Review of adaptation options for Critical Infrastructure (CI) reducing hazard intensity

Deliverable D4.1

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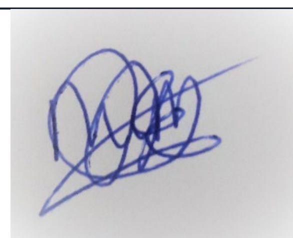
Margreet van Marle	WP Leader		30/10/2024

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Executive summary

This deliverable describes the adaptation options that aim at reducing the intensity of the hazards, rather than adapting the assets (D4.2), network (D4.3) or society (D.4). Several adaptation options have been studied for most hazards; adaptation options to river and coastal flooding are the most abundant in literature. There is an important gap of knowledge in adaptation options that address multi-hazard risk, including compound, consecutive, and cascading events.

Reduction of coastal and riverine floods by construction of seawalls and dikes is the most studied adaptation option, and its costs and benefits have been quantified on the pan-European scale. Also, there are some attempts to monetise the effectiveness of retention areas, nature-based/vegetation solutions, beach nourishment and construction of reservoirs/dams in model studies on large spatial scales. Other adaptation options, like floodplain widening and afforestation are typically studied on a smaller, river basin scale. There has been much less attention for the other hazards. In the case of pluvial flooding, the adaptation options are to increase infiltration or drainage capacity, but these are typically studied on a smaller, mostly urban, scale. Adaptation options for drought focus on water retention, water efficiency, water circularity, desalination, and interbasin water transfer schemes. Adaptation options for heatwaves largely rely on green-blue infrastructure and changes to urban morphology. For wildfires, measures aim to reduce wildfire ignition, spread, and intensity. In the case of windstorms, vegetation management and clearance of vegetation along the right-of-way are the main measures. In the case of landslides, slope stabilisation, erosion control, and deviating or containing landslides are common measures. No adaptation options at the hazard level were identified for earthquakes; while not applicable only to earthquakes, the relevance of early warning and preparedness are highlighted for this hazard. Finally, no models for adaptation options to multi-hazard risk have been identified; this remains an urgent area of research towards developing infrastructure resilience.

This review acknowledges that adaptation must take place not only by reducing the intensity or extent of hazards, but also by reducing the vulnerability of infrastructure assets and networks; however, implementing measures at this level makes it possible to focus on residual risk when implementing measures that reduce vulnerability.

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1. Introduction

Infrastructural improvement and development are processes that involve an extended planning horizon, given the long lead-time required to carry out these projects and the extended lifetime expected of infrastructure. With climate changing quickly, infrastructure may be impacted more frequently and severely by climate hazards than it had been in the past (European Commission, 2021b; Ganteaume et al., 2021; IPCC, 2023). Simultaneously, the need for infrastructural development is continuously changing as populations grow or shrink. As a result of these conditions, assets that are built to be relatively long-lasting may see their lifespan shortened (Chester et al., 2020; European Commission, 2021a; Reale, 2023; Rosenzweig et al., 2011). To prevent this, existing systems and infrastructure we develop for the future must be adapted to cope with the wide range of climate conditions it is bound to experience throughout its lifetime (Hallegatte, 2009).

The ultimate goal of MIRACA Work Package 4 (WP4) aims to appraise the adaptation strategies that are available for critical infrastructure (CI) to multiple climate hazards, outline the benefits that can be gained from adopting these strategies, explain how no-regret options can be identified, and present 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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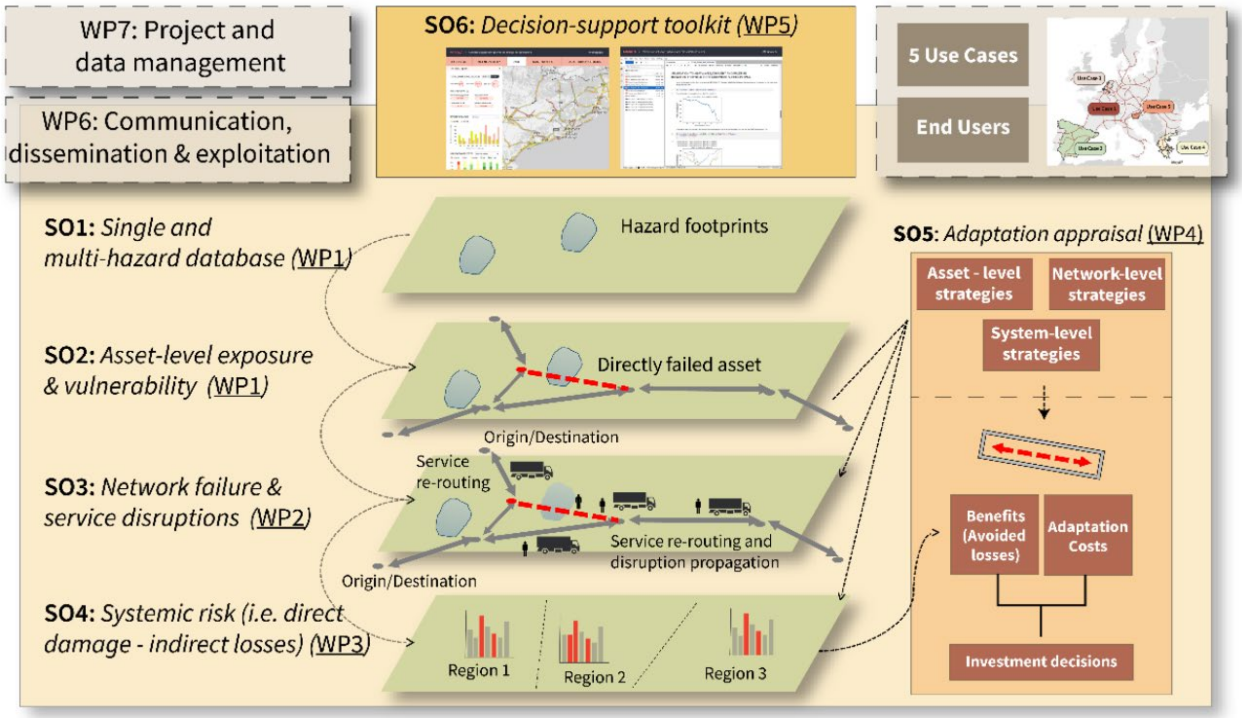

Figure 1. *MIRACA Framework composed by multiple levels: Hazard-level, asset-level, network-level, and system-level.*

As part of WP4, each level of adaptation will be explored in a dedicated deliverable. The adaptation processes at each of these levels 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.

This Deliverable 4.1 focusses on adaptation strategies to improve infrastructure resilience at Level 1: Reducing the hazard intensity infrastructure is exposed to. Deliverables 4.2-4.4 will explore strategies to improve resilience through asset-, 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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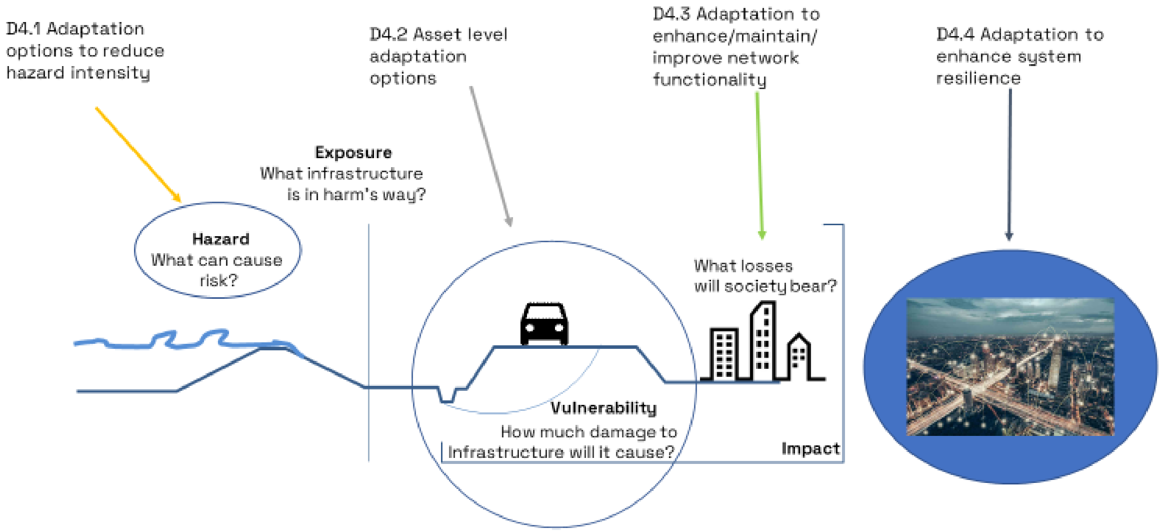

Figure 2. *Focus for each of the deliverables within Work Package 4 (WP4) Adapted from Bles et al. (2018)*

The intensity of a hazard determines its potential to cause damage to critical infrastructure; it is determined by variables such as inundation depth for floods, wind speeds for windstorms, and peak ground acceleration for earthquakes. On the other hand, resilience, is the ability of infrastructure to resist, absorb, accommodate, adapt to, transform, and recover from the effects of a hazard in a timely and efficient manner, including through the preservation and restoration of its essential basic structures and functions through risk management (for definitions, refer to Section 2 of MIRACA Deliverable 1.1).

Critical Infrastructure is affected by natural hazards in different ways. What complicates this is that natural hazard modelling is not common practice for every hazard, which means that the same level of detail model output is not available for every hazard (Figure 3, based on the literature reviewed). This results in, for example, high-detailed hazard maps with return periods and intensities for one hazard, whereas for other hazards (e.g., landslides and wildfires) mostly susceptibility maps are available; deliverable D1.2 of this project will explore the data and model availability for all hazards to greater detail.

When incorporating climate change and/or adaptation options this means that different approaches are needed. Given this condition, there is no universal method to appraise adaptation measures for all hazards, but these should be developed considering both: the relevant mechanisms through which climate hazards affect infrastructure and the available risk and resilience assessment models used to quantify these mechanisms.

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Within MIRACA, the hazards to be studied are flooding, drought, heat waves, wildfires, windstorms, landslides, and earthquakes. While Work Package 1 will explore in detail the risk modelling processes and data gaps for each hazard, in WP4 the relevant mechanisms in which hazards affect CI and the general modelling capability for each hazard will be briefly covered. The most relevant strategies to reduce hazard intensity will then be presented linked to the hazard they primarily target. In cases where multiple benefits can be achieved through a single measure, this will also be indicated. For example, afforestation implemented to reduce drought can also reduce flooding by increasing soil water retention potential (EEA, 2015). Strategies are presented as groups of measures that achieve the intended purpose of reducing the intensity of a climate hazard. The individual measures composing each strategy can then be selected based on case-specific conditions.

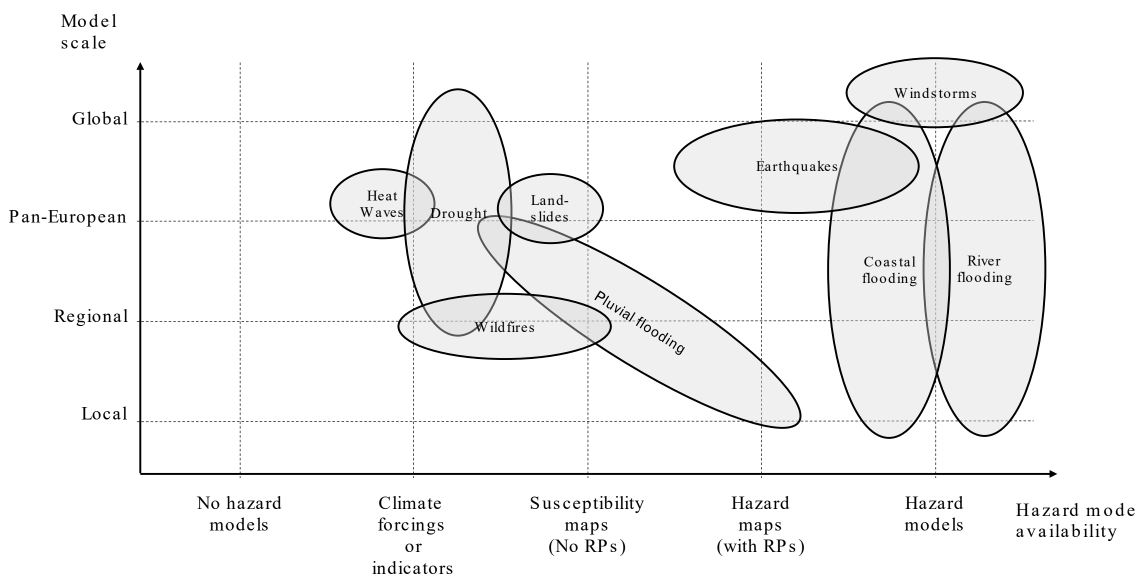

Figure 3. *Prevalent data availability and scale for each hazard. Full hazard models that can give insight into current and future hazard intensity and frequency are available for some hazards. Hazard maps linking intensity to return periods (RPs) exist for some hazards, while others use susceptibility maps or indicators.*

It is important to mention that many strategies often influence several aspects of the interaction between infrastructure and climate hazards simultaneously, consequently, some adaptation strategies that reduce the intensity of the hazards infrastructure is exposed to may also play a role in asset vulnerability. For this reason, some adaptations may be repeated in D4.2-D4.4.

