Review of asset-level adaptation options for Critical Infrastructure (CI)

Deliverable D4.2

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Executive summary

This deliverable covers adaptation options that aim at adapting the assets of critical infrastructure (CI) networks. An inventory of adaptation options for each infrastructure sector to multiple climate and geohazards is presented, and a few options are more deeply described to bring insight into asset-level adaptation modelling methods.

For most hazards, adaptation options at the asset-level do exist, with the largest number of options for flooding (43 applicable measures) and the smallest for landslides and heatwaves (8 each). For flooding, the options focus on reducing the exposure of vulnerable CI to water, by elevating assets or components or using floodproofing methods. Most adaptation options for earthquakes and windstorms revolve around making structures stronger against the hazard or dissipating the energy of the hazard; this is consistent across most infrastructure sectors. Drought and heatwaves present different challenges for infrastructure sectors which has inspired diverse adaptation responses. For the transport, power, and telecommunications sectors, technical responses related to cooling are prevalent, while education and healthcare have focused more on keeping the occupants safe and comfortable.

The explored adaptation options reduce the vulnerability or exposure of an asset to a hazard, or they reduce the consequences resulting from asset disruption. How these adaptations can be modelled at an asset level is presented in examples for different infrastructure sectors and hazards. In each example, the benefits, co-benefits and possible trade-offs of adaptation options are presented, along with ways to quantify them or integrate them into a monetary valuation. Some adaptation options are beneficial for two or more hazards; however, others have trade-offs, reducing the risk to that asset from one hazard but increasing the risk from another at the same time. This highlights that, even at an asset level, the adoption of multi-hazard methods is necessary to fully capture the effects of adaptations and to reduce the risk of maladaptation.

Challenges remain in incorporating uncertainty in hazard, risk, and adaptation modelling. Furthermore, data on the costs of adaptation option and the current adaptation status of infrastructure is necessary. The creation of additional vulnerability data to capture the performance of adapted assets can improve adaptation modelling, as well as improved data of the assets, such as building materials, construction dates and codes observed.

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1. Introduction

Infrastructural development and improvement are processes that involve a long planning horizon, given the long lead-time required to carry out these projects and the extensive expected lifetime of infrastructure. In a rapidly changing climate, infrastructure may be impacted more frequently and severely by climate hazards than it has been in the past (European Commission, 2021; European Environment Agency, 2024; Ganteaume et al., 2021; IPCC, 2023). Simultaneously, the need for infrastructure development is continuously changing as population grows (or shrinks). As a result of these conditions, assets that are built to be long-lasting may see their lifespan shortened (Chester et al., 2020; European Commission, 2021; Reale, 2023; Rosenzweig et al., 2011). To prevent this, both existing systems and new infrastructure developments must be adapted, to cope with the wide range of climate conditions they are bound to experience throughout their lifetime (Hallegatte, 2009).

The goal of MIRACA Work Package 4 (WP4) is to appraise the adaptation strategies that are available for critical infrastructure (CI) to multiple climate hazards, to outline the benefits that can be gained from adopting these strategies, and to explain how no-regret options can be identified, while presenting possible trade-offs between options.

The MIRACA project framework (Figure 1), integrates several infrastructure systems that provide basic services to the population and enable communities to operate. The CI systems within the scope of this project include transport (road, rail, waterways), power, telecommunications, healthcare, and education infrastructure. To minimise the service disruption caused by climate hazards affecting these systems, adaptation strategies can be implemented which improve resilience by interacting with infrastructure and climate hazards at different levels:

1. **Level 1**. Reducing the intensity of the hazards CI is exposed to.
2. **Level 2**. Reducing the vulnerability of individual infrastructure assets to climate hazards.
3. **Level 3**. Reducing the vulnerability of the network to the failure of certain assets
4. **Level 4**. Reducing the systemic vulnerability to network failures

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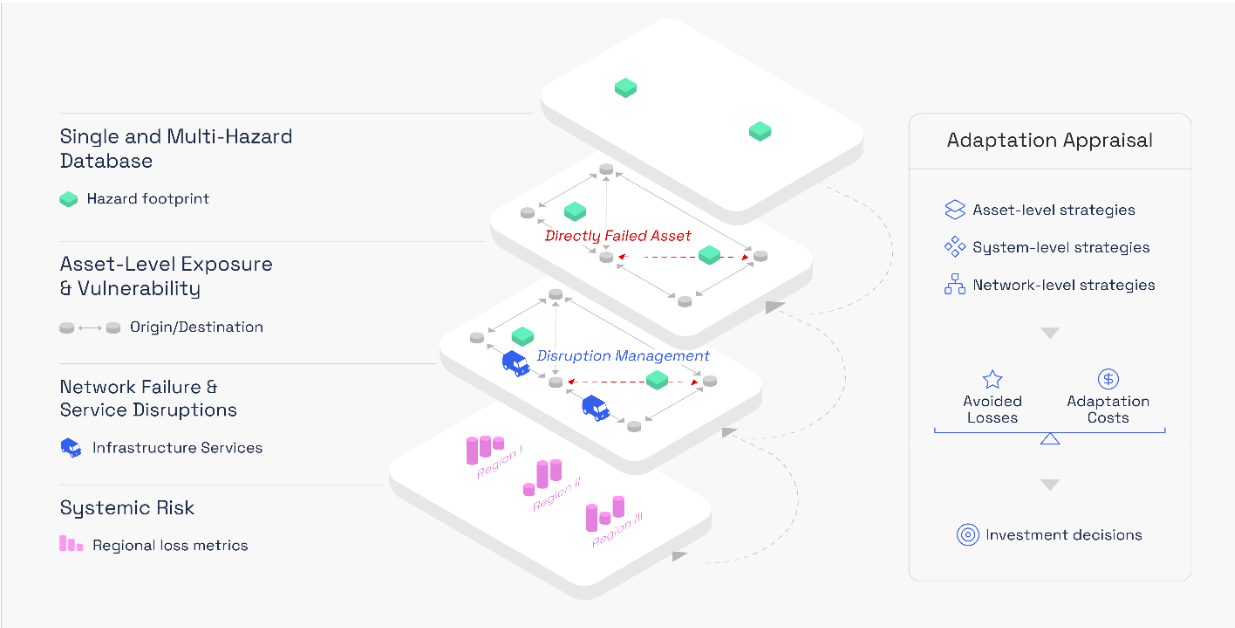

Figure 1. *MIRACA Framework composed by multiple levels: Hazard-level, asset-level, network-level, and system-level.*

In WP4, each level of adaptation will be explored in a dedicated deliverable. The adaptation processes at each of these levels (Figure 1) take place at very different spatial and economic scales; they are financed through different means and involve stakeholders with diverging responsibilities, decision processes, and priorities. Understanding how interventions at different levels can best contribute to an overall benefit to society is necessary to appraise adaptation strategies holistically. For example, when facing river flooding, a government may have to decide between widening floodplains and elevating dikes, while a railway company may focus on asset and network level actions such as flood-proofing a specific station or building a new track through a different route. While all levels of adaptation may not be relevant for any single stakeholder, accounting for the benefits attained through all the levels is relevant in defining the most attractive adaptation strategy for the common good.

This Deliverable 4.2 focusses on adaptation strategies to improve infrastructure resilience at Level 2: Asset-level adaptation. Deliverables 4.1, 4.3, and 4.4 explore strategies to improve resilience through hazard-, network-, and system-level adaptation (Figure 2), followed by a cost-benefit analysis in D4.5 and strategy development in D4.6.

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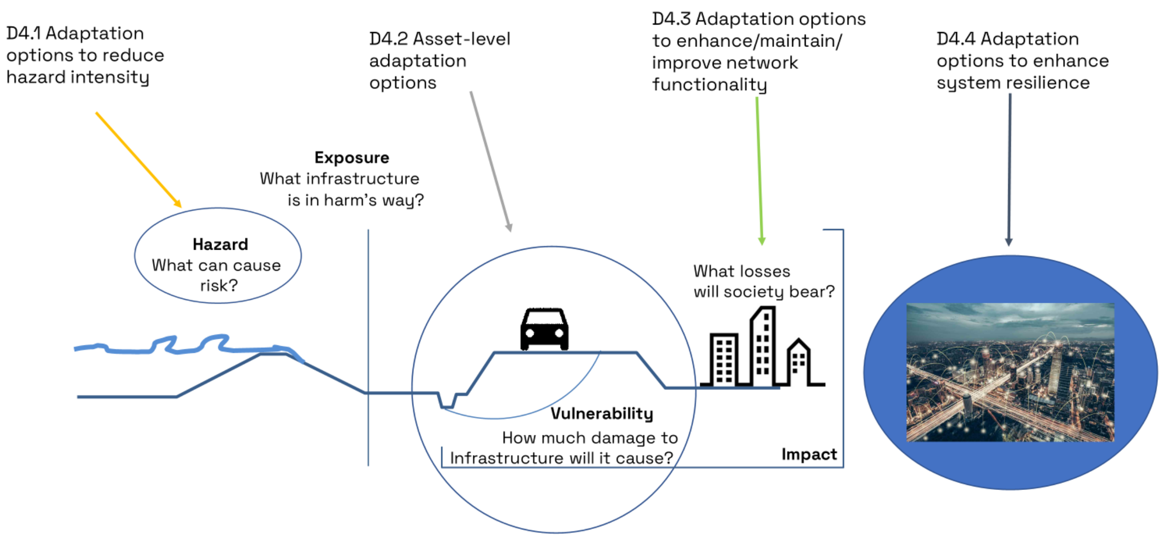

Figure 2. *Focus for each of the deliverables within Work Package 4 (WP4) Adapted from Bles et al. (2018)*

At the asset level, the effect of adaptation options in the performance of infrastructure is reflected in the fragility and vulnerability functions of assets – these concepts are introduced in deliverable D1.1 of MIRACA. In short, a fragility function or fragility curve of an asset describes the probability of reaching or exceeding a particular damage state (or one of various damage states) given a certain hazard intensity. The vulnerability function of an asset describes the potential damage to the asset given a certain hazard intensity. So the main difference between fragility and vulnerability functions is that the first links the probability of damage and hazard intensity, while the second links the potential damage and the hazard intensity (Nirandjan et al., 2024).

1.1. How does adaptation at asset level work

Asset-level adaptation of CI to climate change is done with respect to the hazards that an asset will be exposed to and is narrowly linked to the way in which an asset and the hazard interact. Because of this, the physical conditions leading to asset damage (such as water, heat, wind), the onset of these conditions (slow onset stress or sudden shock), and the asset-specific attributes that make it vulnerable to the hazard (construction material, mode of operation, etc) should be considered before effective adaptations can be implemented (Burton et al., 2005; de Paor et al., 2024). There may be several adaptation options that can reduce the impact of a hazard; however, further considerations must be taken to determine the viability of the adaptation option and

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the benefits expected from it (Burton et al., 2005). Some elements to consider before selecting an adaptation option are the following:

- *Asset type*. Some adaptation options may only be viable for specific asset types or designs, for example to short bridges as and not to all bridges, or only for buildings with parking or storage in the lower levels and not to any type of building (USAID, 2015).
- *Asset life cycle stage*. Whether the asset is being planned and not yet built, already built and operational, or in need of major maintenance determines the viability (and costs and benefits) of many adaptation options (de Paor et al., 2024). Already considering the climate hazards an asset will experience throughout its entire lifecycle *at the planning stage* will often be less costly than adapting or 'retrofitting' assets that are already operational. This is especially the case if the intervention requires temporarily shutting the asset off or modifying other assets. For example, raising a railway bridge will also require raising the tracks leading up to the bridge, and rail traffic is likely to be disrupted during this intervention. Furthermore, early involvement of all relevant parties in adaptation planning can help ensure buy-in into the project and prevent barriers from arising at a later stage (de Paor et al., 2024).
- *Disaster risk management (DRM) cycle stage*. Adaptations may be implemented prior to the emergence of a hazardous condition (prevention and preparedness), upon the occurrence of the hazard (response), or after the hazard has receded and CI is brought back into operation (recovery) (Figure 3) (de Paor et al., 2024).

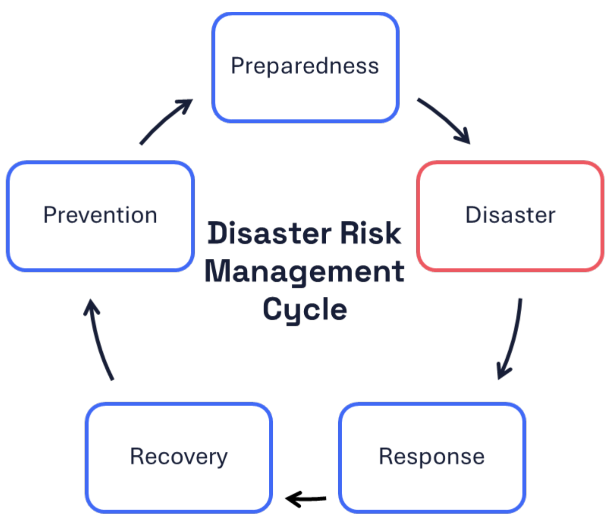

Figure 3. *Disaster Risk Management Cycle.*

- *Timeline of adaptation*. Some adaptations may be short-term solutions, while others are intended to last on the long-term. A more expensive, long-term

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adaptation may be attractive for an asset that will remain operational for a prolonged period, but not for one that will be decommissioned or replaced soon, in which case a short-term solution may suffice. On the other hand, investment in short-term solutions may compete for resources with longer term solutions (Lu & Nakhmurina, 2024).

- *Stakeholder involvement*. Different stakeholders will have to be involved depending on the asset that must be adapted and how it relates to other assets. Infrastructure owners and operators must frequently be involved in asset-level adaptations, but engaging stakeholders such as government entities, landowners, and users among others may also be necessary (de Paor et al., 2024).
- *Benefits*. Adaptation options may bring benefits to an infrastructure owner/operator. Those are directly linked to key performance indicators used by an operator/owner of an infrastructure asset. For example, accessibility to energy to the end user.
- *Co-benefits*. Adaptation options may bring additional benefits beyond what is linked to KPIs. An environmental co-benefit could be greenhouse gas reduction or improved air quality (Bles et al., 2023). An example of this is the use of green roofs to reduce heat stress and stormwater runoff, which brings environmental and social co-benefits, specifically, habitat creation for improved biodiversity and creation of spaces for socialization and community connection (O'Hara et al., 2022).
- *Trade-offs*. Some adaptation options may have negative implications which must be considered to prevent unintended consequences, such as additional maintenance costs or an increase in noise pollution. For example, using air cooling in data centres to reduce the impact of droughts may lead to a higher energy consumption (Anderson, 2023).
- *Urgency of action*: Whether an asset is imminently exposed to hazards is a factor when prioritising interventions. For example, thresholds exist upon which a system may become more frequently disrupted. Considering procurement and construction lead time when evaluating urgency of adaptations is necessary, as some projects may take long to complete (UNECE Inland Transport Committee, 2024). When an asset is damaged, the concept of 'build back better' includes building resilience during the reconstruction/recovery process to prevent recurrence of damages. (United Nations Office for Disaster Risk Reduction, 2017).
- *Alignment with national strategies & priorities.* Some adaptation measures may better align with other priorities, such as national strategies, in terms of their benefits or co-benefits. While this consideration is not related to the effectiveness of the adaptation measure, it may expedite planning, funding and execution. Furthermore, the identification of new risks or viable adaptation

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strategies should be considered when the national adaptation strategies are created and reviewed (European Commission, 2023).

This deliverable aims to give a birds-eye overview of proven and emerging adaptation options for common CI assets and to provide a starting point in understanding their viability and how their benefits of implementation can be estimated. Furthermore, a selected set of adaptations will be described in more depth.

Adaptation options can be modelled qualitatively, quantitatively, and semi-quantitatively. When qualitative methods are used, the aim is to describe whether and how an adaptation will be beneficial. In a fully quantitative model, the numerical benefits and trade-offs associated with an adaptation are determined and compared. It is often the case that a full quantitative analysis is not possible (e.g., when there is insufficient data) to appraise an adaptation option, in which case semi-quantitative methods can be adopted. In this deliverable, some methods that have been used to quantitatively appraise adaptation options are presented and some new metrics to appraise options that have not been applied before are proposed.

The outcomes of adaptation models can be used to inform decisions and analyse their implications for different stakeholders. Mapping the stakeholder field and understanding who pays for and who benefits from adaptation can bring clarity to investors and policymakers, for example. Furthermore, exploring how infrastructure systems will respond to hazards under different adaptations can help understand vulnerability hotspots and reveal opportunities to maximise societal benefits.

