Enhancing adaptation and resilience indicators in the ENTSO-E TYNDP CBA framework | Part 3

November 13, 2025

Climate Adaptation and Critical Infrastructure: Multi-level, Multi-system, Multi-hazard

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This project has received funding from the European Union's Horizon Europe research and innovation programme under grant agreement No. 101004174.

Adapting to increasing intensity and occurrence of climate extremes

Increasingly interconnected infrastructure systems

Increasing shortage of personnel and material across operators

Aging infrastructure

Energy transition

Digitalization

A framework for multi-level, multi-hazard (and multi-system)

Single and Multi-Hazard Database

Hazard footprint

Asset-Level Exposure & Vulnerability

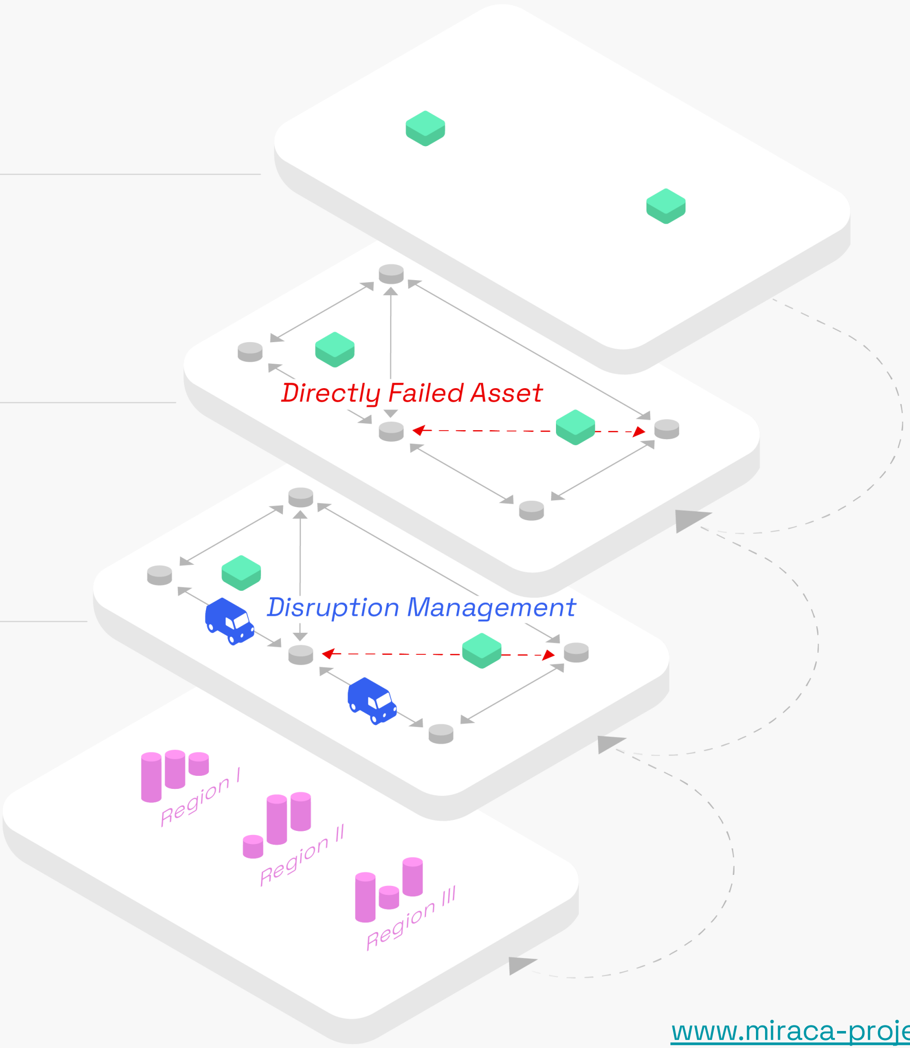
Origin/Destination

Network Failure & Service Disruptions

Infrastructure Services

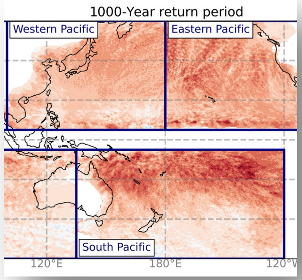
Systemic Risk

Regional loss metrics

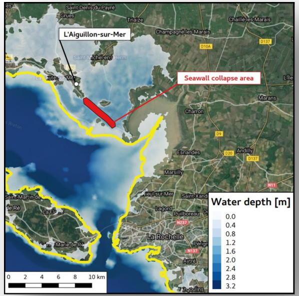


Single and multi-hazard database

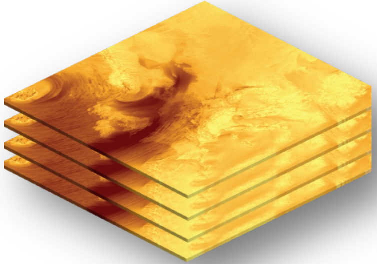
Return-period footprints

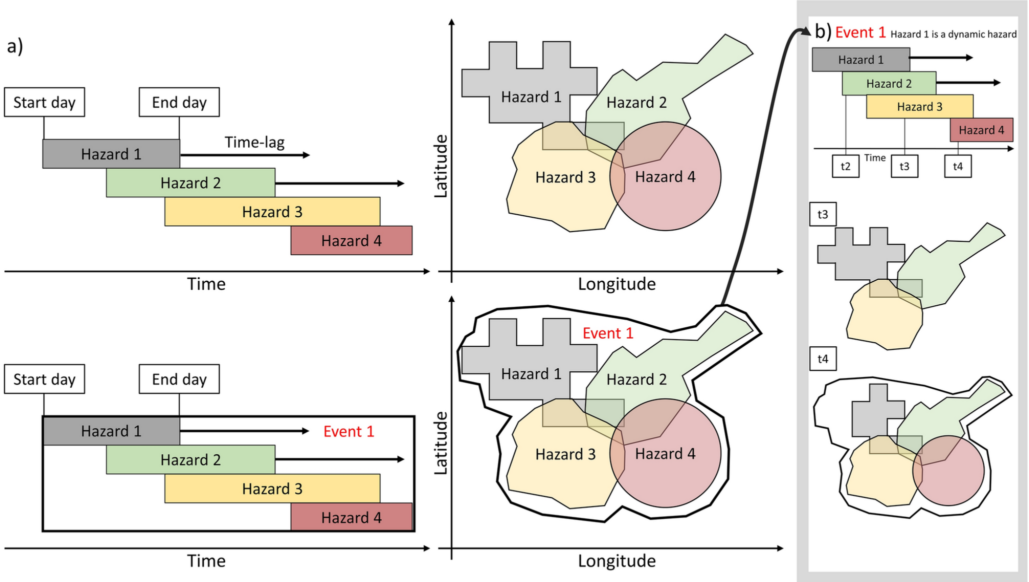


Historic hazard events



Stochastic event sets

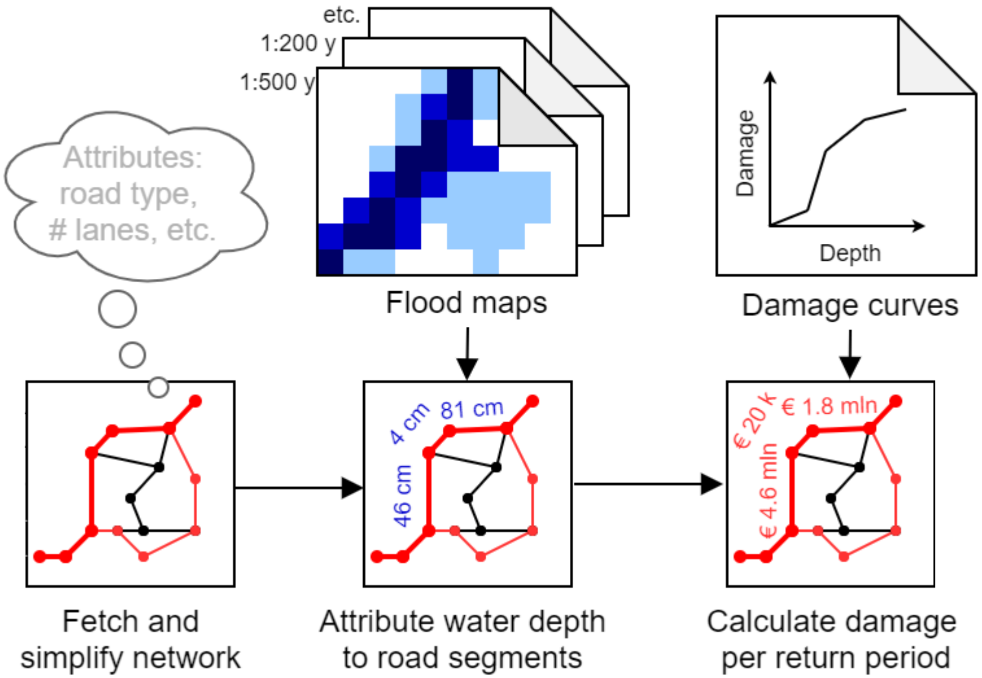




Claassen et al. (2023)

Bloemendaal et al. (2022) Koks et al. (2020, 2023)

Asset-level Exposure and Vulnerability



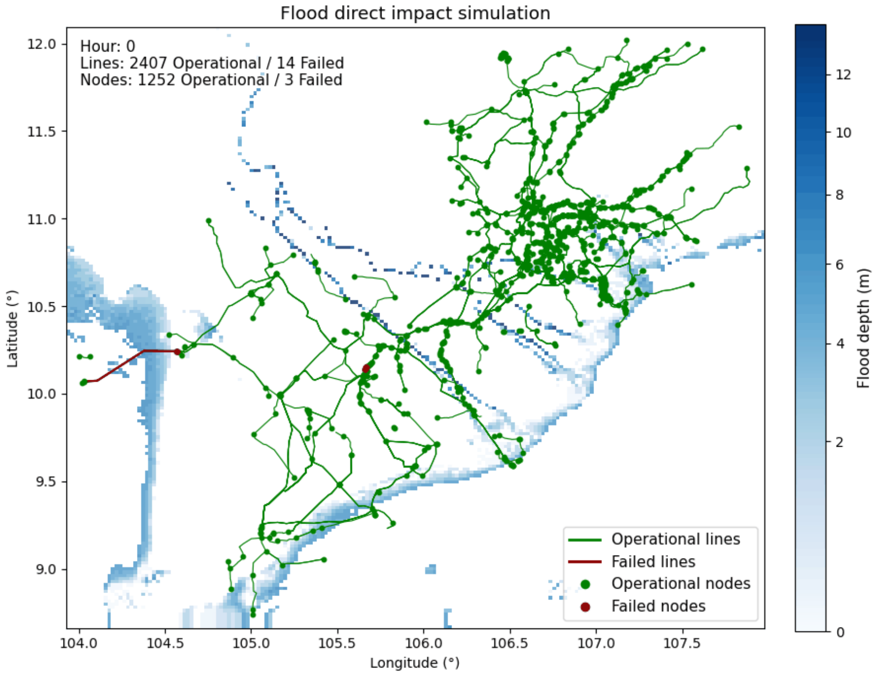
Van Ginkel et al. (2021)