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2. Hazard intensity reduction measures

This chapter describes per hazard, which measures can be taken to reduce the hazard intensity. It starts with measures that reduce the intensity of riverine, coastal, and pluvial flooding (2.1-2.3); and then proceeds with droughts, heatwaves and wildfires (2.4-2.6); windstorms (2.7); landslides (2.8) and earthquakes (2.9), measures that can be used for multiple hazards (2.10), and compounding, consecutive and cascading hazards (2.11).

2.1 Riverine flooding

Riverine or fluvial flooding occurs when a river overflows its banks due to unusually high river flows (Field et al., 2012). High river flow results from abundant precipitation in a catchment or excessive snowmelt. The intensity of riverine flooding is determined by inundation depth, flow speed, flood duration, and debris content (Abu Bakar et al., 2015; Begum et al., 2007; Meresa, 2020). Most infrastructure loses its functionality as it becomes covered by flood waters; however, infrastructure can also be damaged by other processes, such as erosion when large volumes of water flood an area (Bles et al., 2015). Another damage mechanism involves debris and sediment carried by floodwaters which intervene with the infrastructure. Thus, infrastructure resilience can be primarily improved by preventing it from being flooded and by reducing the intensity of the hazard in areas that are reached by it.

Adaptation to reduce the intensity of riverine flooding has taken place progressively through many strategies such as canalisation and damming among other approaches; these applications have often been calculated and modelled to different extent for diverse purposes, such as agricultural or urban development.

Riverine flood modelling is possible at high resolutions, accounting for hazard intensity and return periods. While many models have been used to assess river flooding hazard, their use in appraising adaptation strategies is relatively recent, especially for large spatial scales. Table 1 gives an overview of the studies that modelled the effectiveness of adaptation strategies to riverine flooding over large regions. Few studies tackle more than a single measure, and none were found to consider their combined effect.

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Table 1. *Modelling of adaptation strategies for river flooding. "x" indicates modelling has been done without economic appraisal. "$" indicates modelling has been done including economic appraisal.*

Reference	*Dams*	*Dikes*	*Riverbed and floodplain management*	*Retention areas*	*Afforestation*	*Model*	*Spatial extent*	*Resolution*	*Notes*
(Boulange et al., 2021)	x					H08	Global	50 x 50 km	Role of existing dams in mitigation
(Ward et al., 2017)		$				GLOFRIS	Global	5 x 5 km grid with 1 x 1 km flood maps	
(Dottori et al., 2023)		$		$		LISFLOOD	Pan-European	5 x 5 km grid with 100 x 100 m flood maps	Aquifer recharge out of scope
(Alfieri et al., 2016)		$		$		LISFLOOD	Pan-European	5 x 5 km grid with 100 x 100 m flood maps	Aquifer recharge out of scope
(Dittrich et al., 2019)					$	HEC-HMS	Catchment	NA	10 m – 10 km grid capability
(Johnen et al., 2022)					$	HEC-RAS	Catchment	NA	Irregular mesh
(R M Slomp et al., 2014)		$	$	$		WAQUA-SWAN	Catchment	40 m x 40 m	Room for the river

While many models could be applied to carry out the appraisal of riverine flood adaptation strategies, only a handful are used (Boulange et al., 2021; Dottori et al., 2023; Ward et al., 2017), likely owing to their capacity to assess large areas with high spatial resolution. Several other studies exist; however, they often tackle local scales (Dittrich et al., 2019; Johnen et al., 2022; R M Slomp et al., 2014), or focus on flood vulnerability reduction. The main adaptation strategies used to address riverine flooding, by reducing exposure to the hazard or by reducing the intensity with which it reaches infrastructure, are summarised ahead. Overall, floodplain widening, and the creation of retention and detention areas are generally regarded as most beneficial; however, each case must be studied individually considering local conditions. The use of dikes, especially in areas where these are not widespread, is also beneficial.

2.1.1 Dams and weirs

Dams are structures built across rivers to retain water, creating a storage area behind them; they make it possible to regulate flow of water downstream of the dam

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and to buffer peak flows caused by intense precipitation to prevent flooding (Boulange et al., 2021); by buffering peak flows, flooding downstream can be avoided or the flooding depth can be reduced, limiting the intensity of the flooding. This benefits all the infrastructure that is built downstream of the dam, especially in low-lying areas close to the dammed river. Examples of the use of dams in flood hazard intensity reduction include the Miyagase and Shiroyama dams in Japan, which were reported to have prevented additional 1.1 m of flooding depth during the 2019 typhoon Hagibis (Boulange et al., 2021).

In addition to their role in flood adaptation, the use of dams presents benefits for water availability during periods of scarce precipitation. They are often used for electricity production, irrigation for agriculture, and to allow waterway navigation – which in itself leads to optimization issues because these functions require conservation of water whereas buffering peak flows requires (empty) storage capacity; furthermore, many adverse impacts of dams have been documented and continue to be studied through ongoing research (Schulz & Adams, 2019).

The construction, operation, and maintenance of dams is costly and is often linked to social and environmental externalities: societies can be impacted through forced displacement and vector- and water-borne diseases, in addition to the destruction of the ecosystems occupying the dammed area. Dams affect environmental flows, nutrient transport, and flood regimes, affecting terrestrial ecosystems and aquatic species; these are often disproportionately affected by limiting their possibility to follow a natural reproduction cycle (Lund et al., 2021; Schulz & Adams, 2019).

Existing dams have been modelled globally to assess their contribution to flood risk reduction; while the shortcomings of dam usage are well-documented (prompting extensive removal of dams), a considerable adaptation benefit to flood risk can be derived from them; their existence (and consequences of removal) should thus be considered in adaptation modelling (Boulange et al., 2021).

Weirs perform a similar function as dams in terms of flood protection. Weirs are fixed or movable engineering structures built across streams that function as an obstacle to the flow of water. By regulating the amount of water that is allowed to flow over a weir, it is possible to influence flood depth downstream and the water level upstream of the weir, resulting in a reduction of the damages caused by the flooding (Mahdi & Hillo, 2021). The shortcomings of weirs include the disruption of environmental flows, nutrient transport and riverine regimes, as well as disrupting migration for aquatic species if no wildlife bypasses are considered (Serra-Llobet et al., 2022). Compared to dams, weirs are smaller and less complex flow regulation devices, they are not used for electricity production, and do not provide the same benefits for water availability.

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Figure 4. *Dams and dikes can play a role in reducing flood hazard. Image: Rijkswaterstaat, 2007.*

2.1.2 River dikes

Dikes and levees are structures formed by elevated riverbanks that guide the course of a river, preventing flow from invading the area they protect up to a certain river stage or water level (Dottori et al., 2023). Dikes can be built or raised to increase the streamflow the river can carry before flooding occurs; such adaptations have been historically used and modelled extensively in some regions of Europe and around the world (Dottori et al., 2023). For example, dikes in the Netherlands are a long-standing feature of the landscape; countless structures have been erected and continue to be calculated, built, and maintained to prevent riverine flooding of low-lying areas (Van Steen & Pellenbarg, 2004).

The expansion or heightening of dikes has been observed to produce three main unintended consequences:

1. Disruption of the natural functioning of wetlands and floodplains, since they experience reduced connectivity with the river channel.
2. Increased flood risk downstream of the diked area due to an associated increase in the magnitude of peak flows.

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3. Continued development in flood-prone regions protected by dikes (Dottori et al., 2023; Kaźmierczak et al., 2020).

Adaptation modelling has been done and costs and benefits have been monetised for all of Europe. The modelling has been carried out comparatively with other adaptation strategies (Alfieri et al., 2016; Dottori et al., 2023). The effectiveness of building more or higher dikes varies greatly by region based on geography, expected climate evolution, and degree of current adoption. Dikes can be used to protect large areas in a cost-effective manner; however, in regions that are already extensively protected by dikes, further development may bring relatively small benefits (Dottori et al., 2023).

2.1.3 Riverbed and floodplain management

Widening rivers, lowering floodplains, and removing obstacles in and around the river are strategies to reduce flood hazard by creating space for rivers to safely discharge their flow (Rijke et al., 2012). These measures can help reduce flooding depth.

A well-known project that focused on river widening and lowering floodplains was the Room for the River project in The Netherlands; in this application, new adaptation options were combined with existing flood protection measures to further reduce the likelihood and the intensity of riverine flooding, while achieving healthier natural areas among other benefits (Klijn et al., 2018; Rijke et al., 2012). Modelling for this adaptation measures combined qualitative and quantitative assessment of measures, also considering the environmental and social implications of the interventions in different sections of the Rhine and Meuse River courses (Klijn et al., 2018; R M Slomp et al., 2014).

2.1.4 Detention, retention, and infiltration areas

Detention and retention areas, infiltration basins and recharge wells can be developed to store or capture excess water and reduce peak flows during stormflow, reducing flooding depth. These areas are usually located alongside the river or canal and can be either continuously filled with water or only be engaged during periods of high streamflow. Unlike dikes and levees, these strategies benefit all downstream reaches of the basin (Dottori et al., 2023; Sánchez-Almodóvar et al., 2023).

The use of these areas presents environmental benefits by allowing the natural functioning of floodplains and promoting ecosystem health (Dottori et al., 2023); additional benefits can be identified in drought management, by enabling a larger volume of water to be retained on land through aquifer recharge (Sánchez-Almodóvar et al., 2023). These measures can contribute to increasing the sponge functioning of landscapes (Peng et al., 2022).

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An example of an application of this measure is the construction of a flood retention basin in the area of Feldolling in Bavaria, Germany; the intention of the basin is reducing flood risk from the river Mangfall which flows next to the town (Abdelhamid et al., 2022).

Two downsides of these strategies are the requirement of large surface areas to operate optimally and the risk of creating mosquito breeding areas when the basins are not adequately designed or maintained (Beryani et al., 2021; Dottori et al., 2023).

Adaptation modelling has been done and costs and benefits have been monetised for all of Europe; most regions can derive great benefits from their application, especially where flood hazard is expected to rise sharply (Alfieri et al., 2016; Dottori et al., 2023).

2.1.5 Afforestation

This measure relies on increasing the amount of water demanded by vegetation to reduce run-off generation, and consequently the volume of water reaching the river course which can then cause a flood; these interventions are usually considered for hillslopes and floodplains. Afforestation presents multiple benefits in the form of ecosystem services so it cannot be exclusively considered a flood adaptation measure (Dittrich et al., 2019; Mourad et al., 2022).

Some benefits of afforestation are climate regulation, increased water retention (and reduced soil erosion), embankment and slope stabilisation, carbon storage, improved aesthetic appeal, improvements in air and water quality, and the provision of habitats for biodiversity, among others (Dittrich et al., 2019; Hou et al., 2020; Johnen et al., 2022; Mourad et al., 2022).

Risk of maladaptation linked to afforestation can exist if water availability is insufficient to satisfy the increased demand resulting from the change (Bosch & von Gadow, 1990).

Modelling of afforestation as an adaptation measure against flood risk has been done at a catchment or local scale, however, few larger scale studies exist, and none monetise the measure at a pan-European scale; furthermore, the empirical evidence of the effectiveness of afforestation for flood management is still limited, requiring further studies (Dittrich et al., 2019; Johnen et al., 2022).

2.2 Coastal flooding

Coastal flooding is a hazard that occurs when sea water rises to otherwise dry land, driven by tides, storms, or a combination of both. The main variables determining the intensity of coastal flooding are water level, flow speed, flood duration, rate of water

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rise, and debris content (Kameshwar et al., 2021; Pezza & White, 2021). Sea level rise and land subsidence directly contribute to coastal flooding (Muis et al., 2016). Modelling of adaptation measures to reduce the intensity of coastal hazards has focused on the construction of seawalls and dikes; however, recent research has integrated the use of green infrastructure (coastal vegetation) with grey infrastructure to understand the benefits of maintaining and implementing multiple measures (Mortensen et al., 2023; Tiggeloven et al., 2022; van Zelst et al., 2021).

Table 2 gives an overview of measures that reduce the risk of coastal flooding. Like in river floods, most studies focus on dike construction and sea walls. Studies covering multiple adaptation strategies suggest that a combination of measures allows for optimal benefits to be achieved, outperforming single adaptation measures. The selected strategies must be based on the coastal morphology and site-specific drivers for coastal flooding (Mortensen et al., 2023; Tiggeloven et al., 2022; van Zelst et al., 2021).