Adaptation at the asset level consists of implementing measures that change how each infrastructure asset responds to a hazard. This can be accomplished by reducing the vulnerability of the asset to the hazard, by reducing the exposure of the asset or its components to hazardous conditions, or by reducing the consequence of the asset being affected by the hazard. The specific mechanism that an adaptation measure involves determines how its benefits (avoided asset damage) are quantified.

1.1.1. Vulnerability reduction

Adaptation measures that reduce the vulnerability of an asset are those where a hazard of a given intensity is expected to cause less damage to the CI asset, than it would prior to implementing the adaptation. For example, a school built with unreinforced masonry is expected to experience more damage during an earthquake than one built with reinforced concrete when subjected to the same hazard intensity, making the use of more hazard resistant materials an adaptation that reduces vulnerability (Rincón et al., 2017). In modelling practice, this is reflected as a change in the damage function for the asset as seen in Figure 4.

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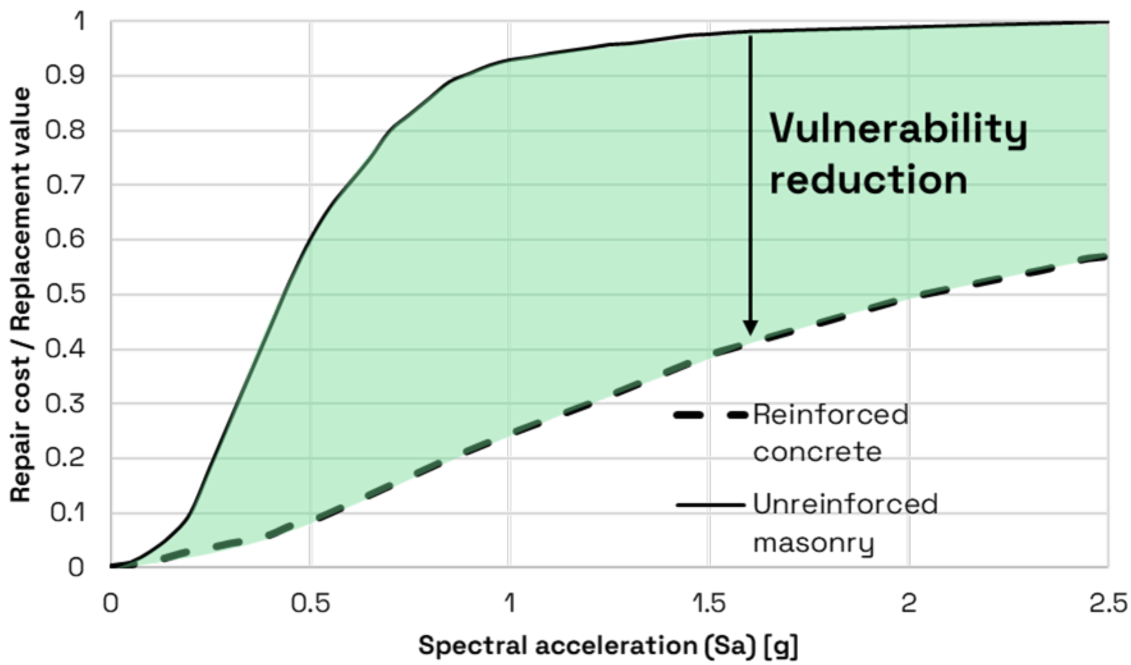

Figure 4. *Vulnerability reduction: Vulnerability curves for a school facility built with unreinforced masonry (baseline) and with reinforced concrete (adapted). Adapted from: Rincón et al., 2017.*

Likewise, vulnerability reduction can be probabilistically described as a hazard becoming *less likely* to cause an asset to be damaged to a certain extent; the probability of being in a damage state given a hazard intensity is reduced. In this context, often the term *fragility* is used. For example, an earthquake is less likely to cause damage to an electrical substation where the components of the substation are anchored, than to an electrical substation where they are not (FEMA, 2003; Lagos et al., 2020). In modelling practice, this is reflected as a shift to the right of the fragility curves of the asset as pictured in Figure 5.

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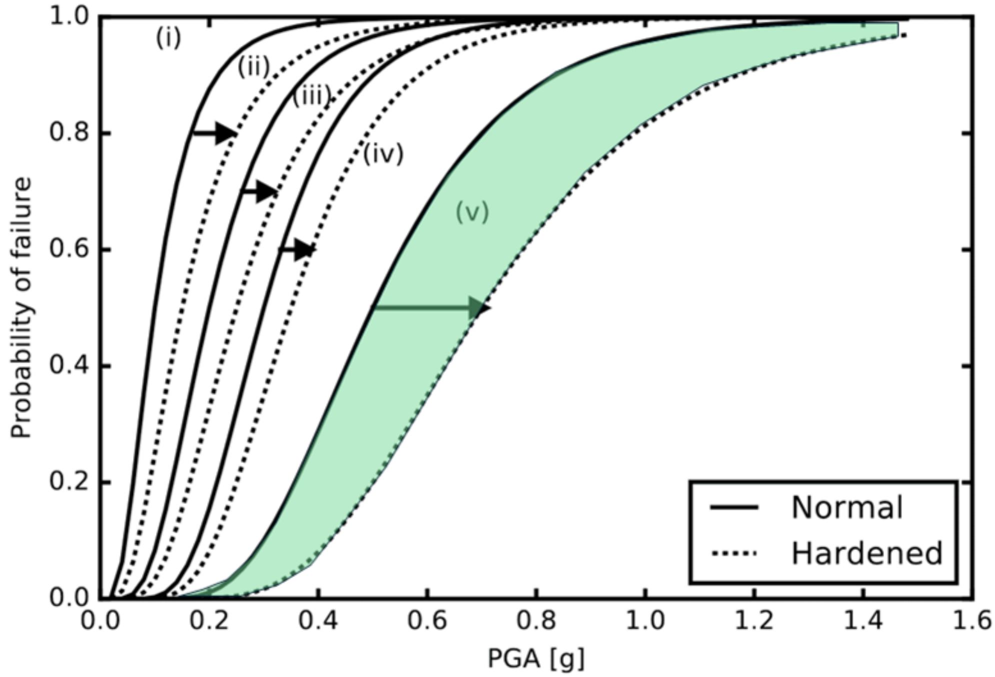

Figure 5. *Vulnerability reduction: Fragility curves for an electrical substation with 5 damage states:* (i) *no damage,* (ii) *minor,* (iii) *moderate,* (iv) *extensive, and* (v) *complete damage, indicating curves for the normal and hardened cases. Adapted from: Lagos et al., 2020.*

1.1.2. Exposure reduction

Some asset-level adaptations reduce the exposure of assets, or components of an asset, to a hazardous condition, preventing any damage to the asset until a higher intensity threshold is reached (De Ruig et al., 2019). An example would be elevating an asset, such as a section of rail tracks, above the expected flood elevation. In this case, the rail tracks would not be expected to suffer any damage until floodwaters rise above the design elevation. In modelling practice, this results in a shift of the vulnerability function as seen in Figure 6.

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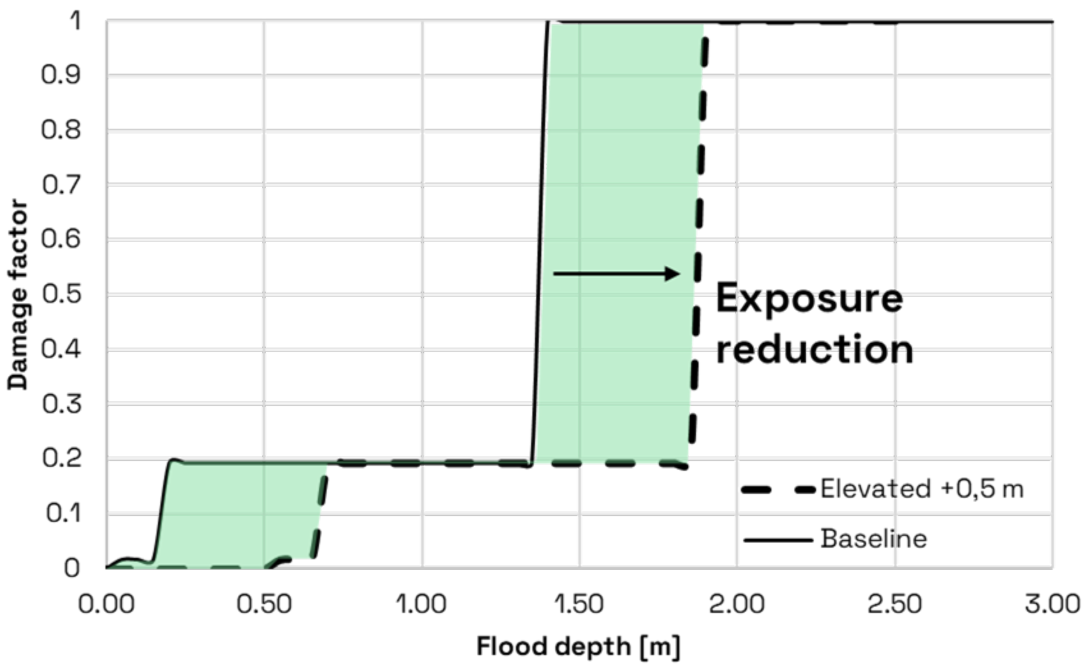

Figure 6. *Exposure reduction: Vulnerability curve of rail infrastructure that has been elevated to reduce the exposure to flooding. Reproduced and adapted from: Kellermann et al., 2015.*

1.1.3. Consequence reduction

Another way in which assets can be adapted is by reducing the consequences of damage to the asset. This can be achieved by designing assets to be damaged in a predictable way that is cheaper, easier, and quicker to repair. This approach often consists of introducing components that are weaker than the rest of the asset. Upon failure, these components make the rest of the asset less likely to be damaged. An everyday example can be seen in electrical fuses, which are ubiquitous in electrical installations to prevent overcurrent damaging a circuit; however, the same principle can be applied to many hazards and assets in adaptation practice. These adaptations can minimise repair costs and reduce the duration of asset outages as seen in Figure 7. Consequence reduction involves a change in the rebound capacity (ability to return to operation) and extensibility (ability to extend performance after disrupting events to avoid sudden and catastrophic failure) of the asset (Seager et al., 2017; Woods, 2015).

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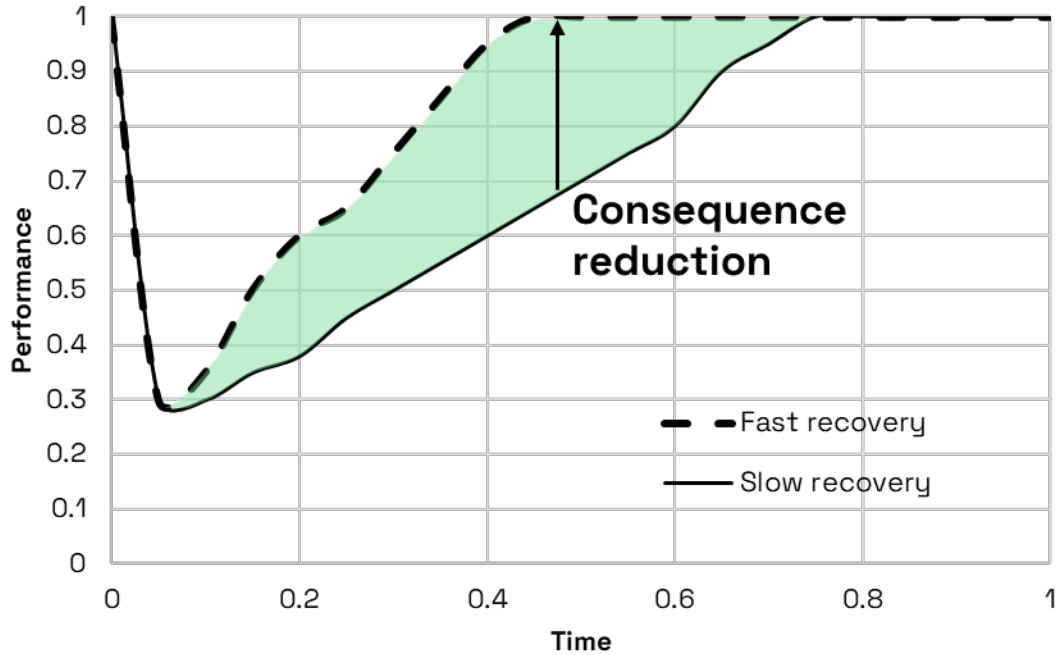

Figure 7. *Consequence reduction: Conceptual plot illustrating an adaptation where the performance of the asset can be reestablished quicker, leading to a fast recovery. Reproduced and adapted from: Hao et al., 2023*

In asset-level adaptation, consequence reduction focuses on the possibility and cost of repairing the asset and bringing it back to operation after it is disrupted by a hazard; however, reducing the consequences of individual asset failure can also reduce impacts at the network and system level by enabling quicker service and operations reestablishment.

1.2. Method

This deliverable provides an overview of adaptation options at asset level. This document is set up as a literature study. We identified what definitions to use for the different sectors and identify what options are available and group the adaptation options. This overview is given in section 1.3. We also reflected on how to include the adaptation measures into (modelling) practice for key adaptation options. This is described in Chapter 3.

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1.2.1. Literature review

A literature review was conducted to identify adaptation measures for each infrastructure to each of the hazards covered in the MIRACA project. The review used published and peer-reviewed journals as sources when these were available. Grey literature and news items were also considered as complementary sources; these include reports on implementation of adaptation measures, guidelines for adaptation, modelling manuals, datasheets from equipment manufacturers, and news reports outlining adaptation responses. We considered sources that described one or more infrastructure-specific adaptations or adaptation technologies for any of the hazards. When the adaptation was only mentioned but not clearly explained, the sources used were further consulted and were included as a reference too. When a source collected adaptations applicable to multiple infrastructures or to multiple hazards, these were also collected. The review was enriched with literature sources used or produced by the project partners. A list of the keywords used in the review can be found in Table 1.

Table 1. *Keywords used for literature review of asset-level adaptation options in D4.2.*

Transport	Power	Telecommunications	Healthcare, education	Hazards	Adaptation Options
Roads: Road, highway, roadway, street, motorway, pavement, embankment	**Different networks:** Power, electricity, oil, gas, fossil fuel, renewable energy	**Buildings:** Data centre, communication centre, telecommunications facility	**Healthcare buildings:** Hospital, clinic, healthcare centre, healthcare facility	**Flooding:** Flood, flooding, pluvial, fluvial, river flood, coastal flood, overflow, extreme rainfall	**Appraisal:** Adaptation appraisal, evaluation, assessment, performance, adaptation measures
Rail: Rail, station, railway, tracks, grade, subgrade, ballast, sleepers, embankment	**Power generation:** Power plant, power station, generation station, hydroelectric, thermal plant	**Equipment:** Antenna, telecommunications cable, cable, fibre optic, coaxial, LAN cable	**Education buildings:** School, university, college, library, laboratory	**Earthquakes:** Earthquake, quake, seismic, seismicity.	**Economic Appraisal:** cost-benefit analysis, multi-criteria analysis, net present value, benefit-cost ratio, cost avoidance
Bridges: Bridge, piles, abutments, decking, bearings, joints, foundation, substructure, superstructure	**Energy transmission:** Power cables, transmission cables, grid, transmission grid, transmission, circuit breaker, substation, transformer, tower, high-voltage			**Landslides:** Landslide, rockfall, mudslide, earthslip, earthfall, mass wasting, soil movement, land movement, slope movement, shallow instability, instability	**Vulnerability reduction:** Vulnerability, damage, damage reduction, prevention, mitigation.

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	network, medium-voltage network				
Tunnels: Tunnel, girder, lattice	**Energy distribution:** Power cables, distribution cables, grid, distribution grid, distribution, substation, transformer, medium-voltage network, low-voltage network			**Wildfires**: Wildfire, forest fire, brush fire, bushfire, fire.	**Risk reduction:** Risk reduction, risk mitigation, probability reduction, climate risk reduction, climate proofing
Airports: Airport, runway, terminal, control tower	**Other power infrastructure:** Pipelines, storage tank, gas storage, oil storage, tank farm, refinery, pumping plant, compressor station			**Windstorms:** Windstorm, wind, extreme wind, hurricane, wind gust, gusts.	**Hazard mitigation:** Hazard mitigation, mitigation, hazard reduction, hazard exposure, hazard-specific searches such as 'Flood mitigation' and 'Flood reduction'
Ports: Port, seaport, waterfront structures, warehouses, harbour, dock, wharf				**Heatwaves**: Heatwave, heat, extreme heat.	**Resilience:** Resilience, resiliency, building resilience, climate resilience, resilient, resilience planning
				Droughts: Drought, dry spell, dry period, water scarcity, water shortage	**Other:** Hardening, strengthening
				Compound: "Hazard 1" and "hazard 2". When the hazards occurred simultaneously, considered as compound **Consecutive**: "Hazard 1" and "hazard 2". When the hazards occurred in close succession but one did not cause the other, considered consecutive. **Cascading**: "Hazard 1" and "hazard 2". When one hazard occurred because of the other, considered cascading.	