Network failure and disruptions

- Estimating and disrupting services by combining:
  - Network information (e.g. topology characteristics)
  - the assets that are potentially vulnerable (hotspot analysis)
  - information about network usage (capacity and usage)

- This information combined allows for more complete stress-testing of networks

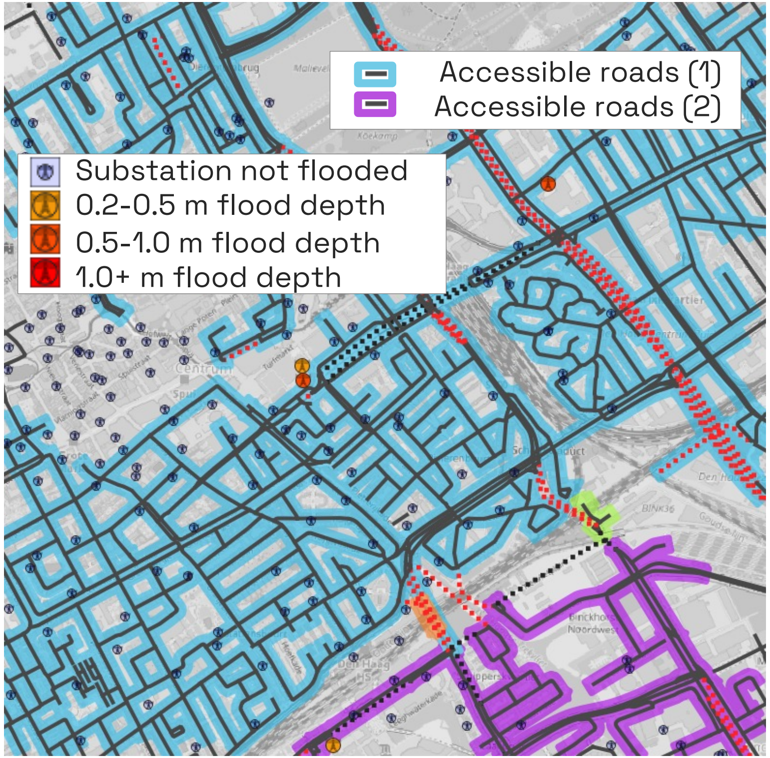
- Resulting in a better estimation of the real consequences (and costs) of disruptions. And helps prioritize investments.



Mengqi et al. (in prep)

System-level risk

- Translating service disruptions into societal impacts.
- Accessibility to local communities may be low in direct financial costs but may have large social welfare costs.
- Moreover, interdependencies between infrastructure systems are crucial in post-disaster recovery

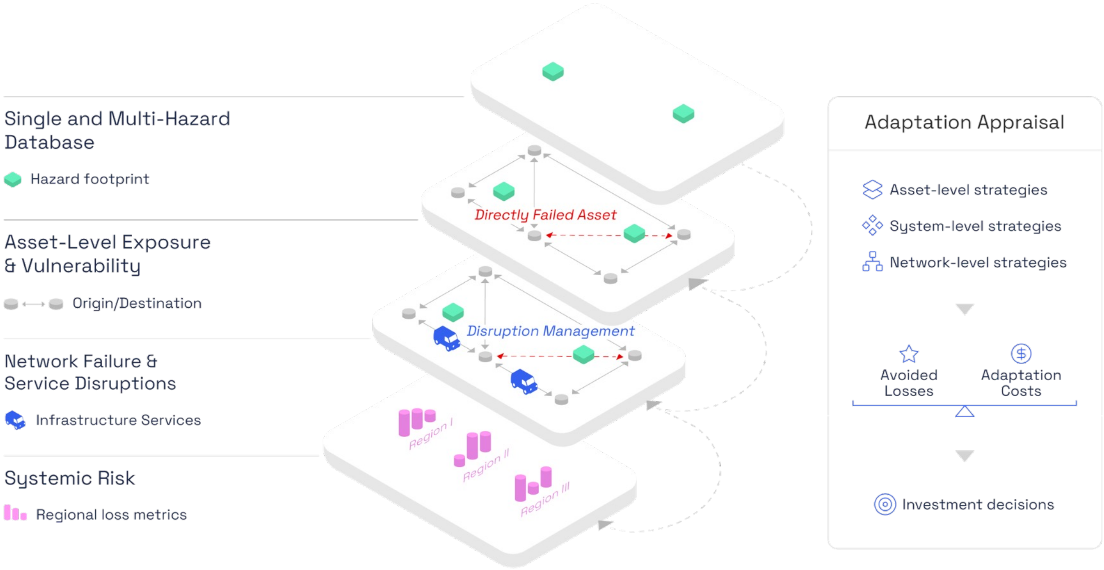


Peregrina et al. (in prep)

ASIAN DEVELOPMENT BANK

Climate adaptation in a multi-level context

Overview of multi-level adaptation

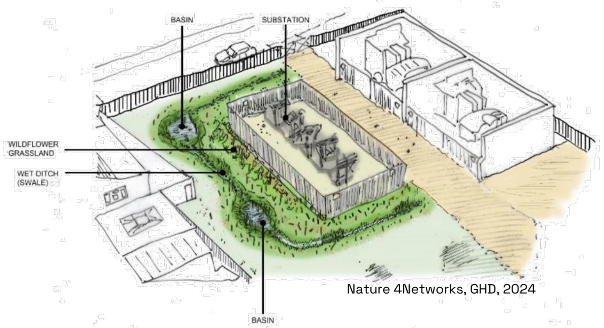


Adaptation: Intentional change to become more resilient to present and future hazards