Table 2. *Adaptation strategies for coastal flooding. "$" indicates modelling has been done including economic appraisal.*

Reference	Seawalls, dikes	Vegetation	Groynes, jetties	Beach nourishment	Model	Spatial extent	Resolution	Notes
(Mortensen et al., 2023)	$	$			GLOFRIS	Global	1 x 1 km	
(Lincke et al., 2019)	$				DIVA, GLOFRIS, LISFLOOD	Pan-European	100 m – 1 km grid	Multiple models
(Tiggeloven et al., 2022)	$	$			Bathtub fill	Global	50 x 50 km	Aqueduct Floods method
(van Zelst et al., 2021)	$	$			Wave attenuation	Global	NA	
(Hinkel et al., 2013)				$	DIVA	Global	Segments	Based on coastline attributes
(Amadio et al., 2022)	$		$		ANUGA	Local	NA	

2.2.1 Seawalls, dikes, and coastal levees

Building or raising dikes or other defences as a protection to coastal flooding is a widely applied adaptation measure in urbanised coastlines. These adaptation strategies

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consist in building a physical barrier that stops sea water from reaching the protected structures behind it, thereby reducing flooding depth. Examples of these barriers can be observed along parts of the coastlines of most European countries.

Dikes and levees can help reduce saltwater intrusion, easing pressure on water resources; however, the construction of coastal protection structures disturbs habitats along the coast and can further affect local ecosystems; tidal channels and marshes have been identified as particularly vulnerable to damage when these adaptation measures are used (Hood, 2004).

Modelling of dikes, sea walls, and coastal levees has been done using various models, recently the work by Amadio et al. (2022); Mortensen et al. (2023); Tiggeloven et al. (2022) is relevant (see Table 2). While these adaptation measures are effective in reducing flood risk, they can often be very costly, especially under high sea level rise (SLR) scenarios. In the case of structural measures, for example, raising seawalls and widening seawalls to keep up with SLR requires continuous investment and increased maintenance (Gutierrez et al., 2023; Lincke et al., 2019; Mortensen et al., 2023; Tiggeloven et al., 2022).

2.2.2 Coastal vegetation, mangroves, and marshes

Coastal vegetation functions by attenuating waves as they approach the shoreline, reducing wave height (van Zelst et al., 2021) and consequently inundation depth; while these ecosystems can be naturally present without human intervention, they have often been degraded and must be recovered to conserve and increase the protection they provide; this is especially true since coastal vegetation itself is among the first exposed to extreme coastal hazards. Coastal vegetation can be used in combination with other defences, such as dikes and levees, to reduce the design requirements of grey infrastructure and abate cost and resource use (Mortensen et al., 2023; van Zelst et al., 2021).

The presence of coastal vegetations, mangroves and marshes can bring co-benefits such as long-term carbon storage, increased water retention and infiltration capacity (sponge function), heat abatement and habitat creation to foster biodiversity, among others (Choi et al., 2021; Peng et al., 2022). These measures also influence the sponge functionality of areas.

The main risk of maladaptation from this measure is linked to the potential increase of vector- and water-borne diseases (Choi et al., 2021).

Restoration and expansion of coastal vegetation including salt marshes and mangroves has been modelled at a global scale, as an individual measure or as a complementary measure to reduce the height needed for dikes and seawalls; while it is

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often insufficient in fully meeting risk reduction targets, it can be valuable in combination with other strategies (Mortensen et al., 2023; van Zelst et al., 2021).

2.2.3 Beach nourishment, tidal river management, and dune systems

Different strategies can be used to increase the size of coastal formations with the intention of reducing coastal flooding intensity. The interplay between sediment transport through rivers, tides, and wind can be used to shape structures along the coast, but direct intervention through beach nourishment is a common measure (Hinkel et al., 2013).

There is growing concern regarding beach nourishment techniques which disturb a mine or borrowing site to feed the nourished site; the concerns focus on the direct habitat destruction that can take place at both sides, but also around the cumulative and long-term effects of such practices, such as changes in turbidity and water chemistry (Greene et al., 2002; Saengsupavanich et al., 2023).

These types of adaptation measures are generally carried out at a local scale and focus on the change of hydrodynamic conditions, sediment regimes, and erosion profiles developed given certain management strategies.

2.2.4 Breakwaters, groynes, and jetties

These adaptation strategies consist of laying long strip structures, usually built from rock or gravel, at or near the coastline to attenuate waves, control coastal erosion, and stabilise tidal inlets. They are often applied in combinations but can also be used individually (Winterwerp et al., 2020).

An adaptation measure which works on a similar principle is the use of coral and oyster reefs which can also help attenuate waves and reduce coastal flooding during storm surges (Kumar et al., 2021).

A common issue with these adaptation techniques is the resulting effect of scouring of the seabed. Scouring destabilises structures and has a detrimental effect for local ecosystems. Other unexpected consequences may arise from structures such as breakwaters limiting sediment availability by reducing wave stirring near the shore (Winterwerp et al., 2020).

Modelling for these structures is usually carried out at an application-specific site or at a local level; consequently, continental scale modelling has not been done. The benefits that can be gained by using breakwaters, groynes and jetties for local applications are well documented.

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2.3 Pluvial flooding

Pluvial flooding arises when the magnitude of rainfall exceeds the drainage capacity of the area and infiltration capacity of the soil. Hence, adaptation could focus on increasing either the drainage or the infiltration capacity. Unlike riverine and coastal flooding, the construction of dikes and dams to prevent pluvial flooding is not effective since the source of pluvial flooding is rainfall over an area.

In urbanised areas, the natural drainage and infiltration capacity is often compromised due to the large share of paved and built-up surfaces. Therefore, urban areas heavily rely on artificial drainage (and sometimes infiltration) systems. Hence, pluvial flooding is often referred to as 'sewer flooding' when it occurs in urban areas (Schanze, 2018). Consequently, most studies on pluvial flooding are carried out on the urban scale, with a focus on drainage design; Mugume et al. (2015), for example, appraise adaptation strategies in the urban drainage system of the city of Kampala, while M. Wang et al. (2017) study sustainable drainage systems in Chizhou city.

Given this urban focus, it is no surprise that adaptation has not been explicitly modelled for pluvial flooding at a continental scale. There have been attempts to model pluvial flooding on a continental scale with a focus on urban areas, however these have not looked into future adaptation and do not capture pluvial flooding affecting infrastructure outside of cities (Bates et al., 2021; Guerreiro et al., 2017). While future scenarios are not explored, existing adaptations have been considered in Bates et al. (2021), pointing to the possibility of extending the application to also consider adaptations for appraisal.

The most prominent adaptation options for pluvial flooding (Table 3) are the creation of permeable areas to reduce run-off generation and the expansion or improvement of the drainage and sewage systems. These processes are modelled using similar techniques as used in the initial drainage or sewer design, however, using different design parameters.

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Table 3. *Modelling of adaptation strategies for pluvial flooding. "x" indicates modelling has been done without economic appraisal. "$" indicates modelling has been done including economic appraisal. Empty spaces indicate that a regional or continental scale model is available, but no future adaptation measures have been considered.*

Reference	Permeable areas for infiltration	Improved drainage systems	Model	Spatial extent	Resolution	Notes
(Mugume et al., 2015)	x	x	SWMM	Catchment	2 m x 2 m (DEM)	Output resolution not indicated
(M. Wang et al., 2017)	x	x	SWMM	Local	NA	Focus on framework for decision-making
(Xie et al., 2023)		$	SWMM	Catchment	Segments	Focus on operational cost
(Guerreiro et al., 2017)			CityCat	Pan-European	25 m x 25 m	No adaptation measures yet Focus on urban flooding only
(Bates et al., 2021)			LISFLOOD FP	Regional	10 m x 10 m	No adaptation measures yet

2.3.1 Permeable areas for infiltration

Several measures have been developed and applied to reduce flooding in urban areas during intense precipitation that overwhelms the sewer system. Some examples are the creation of green roofs and walls, rainwater capture systems, infiltration strips and swales, and pervious pavement among other elements that increase infiltration and reduce or slow down run-off generation (Abebe & Tesfamariam, 2019; Boogaard, 2022; M. Wang et al., 2017), thereby reducing flooding depth and duration.

The elements used to improve infiltration come with benefits usually associated with green spaces, including increased water retention, reduced heat stress, and creation of habitats for biodiversity (Choi et al., 2021).

Some studies point to technology-specific trade-offs which can materialise in applications of urban drainage systems, for example, a potential increase of nocturnal warming and mosquito proliferation due to vegetation, an increase of fertiliser use for green roofs affecting water quality, and increased heat stress due to higher surface temperatures of some permeable pavement (Choi et al., 2021).

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These adaptation measures have been modelled at local and regional scales and have been implemented in various cases. Given the variety of choice of individual measures that can be used to increase infiltration, some authors have developed frameworks to comparatively assess the performance of different combinations (Mugume et al., 2015; M. Wang et al., 2017).

2.3.2 Improved drainage systems

Drainage systems can be expanded or their capacity can be increased to better cope with increased precipitation; however, the use of smart drainage systems is becoming increasingly feasible (Malik et al., 2018). Smart drainage systems are complex instrumented control systems, which combine several monitoring and real-time control technologies to reduce flooding (mostly in urban areas) during intense precipitation. The use of real-time metering and control elements within the network has allowed smart systems to be developed, which adjust their behaviour based on the environmental conditions (Malik et al., 2018). These systems consist of a network of controlled, interoperating elements (such as weirs and pumps) that allow for water to be diverted and drained at an optimal rate with relatively little human effort during intense rainfall (Xie et al., 2023).

Some smart drainage systems can be costly to install and expensive to operate and maintain; however, others have shown to be valuable and inexpensive in some applications (Kändler et al., 2020). While technological progress has increased the feasibility of applying such systems, cyber-security threats are a rising concern for this adaptation measure (Oberascher et al., 2022).

2.4 Drought

Drought hazard occurs when reduced precipitation leads to scarcity of water resources in an area. An unusual low amount of precipitation is referred to as a 'meteorological drought', the resulting soil water deficiency and plant water stress as 'agricultural' drought, and the reduced streamflow and storage in water bodies as 'hydrological drought' (Van Loon, 2015). The mechanisms through which droughts affect infrastructure functions are less studied than for floods. Interactions within systems and across them under drought can be complex (AghaKouchak et al., 2021; Karavitis et al., 2014) and the consequences experienced by each infrastructure system depend on how water is used by the system or interacts with an infrastructure asset or network (Thompson et al., 2019).

Insufficient water availability can constrain the operation of hydropower installations, limit the cooling water available for electricity production and for the

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operation of data centres and other telecom facilities (Díaz et al., 2020; Thompson et al., 2019). Also, reduced water depths impede or limit navigation in waterways (Nouasse et al., 2015) and put restrictions on lock operations to avoid (further) intrusion of salt water into fresh water bodies. Low ground water tables can cause structural damage through land compaction and subsidence (Savonis et al., 2008). Besides having implications on infrastructural service availability, drought can also cause shifts in the demand of infrastructural services. An example of this is the increased import of agricultural (and other) resources to supplement local production shortages, and the increased demand of water supplied through trucks (Mortazavi-Naeini et al., 2019).

Changing drought patterns (along with other climate patterns) and progressive saltwater intrusion (driven by sea level rise, reduced low-flow in rivers, and saltwater upconing) can lead to periodically or permanently limited freshwater resource availability in some regions (Abd-Elaty et al., 2022; Easterling et al., 2012). These processes can strongly influence the infrastructural demand in a region in the long term and in turn, the extent to which infrastructure is affected.

Many indicators and indices have been developed to measure the intensity of different types of drought; while most of them measure precipitation deficit, the time scales at which they are aggregated and specific calculation procedures vary (Ward et al., 2020). Modelling has been done at global and regional levels with resolution ranging from very coarse (250 km x 250 km) to coarse (50 km x 50 km), and it has focused primarily on agricultural impacts (Badora et al., 2023; Caldera & Breyer, 2019; Evans et al., 2023; Kahil et al., 2015; Valerio et al., 2023); in current studies, drought risk is not assessed probabilistically and the implementation of future adaptation measures has not been done (Ward et al., 2020).

Drought adaptation strategies that reduce hazard intensity (Table 4) intend to make more water available during periods of reduced precipitation; these strategies can be grouped into those that improve water retention capacity, those that promote the efficient use of water, and those that rely on water circularity, recovery, and reuse. Additionally, transferring water from one region to another and extracting water from saltwater and air humidity can also be used to reduce drought intensity to an extent. The individual measures used to achieve each purpose depend on the use water is given by each user. Geographical factors play a strong role in the possibilities of adaptation that are adequate and attractive for an area – both as long-term strategic measures, and as short-term palliative or mitigation measures.

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Table 4. *Modelling of adaptation strategies for drought. "x" indicates modelling has been done without economic appraisal. "$" indicates modelling has been done including economic appraisal.*

Reference	Water retention	Water efficiency	Water circularity	Interbasin water transfer	Desalination, water harvesting	Model	Spatial extent	Resolution	Notes
(Badora et al., 2023)	x					SWAT	Catchment	Variable	Focus on agriculture
(Kahil et al., 2015)		$		$		Hydro-economic model	Catchment	NA	Node and link model
(Evans et al., 2023)		x	x			Modelling testbed	NA	NA	Artificial case study
(Valerio et al., 2023)				x		EMODPS	NA	NA	Conceptual model
(Caldera & Breyer, 2019)		$			$	LUT Energy System model	Global	5 km x 5 km	Focus on irrigation demand

2.4.1 Water retention

Water retention strategies aim to manage the amount of water lost to the ocean through river discharge; while this has mostly been done through the construction of dams and the creation of reservoirs, it can also be achieved by reducing run-off and implementing measures to increase water infiltration, such as the development of permeable areas in cities, retention and detention ponds, through improved soil management in agricultural areas and by implementing rainwater capture systems. An example of an adaptation measure focusing on water retention are sponge functioning landscapes, where areas are adapted to retain and 'absorb' excess water resources to be used during times of scarcity (Peng et al., 2022).