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1.2.2. Selection of Key Adaptation Measures and Modelling practices

Nine adaptation options were selected from the overview of references. Our selection aimed at (1) providing a wide overview of different measures at asset level for the different sectors (Transport, Power, Telecommunications, Healthcare, Education) and hazards (Earthquakes, Landslides, Wildfires, Windstorms, Heatwaves, Drought and/or multi-hazard) while (2) putting emphasis on options with a strong link to the MIRACA use cases. Furthermore, we sought to cover different types of adaptation options including (green) Nature Based solutions (NBS) and (grey) engineered hard adaptations. Additionally, we reflected on whether the adaptation option is part of a compound, cascading or consecutive event and if modelling practices are more focused on vulnerability, exposure or consequence reduction. For each of these examples, it is explained how modelling can be done, and how appraisal of pros and cons could be executed, including a characterisation of the type of (co-)benefits.

1.3. Overview of key references for adaptation options

Several overviews of adaptation measures exist which can be used as reference for specific hazard and infrastructure combinations. It is common for these overviews to focus on a single hazard and to collect adaptation measures for multiple infrastructures to that hazard, or the other way around: to focus on a single infrastructure sector and aiming to cover all the applicable hazards. The most relevant overviews are captured and briefly described in Table 2.

In this deliverable, we aim to provide greater depth into specific adaptation options and present how asset-level adaptations can be used in modelling for specific case studies and applications; however, the previously indicated references contain additional adaptation options and further sector- or hazard-specific references that can be consulted.

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Table 2. *Descriptions and references of existing overviews and inventories of adaptation options.*

Description of overview adaptation measures	Key Reference
Inventory of adaptation options against *flooding* for infrastructure assets including *electricity substations and transformers, hospitals, communications buildings, and transportation hubs.*	FloodProbe - Escarameia & Stone, 2013
Inventory of adaptation options for *roads* to multiple climate hazard drivers, including *flooding, landslides, extreme heat, wildfires and extreme wind*	ICARUS - Bles et al., 2023; de Paor et al., 2024
Collection of good practices on sustainable and ecofriendly *roads*, including *flooding, landslides, extreme heat, and wildfires*	Green Roads toolkit - Asian Development Bank, 2024
Modelling framework for estimating risk to *multiple hazards*, such as earthquakes data for *power and transport* installations with anchored and unanchored components.	FEMA HAZUS - FEMA

2. Inventory of adaptation options

This section describes the consolidation of the literature review (See Section Literature review) separated per sector (Transport, Power, Telecommunications, Healthcare and Education). Some of the adaptation measures are applicable to different sectors, which are mostly those that affect buildings (e.g. Education and Healthcare), or that protect against the same hazard. Furthermore, some adaptations are beneficial to several hazards or may present trade-offs with other hazards. For each infrastructure sector, the main adaptation options to each hazard are presented with how they intervene against a hazard at the asset-level. Sector-specific tables compiling the adaptations reviewed can be found in Appendix 1. Asset-level adaptation tables by sector.

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2.1. Transport

2.1.1. Main overview of state-of-the-art

This section provides an overview of various asset-level interventions aimed at enhancing the disaster resilience of different elements of the transport sector, including roads, rail, ports and waterfront assets, airports (including runway, control tower, and facilities), tunnels, and bridges. Each intervention is linked to specific hazards such as floods, earthquakes, landslides, wildfires, windstorms, heatwaves, drought, and in some cases for multi-hazard scenarios as well.

2.1.2. Road network

As can be observed from Table 3, most of the asset level interventions identified for the road network address flood hazards. These include measures such as permeable pavement (Upadhyay et al., 2023), elevating segments (Bles et al., 2016), increasing culvert sizes (Bles et al., 2016), and improving drainage capacity and maintenance (Bles et al., 2016). Some interventions also focus on landslide and drainage management. The interventions are at the asset level (the pavement, roads, or bridges) and also involve management of the slope of adjacent terrain (Bles et al., 2016; de Paor et al., 2024; Vaciago et al., 2011) through surface run-off management or slopes stabilization. These measures are typically to be implemented in areas adjoining the asset, where road asset owners may not have direct jurisdiction. The lack of direct jurisdiction can sometimes be a cause of maladaptation as well, such as slopes that are cut to save space and reduce the burden of land acquisition (Robson et al., 2024).

Measures such as fire breaks (Low et al., 2023; H.-H. Wang et al., 2021), fire walls (Ricci et al., 2022), sprinkler systems (Kurowski & Bradley, 2022), fire and heat-resistant construction address wildfire and heat hazards (de Paor et al., 2024; European Committee for Standardization, 2004, 2005). There are a few examples for wind and drought hazards, such as installation of wind deflectors and pavement material replacement to ensure pavements are made with materials that are less sensitive to consolidation (de Paor et al., 2024).

A research gap remains on measures that protect road infrastructure against earthquakes, wildfires, heatwaves and droughts.

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2.1.3. Rail network

The rail network bears similarities to the road network in being linear infrastructure facilitating transportation, distribution or conveyance. Like (major) roads, railways are often built with some elevation, on embankments or other earthworks (Bles et al., 2016; Jacobs, Trafikverket, 2021). Interventions in the rail network also concentrate significantly on flood-related measures, including elevating segments, increasing drainage capacity, and improving stream connectivity of minor tributaries to main rivers (de Paor et al., 2024). These efforts are crucial during both the design and implementation stages to prevent flood damage and maintain rail functionality. Slope management (de Paor et al., 2024; Vaciago et al., 2011) and fire-resistant construction (European Committee for Standardization, 2004, 2005) are key for landslide and wildfire resilience, respectively. Like roads, there are certain measures that could lie beyond the right of way of the rail network owners especially in the case of rail network on forest land or in mountainous areas. Wind is a significant hazard especially in mountainous areas (J. Wang et al., 2024) and the installation of wind deflectors (de Paor et al., 2024) is a noted solution. Noted interventions for earthquake, wildfires, and windstorms are sparse, highlighting a gap that could be addressed through future research and targeted adaptation strategies.

2.1.4. Bridges

For bridges, the literature is primarily focused on flood protection and seismic resilience (Table A1). In the case of flooding, one of the main risks to bridges comes from scour, where high flows erode the sediment around the bridge's foundations, potentially debilitating them and causing its failure (Hao et al., 2023). Designing bridges to withstand high flows is essential to guarantee their stability in front of flooding. In the case of earthquakes, interventions such as installing structural fuses (FEMA, 2003), remodelling slopes (Vaciago et al., 2011), and reinforcing bridge footings and foundations are essential to ensure bridge stability. Hazard or risk conscious bridge type selection and design, considering future climate separately from historical climate, can enhance resilience (USAID, 2015); choices may be made on the type of expansion joints and the building materials of the bridge, for example (Nasr et al., 2020; USAID, 2015). Debris basins and deflectors can also help protect the bridge from flood debris, however, these require maintenance and may lead to ecological impacts, limiting their applicability (Mai & Nguyen, 2020). Extreme heat is also a significant hazard for bridges; high temperatures can increase the rate of deterioration and cause damage due to thermal expansion. Thermal expansion can also cause movable bridges to become stuck,

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requiring cooling to return to operations (Mariam Ali, 2021; Nasr et al., 2020). Since there are few long-term adaptations for heat, this hazard merits additional attention. The emphasis on adaptations to windstorms and wildfires is minimal as understood from Table A1, indicating potential areas for further development.

2.1.5. Tunnels

Tunnel interventions are geared towards flood, wildfire and landslide protection as indicated in Table A1. Some of the noted interventions include improving linings to prevent ground water infiltration (Upadhyay et al., 2023), increasing drainage and sump pumping (Upadhyay et al., 2023), implementation of fire breaks (Ricci et al., 2022), and slope management (Vaciago et al., 2011) in the vicinity of the tunnel. These interventions are particularly relevant during the design and implementation stages to enhance the structural integrity of tunnels. Fire-resistant construction (European Committee for Standardization, 2004) and deployable sprinkler systems (Kurowski & Bradley, 2022) address wildfire threats. However, interventions for earthquakes are not prominently featured, suggesting areas for future focus. Electrical systems within tunnels (especially tunnels of more than 1 km in length) (European Union Agency for Railways, 2018) is also important and the impact of hazards on the electrical systems in the tunnels remain under-explored. Ventilation is critical for long tunnels (Bring et al., 1997), and any hazard impacting the power supply to the heat, ventilation and air conditioning units could significantly impact people travelling in the tunnel.

2.1.6. Airports

Airport infrastructure is composed of a variety of elements, including buildings, telecommunications installations, and runways and other paved areas. The adaptation options that are available to these infrastructures are very similar to those applicable to other assets of similar construction (Table A1). For example, runway vulnerability is very similar to road vulnerability and several adaptation options may be applicable for airports in the same way they are for roads. These adaptations include improving drainage (Burbidge, 2018; Eurocontrol, 2021) to prevent flooding of runways as well as elevating vulnerable electrical equipment above flooding levels (Burbidge, 2018), reinforcing infrastructure to withstand stronger winds, and resurfacing runways with more heat-tolerant materials against extreme heat, as well as accounting for increased cooling in airport design and retrofit (Burbidge, 2018).

No adaptations were found for landslides; however, there is also limited literature on landslide risk to airports.

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2.1.7. Port and waterfront assets

Port and waterfront interventions are primarily aimed at flood protection (Table A1), with measures such as dry floodproofing (Massachusetts Port Authority, 2014), and breakaway walls for structures and facilities (FEMA, 2021). Fire-resistant construction (European Committee for Standardization, 2004) can help reduce damage from wildfires for structures that are exposed to this hazard. In the case of Oil and gas storage facilities within ports, the adaptation measures are like those for oil and gas infrastructure, and guidance should be sought in those chapters. Similarly, telecommunications equipment within the port can use the same adaptation strategies used in the telecommunications sector. However, the table shows limited emphasis on windstorms drought, landslides and earthquakes, pointing to potential areas for further research and development in port resilience strategies.

In summary, while the table provides a comprehensive overview of climate adaptation interventions across various elements of the transport sector, it also highlights areas that require further exploration.

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Table 3. *Table of adaptation options for the transport sector including roads, railways, ports, airports, tunnels and bridges.*

Asset level adaptations for transport sector	Transport asset						Hazard focus								References
	Road	Rail	Port & waterfront	Airport	Tunnels	Bridge	Flood	Earthquake	Landslide	Wildfire	Windstorm	Heatwave	Drought	Multi-hazard	
Elevating segment above high water level	X	X					X								Bles et al., 2016
Increase culvert size or replace with small bridge	X	X					X								Bles et al., 2016
Increase drainage capacity and maintenance	X	X					X								Bles et al., 2016
Debris basins for bridges						X	X		X					X	Bles et al., 2016
Installation of flexible revetments as armoring or flow deflecting plates						X	X								Bles et al., 2016
Slope management (remodeling, vegetation cover, installing catch trenches, rockfall nets, rock sheds)	X	X			X	X	X		X					X	Bles et al., 2016; G. Vaciago et al., 2011; de Paor et al., 2024
Scour prevention through strengthening of bridge footings and foundation						X	X								Bles et al., 2016; USAID, 2015
Install wind deflectors	X	X				X					X				de Paor et al., 202
Improve stream connectivity	X	X					X								de Paor et al., 2024
Replace pavement material for less sensitive material to consolidation due to drought	X	X											X		de Paor et al., 2024
Structural surcharge to counter uplift					X		X								de Paor et al., 2024
Improve lining to prevent ground water infiltration					X										de Paor et al., 2024
Revised standards for design of excavations and light weight fills					X										de Paor et al., 2024
Heat resistant design	X	X	X			X						X			de Paor et al., 2024; European Commission, 2021
Design buildings as floating or amphibious				X			X								Escarameia & Stone, 2013
Elevating buildings			X	X			X								Escarameia & Stone, 2013; Yang et al., 2018
Fire-resistant construction	X	X	X		X	X				X					European Committee for Standardization, 2004; European Committee for Standardization, 2005; USAID,
Installing structural fuses				X		X		X							Farzampour, 2022; Saravanan et al., 2018
Seismic bracing/anchoring components, isolation and damping				X		X		X							FEMA, 2003; Nakamura & Okada, 2019; Kandemir et al., 2011
Breakaway walls for port structures			X				X								FEMA, 2021
Remodeling the slope	X	X			X	X			X						G. Vaciago et al., 2011; de Paor et al., 2024
Surface protection and erosion control	X	X					X		X					X	G. Vaciago et al., 2011; de Paor et al., 2024
Deployable sprinkler systems					X	X				X					Kurowski & Bradley, 2022
Dry floodproofing			X				X								Massachusetts Port Authority, 2014
Permeable pavement	X						X								Upadhyay et al., 2023
Increasing drainage and sump pumping capacity				X	X		X								Upadhyay et al., 2023; Coalition for Disaster Resilient Infrastructure CDRI; , 2023
Hazard conscious bridge type and components selection						X	X			X		X		X	USAID, 2015
Elevating bridges						X	X								USAID, 2015
Building fire breaks & Fire wall	X	X		X	X	X				X					Wang et al., 2021; Low et al., 2023; Ricci et al., 2022

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2.2. Power

2.2.1. Main overview of state-of-the-art

Different parts of the power system are vulnerable to different hazards; furthermore, failure cascades within power system and to other CI systems are common. Power system failure cascades are bound to occur upon the failure of multiple components (though a single fault can sometimes be tolerated by design) (Diamenu & Normanyo, 2017; Kristjónsson et al., 2013). Table 4 provides a detailed overview of various interventions aimed at enhancing the resilience of the power system (electric power, natural gas, and oil networks) against multiple hazards. These interventions are crucial for ensuring the continuous and reliable operation of power infrastructure during and after extreme weather events and geohazards that may threaten it. The specific interventions, their applicable infrastructure, and the hazards they address are outlined below.

2.2.2. Power generation assets

These assets include generation units such as power plants (thermal, geothermal, nuclear), wind and solar farms, and hydropower plants. Since generation assets are at the source of all power networks, disruptions will cascade to other elements of the power system.

Power generation assets threatened by flooding (or the vulnerable parts of the asset, such as control rooms) can be protected by building them above the expected flooding level (FEMA, 2013; Gkika et al., 2023) or through dry floodproofing (Escarameia & Stone, 2013; FEMA, 2013). Oil and gas refineries are closely related to power generation assets (specifically thermal power plants). Refineries may also be protected through dry flood-proofing, i.e. building a flood wall around the refinery (Hidayat & Thomiyah, 2022). Assets where structural damage lateral loading forces during floods is the main concern can benefit from the installation of breakaway walls. Breakaway walls are non-structural sacrificial walls that are designed to fail before the building structure is damaged (FEMA, 2021). They are commonly used to protect structures from wave action during coastal flooding; consideration should be given to the components that will be flooded when these walls fail.

Earthquakes are also capable of damaging power generation infrastructure. There are three main ways to protect these assets from earthquakes. The first is by

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using seismic isolation and damping technologies which prevent the full force of an earthquake from reaching the vulnerable assets. Devices such as shock absorbers, seismic isolators and viscous (hydraulic) dampers can be used. (Nakamura & Okada, 2019; Sahin, 2014; Xu et al., 2024). Passive, active, and hybrid seismic isolations systems exist (Xu et al., 2024). The second is by bracing and anchoring components within the plant, allowing the building to move as a unit and preventing additional damage within the structure (FEMA, 2003; Lagos et al., 2020). The third is by installing structural fuses. These are sacrificial elements designed to dissipate seismic energy during earthquakes, resulting in damage only to intended elements while maintaining the primary members of the structure undamaged (Saravanan et al., 2018). Fuses can be replaced in an easy and cost-effective manner, reducing repair efforts and recovery times (Saravanan et al., 2018). Some of these technologies are already integrated into newer infrastructural designs but replacement of old installations may bring significant adaptation benefits (Nakamura & Okada, 2019).