Different ways to adapt are difficult to compare:

- Hazard-level
  Nature-Base Solutions
- Asset-level
  Climate-proofing assets
- Network-level
  Increased network redundancy
- System-level
  Demand-side management

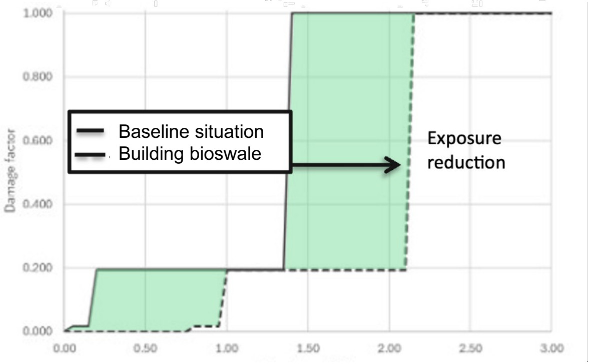
Asset-level adaptation options

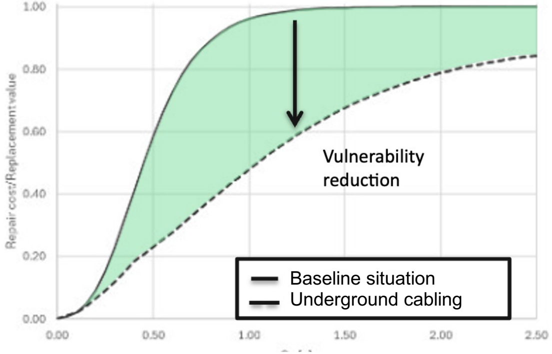


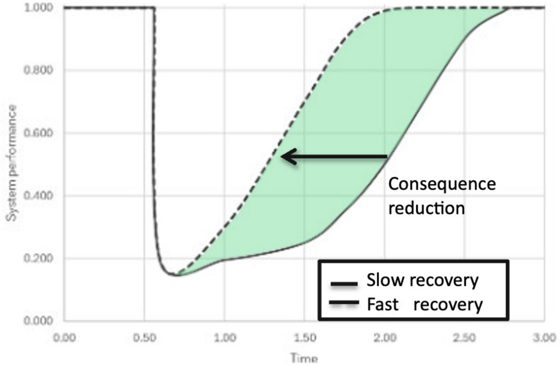
Nature 4Networks, GHD, 2024


Nkt.com


Eenews.net / Duke Energy





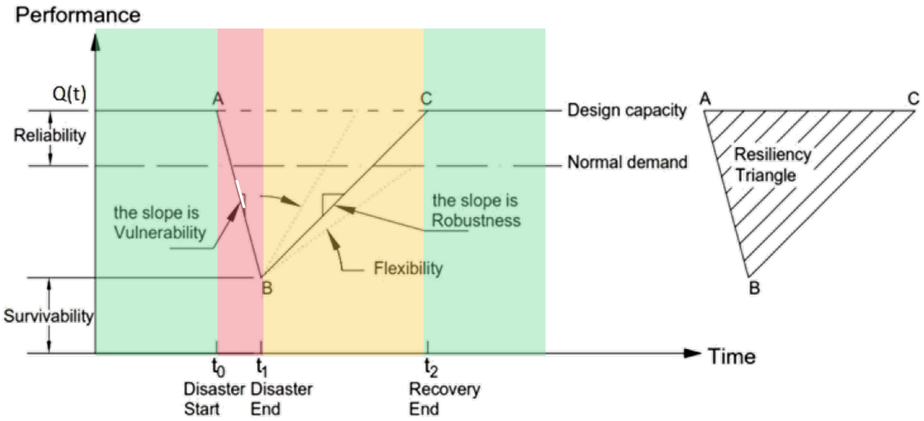


Peregrina et al. (in review)

Network-level adaptation options

- Service metrics for service provision – different ways to measure “Performance”
- Multi-hazards become especially relevant for network-level performance (and adaptation).
- What is disrupted at the same time is relevant, since alternatives (redundant routes) may also become disrupted
- Exploring adaptation related to the resilience triangle

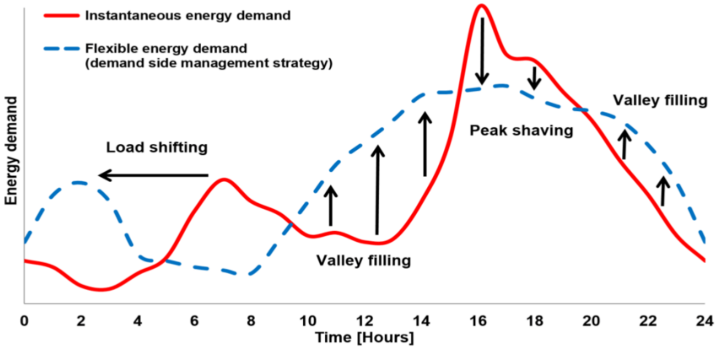
BAM, 2025



Peregrina et al. (in review)

System-level adaptation options

- Focusing on improving resilience of the entire system, which includes end-users and interdependencies
- As such, links strongly to measures that go across systems.
- Demand-side options, such as peak shaving or load shifting
- A key concept here is also moving from asset-level to a corridor-based implementation of climate adaptation (for CI)