The main risks arising from water retention strategies is the creation of stagnant water bodies which often lead to an increase in water- and vector-borne diseases, for example, by providing breeding grounds for mosquitoes (Choi et al., 2021). Co-benefits exist by reducing vulnerability to heat waves, floods, and improving water quality (Choi et al., 2021).

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Water retention strategies have been modelled and some cases exhibit robust behaviour even under large uncertainties, making them attractive adaptation strategies (Badora et al., 2023; Linnerooth-Bayer et al., 2015).

2.4.2 Water efficiency

Reducing the amount of water used allows more users to be satisfied during periods of reduced precipitation, thereby reducing drought intensity. This adaptation measure can be applied by different sectors depending on the way they access and use water. It may be applied permanently or temporarily and can happen spontaneously or as a result of regulation and water use limits under drought conditions (AghaKouchak et al., 2021; Lückerath et al., 2023).

Within the agricultural sector, measures to improve water efficiency include the introduction of drought tolerant crops, crops that require less water to irrigate (Kourgialas et al., 2018), the implementation of high efficiency irrigation systems and precision agriculture techniques (Kahil et al., 2015), and changing sowing dates to match historical periods of increased water availability (Bird et al., 2016). Industrial and energy sectors may consider adopting technologies that are less water-intensive within their operating processes and their facilities. In urban areas, reducing leakages in drinking water supply systems also improves efficiency. Other users and sectors may also improve water efficiency depending on the way the use the resource.

Co-benefits of improving water efficiency exist for some infrastructure systems, such as sewage and energy networks, through reduced sewage production and reduced energy demand for pumping and water treatment (Marinoski et al., 2018). On the other hand, some authors have modelled the implementation of water efficiency policy, concluding that it may lead to a rebound effect, where consumptive users increase their demand upon increase water availability under resource-scarce conditions (Loch & Adamson, 2015). Complementary policy may be required for water efficiency measures to be beneficial.

2.4.3 Water circularity

Reusing water for diverse applications can serve as means to satisfy the requirements of some users and reduce the pressure on local water resources. While some water is inevitably lost to evaporation, a large part of it can often be reused. Water circularity can be implemented through direct or indirect water re-use and in different sectors; the specific conditions that must be met depend on each user (Guerra-Rodríguez et al., 2020). For example, in Israel nearly 90% of all wastewater effluent is reused for non-potable applications, mainly irrigation and industry (Adams et al., 2023).

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Water circularity can cause certain contaminants and pathogens, which may be difficult to remove, to reach potentially harmful levels; the risk of emerging micropollutants and antibiotic resistance genes in pathogens must be considered when implementing water circularity. It is generally the case that circularity can more easily be achieved for non-human consumption such as for industrial uses (Guerra-Rodríguez et al., 2020).

Modelling for water circularity has not been done for large scales, but modelling frameworks capturing the dynamics of a water circular economy have been proposed; current research is seeking to expand the conceptual model to real cases (Evans et al., 2023).

2.4.4 Interbasin water transfer schemes

Developing systems that allow transferring water from water-abundant basins to drought-struck basins can be used as an adaptation measure (Kumar et al., 2021). This process is bound by the availability of water in nearby watersheds and can lead to unequal distribution of water resources, limiting benefits for areas that are not along the course of the transfer system (Costa et al., 2023). Moreover, it can worsen hydrological droughts in the basin of origin. Additionally, a fraction of the water that is transferred is lost to evaporation and infiltration, causing a reduction of total water availability on a larger spatial scale.

Interbasin water transfer projects can be seen around the world; for example, the Tagus-Segura aqueduct in Spain spans 286 km, and is used to transfer water from the Tagus basin to the water-stressed Segura basin (Valerio et al., 2023).

2.4.5 Desalination and atmospheric water harvesting

These two measures rely on extracting water from sources that would conventionally be unavailable for human use. The first one relies on purifying saltwater, while the second one relies on condensing water from the air. Both strategies currently aim to produce water for human consumption and to a lesser extent for industry, therefore, have a relatively minor effects on infrastructure other than the drinking water system itself (Caldera & Breyer, 2019).

Sea water or brackish water desalination can be used as an adaptation measure to provide an additional source of water in regions close to the coast or that have other sources of brackish or saltwater. It has been widely adopted, becoming an important water source for many countries, predominantly to meet domestic and municipal demand (Jones et al., 2019).

Desalination produces highly concentrated brine as a side product which must be managed, usually at high economic or environmental costs; it is also energy intensive,

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making it a costly drought adaptation measure (Jones et al., 2019). Desalination benefits have been assessed globally, but the trade-offs are still poorly understood. Desalination is among the most practiced methods to alleviate drought; however, concerns over environmental and social externalities linked to their widespread use still exist; current research focuses on improving the sustainability of this adaptation measure, for example, by using the brine waste produced for microalgae production (Bas et al., 2023; Caldera & Breyer, 2019)

Atmospheric water harvesting consists of condensing water from humid air. This technology is less explored than desalination, both in modelling and practice, but may develop to represent an attractive measure in regions which have high temperatures and relatively high humidity (Zhang et al., 2022). These systems currently also present limitations on limited water output and high energy cost, as well as environmental and social externalities, such as continuous maintenance requirements, vulnerability to extreme climate conditions, and inequality of access to water (Verbrugghe & Khan, 2023; Zhang et al., 2022). While there are currently few large-scale applications of atmospheric water harvesting systems, significant progress has been made in improving their viability (Verbrugghe & Khan, 2023; Zhang et al., 2022).

2.5 Heat waves

Heat waves result from consecutive days where temperatures exceed a threshold; the specific threshold depends on the region and is defined by the conditions historically experienced by the region. The intensity of heat waves can be described based on the temperature over a surface and the duration of the high temperature spell. (Röthlisberger & Papritz, 2023).

The point at which infrastructure suffers from heat waves depends on each installation, since infrastructure is generally designed to withstand the local temperature range (Mazdiyasni et al., 2019). Some of the effects of heat waves on infrastructure arise directly from high temperatures, as these are outside the built operating conditions of infrastructure; furthermore, the combination of frequency and duration of heat waves also plays an important role on the effect of heatwaves on infrastructure. Some effects of this hazard on infrastructure include insufficient equipment cooling due to limited cool air or cold water, rail buckling and road cracking due to increased thermal expansion, jamming of moveable bridges, and increased resistance in power transmission (Figueiredo et al., 2023; Nguyen & Wang, 2011; Reale, 2023). Other effects on infrastructure result from how it is used during heatwaves, such as increased need for cooling and air conditioning, which can push systems beyond their capacity (Gamarro et al., 2020; Nguyen & Wang, 2011).

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Apart from the direct impact of heatwaves on critical infrastructure, a prolonged period of extreme temperature affects the ability to maintain and manage the infrastructure, as heat conditions can be dangerous for workers' health and safety (Zimmerman, 2020).

The main adaptation strategies that reduce heat wave intensity (Table 5) involve the use of green-blue infrastructure in urban areas, and adapting urban morphology to minimise the amount of heat trapped by allowing increased wind circulation (Kaźmierczak et al., 2020; Reale, 2023).

Modelling of heat waves has been done globally, with a focus on health risk in cities and agricultural areas (producing susceptibility maps with return periods applicable to living organisms); however, literature is much leaner on risk of heat waves for infrastructure and the adaptation of CI to this hazard. Heat wave models with very high resolution are only applicable at local scales (in practice), while models covering large areas have coarse resolution (Ebrey et al., 2021).

Hazard modelling has moved to measuring heat waves by their day and night temperature, duration, and frequency (Mazdiyasni et al., 2019). In the case of infrastructure, it is becoming better understood that the combination of heat waves with high relative humidity can also lead to accelerated corrosion and concrete carbonation (Figueiredo et al., 2023), but this is not considered in most models. At the European level, there have been models developed for specific types of critical infrastructure, such as railways and roads, quantifying the impact from heatwaves in the present and future (Mulholland & Feyen, 2021). Although existing models provide the projected economic impact of heatwaves under future climate scenarios, they do not incorporate the economic benefit from climate adaptation strategies.

No hazard or adaptation models currently capture or simulate the physical processes driving heat waves over large regions, though these processes are a field of active research and are becoming increasingly understood. Capturing these processes would be a step towards large scale spatially explicit adaptation modelling for heat waves (Röthlisberger & Papritz, 2023).

Adaptation modelling at a local scale has focused for example on the indirect impacts of adoption of air conditioning on the electrical grid and in the intensity of the urban heat island effect (Gamarro et al., 2020). There is also research focusing on materials science and construction processes that reduce the vulnerability of infrastructure to heat waves, however, those will be covered as part of D4.2.

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Table 5. *Modelling of adaptation strategies for heat waves. "x" indicates modelling has been done without economic appraisal. "$" indicates modelling has been done including economic appraisal.*

Reference	Green-=blue infrastructure	Urban morphology	Model	Spatial extent	Resolution	Notes
(Mariani et al., 2016)	X		Surface Energy Balance	Local	30 x 30 m	
(Rana et al., 2022)		X	Index	Local	NA	Local index
(Maggiotto et al., 2021)	X	X	Surface Energy Balance	Local	NA	Model combined with thermal comfort index

2.5.1 Green-blue infrastructure

Areas with trees and water bodies are helpful in providing shade and regulating the temperature around them; when widespread, this can provide benefits at a city-wide scale. This is valuable since cities are both: the places where most critical infrastructure is located, and the places where heat waves are most intense due to the urban heat island effect (Kumar et al., 2021; Mariani et al., 2016; Oberascher et al., 2022).

Modelling reveals green blue infrastructure can be an attractive adaptation strategy to reduce the intensity of heat waves, at least at a local (city) scale through actions such as adding urban green areas, green roofs, adding trees, and replacing bare soil with grass (Kaźmierczak et al., 2020; Mariani et al., 2016). At a pan-European scale, this has not been assessed.

2.5.2 Urban morphology

Designing areas to allow for adequate ventilation and minimal heat retention can reduce the intensity of heat waves in some zones (Kaźmierczak et al., 2020; Rana et al., 2022; Reale, 2023). This is relevant at a local scale since it is directed to urban areas. Whether this adaptation can have a larger scale impact on heat wave intensity beyond the urban areas is not well understood.

Specifically in cities, surface energy balance models have also been used to compare the benefit of different adaptation options, such as green infrastructure and the implementation of cooling surface against a no-intervention scenario (Maggiotto et al., 2021).

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2.6 Wildfires

Wildfires occur when vegetation is ignited, leading to an uncontrolled burning of forests, grasslands, and other combustible materials in their vicinity. Wildfires are very complex to predict and model, due to the different factors that influence the ignition and the progression of the events.

Meteorological situations such as drought, amount of potential combustion material (biomass), type of vegetation, topography and wind direction increases the susceptibility to and ultimately also the consequence of a wildfire. When the climate becomes drier in the future, the frequency of wildfires is also expected to increase. Predicting the intensity and duration of a wildfire with a specific return period is very difficult, particularly because the onset and spread of a fire depends on many different site- and situation-specific characteristics.

How wildfires will change in intensity and duration towards the future is not yet clear. When a wildfire occurs, it has a direct effect on people's lives, because their habitat is threatened, and they have to be evacuated. It also has indirect effects on safety of, for example, national highways, railroads, and air quality. This is especially relevant in southern Mediterranean countries, where there is an extension of the wildland-urban interface that leads to both assets and fire ignitions nearby (Ganteaume et al., 2021).

Wildfire occurrence is determined by three factors, which all three need to be met: (1) There should be fuel to burn. This is mostly governed by type and amount of combustible material. When there is no vegetation, a fire is hard to ignite, (2) The climatic conditions. This includes the soil type, presence of litter layer, and meteorological conditions (e.g., relative humidity) that allow the fuel to be dry enough to burn, and (3) the presence of an ignition source (Bradstock, 2010; Chambers et al., 2019). Often in Europe the cause of the ignition source is mostly human lit (albeit not on purpose). However, in the more boreal areas lightning-induced fires occur more frequently.

The progression of fires is influenced in various ways. Dry, hot, and windy climate conditions promote wildfire progression, but it is always in combination with vegetation type, soil type and topography (Canadas et al., 2023; X. Wang & Bocchini, 2023). The type of fire (flaming or smouldering) also influences the speed, size and progression of the fire and is mostly influenced by the soil type in combination with type of vegetation cover (Santoso et al., 2019). Other factors that influence the duration of the event and the intensity are related to the fire response and include the accessibility of locations and the response time by firefighters (Canadas et al., 2023).

Adaptation strategies for wildfire reduction (Table 6) can be split into options that reduce the ignition of a fire, for example, limiting the amount of readily ignitable material, and options that reduce the spread or intensity of the fire.