Power generation assets can be protected from wildfires by creating fire breaks around them (Low et al., 2023; H.-H. Wang et al., 2021), and by installing fire walls within them (or between them in the case of multiple buildings) (European Committee for Standardization, 2004; Ricci et al., 2022). These adaptations reduce the rate of spread of fire to critical components. The use of fire-resistant construction materials should also be considered (European Committee for Standardization, 2004, 2005).

Adaptation options for windstorms and landslides are limited in the case of power generation assets. The use of anchoring and wind-tolerant construction should be considered (European Committee for Standardization, 2010; Hallegatte et al., 2019). Increasing the resistance and stiffness of buildings exposed to landslides (i.e. strengthening) may reduce the damage in case of small, shallow landslides (Vaciago et al., 2011).

Heatwaves can have a detrimental effect on power generation units, reducing their efficiency and cooling capacity (European Commission, 2021; Hallegatte et al., 2019). Considering additional generation and cooling capacity may be adequate to counter these conditions (US Department of Energy, 2016), however, no other adaptation options have been identified.

Droughts also affect power generation in different ways. In the case of hydroelectric plants, there are no asset-level adaptation options, since water is their driving element; hazard- and system-level adaptation measures may still be effective (covered in D4.1 and D4.4). For other generation assets, the use of alternate cooling means (such as air cooling) and of closed-loop cooling systems is possible to minimise water use and enable operation during low water conditions (Hallegatte et al., 2019; US Department of Energy, 2016).

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Table 4. *Table of adaptation options for the power sector including the electric, natural gas, and oil networks.*

Asset level adaptations for power sector	Energy network & assets			Hazard focus								References
	Electric Power Network	Natural Gas Power Network	Oil Network	Flood	Earthquake	Landslide	Wildfire	Windstorm	Heatwave	Drought	Multi-hazard	
Dry floodproofing	Substations, Power Plants	Compressor Stations, Refineries, Storage Tank Farms	Refineries, Pumping Plants	X								FEMA, 2013; Escarameia & Stone, 2013; FEMA, 2013; FEMA, 2021; Hidayat & Thomiyah, 2022
Elevating buildings	Substations, Power Plants	Compressor Stations	Refineries, Storage Tank Farms	X								FEMA, 2013; Gkika et al., 2023; Escarameia & Stone, 2013; FEMA, 2013; Hidayat & Thomiyah, 2022
Elevating sensitive components	Transmission, Distribution	Pipelines, Compressor Stations, Storage Tank Farms	Refineries, Pipelines, Pumping Stations, Storage Tank Farms	X								FEMA, 2013; Gkika et al., 2023; US Department of Energy, 2016; Ebad Sichani et al., 2020; Hallegatte et al., 2019
Building breakaway walls	Power Plants		Refineries	X								FEMA, 2021
Placement of pipelines below elevation of maximum scour and outside limits of lateral channel migration		Pipelines	Pipelines	X								United States Government, 2019; FEMA, 2013
Anchoring components against flotation, lateral movements		Pipelines, Compressor Stations, Storage Tank Farms	Pipelines, Storage Tank Farms	X								United States Government, 2019; FEMA, 2013
Installing breakaway cables	Transmission, Distribution			X			X				X	US Department of Energy, 2016
Reconductoring: Composite-based low sag cables	Transmission, Distribution						X					Chojkiewicz et al., 2024
Reconductoring: Smart Wire Grid (distributed power flow control)	Transmission								X			Chojkiewicz et al., 2024; Sadoudi et al., 2021; Abdin et al., 2019
Heat-tolerant design	Substations, Power Plants	Compressor Stations, Pipelines	Refineries, Pumping Plants						X			Cruz & Krausmann, 2013; European Commission, 2021
Closed-loop water cooling design	Power Plants, Substations	Compressor Stations	Refineries, Pumping Plants							X		Cruz & Krausmann, 2013; European Commission, 2021; Abdin et al., 2019; Hallegatte et al., 2019
Alternate cooling sources	Power Plants	Substations	Refineries, Storage Tank Farms							X		Cruz & Krausmann, 2013; European Commission, 2021; Hallegatte et al., 2019
Fire-resistant construction	Substations, Power Plants	Compressor Stations, Pipelines	Refineries, Pumping Plants, Storage Tank Farms				X					European Committee for Standardization, 2004; European Committee for Standardization, 2005
Installing structural fuses	Power Plants		Refineries		X							Farzampour, 2022; Saravanan et al., 2018
Isolation and damping	Substations, Power Plants	Pipelines, Compressor Stations	Refineries		X							FEMA, 2003; Sahin, 2014; Nakamura & Okada, 2019; Xu et al., 2024
Increasing the resistance and stiffness of the construction (Strengthening)	Substations, Power Plants	Compressor Stations	Refineries, Pumping Plants			X						G. Vaciago et al., 2011; Urlainis & Shohet, 2022
Replace overhead network with aerial-bundled conductors	Distribution							X				Hallegatte et al., 2019
Seismic bracing/anchoring components	Substations, Power Plants, Transmission, Distribution	Pipelines, Compressor Stations, Storage Tank Farms	Refineries, Pipelines, Pumping Plants, Storage Tank Farms		X							Hasanzad & Rastegar, 2022; FEMA, 2003; Nakamura & Okada, 2019; Farzampour, 2022; Saravanan et al., 2018
Use of more durable materials	Transmission, Distribution				X			X			X	Hasanzad & Rastegar, 2022; Vladimir Shamaev et al., 2018; Gupta et al., 2023; Hallegatte et al., 2019
Wind-tolerant construction	Substations, Power Plants	Compressor Stations, Pipelines	Refineries, Storage Tank Farms					X				He et al., 2018; Abdelhady et al., 2022; Popović et al., 2020; Barto & Gardoni, 2021; Hallegatte et al., 2019
Building fire walls	Substations, Power Plants	Compressor Stations, Pipelines, Storage Tank Farms	Refineries, Storage Tank Farms				X					Ricci et al., 2022
Installing load shedding controllers	Substations								X			Sadoudi et al., 2021; Abdin et al., 2019
Building underground power lines	Transmission, Distribution							X				Souto & Santoso, 2020; Popović et al., 2020
Building fire breaks	Substations, Power Plants	Compressor Stations, Pipelines	Refineries, Pumping Plants, Storage Tank Farms				X					Wang et al., 2021; Low et al., 2023
Installing shock absorbers		Pipelines	Pipelines		X							EarthQuake Dampers Ltd, 2024

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2.2.3. Power transmission grid

The power transmission grid is composed of transmission cables which span long distances supported by transmission towers or poles and substations which aid transmission along the line.

Transmission cables are most vulnerable to the effects of heatwaves, wildfires, and windstorms. An effective adaptation option is targeted undergrounding of cables (Souto & Santoso, 2020), which minimises the exposure to these hazards, however, at a large cost (Hallegatte et al., 2019; US Department of Energy, 2016). Underground cables may be vulnerable to other hazards, like flood-induced soil movements or landslides (Koks et al., 2022)Another common option (also applicable to flooding) is the use of breakaway cables, which are designed to safely detach during extreme conditions to prevent cascading failures (US Department of Energy, 2016).

For windstorms, strengthening poles and adding additional support can help reduce damage to poles and transmission lines (US Department of Energy, 2016). In the case of heatwaves and wildfires, an emerging adaptation option known as "reconductoring" entails the replacement of old cables with newer technologies, such as advanced composite-core conductors. This adaptation measure was initially investigated as a means to increase transmission capacity at low cost; power transmission or distribution cables are replaced with new conductors, while conserving the original poles that support them (Chojkiewicz et al., 2024). Reconductoring can be implemented on grids that use aluminium conductor steel reinforced (ACSR) cables. These cables are lighter and thinner, yet stronger than their counterpart. Furthermore, they can withstand higher temperatures and exhibit lower sag (Chojkiewicz et al., 2024). These conductors can also include an optical cable line for temperature and elongation monitoring, allowing power flow control measures to be implemented (Abdin et al., 2019; Sadoudi et al., 2021). They may also include insulation-based wildfire protection (Chojkiewicz et al., 2024). More research is required to determine the viability of this technology, specifically as an adaptation measure.

Earthquakes may also affect the power transmission grid; the use of more durable materials (Gupta et al., 2023; Hasanzad & Rastegar, 2022; Vladimir Shamaev et al., 2018) as well as seismic bracing and additional support can reduce damages (FEMA, 2003; Hasanzad & Rastegar, 2022).

Only some components of the transmission system are vulnerable to flooding, since most of the cables are built well above flooding levels. These components can also be elevated to prevent damages (FEMA, 2013; Gkika et al., 2023).

Drought can cause uneven land subsidence, causing transmission poles to angle and transmission lines to tense or sag; developing adaptation options for this hazard is

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relevant, however, we are currently limited to monitoring the deformation (for example, through remote sensing) (Jin et al., 2022).

While landslides can also damage the transmission grid (poles, in particular), no adaptation options exist to counter this hazard.

2.2.4. Substations

Substations are electrical network assets that are located along the electrical grids to perform various functions, such as transforming or regulating voltage. The adaptations that can benefit specific substations depend on their function and the way they are built. Some relevant aspects include whether they are built in the open or within a building structure and their criticality within the network.

Adaptation options to flooding focus on elevating the substation above flooding levels (FEMA, 2013; Gkika et al., 2023) and the use of dry floodproofing (Escarameia & Stone, 2013; FEMA, 2013). Another adaptation option for substations is the use of amphibious or floating design (Escarameia & Stone, 2013). This allows the possibility of floating above flooded terrain to prevent damage. In the case of floating structures, they are permanently located on water, while amphibious structures are capable of floating when water levels rise but are generally resting on firm ground (de Graaf et al., 2012). Amphibious structures tend to have elevated costs as they require a ground foundation, and a floating foundation; however, they enable the construction of water-sensitive infrastructure on floodplains and other floodable terrain such as water retention areas (de Graaf et al., 2012).

Electric substations can be adapted for earthquakes by bracing and anchoring vulnerable components and using seismic isolation and damping (FEMA, 2003; Nakamura & Okada, 2019; Xu et al., 2024). In the case of landslides, increasing the resistance and stiffness of exposed buildings (i.e. strengthening) may reduce the damage in case of small, shallow landslides (Vaciago et al., 2011). For windstorms, some damage may be mitigated by using wind tolerant construction (European Committee for Standardization, 2010; Hallegatte et al., 2019).

Adaptation of substations to wildfires can happen similarly to the case of power generation plants, by creating fire breaks around them (Low et al., 2023; Wang et al., 2021), and by installing fire walls within them (or between them in the case of multiple buildings) (European Committee for Standardization, 2004; Ricci et al., 2022), as well as using fire-resistant construction materials (European Committee for Standardization, 2004, 2005). The same is the case for droughts, where adaptation options revolve around using alternate means of cooling and closed loop water cooling designs (Hallegatte et al., 2019; US Department of Energy, 2016).

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Several asset-level adaptations exist for heatwaves in sub-stations. Aside from using heat-tolerant design and building in additional cooling capacity into the substation design, substations may be equipped with load shedding controllers (ABB, n.d.), as part of a power flow control system. The use of smart conductors and power flow control systems can enable operators to make better use of available energy across all the assets of the electrical system (ABB, n.d.; Sadoudi et al., 2021). Power flow control occasionally relies on load shedding in emergency situations where demand cannot be met, reducing the service supplied in a controlled manner or by implementing intermittent supply regimes; however, the value comes from "intelligent" shedding, by shedding loads with the least impact (Abdin et al., 2019; Sadoudi et al., 2021).

2.2.5. Power distribution grid

The power distribution grid is meant to deliver electricity to the end users. In some regions, the distribution grid is largely built underground and is therefore less exposed to most hazards addressed in this document. Grids built above ground are more exposed to the elements and therefore, an exposure-oriented adaptation option is the targeted undergrounding of these cables (Hallegatte et al., 2019; US Department of Energy, 2016). Nevertheless, underground grids also have specific vulnerabilities, such as riverbed erosion (during river peak flows) that uncovers cables that were dug under the river bed to cross the river (Koks et al, 2022).

In the case of flooding, elevating components that are under the expected flood level is a viable adaptation measure (FEMA, 2013; Gkika et al., 2023), as well as the use of breakaway cables (US Department of Energy, 2016)

The adaptation options for earthquakes are the use of more durable materials (Gupta et al., 2023; Hasanzad & Rastegar, 2022; Vladimir Shamaev et al., 2018) as well as seismic bracing and additional support can reduce damages (FEMA, 2003; Hasanzad & Rastegar, 2022), particularly for aboveground grids.

In the case of wildfires and windstorms, an additional adaptation option that can be used for the distribution grid is the use of aerial bundled conductors to replace existing bare conductors (Muhs et al., 2020); these offer better resistance to wind (Hallegatte et al., 2019), and also reduce the likelihood of sparks arising from the contact of conductors with vegetation, preventing wildfires from initiating, as opposed to reducing their vulnerability or exposure to them (Hallegatte et al., 2019).

No adaptation options have been identified for landslides and for heat waves for the power distribution grid, these remain as gaps in existing research.

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2.2.6. Oil and gas pipelines

Pipelines are vulnerable to multiple climate hazards; similarly to distribution grids, these pipelines can be built aboveground and underground. Where pipelines are located relative to the ground will determine the specific hazards they are exposed to and the specific adaptation options that are viable for them.

In the case of flooding of above ground pipelines, elevating vulnerable components, such as vents, valves, and pressure regulators, above the expected flooding level is recommended (FEMA, 2013; United States Government, 2019), as well as anchoring pipelines to prevent flotation, collapse, and lateral movements leading to rupture (FEMA, 2013). In the case of underground installations, adaptations rely on burying pipelines below the level of maximum scour and outside the bounds of river channel migration (FEMA, 2013).

Pipelines can be strengthened or hardened against windstorm and earthquake damage, through stiffening of supporting structures and bracing of components and pipes (He et al., 2018). Shock absorbers can also be used for pipelines to improve their resistance to vibration (EarthQuake Dampers Ltd, 2024).

Wildfires can affect pipelines directly or by mobilising debris material upon rainfall or gusts. Fire breaks and fire walls for critical installations are relevant adaptations (Low et al., 2023; Ricci et al., 2022; Wang et al., 2021).

Drought and flooding can cause the ground to compact, shifting and causing damage to pipelines. Remote monitoring can help to improve continuous maintenance and inspection, leading to reduced damage; this includes installing sensing devices to enable this process (Cruz & Krausmann, 2013).

2.2.7. Fuel storage facilities

Fuel storage facilities can be adapted through the same measures as oil and gas pipelines (FEMA, 2013; United States Government, 2019). Strengthening of facility foundations and robust construction can reduce damage from floods, earthquakes, landslides, and windstorms (Escarameia & Stone, 2013; FEMA, 2003, 2013).

Fire walls (Ricci et al., 2022) and fire breaks (Low et al., 2023; H.-H. Wang et al., 2021) can also be used to slow the spread of fire in case of wildfires.

Further research can explore the extent to which fuel storage facilities are affected by drought and possible adaptation options.

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2.3. Telecommunications

Telecommunications assets can be divided into buildings that house telecommunications equipment (e.g., network operations centres, data centres) and equipment and accessories that may be outdoors (e.g., antennas, baseband units, masts). Table 5 provides an overview of various asset-level interventions for climate adaptation of telecommunications assets. It lists specific interventions and relates them to the hazards they address. Each intervention is mapped to specific hazards, highlighting the focus areas and identifying gaps that need further exploration.

For flood hazards, interventions focus on dry floodproofing (buildings and cable ducts) (Anakhov et al., 2020), elevating buildings (Escarameia & Stone, 2013; Gkika et al., 2023), designing as floating or amphibious structures and wet flood-proofing (specifically for data centres) (Escarameia & Stone, 2013), building breakaway walls (FEMA, 2021), and installing breakaway cables (Gkika et al., 2023). Floodproofing and elevating critical infrastructure are essential to maintain communication services during and after flood events.

Earthquake adaptation is addressed through several interventions, including seismic bracing and anchoring components (Nakamura & Okada, 2019), isolation and damping (Anakhov et al., 2020), installing vibration controlling or mitigating systems (International Telecommunication Union (ITU-T), 2012), installing structural fuses with ductile materials and technology (Saravanan et al., 2018), and general strengthening (International Telecommunication Union (ITU-T), 2012). These interventions ensure that telecommunications infrastructure can withstand seismic hazards, protecting both the physical assets and the continuity of essential telecommunication services. Strengthening telecommunications towers and related infrastructure is vital to avoid service disruptions during earthquakes.

Interventions for landslide hazards in telecommunications facilities include avoidance of landslide prone areas and general strengthening of structures (International Telecommunication Union (ITU-T), 2012). This measure is crucial for facilities located in hilly or sloped areas where the possibility of landslides is higher (Vaciago et al., 2011).