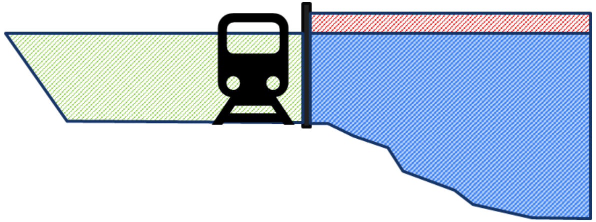


Johra et al. 2019

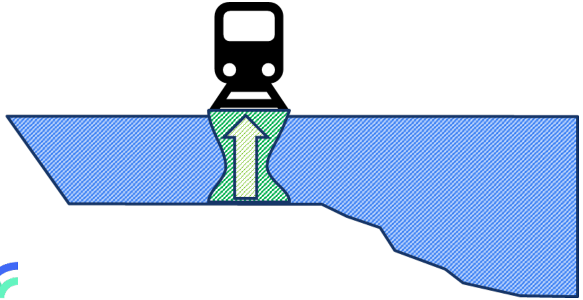
From risk to adaptation appraisal

An example for a railway line

L1: Hazard-level

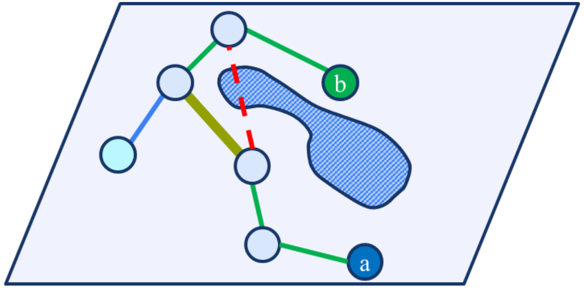


L2: Asset-level



Level	Adaptation
L1: Hazard-level	Building floodwalls
L2: Asset-level	Elevating railways
L3: Network-level	Building new connections (bridges)

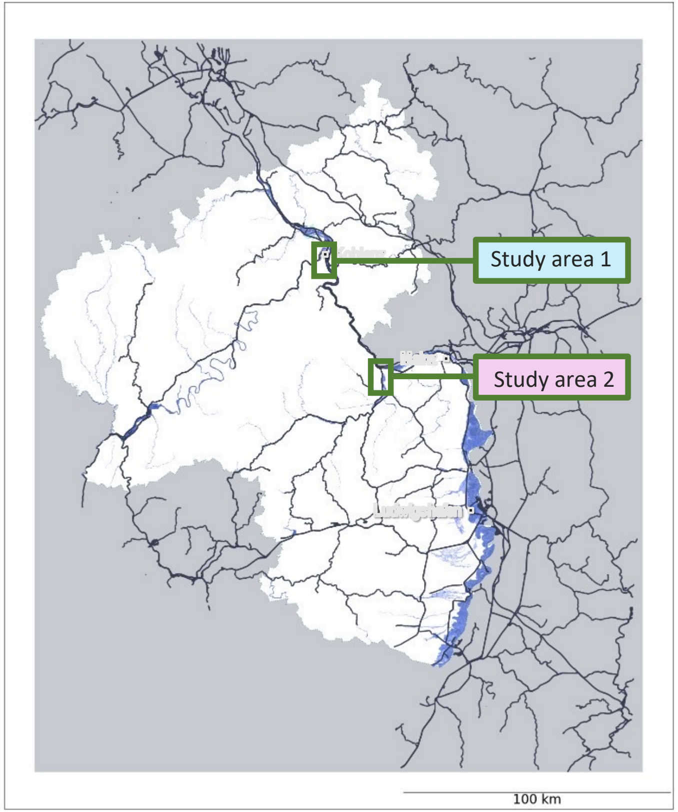
L3: Network-level

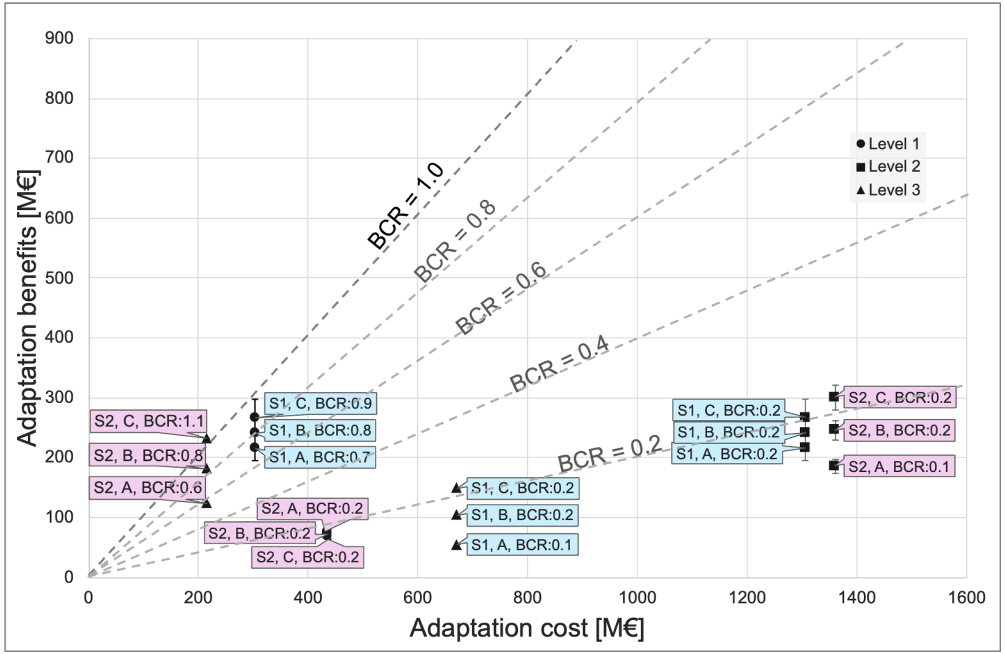


Peregrina et al. (in review)