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Wildfire adaptation modelling at a pan-European scale is lean, largely due to the challenges associated with accurately predicting wildfire occurrence (Canadas et al., 2023; Khabarov et al., 2016). The resolution is relatively coarse (25 km x 25 km) at regional and continental scales (Ebrey et al., 2021).

Table 6. *Modelling of adaptation strategies for wildfires. "x" indicates modelling has been done without economic appraisal.*

Reference	Ignition reduction	Spread and intensity reduction	Model	Spatial extent	Resolution	Notes
(X. Wang & Bocchini, 2023)	x		Finite element model	Regional	Transmission line sections	Focus on risk, not adaptation Power infrastructure
(Romero-Calcerrada et al., 2008)		x	Weights of Evidence method	Regional	25 x 25 m	Focus on risk not adaptation
(Khabarov et al., 2016)	x		Community Land Model	European	25 x 25 km	Focus on quantification of prescribed burning benefit

2.6.1 Ignition reduction

Wildfires are often ignited by human activity and infrastructure, such as sparks generated by metal-to-metal contact in railways and rotating equipment and by power conductor-vegetation contact caused by wind. Preventing wildfires from originating reduces the resources that must be devoted to fire suppression, as well as the hazard that fire-fighters must face in the process (Canadas et al., 2023).

Ensuring adequate clearance is kept between ignitable vegetation and infrastructure can reduce the likelihood of wildfires initiating (X. Wang & Bocchini, 2023). Also, having a clear maintenance of vegetation located next to infrastructure (e.g., regular mowing of verges next to roads or railways) reduces the amount of combustible material and may prevent the occurrence and spread of next-to-infrastructure fires (Tedim et al., 2016). Integrated vegetation management is a route towards achieving this (Renewables Grid Initiative, 2023). Furthermore, in case a wildfire occurs, adequate clearance plays a key role in minimising damage to infrastructure and limiting service interruptions, making vulnerability reduction a co-benefit (Choobineh et al., 2015).

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A strategy to tackle human-lit wildfires involves education and well-distributed information aimed at generating awareness and wildfire hazard understanding, helping prevent wildfire ignition (Canadas et al., 2023; Kotroni et al., 2020; Kurowski & Bradley, 2022).

A more extreme measure for ignition reduction involves fully de-energizing sections of the electrical grid during extreme weather; while this limits the possibility of ignition, it may also affect parts of the population (Abatzoglou et al., 2020).

At a European level, modelling of the quantitative benefit of adaptation options for fire reduction has been studied for the different regions (Mediterranean, Central EU and Baltic Countries, etc…) by measuring the reduction of fire risk in varying climate change scenarios from prescribed burning activities (Khabarov et al., 2016).

2.6.2 Wildfire spread and intensity reduction

Management and suppression practices can be implemented to reduce the spread of uncontrolled wildfires; these practices include prescribed burning, reducing forest density by selective thinning, and strategically creating areas that function as break fires, such as agricultural fields located at specific locations (Canadas et al., 2023). The use of integrated water resources management practices may have potential in reducing susceptibility to wildfires, however, it is currently not fully explored; some research indicates that these practices can be used to reduce wildfire ignition, spread, and intensity (Ihsan Fawzi et al., 2020).

The use of fire-resistant trees and extensive grazing as means of fuel management can also be used (Canadas et al., 2023). Planning zones where recreation activities can safely take place can reduce the spread of wildfires by allowing emergency response when ignitions occur (Romero-Calcerrada et al., 2008). The use of fire-resistant construction materials enables infrastructure to function as a fuel break and a defensible space to contain wildfire spread from reaching further infrastructure.

Having sufficient detection and first response capacity to manage emerging wildfires is necessary for this measure to function (Canadas et al., 2023; Romero-Calcerrada et al., 2008). Firefighting and access route inventories, planning, and training all contribute to effective wildfire management, and to preventing wildfires from reaching critical infrastructure (Kurowski & Bradley, 2022).

2.7 Windstorms

Windstorms are storms characterised by very strong winds, often with violent gusts. The intensity of windstorms is determined by wind speed (Lombardo, 2019);

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infrastructure is frequently affected when debris is blown into roads and rail tracks and when fallen or damaged trees lean against power transmission lines, or when swinging power lines reach nearby vegetation (Spinoni et al., 2020; X. Wang & Bocchini, 2023).

The occurrence of windstorms has been modelled at a pan-European scale based on global circulation model ensembles. There is currently large disagreement among the climate models driving windstorm modelling, leading to high uncertainty in model outputs, especially under future climate conditions (Schelhaas et al., 2010; Severino et al., 2023; Spinoni et al., 2020).

Adaptation strategies for windstorms (Table 7) are mostly supported by semi-quantitative or qualitative assessment. While several asset-specific adaptation strategies for windstorms exist, these will be covered in D4.2.

Table 7. *Modelling of adaptation strategies for windstorms. "x" indicates modelling has been done without economic appraisal.*

Reference	Right of way and clearance	Vegetation management	Model	Spatial extent	Resolution	Notes
(X. Wang & Bocchini, 2023)	x		Finite element method	NA	NA	Conceptual model
(Schelhaas et al., 2010)		x	EFISCEN	Pan-European	250 x 250 km	No future projections

2.7.1 Right-of-way and clearance

Maintaining vegetation that does not grow tall enough to reach power lines (or other assets), as well as guaranteeing clearances around roads, railways, and other infrastructure can reduce the intensity of windstorms. Routinely removing debris that can be blown onto infrastructure during windstorms is a way of limiting how severely infrastructure is affected during events (Spinoni et al., 2020; X. Wang & Bocchini, 2023).

2.7.2 Vegetation management

Pruning and removing branches and trees susceptible to breakage during windstorms in hazard prone areas is a way to reduce debris generation and minimise windstorm intensity. Planting instead vegetation that is tolerant to high wind speeds

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and strong gusts can provide a windbreak function, prevent infrastructure from being reached by severe windstorms (Schelhaas et al., 2010; Spinoni et al., 2020). Creating the conditions for slower tree growth along infrastructure corridors can reduce the need for recurrent cutting (Renewables Grid Initiative, 2023).

2.8 Landslides

Landslides are a hazard that originates from a mass of rock, debris, or earth moving down a slope. The materials may move by falling, toppling, sliding, spreading, or flowing. Among landslides, different typologies are recognized mainly by the kind of material involved and by the movement mechanism. Starting from the work of Varnes (1984), Cruden & Varnes (1993) proposed a taxonomic classification which considers, in addition to the movement mechanism at the initial stage of motion and the material, the state of activity and the rate of movement. Landslides are often caused by seismic activity, rainfall, or any other factor that leads to loss of slope stability. Landslides cause extensive damage to infrastructure; the variables affecting the intensity is the rate of movement of the mass, the depth of the movement, the material and type of movement, and the presence of water (Capobianco et al., 2022). Landslides can progress within seconds, or occur over long periods of time, changing the way in which they affect infrastructure. For example, rock falls may damage sections of rail instantaneously, however, larger scale slow movements can cause extensive damage to entire networks. Corominas et al. (2013) present recommended methodologies for the quantitative analysis of landslide hazard, vulnerability, and risk at different spatial scales.

Susceptibility maps have been developed at a pan-European scale using a semi-quantitative method combining landslide frequency ratios information with a spatial multi-criteria evaluation model of three thematic predictors: slope angle, shallow subsurface lithology and land cover (Wilde et al., 2018). Such maps focus on the landslide spatial distribution only, i.e., the probability of occurrence and the magnitude of the events are not considered, making statistical modelling of landslides very difficult.

Adaptation measures modelling is currently limited to local scales (Ebrey et al., 2021) and relies on semi-quantitative assessment of measures (Capobianco et al., 2022).

The adaptation measures to reduce landslide risk can be divided into two main groups (Capobianco et al., 2022): measures to reduce landslide hazard (e.g., modifying slope geometry or ground water regime, retaining structures to improve the slope stability, erosion control etc.) and measures to reduce landslide consequences (e.g., deviating the path of landslides, dissipating the energy of landslides etc.). **Table *8*** presents available modelling approaches of adaptation strategies for landslides in Europe at different scales.

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In the following, some of the most common mitigation measures to reduce landslide risk are briefly discussed.

Table 8. *Modelling of adaptation strategies for landslides. "x" indicates modelling has been done without economic appraisal. "$" indicates modelling has been done including economic appraisal. Empty spaces indicate that a regional or continental scale model is available, but no future adaptation measures have been considered.*

Reference	Slope stabilisation	Erosion control	Deviating and containing LS	Model	Spatial extent	Resolution	Notes
(Capobianco et al., 2022)	$	$	$	LaRiMiT	Case-specific	NA	Semi-quantitative, non-spatial
(Moos et al., 2016)	x			Regression model	Local	30 m x 30 m	Effect of roots on stability
(Wilde et al., 2018)				ELSUS	Pan-European	200 m x 200 m	Susceptibility maps only

2.8.1 Slope stabilisation

Grey and green infrastructure can be used individually or in conjunction to improve slope stability. Retaining walls and soil nailing are common practices (Capobianco et al., 2022); however, vegetation root systems also play an important role in maintaining slope stability; consequently, conditions that adversely affect slope vegetation can also lead to the occurrence of landslides (Geertsema et al., 2009; Moos et al., 2016). Selecting robust vegetation capable of stabilizing slopes under current and future climatic conditions can reduce the intensity of landslides infrastructure will experience through its lifetime. Slope stabilisation can also include elements of drainage and debris fall protection.

2.8.2 Erosion control

Limiting the mobilisation of soil as a result of erosion can reduce the intensity and likelihood of landslides. Promoting healthy soils that allow for vegetation rooting and techniques such as riprapping and use of turf reinforcement mats also helps limiting erosion, preventing landslides from occurring, or reducing their intensity (Capobianco et al., 2022).

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2.8.3 Deviating or containing landslides

It is possible to use deflection structures or to create paths that guide landslides when they occur. It is also possible to dissipate the energy of landslides when they occur by placing elements in their path, such as debris racks, baffles, check dams, and other barriers; these adaptations have been modelled at local scale (Capobianco et al., 2022).

2.9 Earthquakes

Earthquakes are sudden intense movements at the Earth's surface resulting from the continuous shifting of tectonic plates. Earthquakes are most prevalent near fault lines, where plates meet; however, human-induced earthquakes have also been observed (e.g., Adushkin, 2016). Earthquakes represent a major hazard for critical infrastructure, consequently, especially for structures built on regions with high seismicity, one should also consider the earthquake force during the design and construction (Lackner, 2018).

The severity of earthquakes can be measured in several ways, quantitative or qualitative; it can be measured by its magnitude (energy release), intensity (which, for earthquakes is determined based on damage caused), or through the shaking experienced. Seismic hazard models are commonly based on some parameters of earthquake shaking; shaking is furthermore measured by the peak ground acceleration (PGA), peak ground velocity (PGV), and spectral distribution of the earthquake, that is, the amplitude of seismic waves at different frequencies (Grünthal & Musson, 2020). Earthquakes can cause losses to infrastructure by damaging buildings and pavements, causing railways to bend, pipelines to rupture, and water tables to shift (Grünthal & Musson, 2020).

Earthquake hazard models are available at a pan-European scale for various return periods (Danciu et al., 2021). In general, reducing seismic hazard intensity is currently not feasible in practice; however, earthquake prevention and control may become increasingly feasible as research progresses (Gutierrez-Oribio et al., 2022).

Only human-induced earthquakes may be mitigated by decreasing or in some cases halting the activity that induces them. For example, earthquakes linked to wastewater disposal into deep underground wells in Oklahoma decreased occurring after injections were reduced (Bridegan, 2017). Even if it is not possible to reduce the intensity or avoid a naturally induced earthquake, it is certainly possible to reduce its adverse consequences by taking appropriate protective measures before, during and after an earthquake. Seismic risk-mitigation strategies continue to grow more

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successful as engineers, geologists, seismologists, and other experts innovate new public-safety initiatives in their respective fields. Even though earthquakes hit without warning and cannot be prevented, the basis of a good earthquake safety program is to know what can happen. Although earthquakes occur in an unpredictable manner, various adaptation measures can be taken to reduce the seismic hazard intensity in terms of damages and human lives. These include improving the system of seismic monitoring and development of earthquake early warning systems, especially in earthquake-prone areas, assessing building safety immediately following a seismic event, improving earthquake provisions of building codes and designing strategies for making structures more resistant to earthquakes.

2.10 General hazard reduction measures

Most of the general measures that can be used to tackle multiple hazards, or that are independent of any hazard, focus on reducing the exposure of assets or their vulnerability; as such, they will be explored further in D4.2. One exception is early warning systems and operational response, outlined ahead.

2.10.1 Early warning systems and operational response

Implementation of early warning systems can function as hazard reduction measure for flooding and drought by allowing for operational changes to be implemented. Early warning systems are designed to trigger an alert when certain thresholds are exceeded, such as the exceedance of a typical amount of rainfall (or rainfall deficit). When the threshold is surpassed, the hazard can be quickly identified, communicated, and responded to.