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Table 5. *Table of adaptation options for the telecommunications sector.*

Asset level adaptations for telecommunications sector	Hazard focus								References
	Flood	Earthquake	Landslide	Wildfire	Windstorm	Heatwave	Drought	Multi-hazard	
Dry floodproofing (buildings and cable ducts)	X								FEMA, 2013; Gkika et al., 2023; Escarameia & Stone, 2013; Anakhov et al., 2020
Elevating buildings	X								FEMA, 2013; Gkika et al., 2023; Escarameia & Stone, 2013
Designing as floating or amphibious	X								Escarameia & Stone, 2013
Wet flood-proofing (for data centers)	X								Escarameia & Stone, 2013
Building breakaway walls	X								FEMA, 2021
Installing breakaway cables	X				X			X	US Department of Energy, 2016
Seismic bracing/anchoring components		X							FEMA, 2003; Nakamura & Okada, 2019
Isolation and damping		X							FEMA, 2003; Nakamura & Okada, 2019; Anakhov et al., 2020
Installing vibration controlling or mitigating systems		X							International Telecommunication Union ITU-T, 2012
Installing structural fuses and use of ductile materials and technology		X							Farzampour, 2022; Saravanan et al., 2018; Athanasiou et al., 2023
Increasing the resistance and stiffness of the construction (Strengthening)		X	X		X			X	G. Vaciago et al., 2011; Athanasiou et al., 2023; Balkaya, 2024; Anakhov et al., 2020; International Telecommunication Union ITU-T, 2012
Building fire breaks				X					Wang et al., 2021; Low et al., 2023; International Telecommunication Union ITU-T, 2012
Building fire walls				X					Ricci et al., 2022
Fire-resistant construction				X					European Committee for Standardization, 2004; European Committee for Standardization, 2005; Anakhov et al., 2020; International Telecommunication Union ITU-T, 2012
Shrouding (radomes and enclosures)					X				Halat et al., 2015
Heat-tolerant design						X			European Commission, 2021
Closed-loop cooling systems							X		Anderson, 2023
Air-side economizers							X		Anderson, 2023

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Wildfire adaptation in telecommunications facilities includes building fire breaks (Low et al., 2023), constructing fire walls (Ricci et al., 2022), and fire-resistant construction (Anakhov et al., 2020). These measures ensure that telecommunications facilities can withstand and prevent the spread of fires, thereby safeguarding the infrastructure and maintaining service continuity. Wildfires can severely impact communication services (The Canadian Press, 2024), making these interventions crucial.

For windstorms, the interventions focus on installing breakaway cables (US Department of Energy, 2016) and shrouding (radomes and enclosures) (Halat et al., 2015). Ensuring that telecommunications facilities can withstand strong winds is vital to maintain the integrity of the infrastructure and the safety of the services.

Heatwave adaptation interventions include heat-tolerant design and construction materials (European Commission, 2021), closed-loop cooling systems, and air-side economizers (Anderson, 2023).

In summary, while the table provides a detailed overview of climate adaptation interventions for telecommunications facilities, it also highlights areas requiring further exploration, such as additional measures for landslides, windstorms, and heatwaves. Addressing these gaps will enhance the overall resilience of telecommunications facilities against various environmental hazards, ensuring continuous and reliable communication services during and after extreme weather events.

2.4. Building adaptations

2.4.1. Healthcare

Table 6 provides a comprehensive overview of various asset-level interventions for climate adaptation of healthcare facilities. It maps each intervention to specific hazards, highlighting the focus areas and identifying the gaps that need further exploration.

For flood hazards, interventions include both dry and wet floodproofing methods (Escarameia & Stone, 2013), elevating buildings (Green Climate Fund, 2021), and designing as floating or amphibious structures (Escarameia & Stone, 2013). Building breakaway walls (FEMA, 2021) may play a crucial role in some cases. Ensuring the resilience of healthcare facilities during floods is vital as these facilities are critical for providing continuous medical care and emergency response.

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Table 6. *Table of adaptation options for the healthcare sector.*

Asset level adaptations for healthcare sector	Hazard focus								References
	Flood	Earthquake	Landslide	Wildfire	Windstorm	Heatwave	Drought	Multi-Hazard	
Dry floodproofing	X								FEMA, 2013; Gkika et al., 2023; Escarameia & Stone, 2013
Elevating buildings	X								FEMA, 2013; Gkika et al., 2023; Escarameia & Stone, 2013; Green Climate Fund, 2021
Designing as floating or amphibious	X								Escarameia & Stone, 2013
Wet flood-proofing	X								Escarameia & Stone, 2013
Building breakaway walls	X								FEMA, 2021
Installing breakaway cables	X				X			X	US Department of Energy, 2016
Seismic bracing/anchoring components		X							FEMA, 2003; Nakamura & Okada, 2019
Isolation and damping		X							FEMA, 2003; Nakamura & Okada, 2019
Installing structural fuses and use of ductile materials and technology		X							Farzampour, 2022; Saravanan et al., 2018; Athanasiou et al., 2023
Increasing the resistance and stiffness of the construction (Strengthening)		X	X		X			X	G. Vaciago et al., 2011; Athanasiou et al., 2023; Balkaya, 2024
Building fire breaks				X					Wang et al., 2021; Low et al., 2023
Building fire walls				X					Ricci et al., 2022
Fire-resistant construction				X					European Committee for Standardization, 2004; European Committee for Standardization, 2005
Heat-tolerant design (building materials, green roofs)						X			European Commission, 2021; O'Hara et al., 2022
Closed-loop cooling systems							X		Anderson, 2023
Air-side economizers							X		Anderson, 2023
On-site water storage							X		Green Climate Fund, 2021

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Earthquake adaptation is addressed through several interventions, including seismic bracing and anchoring components (FEMA, 2003); isolation and damping (Nakamura & Okada, 2019); and installing structural fuses with ductile materials and technology (Athanasiou et al., 2023). These interventions improve the performance of the healthcare buildings and ensure that they can resist seismic loads, protecting both occupants and infrastructure. Strengthening healthcare facilities is essential to maintain operations during and after earthquakes, especially given the critical nature of medical services. Although strengthening might be a difficult strategy to quantify reliably (given the inherent complexity of most structural and non-structural components of the healthcare facilities), the range of possible solutions (and costs) for increasing strength is relatively large. Thus, this strategy is the most often employed because it allows the engineer to fine-tune a design approach to meet an owner's budget and risk management criteria (FEMA 2004).

Interventions for landslide hazards in healthcare facilities are limited, with a focus on strengthening (Balkaya, 2024) the structures, e.g. by closing the openings or coating the wall with wire mesh (Purwitaningsih & Asano, 2024). This measure is crucial for facilities located in hilly or sloped areas where the possibility of landslides is higher. This approach is typically applicable only in relation to relatively shallow slides, since it is practically impossible to build structures capable of withstanding the impact from deep-seated larger landslides. It is also noted that this approach is strongly case dependent, in the sense that the characteristics of the healthcare facility, its relative position with respect to the landslide zone and the soil-rock properties play an important role in any strengthening decision (Vaciago et al., 2011).

Wildfire adaptation in healthcare facilities includes building fire breaks (H.-H. Wang et al., 2021), constructing fire walls (Ricci et al., 2022), installing HEPA filtration systems (Joseph et al., 2020) and fire-resistant construction (European Committee for Standardization, 2004).

Interventions for windstorms focus on strengthening of buildings and structures to withstand stronger winds (Leal Filho et al., 2023).

Heatwave adaptation interventions include heat-tolerant design and construction materials (O'Hara et al., 2022), such as green roofs to ensure buildings remain habitable and safe during extreme heat events (O'Hara et al., 2022). For drought, interventions such as closed-loop cooling systems and air-side economizers (Anderson, 2023), along with on-site water storage (Green Climate Fund, 2021) are essential. These measures help to conserve water, ensure a sustainable water supply. Ensuring thermal comfort and water availability in healthcare facilities during heatwave and drought conditions is critical for patient care and overall facility operations.

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In summary, while the table provides a detailed overview of climate adaptation interventions for healthcare facilities, it also highlights areas requiring further exploration, such as additional measures for landslides, windstorms, and heatwaves. Addressing these gaps will enhance the overall resilience of healthcare facilities against various environmental hazards, ensuring they can continue to provide essential services during and after extreme weather events.

2.4.2. Education

Table 7 provides a comprehensive overview of various asset-level interventions for climate adaptation of education facilities. It lists specific interventions and correlates them with the relevant hazards they address, such as floods, earthquakes, landslides, wildfires, windstorms, heatwaves, drought. Each intervention is mapped to specific hazards, highlighting the focus areas and identifying gaps that need further exploration.

For flood hazards, interventions focus on both dry (Escarameia & Stone, 2013) and wet floodproofing methods, elevating buildings (INEE & The World Bank GFDRR, 2009), and elevating vulnerable components such as electrical, mechanical, and plumbing systems (INEE & The World Bank GFDRR, 2009) (Table A5). Designing facilities as floating or amphibious structures (Escarameia & Stone, 2013) and building breakaway walls (FEMA, 2021) also play a crucial role in flood management. Educational facilities are often used as emergency shelters (López Plazas et al., 2023) and are critical not only as a place of learning, but also as a place for managing psychosocial stress during emergencies (Pacheco et al., 2022).

Earthquake adaptation is addressed through several interventions, including strengthening of structures (Rincón et al., 2017), seismic bracing and anchoring components (INEE & The World Bank GFDRR, 2009), isolation and damping (Nakamura & Okada, 2019), and installing structural fuses with ductile materials (INEE & The World Bank GFDRR, 2009) and technology. These interventions ensure that the buildings can withstand seismic hazard, protecting the occupants and infrastructure. In earthquake prone countries, efforts are required to ensure new school buildings are built to adequate standards (using new seismic code provisions) and that unsafe (usually old) school buildings are replaced (Rincón et al., 2017).

Interventions for landslide hazards in educational facilities are limited, with a focus on strengthening the structures (Vaciago et al., 2011). This measure is crucial for facilities located in hilly or sloped areas, where the possibility of landslides is higher. Landslides affecting the utility network and thereby having indirect impact on the

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accessibility and usability of educational facilities is a research gap that is worth exploring.

Wildfire adaptation in education facilities includes building fire breaks (H.-H. Wang et al., 2021), constructing fire walls (Ricci et al., 2022), fire-resistant construction, and installing external sprinkler systems (INEE & The World Bank GFDRR, 2009). They ensure that the facilities can withstand and prevent the spread of fires, thereby safeguarding the facility and the people within.

For windstorms, the interventions focus on wind-tolerant construction and bracing of internal components (INEE & The World Bank GFDRR, 2009).

Heatwave adaptation interventions (European Commission, 2021) includes heat-tolerant design and construction materials, which are crucial during the design and implementation phases to ensure buildings remain habitable and safe during extreme heat events (López Plazas et al., 2023). For drought, interventions such as rainwater harvesting and water-efficient facilities and practices (like float valves and vermicomposting) are essential (Srishti Singh & Janki Shah, 2022). These measures help to catch rainwater, conserve water, and ensure a sustainable water supply during drought conditions. Interventions to address the concern of thermal comfort (Conte Keivabu, 2024) and ensuring water availability in educational facilities (Abnett, 2023), especially during heat wave conditions require more focus.

In summary, while the table provides a detailed overview of climate adaptation interventions for education facilities, it also highlights areas requiring further exploration, such as additional measures for windstorms, heatwaves, droughts, and landslides. Addressing these gaps will enhance the overall resilience of education facilities against various environmental hazards.

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Table 7. *Table of adaptation options for the education sector.*

Asset level adaptations for education sector	Hazard focus								References
	Flood	Earthquake	Landslide	Wildfire	Windstorm	Heatwave	Drought	Multi-Hazard	
Dry floodproofing	X								FEMA, 2013; Gkika et al., 2023; Escarameia & Stone, 2013; Massachusetts Port Authority, 2014; INEE & The World Bank GFDRR, 2009
Wet floodproofing	X								INEE & The World Bank GFDRR, 2009
Elevating buildings	X								FEMA, 2013; Gkika et al., 2023; Escarameia & Stone, 2013; Massachusetts Port Authority, 2014; INEE & The World Bank GFDRR, 2009
Elevating vulnerable components (electrical, mechanical, plumbing systems, valuable equipment)	X								INEE & The World Bank GFDRR, 2009
Designing as floating or amphibious	X								Escarameia & Stone, 2013; Massachusetts Port Authority, 2014
Building breakaway walls	X								FEMA, 2021
Seismic bracing/anchoring components		X							FEMA, 2003; Nakamura & Okada, 2019; Farzampour, 2022; Saravanan et al., 2018; INEE & The World Bank GFDRR, 2009
Isolation and damping		X							FEMA, 2003; Nakamura & Okada, 2019
Installing structural fuses and use of ductile materials and technology		X							Farzampour, 2022; Saravanan et al., 2018; INEE & The World Bank GFDRR, 2009
Increasing the resistance and stiffness of the construction (Strengthening)		X	X						G. Vaciago et al., 2011
Building fire breaks				X					Wang et al., 2021; Low et al., 2023; INEE & The World Bank GFDRR, 2009
Building fire walls				X					Ricci et al., 2022
Fire-resistant construction				X					European Committee for Standardization, 2004; European Committee for Standardization, 2005; INEE & The World Bank GFDRR, 2009
Installing external sprinkler systems				X					INEE & The World Bank GFDRR, 2009
Wind-tolerant construction					X				INEE & The World Bank GFDRR, 2009
Bracing of internal components					X				INEE & The World Bank GFDRR, 2009
Heat-tolerant design and construction materials						X			European Commission, 2021; Srishti Singh & Janki Shah, 2022
Rainwater harvesting							X		Srishti Singh & Janki Shah, 2022
Water-efficient facilities and practices (float valves, vermicomposting)							X		Srishti Singh & Janki Shah, 2022

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2.5. Compound, consecutive, and cascading hazards

Adaptation of critical infrastructure must consider that assets may be exposed to multiple hazards during their lifetime, with them possibly occurring simultaneously, in close succession, or resulting from each other. These are referred to as compound, consecutive, and cascading hazards (Chen & Greenberg, 2022; Claassen et al., 2023; de Ruiter et al., 2020). Because of this, adaptation to a hazard must consider possible trade-offs that exist with other hazards. For example, an elevated building may perform better against floods, but at the same time become more vulnerable to landslides and seismic risk. On the other hand, there are adaptation strategies that can be beneficial for multiple hazards. For instance, planning of urban green spaces may reduce vulnerability to both pluvial flooding and heat waves (Graça et al., 2022).

When considering multi-hazards, an interplay exists between hazards, risks, and adaptation measures taken, as well as the timing of such measures; measures that may not be viable when considering a single sector may become more attractive when multiple sectors are considered, or vice versa (Schlumberger et al., 2024).

While, depending on its geographical location, there are many combinations of multi-hazards that infrastructure may be exposed to, the most prevalent hazard pairs are 1) heatwaves and droughts and 2) heatwaves and extreme winds (Claassen et al., 2023); however, the prevalence is geographically variable (Claassen et al., 2023; Forzieri et al., 2016). Analysing the specific hazards that are most frequently experienced at a location can help select adaptation measures to prevent damage from current hazards; however, research continues to understand the occurrence of future multi-hazards.

As an additional component of multi-hazards, failed infrastructure itself can lead to other cascading hazards. An example of this is the failure of energized power lines which can cause sparks and lead to the ignition of wildfires (Hallegatte et al., 2019; Muhs et al., 2020; Z. Wang et al., 2023). Use of breakaway cables, for example, can ensure the safe failure of critical infrastructure and prevent further cascading hazards (US Department of Energy, 2016).

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2.6. Summary and Gap analysis

The inventory of asset-level adaptation options for the transport, power, telecommunications, healthcare, and education sectors reveals several research gaps in disaster and climate resilience.

In most sectors (excluding transportation), there is a gap in asset-level adaptation measures against landslides. In the case of roads and railways, several adaptation options and construction practices exist to stabilise the terrain around them and reduce the likelihood or consequence of landslides, but avoiding areas subject to landslides is the most cited measure for other infrastructure assets. For the transport sector few adaptations exist against earthquakes, windstorms, and droughts.

Adaptation options for the power sector exist for all the hazards, however, these depend specifically on the asset that is being adapted within the power system. Existing sector-specific design and construction standards provide network reliability; however, they are not specifically connected to climate threats. Research for adaptation of the oil and gas networks and their fuel storage is scarce.