From risk to adaptation appraisal

An example for a railway line

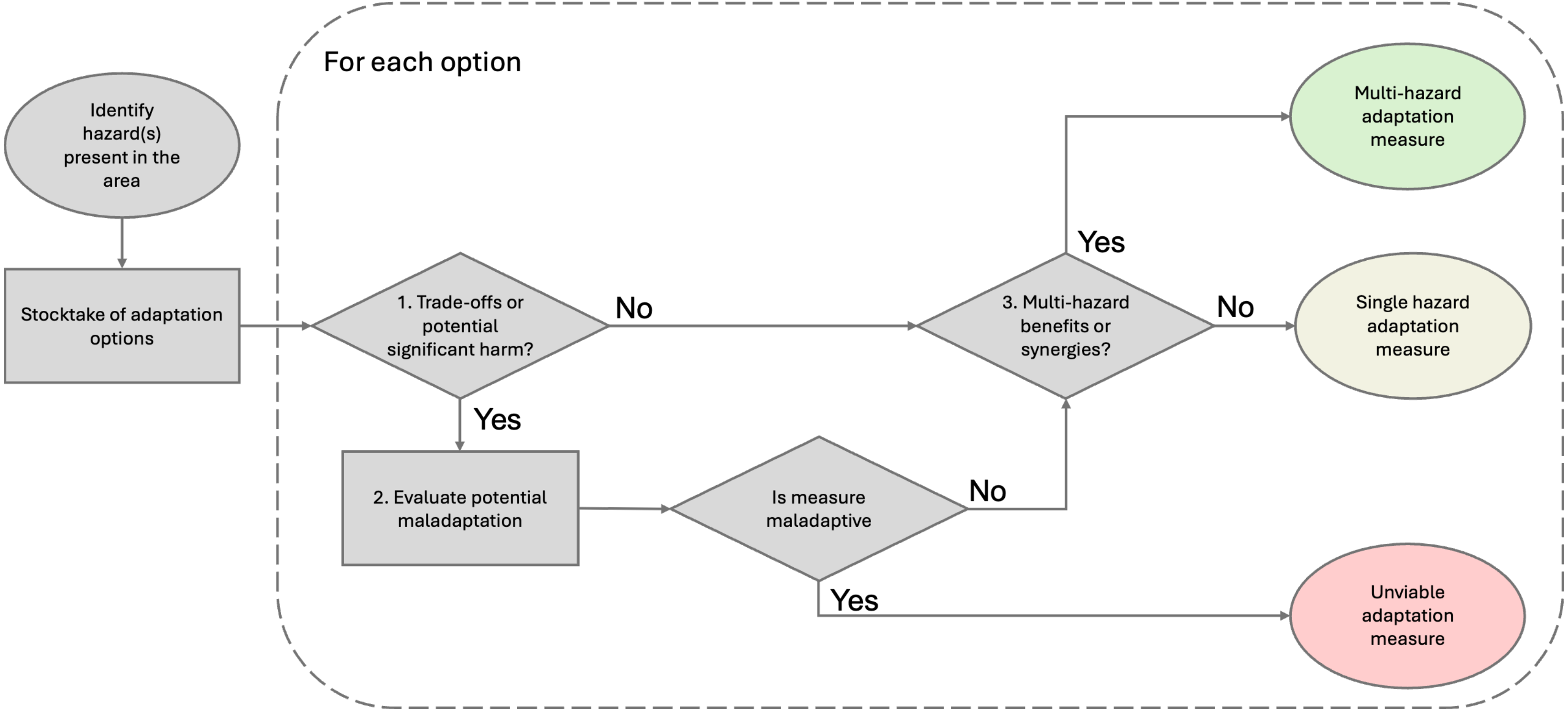




Peregrina et al. (in review)