Targeted actions triggered ahead of a climate event can influence the intensity of the hazard and thus reduce the extent to which critical infrastructure is affected. Some examples of how early warning systems can be used are:

- Floods. Flood control is possible in some river systems by opening or shutting specific locks, gates, and other control devices to direct and regulate flow. Through improved real-time monitoring, full modelling capacity, and understanding of river systems it is increasingly possible to adjust operating conditions in an agile manner. This can, to an extent, help avoid or ameliorate flooding (Harrigan et al., 2023; Van Der Werf et al., 2023; H. Wang et al., 2023).
- Drought. Similarly to floods, when precipitation deficits are identified, water consumption policies and reservoir operations can be adjusted to reduce the rate at which water is drained from river systems (Harrigan et al., 2023; Noguera et al.,

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2023). In the case of droughts, forecasts are frequently based on indicator trends based on precipitation deficits (Noguera et al., 2023).

- Earthquakes. Early warning of impending earthquakes can be instrumental in reaching safe locations upon the occurrence of a hazardous event, but also in reducing the downtime of infrastructure systems (Cremen & Galasso, 2020).

A detailed plan to respond to climate emergencies upon detection of any hazard is necessary for operational response. It should be known by all relevant stakeholders and include the steps that must be taken when specific climate hazards arise.

2.11 Compound, consecutive, and cascading hazards

Individual hazards represent a risk to critical infrastructure through a large variety of mechanisms; it is often the case, however, that a region is exposed to more than a single hazard simultaneously, or within a short time span, constituting a multi-hazard risk. In these cases, the risk presented to infrastructure can often be greater than that presented by the sum of the individual hazards. Systematically understanding and managing the risk posed by multiple hazards is an active field of research (Hochrainer-Stigler et al., 2023). Adequate design of adaptation measures to endure multiple hazards is essential to ensure their robustness in a changing climate. For example, designing flood defence systems that consist of components to protect from coastal flooding but can accommodate the case of high river discharges (i.e. storm surge barriers), accompanied by dikes along the tidal river areas can be valuable in some areas, as the hazards are likely to materialise simultaneously due to either a common cause, or one hazard triggering the other.

At least three main complex hazards can be identified: compound, consecutive, and cascading hazards.

- Compound hazards are those where two or more hazards occur simultaneously (occasionally due to the same cause), interacting and causing impacts different than the sum expected of the individual hazards (Hochrainer-Stigler et al., 2023). An example of compound hazards is compound flooding, where extreme tides (driver of coastal flooding) and high river discharge (driver of riverine flooding) co-occur, causing a disproportionately large flood (Catto & Dowdy, 2021).
- Consecutive hazards are those which occur close to each other, both spatially and temporally; the first event causes damage or accentuates vulnerability, and the second one follows before the affected systems are allowed to fully recover (de Ruiter & van Loon, 2022; Hochrainer-Stigler et al., 2023). The hazard mechanisms of consecutive events can be different from those of the individual components. An example of consecutive hazards would be a typhoon followed by an earthquake, which causes mudslides. Other effects may be overwhelmed

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emergency responders and pressures on the health and financial systems (de Ruiter et al., 2020). It can also be the case that multiple hazards originate from the same prevailing conditions but materialise over a larger time span. Such is the case of a series of floods or consecutive drought years during periods of abnormal precipitation occurring closely together while not necessarily being caused by each other (Moftakhari & Aghakouchak, 2019; Sun et al., 2023).

- Cascading hazards occur when a triggering interrelationship between hazards happens, where one hazard directly leads to (or sets the conditions for) the occurrence of a subsequent hazard (Chen & Greenberg, 2022; Hochrainer-Stigler et al., 2023; Moftakhari & Aghakouchak, 2019). Some interactions between natural hazards can be intuitive while others are difficult to anticipate. An earthquake can damage a dike or a dam and cause a flood or a landslide to occur; it can also lead to the occurrence of a tsunami, causing coastal flooding (Chen & Greenberg, 2022). Soil water repellence caused by drought can reduce the soil infiltration capacity and lead to pluvial and riverine flooding when precipitation occurs (Gimbel et al., 2016). A wildfire may reduce water demand over an affected region, leading to an increase in run-off and flooding; run-off may also carry more debris than it regularly would, leading to more severe hazard conditions and more challenging recovery processes (Kemter et al., 2021; Moftakhari & Aghakouchak, 2019).

Since the conditions under which hazards interact depend on many factors, hazards that tend to occur as compound, consecutive, or cascading hazards are listed ahead and the mechanisms behind each are briefly explained. When selecting adaptation strategies, understanding the interplay each will have with infrastructure in the area can be beneficial in selecting robust strategies.

Compound flooding: River, coastal, and pluvial flooding can often occur simultaneously, in different combinations. Adaptation measures must be capable of managing the risks of one hazard without increasing the risk for other hazards. The Maeslant barrier, a storm surge barrier in The Netherlands, is an example of such design.

Flooding – Drought: Droughts can set the ground for intense flooding when precipitation occurs. Preventing soil from drying out during drought can help maintain stability upon intense precipitation, avoiding landslides and riverbank failure. Anticipating increased run-off, erosion, and debris in flooding during and after drought conditions is important as these factors may accentuate the intensity of the hazard. Climate-aware afforestation can reduce the intensity of both hazards.

Flooding – Heat waves: Heat waves can contribute to flooding by accelerating snowmelt and favouring rainfall over snowfall. Heat waves can limit refreezing and further affect snowpack retention, exacerbating the intensity of flooding (Easterling et

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al., 2012). The introduction of green-blue infrastructure can reduce the intensity of both hazards. Additionally, adequate forecasting, supported by the physical drivers of heat waves and their effect on flooding can be used to adjust operating conditions and minimise flooding intensity.

Flooding – Windstorms: Windy conditions accentuate the damaging potential of floods. Reducing debris generation can be beneficial to reduce the hazard. Vegetation selection and management can be used to reduce de intensity of both hazards.

Flooding – Landslides: Flood waters can cause erosion and reduces soil and slope stability, leading to landslides and embankment failures. The contrary sequence is also possible, where landslides can lead to obstructions and force water to shift paths and flow through areas that would otherwise be dry, causing floods. Reducing the intensity of either hazard will likely reduce the intensity of both, due to their reinforcing mechanism. Afforestation and soil management can also reduce the intensity of both hazards.

Coastal flooding – Earthquake: Earthquakes can trigger tsunamis, which can in turn cause extensive coastal flooding. Seawalls and preparation plans that consider this potential hazard cascade can help reduce impacts.

Drought – Heat waves: Dry conditions favour the occurrence of heat waves by reducing the amount of energy that can be absorbed by water. High temperatures promote evaporation and drying, often exacerbating drought hazard. The co-occurrence of both hazards is among the most common compound hazards. Afforestation and green-blue infrastructure can reduce the intensity of both hazards.

Drought – Wildfire: Dry conditions are often conductive to the emergence of wildfires; wildfires desiccate the soil through their heat and can exacerbate drought conditions. Additionally, loss of vegetation leads to reduced water infiltration and diminished water quality.

Drought – Windstorm: The co-occurrence of dry and windy circumstances can be damaging to vegetation; when it affects areas without vegetation it can lead to accelerated wind erosion and events such as dust storms (Hojan et al., 2019; Saco et al., 2021).

Drought – Landslide: Drought can deteriorate vegetation and affect slope stability. Additionally, drying out of land masses can cause them to become destabilised when water becomes available, leading to the occurrence or acceleration of landslides (Handwerger et al., 2019; Saco et al., 2021).

Wildfire – Windstorm: Wildfire progression is favoured by windy conditions; wind carries ignited debris which can then further propagate a wildfire. Wind can also cause ignition sources to materialise such as sparks caused by disturbed electrical equipment.

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Wildfire – Landslide: Damaged or destroyed vegetation can lead to loss of stability in slopes and cause landslides. Identifying slopes which have become vulnerable to landslides after a wildfire can enable reacting to the threat.

3. Discussion and recommendations

This chapter has presented the main adaptation strategies that operate by reducing the hazard intensity and the exposure of infrastructure to climate hazards. The strategies are composed by grouping individual measures based on the way they operate.

3.1 Adaptation at the hazard level

Literature on adaptation strategies that reduce the hazard intensity is most available for flooding and, to a lesser extent, for drought. Most of the literature for other climate hazards focuses on reducing vulnerability to the hazards, rather than the hazard intensity or the exposure to the hazards.

The resolution and the extent of adaptation modelling is variable by hazard and modelling approach. In cases where high resolution models exist and spatially explicit infrastructure data is available, it is feasible to assess asset-specific benefits derived from adaptations. This can be used towards an actionable, spatially disaggregated appraisal of adaptation strategies.

Even though this report focuses on adaptation at the hazard source level, it is relevant to mention that the options investigated benefit specific assets to different extents. This is dependent on the mechanism through which infrastructure assets are affected by each hazard; for example, river dikes are effective in reducing flooding over roads and rails, however, the benefit to overhead electricity lines is negligible. On the flipside, water retention can be very valuable to maintain hydroelectric facilities operational during droughts but may have a less relevant impact on roads and rails. This points to the relevance of analysing the effects of hazards and adaptations for each type of asset-hazard pair. In the case of MIRACA, each use-case may rely on different datasets depending on the infrastructure under study and the hazards present in the area. The use of datasets and approaches that monetize adaptations and that consider multiple adaptation options give relevant context for comparison with other adaptation options, as opposed to datasets that address a single option or arrive at a non-monetary result. In the context of MIRACA, the assumptions made for all exposed assets in adaptation models (primarily buildings in urban areas and crops in rural areas) must be revisited to focus on critical infrastructure, specifically.

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3.2 Compound, consecutive, and cascading hazards

Considering multi-hazard risk beyond its individual composing hazards when developing adaptation strategies is also relevant. In this report, we explore how some adaptation strategies that were described can be applied to improve resilience towards common multi-hazards. Determining the hazards that infrastructure in an area may be exposed to is the first step to define which hazard-level adaptations best reduce risk.

Deepening understanding of the underlying mechanisms driving multi-hazard risk can help guide the design of adaptation strategies that are better able to cope with multiple hazards with increased frequency and intensity.

Many challenges remain when modelling risk for compound, consecutive, and cascading hazards. This adds to the complexity that adaptation modelling for individual hazards already presents. The main challenges relate to incompatible types of models used (and the different inputs required, and outputs produced), variability in the scales covered (from local to global), and the spatial and temporal resolution of the models (metres to kilometres, and hourly to monthly, respectively). Since not all models are suited for a fully quantitative appraisal approach, the use of semi-quantitative or qualitative appraisal methods for adaptation strategies may be best fit for some hazards. While some literature addresses adaptation strategies for compound flooding, very sparse literature exists for adaptation to other multi-hazards. The relative maturity of hazard models for compound flooding (especially river and coastal) makes it possible to model adaptation with more ease than for most other hazards.

The performance of adaptation measures for multiple hazards is still poorly modelled; however, when appraising adaptation strategies, measures that can be used to tackle single hazards and are robust in front of multiple hazards should be considered. Furthermore, when adequately selected, some measures may contribute to reducing risk of more than a single hazard.

3.3 Creating adaptation strategies for CI

Another area requiring additional research is the interaction of multiple adaptation measures when building adaptation strategies. Research suggests that synergies can be achieved by combining multiple measures to face climate risk. The most effective measures to implement are largely dependent on the geography-specific conditions of each region, the relevant hazard mechanisms through which climate hazards affect infrastructure (in present and future climate), and the current state of adaptation (sometimes called "adaptation capacity").

Reducing hazard intensity when planning for adaptation of critical infrastructure – and accounting for measures that have already been implemented – can be valuable

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input for selecting adaptation measures that reduce the vulnerability to climate hazards. Reducing the hazard at the source makes it possible to later focus on tackling the residual risk through reduced vulnerability.

The insights produced by this deliverable are well-aligned with other research that has been produced by the European Union on adaptation. We present the diversity of measures that are viable for different hazards, the geographically specific challenges that exist when adapting, and the attractiveness of using both green and grey measures in the adaptation process. The focus on the hazard component of risk ensures that the measures presented are relevant for CI systems while leaving the CI vulnerability component of risk to be explored in Deliverable 4.2.

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4. References

Abatzoglou, J. T., Smith, C. M., Swain, D. L., Ptak, T., & Kolden, C. A. (2020). Population exposure to pre-emptive de-energization aimed at averting wildfires in Northern California. *Environmental Research Letters*, *15*(9), 094046. https://doi.org/10.1088/1748-9326/aba135

Abd-Elaty, I., Kuriqi, A., Bhat, S. A., & Zelenakova, M. (2022). Sustainable management of two-directional lateral and upconing saltwater intrusion in coastline aquifers to alleviate water scarcity. *Hydrological Processes*, *36*(9). https://doi.org/10.1002/hyp.14646

Abdelhamid, M., Junger, D., & Beckhaus, K. (2022). *Construction of a cut-off wall using Mixed-In-Place technology for a flood retention basin in southern Germany*. Indian Geotechnical Conference IGC 2022, Kochi.