Regarding the healthcare and education sectors, although several adaptation measures exist for the different hazards, challenges can be found when modelling adaptation for them. Buildings used as schools and hospitals are sometimes built over time, in stages, and to different codes, making each a unique case. Furthermore, they can serve different needs (e.g., a school vs a hospital), be built at different scales (from minor facilities to large complexes), and with a variety of building materials. Although the adaptation options available to them are very similar, the cost and effectiveness of adaptation measures is strongly case-dependent. Focused studies are necessary to identify measures that reduce the indirect effects on the accessibility and functionality of educational and healthcare facilities due to impacts on roads and utilities. Additionally, interventions to improve thermal comfort and water availability in educational and healthcare facilities demand more attention, especially in the context of a changing climate.

Asset-level interventions for windstorm protection across multiple sectors remain significantly underexplored.

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3. Applicability in modelling practices

This chapter reflects on how adaptation options on asset-level can be reflected in CI models and in the economic appraisal of adaptation options. We start with briefly introducing the methods that can be used for economic appraisal (section 3.1). For a selection of adaptation options (introduced in section 3.2) we then describe in more detail how appraisal can be done (section 3.3).

3.1. Brief overview of economic appraisal methods for adaptation options

There are several widely used economic appraisal methods, that may be used for climate adaptation evaluation. The economic assessment of adaptation measures needs to consider future climate uncertainties and risks for implementation. It should account for long timescales, potential network interdependencies, and various uncertainties (Tröltzsch et al., 2016). In practice, one typically needs to combine the use of quantitative data with expert judgement to gain a complete overview of costs and benefits (or more broadly: pros and cons).

The CEDR funded WATCH project developed a Socio-Economic Analysis Framework applied for road infrastructure while considering different life-cycling stages (design, maintenance). This framework (Figure 8) helps to select from three main evaluation methods: Multi-Criteria Analysis (MCA), Life-Cycle Costing (LCC), Cost-Effectiveness Analysis (CEA). The choice of method depends on three key factors: the needs and the availability and quality of the data used in the assessment. These methods are very much in line with the overview given by the UNFCC on assessing costs and benefits of adaptation options (Figure 8). Here, we mention the three main traditional economic methods; however, we want to take note that other recent developments in economic appraisal of adaptation options exist and have been described during the ECONADAPT project (Tröltzsch, J. et al., 2016). These also include explicit covering of uncertainty framing (e.g. iterative risk management) and Economic decision-making under uncertainty. However, these methods are quite complex and not targeted specifically to infrastructure.

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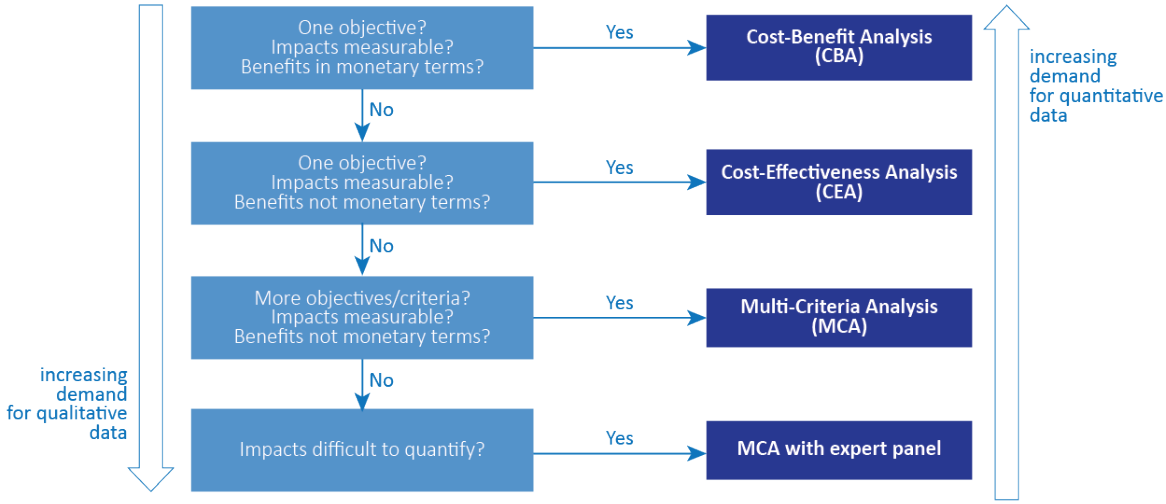

Figure 8. *Flowchart for choosing between three economic evaluation methods: MCA, CBA, and CEA. Adapted from UNFCCC, 2011.*

3.2. Description of selected adaptation measures

For several key adaptation measures (Table 8) we will demonstrate how these could potentially be used in modelling practice. A description of each of the chosen adaptation measure is provided in this section with additional detail on the effectiveness of the adaptation towards a hazard and other infrastructures that may potentially also benefit from this adaptation.

In accordance with the relevant considerations that were indicated in Section 1.1, the stage in the DRM cycle at which the adaptation is applicable is indicated, as well as any relevant asset lifecycle considerations to be made. The way in which the adaptation intervenes in the interaction between asset and hazard is also described, along with complexity of the adaptation, expected lifetime and applicability to multi-hazard modelling.

The adaptation costs and associated benefits and co-benefits re listed along with metrics that can be used to quantify them. We make a distinction between benefits that can be determined and used by the operator of a service and co-benefits that are related, associated benefits which do not directly serve the operator. The co-benefits can be linked to other policies that may also influence the decision-making process. The adaptation options presented here may be combined with other measures to support adaptation to multiple climate impact drivers or of different infrastructure types.

The adaptation options were selected based on the inventory of Chapter 1.3 and cover the five infrastructure sectors (Transport, Power, Telecommunications, Healthcare and Education), the different hazards (Flooding, Heatwaves, Windstorms, Wildfires, Drought,

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Earthquakes and Landslides), and potentially fit the different Use Cases as described by MIRACA D5.4. This selection of adaptation measures can be considered as archetypical examples of asset-level adaptation that reduce vulnerability, exposure, or the consequence of asset failure; as such, similar modelling approaches may be feasible for other infrastructure assets.

Table 8. *Example adaptation measures with some key information on sector, hazard and the way through which the asset is adapted: Reducing vulnerability (V), exposure (E) or consequence of failure (C).*

Sector	Intervention	Hazard	V	E	C
Transport (road)	Increase drainage capacity	Flood	Yes	Yes	Yes
Transport (road and rail)	Elevating road and rail	Flood	Yes	Yes	No
Transport (rail)	Cooling of bridges	Heatwave	Yes	No	Yes
Power and telecommunications	Elevating substations	Flooding	Yes	Yes	Yes
Power	Undergrounding electrical cables	Wind, wildfire (cascading event)	Yes	Yes	Yes
Telecommunications	Wet floodproofing	Flood	Yes	Yes	Yes
Education and healthcare (building)	Cool roofs	Heatwave	Yes	Yes	No
Education and healthcare (building)	Structural retrofitting and strengthening	Earthquake, landslide	Yes	No	No
Power and telecommunications	Closed loop cooling water systems	Drought, Heatwave	Yes	No	No

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3.3. How to model adaptation measures

3.3.1. Increase drainage system by increasing culvert size

Adaptation option		Increase drainage systems of road infrastructure
Hazard or multi-hazard		Flooding due to river floods and extreme precipitation
Critical contextual information		Road drainage plays a crucial role in preventing flooding, because it collects and discharges the water, and this way prevents flooding and pooling of the road and its surroundings. Furthermore, it allows rivers and streams to flow without disrupting the road. Specific objects in improving road drainage include surface water drainage (gutters, ditches, curbs), stormwater drainage (to redirect rainwater to municipal stormwater management systems, mostly in urban settings), culverts and bridges.
Effectiveness of adaptation option		Increased drainage functionality will result in less road flooding because drainage systems with a higher capacity can cope with flooding with a higher return period. This makes the road less vulnerable for flooding.
Applicability for other infrastructure types		Similar to rail infrastructure
Part of DRM cycle		Preparedness
Part of Life Cycle Stage		Construction phase
Model representation	Vulnerability reduction	Better or increased drainage would result in a lower vulnerability to damages, requiring a higher hazard intensity to result in the same damage to a road infrastructure asset.
	Exposure reduction	In case of 1D-2D hazard modelling changes in drainage design can be included in hazard modelling. When evaluating the adaptation option benefits can be determined quantitatively by calculating the differences in damages and losses.
	Consequence reduction	Increasing drainage capacity speeds up the discharging of flood waters, resulting in shorter road blockage time.
Uncertainties		In the design of the drainage systems, the design discharge volume at a design return period is estimated. These are derived from hydrological and climate models, introducing probabilistic and scenario uncertainties.
Implementation time, complexity		Installing drainage systems requires reconstruction of the road network
Lifetime of adaptation option		Drainage systems are designed for a design life varying from 50-120 years and requires regular maintenance.
Compound/Cascading		-
Valuation	Cost	Costs can vary depending on geographical location and characteristics of the objects. In the case of culverts, Costs vary based on size and material of culvert used. Also, site characteristics such as sub surface characteristics will influence costs in preparing the site for- and during installation. Culverts

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		come with a certain level of maintenance including cleaning of clogged materials. Installing new culverts requires reconstruction, and therefore is relatively expensive. The cost of installing a drainage intake is ~€2,500 (2023 prices)(Bles & Sardjoe, 2021) while the cost of drainage is estimated at ~€175/m (Deltares, 2020)
	Benefits and co-benefits	**Benefit 1**: Safety <u>Effect or expected outcome</u>: less water on the road results in less accidents due to slippery roads. <u>Parameter for assessing magnitude of effect</u>: number of accidents or loss of service <u>Evaluation</u>: Economic valuation of the reduced risk due to decreased injuries
		Benefit 2: Accessibility. <u>Effect or expected outcome</u>: Less disruptions of the road <u>Parameter for assessing magnitude of effect</u>: Road closure time, extra travel time <u>Evaluation</u>: Monetary valuation of the repairs of the damages and time valuation of losses due to closure of the road
		Co-benefit 3: Biodiversity and ecosystem effects <u>Effect or expected outcome:</u> Better water quality due to better controlled water outflow into rivers. Less flooding of the surroundings due to better drainage <u>Parameter for assessing magnitude of effect:</u> Area of affected biodiversity. Number of days in decrease of water quality <u>Evaluation</u>: quantification of potential damages to biodiversity and ecosystem
Relevant data and data sources		Bles, T., van Marle, M., de Jonge, A., de Bel, M., Fonseca, A., Stine Dybkjær, Trine Toft Andersen, Kim Madsbjerg, Ida Bülow Gregersen, & Martin Lamb. (2023, July). *Guidelines on using performance metrics to make the case for adaptation as part of the ICARUS project, CEDR*. https://icarus.project.cedr.eu/wp-content/uploads/2023/09/D2.2-ICARUS-Guidelines-on-using-performance-metrics-to-make-the-case-for-adaptation.pdf Hu, H., Yang, H., Wen, J., Zhang, M., & Wu, Y. (2023). An Integrated Model of Pluvial Flood Risk and Adaptation Measure Evaluation in Shanghai City. *Water (Switzerland)*, *15*(3). https://doi.org/10.3390/w15030602

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3.3.2. Elevating roads and rail above flood level

Adaptation option		Elevating roads and railroads
Hazard or multi-hazard		Flooding
Critical contextual information		The required road/railway elevation is considered early in the project planning and design, as it is narrowly connected with the route the infrastructure will follow. Elevating sections of road or rail after the infrastructure has been built also demands considering the adjacent sections; this is especially true for rail infrastructure, where gentle slopes are required.
Effectiveness		Elevating roads and rails is typically effective by preventing contact of the infrastructure with water. Nevertheless, infiltration of flood waters in the embankment may destabilize the embankment, which is a concern especially for railways.
Applicability for other infrastructure types		Applicable to most buildings, and to most infrastructure components
Part of DRM cycle		Preparedness
Part of Life Cycle Stage		Design, operation and maintenance phases
Model representation	Vulnerability reduction	In coarse-resolution flood models (say 100*100 m) that cannot represent the embankment in their elevation model, the embankment can be incorporated in the damage curve
	Exposure reduction	In high-resolution flood models, elevated infrastructure will not be affected until a flooding threshold is reached.
	Consequence reduction	Not applicable
Uncertainties		Similarly to drainage systems, infrastructure elevation is based on an expected flooding level subject to climate change. The projected rainfall and expected flooding exhibit uncertainties.
Implementation time, complexity		Easy to implement at the design and planning stage. Medium to high complexity to implement for existing infrastructure.
Lifetime of adaptation option		30+ years
Compound/Cascading		-
Valuation	Cost	Cost of adaptation depends mostly on whether the project is at a planning phase (from €300/m for 1 m elevation per lane for roads) or already built and requiring retrofitting (€6,000/m for 1 m elevation per lane for roads – in the Netherlands). The cost of removing and rebuilding existing infrastructure drives the difference in cost between elevating infrastructure at the planning phase compared to retrofitting it (Bles & Sardjoe, 2021). It may be necessary to acquire land, temporally or permanently, when elevating infrastructure. This may have high costs associated to land acquisition, furthermore, significant social costs. Both costs strongly depend on the location of the project (due to varying real estate costs, land uses, etc). Building on pillars or as a viaduct can reduce the

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		permanent land required but has higher construction costs (Trabo et al., 2013).
	Benefits and co-benefits	**Benefit 1**: Safety Effect or expected outcome: less water on roads and rail tracks results in safer routes Parameter for assessing magnitude of effect: number of accidents or loss of service Evaluation: Economic valuation of decreased injuries
		Benefit 2: Accessibility. Effect or expected outcome: Less disruptions of road and rail routes Parameter for assessing magnitude of effect: Road and rail closure time, extra travel time, extra travel distance Evaluation: Monetary valuation of the repairs of the damages and valuation of time losses and additional freight costs from longer routes resulting from route disruption
		Trade-off 1: Potentially increased impact from other hazards Unintended effect: Elevating structures and equipment increases earthquake vulnerability (De Ruiter et al., 2021) and exposure to higher wind intensity (Abdelfatah et al., 2022); Parameter for assessing magnitude of effect: Monetary valuation of impact from changes in vulnerability/exposure to other hazard conditions Evaluation: Monetary valuation of the repairs of damaged assets and valuation of time losses and additional freight costs from longer routes resulting from route disruption
Relevant data and data sources		Flyvbjerg, B., Bruzelius, N., & van Wee, B. (2008). Comparison of Capital Costs per Route-Kilometre in Urban Rail. *European Journal of Transport and Infrastructure Research*. https://arxiv.org/ftp/arxiv/papers/1303/1303.6569.pdf Jacobs, Trafikverket. (2021). *New Main Lines Cost Benchmarking Study*. https://bransch.trafikverket.se/contentassets/60ecb96cb94a4cac994aae8bea032992/18-maj-2021/new-main-lines---ru205---cost-benchmarking-study.pdf Trabo, I., Landex, A., Nielsen, O. A., & Schneider-Tilli, J. E. (2013). *Cost benchmarking of railway projects in Europe – can it help to reduce costs?* https://backend.orbit.dtu.dk/ws/portalfiles/portal/106565055/RailCPH_010213.pdf

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3.3.3. Cooling down bridges during extreme heat

Adaptation option		Cooling of bridges
Hazard or multi-hazard		Heatwaves
Critical contextual information		This adaptation consists of reducing the temperature of bridges by pouring water on them, by using a cooling system, or by shielding parts of the structure from the sun. This measure is most common for movable bridges, which may become stuck and malfunction due to thermal expansion at high temperatures; however, it may also be applicable for other bridges that suffer from negative effects at high temperature conditions.
Effectiveness of adaptation option		Cooling the steel elements of bridges is a way to remove heat from the structure and prevent it from expanding. The chemical properties of the water used may damage the bridge, thus, using water of adequate quality is necessary.
Applicability for other infrastructure types		Possibly rail tracks to prevent buckling
Part of DRM cycle		Preparedness, Response
Part of Life Cycle Stage		Operation and maintenance
Model representation	Vulnerability reduction	In a cooled bridge, the damage suffered due to mechanical malfunctions and the resulting service disruption could be reduced. The impacts can be reflected as changes to the fragility curve.
	Exposure reduction	Not applicable
	Consequence reduction	Upon failure, the recovery time of a malfunctioning bridge could be based on the possibility of deploying bridge cooling equipment. Bridges that are cooled begin recovery from the moment cooling begins, and bridges that are not cooled only recover after local temperatures decrease.
Uncertainties		The temperature at which a bridge will malfunction depends on the bridge design and conditions, making it bridge-specific, which is an important source of uncertainty.
Implementation time, complexity		This adaptation can be quickly implemented at a relatively low cost; however, it can become expensive to maintain in the long term.
Lifetime of adaptation option		This measure is most adequate as a short-term measure (1-5 years) since pumps, hoses, and vehicles used for bridge cooling must be continuously maintained and renewed in addition to ongoing operational expense.
Compound/Cascading		Cooling of bridges may exacerbate drought conditions
Valuation	Cost	This can be done as a relatively low-cost, short-term response measure, when it relies on spraying cooling water. Operational and maintenance costs are likely to outweigh the upfront investment required in pumps, hoses, and watering vehicles in the long term. Temperature measurements and detailed bridge models can be used to trigger preventive maintenance. Higher temperatures may cause more bridges to require cooling becoming an operational burden.