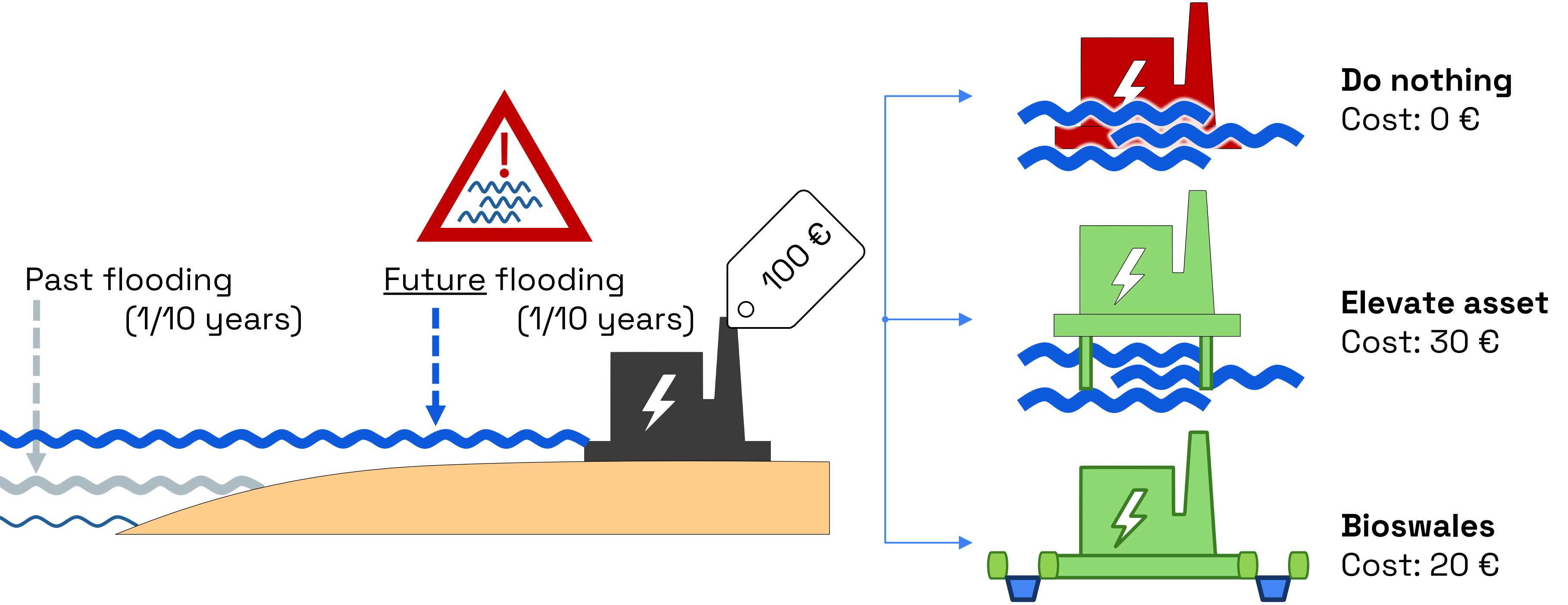
Climate adaptation in a multi-hazard context: an example

Climate adaptation in a multi-hazard context



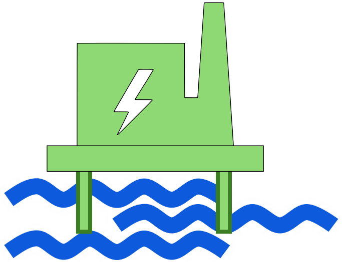
Peregrina et al. (in review)

Climate adaptation in a multi-hazard context
Past and future flooding, past and future storms



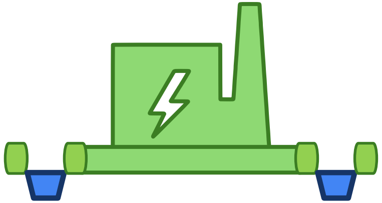
Increasing flood risk is expected ➔ Two adaptation options are identified

Climate adaptation in a multi-hazard context
Past and future flooding, past and future storms

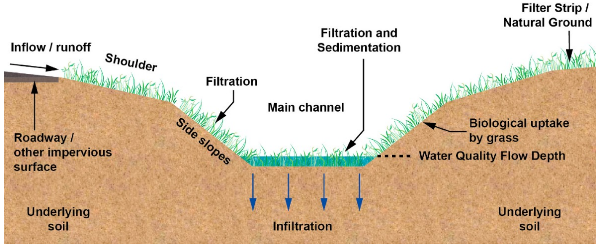


Elevate asset

PSEG Substation
Newark, USA



Bioswales

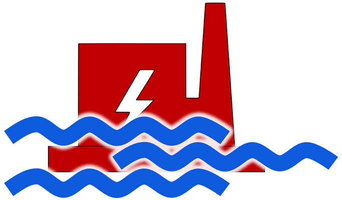


Ekka et al, 2021

Elevating assets prevents damage from even extreme (1/100 year) floods.
Bioswales can be overwhelmed in extreme events, failing beyond 1/10 year floods

Climate adaptation in a multi-hazard context

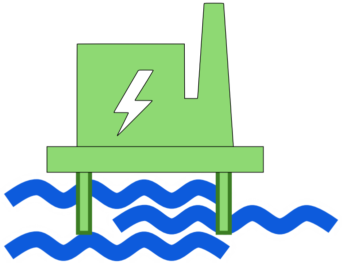
Past and future flooding, past and future storms



Do nothing
Cost: 0 €

Ineffective
1/10 y: 100 € (destroyed)
1/100 y: 100 € (destroyed)

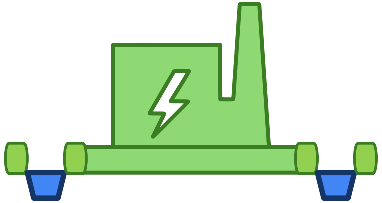
EAD: 14.8 €/y
Benefits: 0 €
BCR: *0*



Elevate asset
Cost: 30 €

Always effective for floods
1/10 y: 0 € (protected)
1/100 y: 0 € (protected)