Abebe, Y., & Tesfamariam, S. (2019). Climate Change Impact and Adaptation for Urban Drainage Systems. In E. Bastidas-Arteaga & M. G. Stewar (Eds.), *Climate Adaptation Engineering* (pp. 73–98). Elsevier. https://doi.org/10.1016/B978-0-12-816782-3.00003-6

Abu Bakar, S. H., Tahir, W., Wahid, M. Ab., Mohd Nasir, S. R., & Hassan, R. (Eds.). (2015). *ISFRAM 2014: Proceedings of the International Symposium on Flood Research and Management*. Springer Singapore. https://doi.org/10.1007/978-981-287-365-1

Adams, H., Messner, E., Sinicropi, P., Steinle-Darling, E., & Crespo, E. (2023). Learning From Water Reuse in Israel. *Journal AWWA*, *115*(4), 72–75. https://doi.org/10.1002/awwa.2092

Adushkin, V. V. (2016). Tectonic earthquakes of anthropogenic origin. *Izvestiya, Physics of the Solid Earth*, *52*(2), 173–194. https://doi.org/10.1134/S1069351316020014

AghaKouchak, A., Mirchi, A., Madani, K., Di Baldassarre, G., Nazemi, A., Alborzi, A., Anjileli, H., Azarderakhsh, M., Chiang, F., Hassanzadeh, E., Huning, L. S., Mallakpour, I., Martinez, A., Mazdiyasni, O., Moftakhari, H., Norouzi, H., Sadegh, M., Sadeqi, D., Van Loon, A. F., & Wanders, N. (2021). Anthropogenic Drought: Definition, Challenges, and Opportunities. *Reviews of Geophysics*, *59*(2). https://doi.org/10.1029/2019RG000683

Alfieri, L., Feyen, L., & Di Baldassarre, G. (2016). Increasing flood risk under climate change: A pan-European assessment of the benefits of four adaptation strategies. *Climatic Change*, *136*(3–4), 507–521. https://doi.org/10.1007/s10584-016-1641-1

Amadio, M., Essenfelder, A. H., Bagli, S., Marzi, S., Mazzoli, P., Mysiak, J., & Roberts, S. (2022). Cost-benefit analysis of coastal flood defence measures in the North Adriatic Sea. *Natural Hazards and Earth System Sciences*, *22*(1), 265–286. https://doi.org/10.5194/nhess-22-265-2022

Badora, D., Wawer, R., & Król-Badziak, A. (2023). Modelling 2050 Water Retention Scenarios for Irrigated and Non-Irrigated Crops for Adaptation to Climate Change Using the SWAT Model: The Case of the Bystra Catchment, Poland. *Agronomy*, *13*(2). https://doi.org/10.3390/agronomy13020404

Bas, T. G., Fariña, R., Gallardo, F., & Vilches, M. (2023). Economic–Financial Assessment of Seawater Desalination Plants in Northern Chile to Reduce Hydric Scarcity and a

This project has received funding from the European Union's Horizon Europe research and innovation programme under grant agreement No. 101093854

Proposal for the Environmental and Sustainable Use of Brine Waste by Cultivating the Microalga Dunaliella salina to Produce β-Carotene. *Processes*, *11*(6), 1668. https://doi.org/10.3390/pr11061668

Bates, P. D., Quinn, N., Sampson, C., Smith, A., Wing, O., Sosa, J., Savage, J., Olcese, G., Neal, J., Schumann, G., Giustarini, L., Coxon, G., Porter, J. R., Amodeo, M. F., Chu, Z., Lewis-Gruss, S., Freeman, N. B., Houser, T., Delgado, M., … Krajewski, W. F. (2021). Combined Modeling of US Fluvial, Pluvial, and Coastal Flood Hazard Under Current and Future Climates. *Water Resources Research*, *57*(2). https://doi.org/10.1029/2020WR028673

Begum, S., Stive, M. J. F., & Hall, J. W. (2007). *Flood risk management in Europe: Innovation in policy and practice*. Springer.

Beryani, A., Goldstein, A., Al-Rubaei, A. M., Viklander, M., Hunt, W. F., & Blecken, G.-T. (2021). Survey of the operational status of twenty-six urban stormwater biofilter facilities in Sweden. *Journal of Environmental Management*, *297*, 113375. https://doi.org/10.1016/j.jenvman.2021.113375

Bird, D. N., Benabdallah, S., Gouda, N., Hummel, F., Koeberl, J., La Jeunesse, I., Meyer, S., Prettenthaler, F., Soddu, A., & Woess-Gallasch, S. (2016). Modelling climate change impacts on and adaptation strategies for agriculture in Sardinia and Tunisia using AquaCrop and value-at-risk. *Science of the Total Environment*, *543*, 1019–1027. https://doi.org/10.1016/j.scitotenv.2015.07.035

Bles, T., Bessembinder, J., Chevreuil, M., Danielsson, P., Falemo, S., & Venmans, A. (2015). *ROADAPT Roads for today, adapted for tomorrow. Guidelines.*

Boogaard, F. C. (2022). Spatial and Time Variable Long Term Infiltration Rates of Green Infrastructure under Extreme Climate Conditions, Drought and Highly Intensive Rainfall. *Water (Switzerland)*, *14*(6). https://doi.org/10.3390/w14060840

Bosch, J. M., & von Gadow, K. (1990). Regulating Afforestation for Water Conservation in South Africa. *South African Forestry Journal*, *153*(1), 41–54. https://doi.org/10.1080/00382167.1990.9629032

Boulange, J., Hanasaki, N., Yamazaki, D., & Pokhrel, Y. (2021). Role of dams in reducing global flood exposure under climate change. *Nature Communications*, *12*(1). https://doi.org/10.1038/s41467-020-20704-0

Bradstock, R. A. (2010). A biogeographic model of fire regimes in Australia: Current and future implications: A biogeographic model of fire in Australia. *Global Ecology and Biogeography*, *19*(2), 145–158. https://doi.org/10.1111/j.1466-8238.2009.00512.x

Bridegan, T. (2017). Not So Natural: Manmade Earthquakes in Oklahoma and the Measured Response to Mitigate Them. *Georgetown Environmental Law Review*, *29*(2).

Caldera, U., & Breyer, C. (2019). Assessing the potential for renewable energy powered desalination for the global irrigation sector. *Science of The Total Environment*, *694*, 133598. https://doi.org/10.1016/j.scitotenv.2019.133598

Canadas, M. J., Leal, M., Soares, F., Novais, A., Ribeiro, P. F., Schmidt, L., Delicado, A., Moreira, F., Bergonse, R., Oliveira, S., Madeira, P. M., & Santos, J. L. (2023). Wildfire mitigation and adaptation: Two locally independent actions supported by different policy domains. *Land Use Policy*, *124*, 106444. https://doi.org/10.1016/j.landusepol.2022.106444

This project has received funding from the European Union's Horizon Europe research and innovation programme under grant agreement No. 101093854

Capobianco, V., Uzielli, M., Kalsnes, B., Choi, J. C., Strout, J. M., Von Der Tann, L., Steinholt, I. H., Solheim, A., Nadim, F., & Lacasse, S. (2022). Recent innovations in the LaRiMiT risk mitigation tool: Implementing a novel methodology for expert scoring and extending the database to include nature-based solutions. *Landslides*, *19*(7), 1563–1583. https://doi.org/10.1007/s10346-022-01855-1

Catto, J. L., & Dowdy, A. (2021). Understanding compound hazards from a weather system perspective. *Weather and Climate Extremes*, *32*. https://doi.org/10.1016/j.wace.2021.100313

Chambers, J. C., Brooks, M. L., Germino, M. J., Maestas, J. D., Board, D. I., Jones, M. O., & Allred, B. W. (2019). Operationalizing Resilience and Resistance Concepts to Address Invasive Grass-Fire Cycles. *Frontiers in Ecology and Evolution*, *7*, 185. https://doi.org/10.3389/fevo.2019.00185

Chen, J., & Greenberg, M. (2022). Cascading hazards and hazard mitigation plans: Preventing cascading events in the United States. *Risk, Hazards and Crisis in Public Policy*, *13*(1), 48–63. https://doi.org/10.1002/rhc3.12220

Chester, M. V., Underwood, B. S., & Samaras, C. (2020). Keeping infrastructure reliable under climate uncertainty. *Nature Climate Change*, *10*(6), 488–490. https://doi.org/10.1038/s41558-020-0741-0

Choi, C., Berry, P., & Smith, A. (2021). The climate benefits, co-benefits, and trade-offs of green infrastructure: A systematic literature review. *Journal of Environmental Management*, *291*. https://doi.org/10.1016/j.jenvman.2021.112583

Choobineh, M., Ansari, B., & Mohagheghi, S. (2015). Vulnerability assessment of the power grid against progressing wildfires. *Fire Safety Journal*, *73*, 20–28. https://doi.org/10.1016/j.firesaf.2015.02.006

Corominas, J., Van Westen, C., Frattini, P., Cascini, L., Malet, J.-P., Fotopoulou, S., Catani, F., Van Den Eeckhaut, M., Mavrouli, O., Agliardi, F., Pitilakis, K., Winter, M. G., Pastor, M., Ferlisi, S., Tofani, V., Hervás, J., & Smith, J. T. (2013). Recommendations for the quantitative analysis of landslide risk. *Bulletin of Engineering Geology and the Environment*. https://doi.org/10.1007/s10064-013-0538-8

Costa, A. C., Dupont, F., Bier, G., van Oel, P., Walker, D. W., & Martins, E. S. P. R. (2023). Assessment of aquifer recharge and groundwater availability in a semiarid region of Brazil in the context of an interbasin water transfer scheme. *Hydrogeology Journal*. https://doi.org/10.1007/s10040-023-02612-x

Cremen, G., & Galasso, C. (2020). Earthquake early warning: Recent advances and perspectives. *Earth-Science Reviews*, *205*, 103184. https://doi.org/10.1016/j.earscirev.2020.103184

Cruden, D., & Varnes, D. (1993). *Landslide types and processes. In: Turner AT, Schuster RL (eds) Landslides—Investigation and mitigation. Transportation Research Board* (Special Report 247; pp. 36–75). National Academy Press.

Danciu, L., Nandan, S., Reyes, C., Basili, R., Weatherill, G., Beauval, C., Rovida, A., Vilanova, S., Sesetyan, K., Bard, P.-Y., Cotton, F., Wiemer, S., & Giardini, D. (2021). *The 2020 update of the European Seismic Hazard Model—ESHM20: Model Overview*. EFEHR European Facilities of Earthquake Hazard and Risk. https://doi.org/10.12686/A15

This project has received funding from the European Union's Horizon Europe research and innovation programme under grant agreement No. 101093854

de Ruiter, M. C., Couasnon, A., van den Homberg, M. J. C., Daniell, J. E., Gill, J. C., & Ward, P. J. (2020). Why We Can No Longer Ignore Consecutive Disasters. *Earth's Future*, *8*(3). https://doi.org/10.1029/2019EF001425

de Ruiter, M. C., & van Loon, A. F. (2022). The challenges of dynamic vulnerability and how to assess it. *iScience*, *25*(8), 104720. https://doi.org/10.1016/j.isci.2022.104720

Díaz, A. J., Cáceres, R., Torres, R., Cardemil, J. M., & Silva-Llanca, L. (2020). Effect of climate conditions on the thermodynamic performance of a data center cooling system under water-side economization. *Energy and Buildings*, *208*, 109634. https://doi.org/10.1016/j.enbuild.2019.109634

Dittrich, R., Ball, T., Wreford, A., Moran, D., & Spray, C. J. (2019). A cost-benefit analysis of afforestation as a climate change adaptation measure to reduce flood risk. *Journal of Flood Risk Management*, *12*(4). https://doi.org/10.1111/jfr3.12482

Dottori, F., Mentaschi, L., Bianchi, A., Alfieri, L., & Feyen, L. (2023). Cost-effective adaptation strategies to rising river flood risk in Europe. *Nature Climate Change*. https://doi.org/10.1038/s41558-022-01540-0

Easterling, D., Rusticucci, M., Semenov, V., Alexander, L. V., Allen, S., Benito, G., Cavazos, T., Nicholls, N., Easterling, D., Goodess, C., Kanae, S., Kossin, J., Luo, Y., Marengo, J., McInnes, K., Rahimi, M., Reichstein, M., Sorteberg, A., Vera, C., … Midgley, P. (2012). *Special Report of the Intergovernmental Panel on Climate change. Chapter 3. Changes in Climate Extremes and their Impacts on the Natural Physical Environment* (pp. 109–230). Cambridge University Press.

Ebrey, R., de Ruiter, M., Botzen, W., Koks, E., Aerts, J., Wens, M., Bloemendaal, N., Wouters, L., Robinson, P., Mol, J., Nirandjan, S., Tesselaar, M., Bosello, F., Mysiak, J., Scoccimarro, E., Mercogliano, P., Bacciu, V., Trabucco, A., Bigano, A., … Lefebre, F. (2021). *Comprehensive Desk Review: Climate Adaptation Models and Tools, STUDY ON ADAPTATION MODELLING FOR POLICY SUPPORT (SAM-PS)*.

EEA. (2015). *Water-retention potential of Europe's forests: A European overview to support natural water retention measures.* Publications Office. https://data.europa.eu/doi/10.2800/790618

European Commission. (2021a). *Commission Notice—Technical guidance on the climate proofing of infrastructure in the period 2021-2027*.