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		Long-term measures must consider retrofitting the bridge to remain operational at higher temperature. For the Netherlands, cooling movable bridges using water has been reported to cost up to €8,000 per day, per bridge, due to costs of materials, personnel, and reduced road capacity and thus road availability (Bles & Sardjoe, 2021). As a more permanent solution, a temperature control system was installed to cool the pedestals of the Hammersmith Bridge (~200 m suspension bridge) for £420,000 in the UK (2022 prices) (Hammersmith & Fulham Council, 2022)
	Benefits and co-benefits	**Benefit 1**: Accessibility Effect or expected outcome: Less disruption of roads, railways, and inland waterways due to malfunctioning bridges Parameter for assessing magnitude of effect: Repairs of the damages, periods of closure of roads, railways, and waterways. Extra travel time and distance. Access for emergency services. Evaluation: Monetary valuation of the repairs of the damages and time valuation of losses due to closure of the roads, railways, and waterways.
Relevant data and data sources		BBC. (2022, July 14). *Hammersmith Bridge wrapped in foil during heatwave*. https://www.bbc.com/news/uk-england-london-62162687 Gemeente Amsterdam. (2024, June 24). *Hete bruggen, natte voeten*. https://www.amsterdam.nl/nieuws/nieuwsoverzicht/hete-bruggen-natte-voeten/ Hammersmith & Fulham Council. (2022). *Keeping Hammersmith Bridge cool – and open – in the heatwave*. https://www.lbhf.gov.uk/news/2022/07/keeping-hammersmith-bridge-cool-and-open-heatwave Mariam Ali. (2021, June 25). Heat Wave: Cooling down our Roads and Bridges. *Seattle Department of Transportation Blog*. https://sdotblog.seattle.gov/2021/06/25/heat-wave-cooling-down-our-roads-and-bridges/ Said, M. (2018, November 16). *Reactieve oplossingen vinden we niet meer acceptabel* [Interview]. https://klimaatadaptatienederland.nl/actueel/actueel/interviews/interview-said/ Tim Haymore. (2023, July 1). *Bridge Cooling*. https://medium.com/@timhaymore/bridge-cooling-c1e56e4e09e5 VIKTOR. (2020, March 12). *Automated measurements to anticipate dilation of the Binnenhavenbrug*. https://www.viktor.ai/customer-cases/9/digital-twin-python-bridge

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3.3.4. Elevating electrical substations above flooding level

Adaptation option		Elevating substations
Hazard or multi-hazard		Flooding (riverine, pluvial, or coastal)
Critical contextual information		Substations serve diverse purposes in a power grid, such as transforming energy to a lower voltage and regulating it for distribution. They are generally capable of withstanding rain and wind, but flooding will damage electrical components upon contact. Some substations are already designed to withstand flooding to an extent, with vulnerable components already elevated off the ground
Effectiveness of adaptation option		Increased elevation effectively prevents the contact between water and vulnerable components.
Applicability for other infrastructure types		Applicable to most infrastructure.
Part of DRM cycle		Prevention
Part of Life Cycle Stage		Design and Construction phases
Model representation	Vulnerability reduction	Elevating substations primarily works through exposure reduction, however, if only some components are elevated, the vulnerability of the overall asset can be used to reflect this.
	Exposure reduction	If modelling is done using depth-damage functions, adaptation can be considered by subtracting the elevation from the flooding depth in the asset damage function.
	Consequence reduction	If only some components are elevated, the recovery time of the asset will be dictated by the components that remain exposed and therefore result damaged.
Uncertainties		During floods, electricity supply may be preventatively disconnected to reduce risk of electrocution and power network damage. This introduces uncertainty when measuring service provision.
Implementation time, complexity		Elevating an entire substation requires reconstruction. Elevating some components may require shut downs.
Lifetime of adaptation option		The elevation es expected to last as long as the substation. If the foundations or the entire area are elevated, future constructions may benefit from pre-existing elevation.
Compound/Cascading		Disruption of the electricity network can lead to cascading failures within the network as well as cascading failures of other systems.
Valuation	Cost	The cost of elevating substations depends on the size of the substation, how much it is elevated, and the means used to accomplish the elevation. If a substation is built on a mound, substantial amounts of soil may result in costly adaptation. If it is raised on stilts or pillars, foundation costs and stairs and ladders for component access will be most relevant. The estimated cost for elevating a building above flooding level in the US is reported in

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		the range of ~$19,000-194,000 depending on the type of building and how much it must be elevated (Aerts, 2018).
	Benefits and co-benefits	**Benefit 1:** Safety Effect or expected outcome: Reducing the interactions of flood water with energized electrical components prevents electrocution of people and animals Parameter for assessing magnitude of effect: Number of casualties, number of injuries Evaluation: Economic valuation of the reduced risk due to decreased injuries
		Benefit 2: Network availability Effect or expected outcome: Adapted assets remain operational and undamaged during flood conditions. When only some components are adapted: Damaged components are non-critical or have on-site spares that are easily replaced, allowing swift recovery of network availability. Parameter for assessing magnitude of effect: Availability of network Evaluation: Monetary valuation of the repairs of damaged components and time valuation of losses due to load not delivered (value of lost load)
		Trade-off 1: Potentially increased impact from other hazards Unintended effect: Elevating structures and equipment increases their vulnerability to earthquakes (De Ruiter et al., 2021) and exposes the asset to higher wind intensity (Abdelfatah et al., 2022); Parameter for assessing magnitude of effect: Monetary valuation of impact from changes in vulnerability/exposure to other hazard conditions Evaluation: Monetary valuation of the repairs of damaged components and time valuation of losses due to load not delivered (value of lost load)
Relevant data and data sources		Bollinger, L. A., & Dijkema, G. P. J. (2016). Evaluating infrastructure resilience to extreme weather – the case of the Dutch electricity transmission network. *European Journal of Transport and Infrastructure Research*. https://doi.org/10.18757/EJTIR.2016.16.1.3122 Frank Wester. (2013, November 4). *Water en hoogspanning een goede combinatie?* E-symposium Meerlaagse Veiligheid & Vitale Infrastructuur, Arnhem. https://movares.nl/wp-content/uploads/2013/11/E-symposium-Meerlaagse-Veiligheid-Vitale-Infrastructuur-TenneT.pdf

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3.3.5. Underground electricity networks

Adaptation option		Undergrounding of electricity cables
Hazard or multi-hazard		Exposure to flooding, extreme wind, wildfire
Critical contextual information		Electricity cables, particularly in the distribution network, can be built above ground or underground. Above ground cabling is exposed to hazardous conditions more often than underground cabling.
Effectiveness of adaptation option		Burying electrical cables underground can effectively reduce their exposure to extreme weather events.
Applicability for other infrastructure types		Telecommunications cables, some pipelines.
Part of DRM cycle		Preparedness
Part of Life Cycle Stage		Design, construction, maintenance phases
Model representation	Vulnerability reduction	In the case of wildfires, underground cables will no longer be exposed to the fire directly, but they may still be exposed to elevated temperatures. These should still be considered.
	Exposure reduction	Underground cables are not expected to be exposed to treefalls and extreme winds but may be exposed to soil movements and damage due to erosion during flooding
	Consequence reduction	Buried cables require longer to repair, thus the consequence of disruption may increase – the measure assumes that the reduction in frequency of failure will be more relevant than the increase in repair time upon failure.
Uncertainties		Failure of buried cables depends on many factors, such burying depth, antecedent soil moisture, and age/condition of cable, which introduces uncertainties. The intensity of wildfires and the ground conditions during their occurrence are complex to model and contain uncertainties themselves.
Implementation time, complexity		Low complexity, high cost, long implementation time
Lifetime of adaptation option		30+ years
Compound/Cascading		Yes, Floods, windstorms, and wildfires. Also reduce probability of sparking fires upon cable failure leading to wildfire cascade.
Valuation	Cost	Costs depend on distance undergrounded, and on the conditions of the built infrastructure. There may be high costs from digging through existing landscape and repairing it (gardens, sidewalks, etc), but not an issue if done from the planning stage of infrastructure. Costs for burying overhead lines range between ~$300,000-1.5 million/km (compared to ~$80,000-240,000/km for suspended wires) (Hallegatte et al., 2019) Costs associated to resolving space conflicts with other underground lines may arise.
	Benefits and co-benefits	**Benefit 1**: Safety Effect or expected outcome: Less failed cables lead to less hazardous conditions and cascading effects.

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		Parameter for assessing magnitude of effect: Number of casualties, number of injuries Evaluation: Economic valuation of the reduced risk due to decreased injuries
		Benefit 2: Availability of network Effect or expected outcome: Adapted assets remain operational and undamaged during flood, wildfire, windstorm conditions. Less damage to cables. Parameter for assessing magnitude of effect: Repairs of damages, network disruptions, loss of power. Evaluation: Monetary valuation of the repairs of damaged assets and time valuation of losses due to load not delivered (value of lost load).
		Trade-off 1: Increased repair and maintenance costs Effect or expected outcome: Underground assets will take longer and be costlier to repair and maintain when damaged. Parameter for assessing magnitude of effect: Time and cost for repairs Evaluation: Valuation of added repair and maintenance costs for underground cables
Relevant data and data sources		Hallegatte, S., Rentschler, J., & Rozenberg, J. (2019). *Lifelines: The Resilient Infrastructure Opportunity*. Washington, DC: World Bank. https://doi.org/10.1596/978-1-4648-1430-3 Muhs, J. W., Parvania, M., & Shahidehpour, M. (2020). Wildfire Risk Mitigation: A Paradigm Shift in Power Systems Planning and Operation. *IEEE Open Access Journal of Power and Energy*, *7*, 366–375. https://doi.org/10.1109/OAJPE.2020.3030023 US Department of Energy. (2016, September). *Climate Change and the Electricity Sector Guide for Climate Change Resilience Planning*. https://toolkit.climate.gov/sites/default/files/Climate%20Change%20and%20the%20Electricity%20Sector%20Guide%20for%20Climate%20Change%20Resilience%20Planning%20September%202016_0.pdf Wang, Z., Wara, M., Majumdar, A., & Rajagopal, R. (2023). Local and utility-wide cost allocations for a more equitable wildfire-resilient distribution grid. *Nature Energy*, *8*(10), 1097–1108. https://doi.org/10.1038/s41560-023-01306-8

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3.3.6. Wet flood-proofing data centres

Adaptation option		Wet floodproofing of data centres
Hazard or multi-hazard		Flooding (riverine, pluvial, or coastal)
Critical contextual information		Wet floodproofing consists of designing installations to allow flood water to safely enter and leave a building without causing damage. This type of adaptation requires that the floors that may be flooded do not host any equipment that may be damaged by water, or any critical back-up equipment such as power generators. In wet floodproofing, openings are provided for the ingress and egress of floodwater and objects that may obstruct free flow of water or debris during a flood must be removed. The bottom floors of buildings that rely on wet floodproofing can be used as parking or storage outside of flood conditions.
Effectiveness of adaptation option		Allowing water to flood and drain from the building freely reduces the strain on the building foundations and the likelihood of structural damage. Some losses may still come from damage to walls, floors, and loss of any items stored in flooded floors.
Applicability for other infrastructure types		Buildings where the bottom floors can be safely flooded
Part of DRM cycle		Preparedness
Part of Life Cycle Stage		Planning
Model representation	Vulnerability reduction	The vulnerability of the asset is reduced while flooding depth remains below the occupied levels.
	Exposure reduction	If modelling is done using depth-damage functions and it is assumed the building suffers no damage from water entering floodable levels, adaptation can be considered by subtracting the elevation of the floodable floors from the flooding depth in the asset damage function.
	Consequence reduction	The recovery time of the asset will be dictated by the components that are exposed; fewer damages lead to a quicker recovery.
Uncertainties		The loss of contents of floodable levels of wet flood-proofed buildings are case-specific, as well as the repairs needed for floors and walls after the flood, which introduces uncertainties in direct damages.
Implementation time, complexity		Low complexity and fast implementation for new buildings. High complexity and medium implementation time for existing buildings; some walls may need to be rebuilt, and vulnerable equipment moved from lower to upper levels.
Lifetime of adaptation option		Long-term. Floodproofing es expected to last as long as the data centre.
Compound/Cascading		-
Valuation	Cost	Costs for wet-proofing data centres fall under two categories, the first are structural measures to prevent floodwaters from damaging

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		the building, and the second are the costs of the additional space necessary to place the equipment from the floodable levels. Costs for wet-floodproofing are reported at ~$525/m^2 based on a 20,000 ft^2 (1858 m^2) building (2020 prices) (Regional Planning and Environmental Division South, 2021)
	Benefits and co-benefits	**Benefit 1:** Network availability Effect or expected outcome: Adapted assets remain operational and undamaged during flood conditions. Parameter for assessing magnitude of effect: Availability of network. Evaluation: Monetary valuation of the repairs of damaged assets, valuation of losses due to service disruption. **Benefit 2:** Data integrity Effect or expected outcome: Adapted assets remain undamaged during flood conditions. Parameter for assessing magnitude of effect: Loss of data, time spent on data recovery. Evaluation: Monetary valuation of data losses, time valuation of data recovery efforts.
Relevant data and data sources		Aerts, J. C. J. H., Barnard, P. L., Botzen, W., Grifman, P., Hart, J. F., De Moel, H., Mann, A. N., De Ruig, L. T., & Sadrpour, N. (2018). Pathways to resilience: Adapting to sea level rise in Los Angeles. *Annals of the New York Academy of Sciences*, *1427*(1), 1–90. https://doi.org/10.1111/nyas.13917 de Graaf, R., Roeffen, B., Lindemans, W., Czapiewska, K., de Jong, P., & Dal Bo Zanon, B. (2012). *FloodProBE D4.3: Technologies for floodproofing "hotspot" buildings*. http://www.floodprobe.eu/partner/assets/documents/Technologiesforflood-proofinghotspotbuildings_DeltaSync_18032013.pdf Das, S., Panda, K. G., Sen, D., & Arif, W. (2019). Risk-aware last-minute data backup in inter-datacenter networks. *IET Networks*, *8*(5), 307–320. https://doi.org/10.1049/iet-net.2018.5107

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3.3.7. Cool roofs in schools and hospitals

Adaptation option		Use of green roofs for buildings
Hazard or multi-hazard		Exposure to extreme heat during heatwaves
Critical contextual information		Keeping buildings cool during extreme heat provides shelter for the people occupying the building and the contents held inside. Green roofs are roof areas of new or existing buildings that have been designed as green spaces. They can be either extensive (shallow soil) or intensive (deep soil) which will determine the species they can sustain and the infrastructural complexity they involve. Green roofs are nature-based solutions that have co-benefits in flooding and drought, as well social and environmental co-benefits, like creating areas for socialization and improving air quality.
Effectiveness of adaptation option		Green roofs reduce the temperature of the building roof by providing shade and cooling air through evapotranspiration, in addition to providing additional mass that must be heated (planter soil). The adoption of green roofs reduces the temperature experienced inside of buildings during heat waves, reducing the exposure of occupants to dangerous conditions (without air conditioning) or reducing the energy demand (with AC).
Applicability for other infrastructure types		Building structures, similar concepts for open spaces are green landscapes.
Part of DRM cycle		Preparedness
Part of Life Cycle Stage		Design, construction, operation, maintenance phases
Model representation	Vulnerability reduction	The vulnerability of the building as an asset could be reduced in a model that considers the probability that a facility remains operational depending on heat exposure of buildings with and without green roofs.
	Exposure reduction	If the inside temperature of buildings is studied, modelling green roofs could be considered by reducing the exposure of people or components to high temperatures.
	Consequence reduction	Not applicable
Uncertainties		Green roofs are an umbrella term for many different designs and structures, which introduces uncertainty. Green roofs have diverse levels of development and do not perform uniformly. Buildings may structurally support different fractions of green roof coverage (or none)
Implementation time, complexity		Low complexity for structurally viable buildings. Will require upfront costs and continuous maintenance.
Lifetime of adaptation option		Highly variable, from 10 years to 50+ years depending on design
Compound/Cascading		Yes, floods, droughts, heatwaves
Valuation	Cost	Costs depend on the size of green roof, whether the surface is use is extensive or intensive, the construction materials and drainage system, and the type of soil and vegetation used. The average cost

