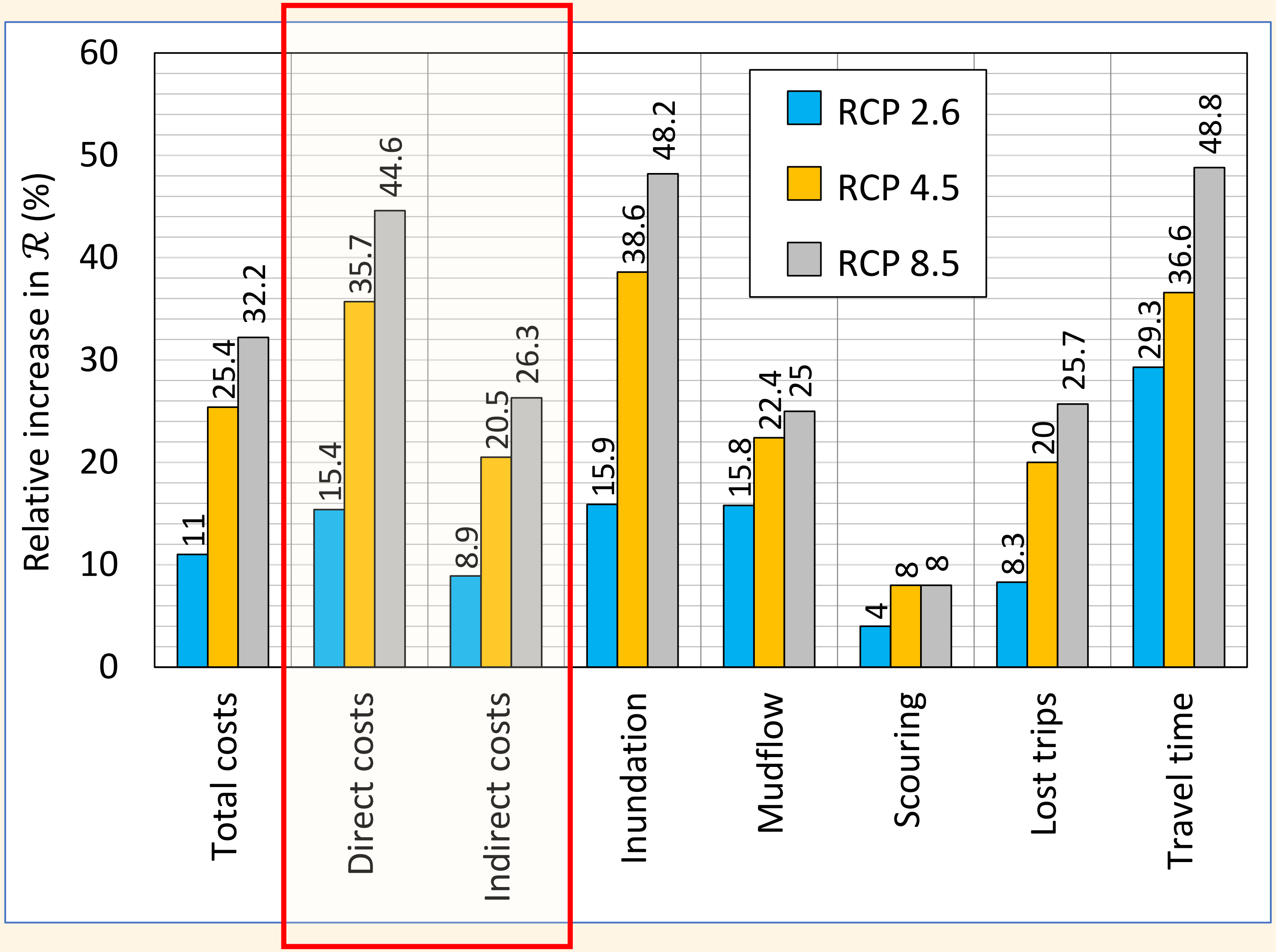




	Recurrence Period							Annualized Costs	Percentage increase
Scenario	2	10	50	100	250	500	1000	$\mathcal{R}$ [Mio CHF]	
Base	34	58	82	91	103	115	130	22.45	-
RCP 2.6	38	65	88	95	107	118	131	24.91	10.96 %
RCP 4.5	44	72	94	100	116	126	138	28.15	25.39 %
RCP 8.5	47	75	97	102	115	128	142	29.68	32.2 %

Results: Climate change stress tests

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



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