EAD: 0 €/y
Benefits: 199 €
BCR: *199/30 ➔ ~6.6*



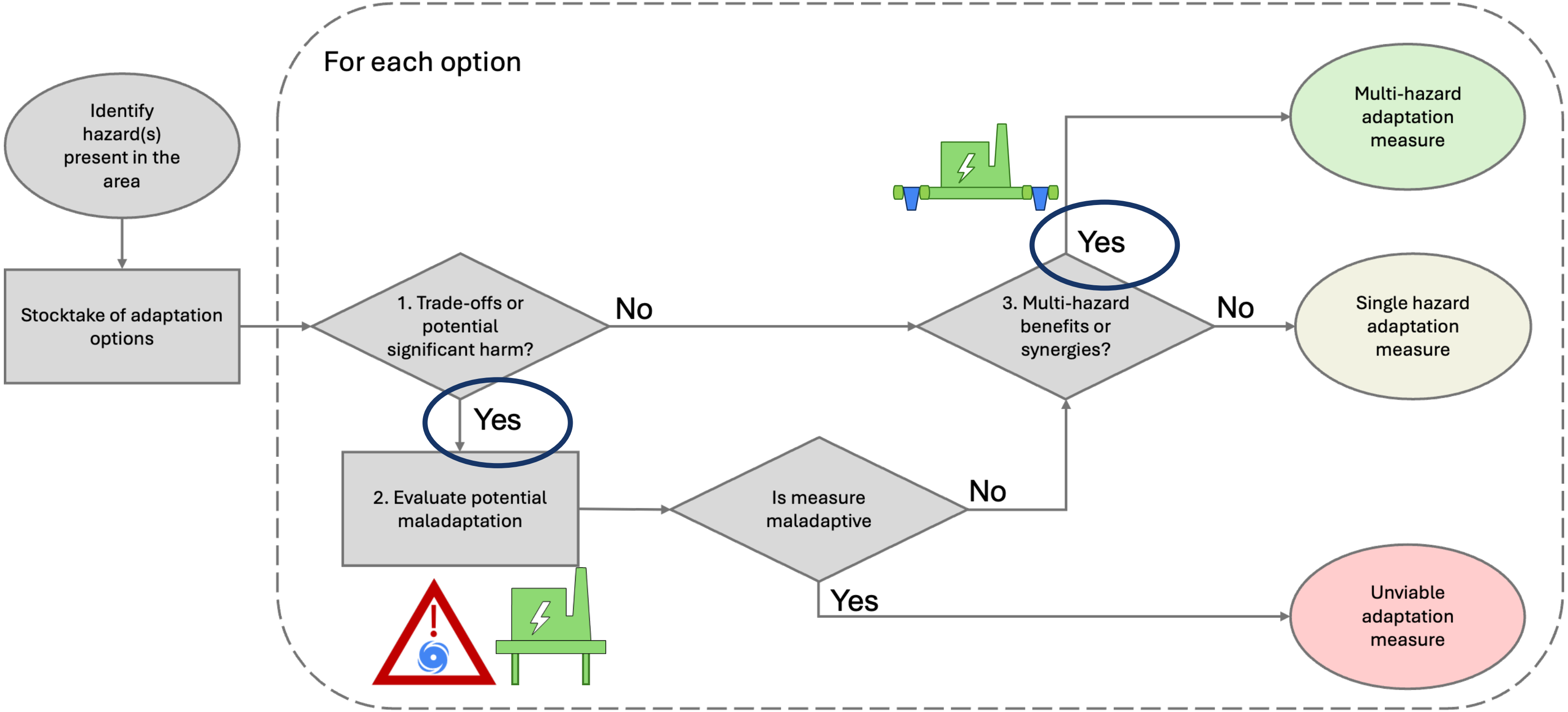
Bioswales
Cost: 20 €

Effective with minor floods
1/10 y: 0 € (protected)
1/100 y: 100 € (destroyed)

EAD: 1.3 €/y
Benefits: 182 €
BCR: *182/20 ➔ ~9.1*

Even with the residual risk from extreme flooding events, bioswales have better BCR

Climate adaptation in a multi-hazard context



In a MH context, elevated assets are more vulnerable to extreme wind
... And bioswales provide benefits towards other hazards too...

Climate adaptation in a multi-hazard context

Past and future flooding, past and future storms

Elevate asset

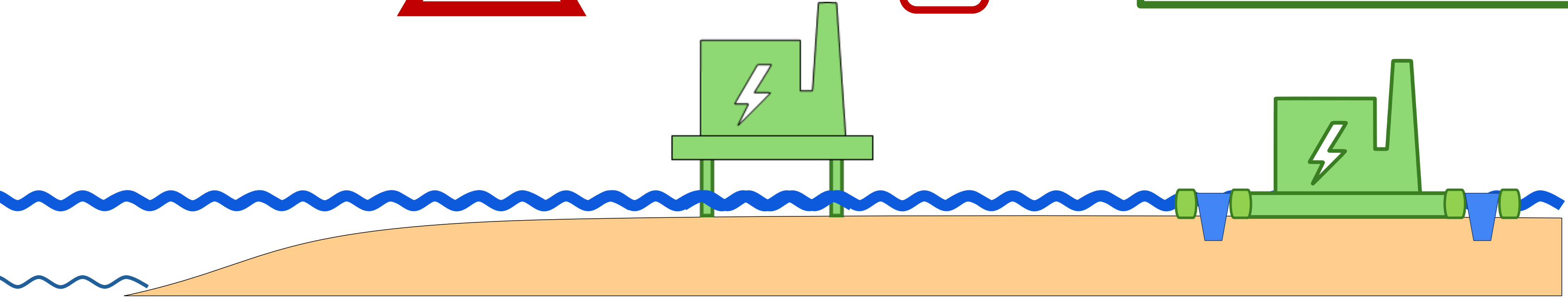
Additional EAD (wind): 5.2 €/y

Single hazard BCR: 6.6
Multi-hazard BCR: 5.1

Flood-proof asset

Additional EAD (wind): 0 €/y

Single hazard BCR: 9.1
Multi-hazard BCR: 9.1



This makes bioswales an even more attractive option in this case

Some final words

- To move forward, we should mostly think about how to connect all elements, and what our final metrics (e.g., a Net Present Value) are, not necessarily building the most complex models that can capture everyone and everything.

- Collaborations are key! We cannot solve this as academics/scientist alone. Without properly understanding the effectiveness and costs of adaptation, its hard to truly inform decision-making

Thank you

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