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		for green roof installation in Germany is reported at \$15-45/m². Intensive green roofs are more expensive (~\$270-409/m²) than extensive ones (~\$10-112/m²) (2008-2021 prices) (O'Hara et al., 2022). Structural reinforcements to support green roofs (when necessary) are additional upfront costs. Maintenance costs can also be expected, though low maintenance green roofs exist. Costs are expected to fall as adoption increases.
	Benefits and co-benefits	**Benefit 1**: Cooling Effect or expected outcome: Surface temperature of roofs reduced. Interior temperature of buildings reduced. Parameter for assessing magnitude of effect: Number of medical emergencies and deaths in hospitals and schools. Availability of facility as climate shelter. Evaluation: Economic valuation of the reduced risk of medical emergency and death due to heat exposure.
		Benefit 2: Water retention Effect or expected outcome: During extreme rainfall, urban water run-off is reduced Parameter for assessing magnitude of effect: run-off, groundwater infiltration Evaluation: Monetary valuation of the repairs of the damages and time valuation of losses due to pluvial flooding
		Co-benefit 3: Social, environmental, ecosystem and biodiversity effects Effect or expected outcome: Creation of areas for socialization, improved air quality, reduced noise, creation of areas for biodiversity in cities. Parameter for assessing magnitude of effect: Usable floor area, level of particle matter and noise, level of greening or green area. Evaluation: Number of users of the area, number of affected individuals by air and noise pollution, valuation of provision of environmental goods
Relevant data and data sources		*European Commission. (2021, September 16). Commission Notice—Technical guidance on the climate proofing of infrastructure in the period 2021-2027.* https://op.europa.eu/en/publication-detail/-/publication/23a24b21-16d0-11ec-b4fe-01aa75ed71a1/language-en IPCC. (2023). *Climate Change 2022 – Impacts, Adaptation and Vulnerability: Working Group II Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* (1st ed.). Cambridge University Press. https://doi.org/10.1017/9781009325844 Macintyre HL, Heaviside C (2019). Potential benefits of cool roofs in reducing heat-related mortality during heatwaves in a European city, *Environment International*, 127:430-441, https://doi.org/10.1016/j.envint.2019.02.065. O'Hara, A. C., Miller, A. C., Spinks, H., Seifert, A., Mills, T., & Tuininga, A. R. (2022). The Sustainable Prescription: Benefits of Green Roof Implementation for Urban Hospitals. *Frontiers in Sustainable Cities*, *4*, 798012. https://doi.org/10.3389/frsc.2022.798012

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3.3.8. Structural retrofitting of schools and hospital buildings

Adaptation option		Structural retrofit of building structures
Hazard or multi-hazard		Exposure to earthquakes, windstorms, landslides
Critical contextual information		Structures may become damaged by seismic loads. While new buildings are designed and constructed to meet seismic safety requirements, older buildings designed with low, or no seismic code provisions may need to be either improved (retrofitted) or demolished and rebuilt. Structural retrofitting can be accomplished in some cases by directly reinforcing the structure of the building, for example by using a structural building envelope or by providing larger structural elements. Isolation, energy dissipation, and damping technologies can also be used as adaptation options to reduce the response of the buildings to seismic loads and therefore the expected seismic damages. Critical buildings (schools and hospitals) may be impacted by the landslide movement depending on the landslide type and size, their structural characteristics (e.g., material, height, age) as well as their location with respect to the landslide zone. The retrofitting may include eliminating openings that are weak points in the wall in resisting debris and coating the wall with other materials.
Effectiveness of adaptation option		Retrofitted structures are less vulnerable to seismic and landslide hazards.
Applicability for other infrastructure types		Most buildings (and bridges)
Part of DRM cycle		Preparedness
Part of Life Cycle Stage		Operation and maintenance phases
Model representation	Vulnerability reduction	Retrofitted buildings are less likely to be damaged during an earthquake. Damage to retrofitted buildings reduced at a given earthquake intensity.
	Exposure reduction	Not applicable
	Consequence reduction	Not applicable
Uncertainties		The extent to which a building can be retrofitted will depend on the original construction and conditions of the location
Implementation time, complexity		Low to high complexity, short to long implementation time, depending on building being retrofit
Lifetime of adaptation option		30+ years
Compound/Cascading		-
Valuation	Cost	Cost depends on the specific building, terrain, and retrofitting method. For example, the cost of structural retrofitting of 158

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		schools with framed structures in Iran ranged between \$20.41-226.24/m^2 (Jafarzadeh et al., 2014), however these figures depend on the specific case at hand.
	Benefits and co-benefits	**Benefit 1**: Safety Effect or expected outcome: Likelihood of building collapse reduced. Parameter for assessing magnitude of effect: Number of casualties, number of injuries Evaluation: Monetary valuation of the reduced risk due to decreased injuries
		Benefit 2: Availability of asset Effect or expected outcome: Adapted assets remain operational and undamaged due to earthquake. Less damage to infrastructure. Parameter for assessing magnitude of effect: Repairs of damages, users (patients or students) not served. Evaluation: Monetary valuation of the repairs of damaged assets, valuation of reduced risk due to lack of healthcare for patients, valuation of school hours lost by students.
		Co-benefit 3: Reduced vulnerability to other hazards Effect or expected outcome: In the case of an enveloping structure, insulation can be cost-effectively added. Improved resistance to wind forces, landslides. Parameter for assessing magnitude of effect: Cost of insulation. Repairs of damages Evaluation: Cost savings of insulation during seismic retrofitting. Monetary valuation of the repairs of damaged assets from wind damage.
Relevant data and data sources		Balkaya, C. (2024). Testing and Modelling of Building Envelope Retrofit System for Rapid Seismic Strengthening of Important RC Buildings. *Modelling and Simulation in Engineering*, *2024*(1), 6730349. https://doi.org/10.1155/2024/6730349 Purwitaningsih S., Asano J., (2024) Pre-disaster adaptation strategies for houses in landslide-prone residential area, case study of Giripurno Village, Borobudur Sub-District, Central Java, Indonesia, International Journal of Disaster Risk Reduction 101, 104211, ISSN 2212-4209, https://doi.org/10.1016/j.ijdrr.2023.104211 Rincón, R., Yamin, L., & Becerra, A. (2017). *Seismic Risk Assessment of Public Schools and Prioritization Strategy for Risk Mitigation*. https://www.eeri.org/images/sesi/2981.pdf Xu, G., Guo, T., Li, A., Zhang, H., Wang, K., Xu, J., & Dang, L. (2024). Seismic resilience enhancement for building structures: A comprehensive review and outlook. *Structures*, *59*, 105738. https://doi.org/10.1016/j.istruc.2023.105738 Miyamoto HK, Gilani A, Erdurmus SB, Akdogan M (2009). Development of Guidelines and Effective Retrofit Strategies for Public Schools and Hospitals in Istanbul, Turkey, ATC and SEI, Conference on Improving the Seismic Performance of Existing Buildings and Other Structures. ASCE, 268–280. https://doi.org/10.1061/41084(364)26.

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3.3.9. Closed loop water cooling systems

Adaptation option		Closed loop cooling systems for infrastructure
Hazard or multi-hazard		Drought, heatwave
Critical contextual information		Water is frequently used as a cooling liquid in critical infrastructure, especially in the energy and telecommunications sectors for assets such as power plants and data centres. Water is frequently used and discarded, requiring large withdrawals of water to keep the systems operational, which may not be possible in times of drought. Closed loop cooling systems aim to reduce the amount of water lost and the amount of make-up water needed to keep the systems operational. This is achieved by treating cooling and blowdown water and reusing it; furthermore, technology exists to recover water vapour from the evaporating water of cooling towers. Closed loop systems are common in new infrastructure, but less so in some older installations. Evaporating water recovery is less common.
Effectiveness of adaptation option		Closed loop water systems are effective against drought since they use less water than open or once-through systems
Applicability for other infrastructure types		Pumping stations, compressor stations, power plants, other infrastructure that uses water cooling
Part of DRM cycle		Preparedness
Part of Life Cycle Stage		Design, operation and maintenance phases
Model representation	Vulnerability reduction	Asset is no longer vulnerable to drought conditions since it operates with reduced water inputs
	Exposure reduction	Not applicable
	Consequence reduction	Not applicable
Uncertainties		Water make-ups are necessary due evaporative loss and to maintain water quality. The amount of make-up water necessary to meet these conditions is uncertain.
Implementation time, complexity		High complexity, generally best done from the planning stage though retrofitting is possible, short implementation time in new facilities, potentially long implementation time in existing facilities
Lifetime of adaptation option		20-30 years
Compound/Cascading		Yes, heatwave/drought conditions are common hazard pairs, and heat increases the cooling required.
Valuation	Cost	Cost depends on the size of the cooling system and the application. Costs are lower if the water quality requirements are not stringent and if water quality is maintained during the process.
	Benefits and co-benefits	**Benefit 1**: Availability of asset Effect or expected outcome: Adapted assets remain operational during drought conditions

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		Parameter for assessing magnitude of effect: Users not served (electricity or telecommunications). Evaluation: Monetary valuation of losses due to load not delivered (value of lost load). Valuation of losses due to service disruption and data loss.
		Co-benefit 2: Reduced environmental discharges Effect or expected outcome: Less warm cooling water is discharged to the environment Parameter for assessing magnitude of effect: Water quality parameters Evaluation: Compliance with water quality parameters
		Co-benefit 3: Reduced water consumption Effect or expected outcome: Less make-up water is required for cooling Parameter for assessing magnitude of effect: Water usage Evaluation: Compliance with sustainability goals
Relevant data and data sources		Abdin, A. F., Fang, Y.-P., & Zio, E. (2019). A modeling and optimization framework for power systems design with operational flexibility and resilience against extreme heat waves and drought events. *Renewable and Sustainable Energy Reviews*, *112*, 706–719. https://doi.org/10.1016/j.rser.2019.06.006 Anderson, G. (2023). *Drought and Extreme Heat Impacts to Data Centers in Northern California* (LLNL--TR-852189, 2229581, 1079043; p. LLNL--TR-852189, 2229581, 1079043). https://doi.org/10.2172/2229581 Hallegatte, S., Rentschler, J., & Rozenberg, J. (2019). *Lifelines: The Resilient Infrastructure Opportunity*. Washington, DC: World Bank. https://doi.org/10.1596/978-1-4648-1430-3 Breakthrough Technologies. (2024). *ALI: A Water Recovery Solution for Cooling Towers*. https://www.bt-tech.com/how-to-improve-cooling-tower-efficiency/

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4. Discussion and recommendations

In this deliverable adaptation at the asset-level is explored for the transport, power, telecommunications, healthcare, and education sectors. We give a birds-eye view of existing adaptation options in the literature and explore a set of adaptation options to a greater depth. We reflect on how these options can be included into modelling practice, either in terms of reducing asset vulnerability, exposure, or consequence of failure.

We find that the parameters for assessing benefits are rather consistent across multiple sectors, focusing on improved safety, reduced damage, and improved service. Environmental and social benefits are also similar for all infrastructure sectors. In healthcare and education, most emphasis lies on safety and social benefits, while in transportation, power, and telecommunications the emphasis lies on service provision.

The asset lifecycle plays an important role regarding which adaptations are feasible to implement. However, inventories of adaptations that deeply explore asset lifecycle implications in the implementation of adaptations are limited to only roads. Inventories for other sectors pay little attention to the lifecycle phase, exploring this as well is a research gap.

The DRM cycle stages where adaptations can be implemented are more flexible, but it is common to see adaptation through vulnerability reduction in the preparedness stage, exposure reduction in the prevention stage, and consequence reduction in preparedness, response, and recovery stages.

Adaptation options for most hazard-infrastructure pairs exist, but the number of options is highly variable between hazard-asset pairs. We find that there are many adaptation options for flooding across most infrastructure sectors. These often rely on elevating assets or components above flooding height and on flood-proofing infrastructure. In contrast, there are very few asset-level adaptations for landslides, where hazard-level adaptations are much more common (see MIRACA D4.1). For heatwaves, windstorms, and earthquakes, common adaptations are the strengthening and improving the design or building materials to better tolerate hazards (reducing vulnerability). The use of sacrificial elements, which are designed to fail before infrastructure suffers extensive damage, is also a common way to reduce the consequence of hazards, for example earthquakes (structural fuses), floods and windstorms (breakaway walls and cables), and wildfires (sprinkler systems). These adaptations are especially relevant for expensive, critical, or valuable assets.

Literature on adaptation options for multi-hazards is relatively scarce. While adaptations that bring benefits for two or more hazards exist, studies tend to focus on a single hazard (i.e., only for one of the hazards is considered at a time). Furthermore, trade-offs with other hazards are rarely quantified, since hazard modelling can no longer be

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constrained to the hazard where the benefits are expected. To fully capture adaptation to multi-hazards, one would also need to model the hazard(s) for which potential trade-offs may occur. This will typically require (much) more complex modelling approaches. One way forward is developing and validating multi-hazard vulnerability data for different asset-types, that is required for multi-hazard adaptation modelling. Another way forward is targeting prevalent hazard pairs. For example, the combined effect of heatwaves and droughts in cooling processes can affect many infrastructure assets; researching and developing alternative cooling technologies and how they perform in heatwave and drought conditions could benefit several sectors.

Research into nature-based asset-level adaptations is also scarce; most adaptation options are grey adaptations. One noteworthy green adaptation option is green roofs, which aside from providing benefits towards multiple hazards (heat, flooding, drought), also bring social and environmental co-benefits. This adaptation can be applied in most building structures.

Some adaptation options are easier to represent in models than others. The risk of this is that quantitative modelling studies might be biased towards easy-to-model adaptation options, which are not necessarily always the best options. In many cases, adaptations are considered qualitatively; detailed quantitative models are less common. One reason for this (e.g., in flood modelling) is that hazard models are already 'hungry for details' (Bates, 2023); models that also seek to represent adaptation are even more so. However, data barriers still exist regarding existing adaptations, and modelling must rely on strong assumptions to estimate hazard conditions .

Differences exist in risk and adaptation modelling between quick onset hazards, such as flooding and windstorms (where assets are immediately damaged) and slow onset hazards, such as drought and heat waves (where deterioration is accelerated but asset failure is often not imminent). Future research can be enriched by considering this difference in the methods used.

Existing technical standards for structural design of infrastructure (i.e., Eurocodes) dictate requirements for structures to tolerate historical conditions; however, incorporating accounting for climate change into the codes will better support asset-level climate adaptation. A new, Second Generation of the Eurocodes will consider climate change impacts and will cover the construction of new structures and the retrofitting of existing ones (European Environment Agency, 2024). Designing infrastructure anticipating future hazards over the entire lifetime of the asset prevents having to retrofit assets, which can be much more expensive.

Maintenance of existing infrastructure is a critical but often underemphasised aspect of asset-level adaptation. For example, in the case of drainage systems, maintenance is necessary for adequate functioning: flood damage to an asset where

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drainage is poorly maintained can be significantly higher than for a similar asset with well-maintained drainage. 'Business-as-usual' practices can obscure the divergence between adequately and inadequately maintained infrastructure.

Uncertainty remains a challenging part of risk and adaptation modelling. In some cases, there is insufficient asset-level data to determine the costs and benefits of adaptation precisely. Data on the degree of implementation of asset-level adaptations is extremely limited, even more so than in hazard-level adaptations. This introduces uncertainty in the baseline conditions of assets. Data on cost of adaptations and asset recovery is also limited and highly (geographical) context-dependent, which hampers the transfer and application of adaptation models across regions. Information regarding the size or precise location of assets may also be limited, in which case satellite imagery can be helpful. Information about the material, year of construction of assets, and applicable codes at the time is often important for quantifying vulnerability (and potential improvements); however, this data is also limited. Some information may be available through the feature attributes recorded in OpenStreetMap and other data sources. All assumptions made to supplement data gaps will introduce uncertainty into the adaptation costs and the associated benefits; however, they may suffice to identify no-regret options and to single out unfeasible alternatives.

Improving the quality of asset-level data can help reduce uncertainty. Practitioners may have much of the information that researchers are missing, however, this information is typically not presented in a form that fits the type of models used by researchers. Researchers working on adaptation of critical infrastructure should continue working together with infrastructure operators to tackle these challenges.

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