European Commission. (2021b). *Forging a climate-resilient Europe—The new EU Strategy on Adaptation to Climate Change*. European Commission. https://eur-lex.europa.eu/legal-content/EN/ALL/?uri=COM:2021:82:FIN

Evans, B., Khoury, M., Vamvakeridou-Lyroudia, L., Chen, O., Mustafee, N., Chen, A. S., Djordjevic, S., & Savic, D. (2023). A modelling testbed to demonstrate the circular economy of water. *Journal of Cleaner Production*, *405*, 137018. https://doi.org/10.1016/j.jclepro.2023.137018

Field, C., Barros, V., Stocker, T., Qin, D., Dokken, D., Ebi, K., Mach, K., Mastrandrea, M., Plattner, G.-K., Allen, S., Tignor, M., & Midgley, P. (2012). *IPCC, 2012: Glossary of Terms in Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation* (pp. 555–564).

Figueiredo, E., Santos, L. O., Moldovan, I., Kraniotis, D., Melo, J., Dias, L., & Coelho, G. B. A. (2023). A Roadmap for an Integrated Assessment Approach to the Adaptation of

This project has received funding from the European Union's Horizon Europe research and innovation programme under grant agreement No. 101093854

Concrete Bridges to Climate Change. *Journal of Bridge Engineering*, *28*(6), 03123002. https://doi.org/10.1061/JBENF2.BEENG-5735

Gamarro, H., Ortiz, L., & González, J. E. (2020). Adapting to Extreme Heat: Social, Atmospheric, and Infrastructure Impacts of Air-Conditioning in Megacities—The Case of New York City. *ASME Journal of Engineering for Sustainable Buildings and Cities*, *1*(3), 031005. https://doi.org/10.1115/1.4048175

Ganteaume, A., Barbero, R., Jappiot, M., & Maillé, E. (2021). Understanding future changes to fires in southern Europe and their impacts on the wildland-urban interface. *Journal of Safety Science and Resilience*, *2*(1), 20–29. https://doi.org/10.1016/j.jnlssr.2021.01.001

Geertsema, M., Schwab, J. W., Blais-Stevens, A., & Sakals, M. E. (2009). Landslides impacting linear infrastructure in west central British Columbia. *Natural Hazards*, *48*(1), 59–72. https://doi.org/10.1007/s11069-008-9248-0

Gimbel, K. F., Puhlmann, H., & Weiler, M. (2016). Does drought alter hydrological functions in forest soils? *Hydrology and Earth System Sciences*, *20*(3), 1301–1317. https://doi.org/10.5194/hess-20-1301-2016

Greene, K., Fisheries, M., Shepard, M., Dunlap, R., & Dolah, B. V. (2002). *Beach Nourishment: A Review of the Biological and Physical Impacts*. ASMFC.

Grünthal, G., & Musson, R. M. W. (2020). Earthquakes, Intensity. In H. K. Gupta (Ed.), *Encyclopedia of Solid Earth Geophysics* (pp. 1–7). Springer International Publishing. https://doi.org/10.1007/978-3-030-10475-7_23-1

Guerra-Rodríguez, S., Oulego, P., Rodríguez, E., Singh, D. N., & Rodríguez-Chueca, J. (2020). Towards the implementation of circular economy in the wastewater sector: Challenges and opportunities. *Water (Switzerland)*, *12*(5). https://doi.org/10.3390/w12051431

Guerreiro, S., Glenis, V., Dawson, R., & Kilsby, C. (2017). Pluvial Flooding in European Cities—A Continental Approach to Urban Flood Modelling. *Water*, *9*(4), 296. https://doi.org/10.3390/w9040296

Gutierrez, A. M. J., Chan, A., Del Pilar, E., Mansilla, M. M., & Tee, M. (2023). *Developing a Localized Disaster Risk Management Framework with an Introduced Optimal Flood Barrier in the Philippines* [Preprint]. SSRN. https://doi.org/10.2139/ssrn.4326539

Gutierrez-Oribio, D., Stefanou, I., & Plestan, F. (2022). *Passivity-based control of underactuated mechanical systems with Coulomb friction: Application to earthquake prevention*. https://doi.org/10.48550/ARXIV.2207.07181

Hallegatte, S. (2009). Strategies to adapt to an uncertain climate change. *Global Environmental Change*, *19*(2), 240–247. https://doi.org/10.1016/j.gloenvcha.2008.12.003

Handwerger, A. L., Huang, M. H., Fielding, E. J., Booth, A. M., & Bürgmann, R. (2019). A shift from drought to extreme rainfall drives a stable landslide to catastrophic failure. *Scientific Reports*, *9*(1). https://doi.org/10.1038/s41598-018-38300-0

Harrigan, S., Zsoter, E., Cloke, H., Salamon, P., & Prudhomme, C. (2023). Daily ensemble river discharge reforecasts and real-time forecasts from the operational Global Flood Awareness System. *Hydrology and Earth System Sciences*, *27*(1), 1–19. https://doi.org/10.5194/hess-27-1-2023

This project has received funding from the European Union's Horizon Europe research and innovation programme under grant agreement No. 101093854

Hinkel, J., Nicholls, R. J., Tol, R. S. J., Wang, Z. B., Hamilton, J. M., Boot, G., Vafeidis, A. T., McFadden, L., Ganopolski, A., & Klein, R. J. T. (2013). A global analysis of erosion of sandy beaches and sea-level rise: An application of DIVA. *Global and Planetary Change*, *111*, 150–158. https://doi.org/10.1016/j.gloplacha.2013.09.002

Hochrainer-Stigler, S., Šakić Trogrlić, R., Reiter, K., Ward, P. J., de Ruiter, M. C., Duncan, M. J., Torresan, S., Ciurean, R., Mysiak, J., Stuparu, D., & Gottardo, S. (2023). Toward a framework for systemic multi-hazard and multi-risk assessment and management. *iScience*, *26*(5), 106736. https://doi.org/10.1016/j.isci.2023.106736

Hojan, M., Rurek, M., Wiecław, M., & Krupa, A. (2019). Effects of extreme dust storm in agricultural areas (Poland, the Greater Lowland). *Geosciences (Switzerland)*, *9*(3). https://doi.org/10.3390/geosciences9030106

Hood, W. G. (2004). Indirect Environmental Effects of Dikes on Estuarine Tidal Channels: Thinking Outside of the Dike for Habitat Restoration and Monitoring. In *Estuarine Research Federation Estuaries* (Vol. 27, Issue 2, pp. 273–282).

Hou, G., Delang, C. O., & Lu, X. (2020). Afforestation changes soil organic carbon stocks on sloping land: The role of previous land cover and tree type. *Ecological Engineering*, *152*. https://doi.org/10.1016/j.ecoleng.2020.105860

Ihsan Fawzi, N., Rahmasary, A. N., & Qurani, I. Z. (2020). Minimizing carbon loss through integrated water resource management on peatland utilization in Pulau Burung, Riau, Indonesia. *E3S Web of Conferences*, *200*, 02019. https://doi.org/10.1051/e3sconf/202020002019

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

Johnen, G., Sapač, K., Rusjan, S., Zupanc, V., Vidmar, A., & Bezak, N. (2022). Modelling and Evaluation of the Effect of Afforestation on the Runoff Generation Within the Glinščica River Catchment (Central Slovenia). In Z. and H. T. and P. P. Ferreira Carla S. S.and Kalantari (Ed.), *Nature-Based Solutions for Flood Mitigation: Environmental and Socio-Economic Aspects* (pp. 215–231). Springer International Publishing. https://doi.org/10.1007/698_2020_649

Jones, E., Qadir, M., van Vliet, M. T. H., Smakhtin, V., & Kang, S. mu. (2019). The state of desalination and brine production: A global outlook. *Science of the Total Environment*, *657*, 1343–1356. https://doi.org/10.1016/j.scitotenv.2018.12.076

Kahil, M. T., Dinar, A., & Albiac, J. (2015). Modeling water scarcity and droughts for policy adaptation to climate change in arid and semiarid regions. *Journal of Hydrology*, *522*, 95–109. https://doi.org/10.1016/j.jhydrol.2014.12.042

Kameshwar, S., Park, H., Cox, D. T., & Barbosa, A. R. (2021). Effect of disaster debris, floodwater pooling duration, and bridge damage on immediate post-tsunami connectivity. *International Journal of Disaster Risk Reduction*, *56*, 102119. https://doi.org/10.1016/j.ijdrr.2021.102119

Kändler, N., Annus, I., Vassiljev, A., & Puust, R. (2020). Real time controlled sustainable urban drainage systems in dense urban areas. *Journal of Water Supply: Research and Technology - AQUA*, *69*(3), 238–247. https://doi.org/10.2166/aqua.2019.083

This project has received funding from the European Union's Horizon Europe research and innovation programme under grant agreement No. 101093854

Karavitis, C. A., Tsesmelis, D. E., Skondras, N. A., Stamatakos, D., Alexandris, S., Fassouli, V., Vasilakou, C. G., Oikonomou, P. D., Gregorič, G., Grigg, N. S., & Vlachos, E. C. (2014). Linking drought characteristics to impacts on a spatial and temporal scale. *Water Policy*, *16*(6), 1172–1197. https://doi.org/10.2166/wp.2014.205

Kaźmierczak, A., Bittner, S., Breil, M., Coninx, I., Johnson, K., Kleinenkuhnen, L., Kochova, T., Lauwaet, D., Nielsen, H. Ø., Smith, H., & Zandersen, M. (2020). *Urban adaptation in Europe: How cities and towns respond to climate change.* (12/2020). European Environmenal Agency. https://data.europa.eu/doi/10.2800/324620

Kemter, M., Fischer, M., Luna, L. V., Schönfeldt, E., Vogel, J., Banerjee, A., Korup, O., & Thonicke, K. (2021). Cascading Hazards in the Aftermath of Australia's 2019/2020 Black Summer Wildfires. *Earth's Future*, *9*(3). https://doi.org/10.1029/2020EF001884

Khabarov, N., Krasovskii, A., Obersteiner, M., Swart, R., Dosio, A., San-Miguel-Ayanz, J., Durrant, T., Camia, A., & Migliavacca, M. (2016). Forest fires and adaptation options in Europe. *Regional Environmental Change*, *16*(1), 21–30. https://doi.org/10.1007/s10113-014-0621-0

Klijn, F., Asselman, N., & Wagenaar, D. (2018). Room for rivers: Risk reduction by enhancing the flood conveyance capacity of The Netherlands' large rivers. *Geosciences (Switzerland)*, *8*(6). https://doi.org/10.3390/geosciences8060224

Kotroni, V., Cartalis, C., Michaelides, S., Stoyanova, J., Tymvios, F., Bezes, A., Christoudias, T., Dafis, S., Giannakopoulos, C., Giannaros, T. M., Georgiev, C., Karagiannidis, A., Karali, A., Koletsis, I., Lagouvardos, K., Lemesios, I., Mavrakou, T., Papagiannaki, K., Polydoros, A., & Proestos, Y. (2020). DISARM Early Warning System for Wildfires in the Eastern Mediterranean. *Sustainability*, *12*(16), 6670. https://doi.org/10.3390/su12166670

Kourgialas, N. N., Anyfanti, I., Karatzas, G. P., & Dokou, Z. (2018). An integrated method for assessing drought prone areas—Water efficiency practices for a climate resilient Mediterranean agriculture. *Science of the Total Environment*, *625*, 1290–1300. https://doi.org/10.1016/j.scitotenv.2018.01.051

Kumar, P., Debele, S. E., Sahani, J., Rawat, N., Marti-Cardona, B., Alfieri, S. M., Basu, B., Basu, A. S., Bowyer, P., Charizopoulos, N., Gallotti, G., Jaakko, J., Leo, L. S., Loupis, M., Menenti, M., Mickovski, S. B., Mun, S. J., Gonzalez-Ollauri, A., Pfeiffer, J., … Zieher, T. (2021). Nature-based solutions efficiency evaluation against natural hazards: Modelling methods, advantages and limitations. *Science of the Total Environment*, *784*. https://doi.org/10.1016/j.scitotenv.2021.147058

Kurowski, M., & Bradley, A. (2022). *Wildfire adaptations for resource roads in British Columbia*. https://www2.gov.bc.ca/assets/gov/farming-natural-resources-and-industry/natural-resource-use/resource-roads/engineering-publications-permits/fpinnovations/wildfire_adaptations_for_resource_roads.pdf

Lackner, S. (2018). *Earthquakes and Economic Growth*.

Lincke, D., Hinkel, J., van Ginkel, K., Jeuken, A., Botzen, W., Tesselaar, M., Scoccimarro, E., & Ignjacevic, P. (2019). *D2.3 Impacts on infrastructure, built environment, and transport Deliverable of the H2020 COACCH project*.

This project has received funding from the European Union's Horizon Europe research and innovation programme under grant agreement No. 101093854

Linnerooth-Bayer, J., Dubel, A., Sendzimir, J., & Hochrainer-Stigler, S. (2015). Challenges for mainstreaming climate change into EU flood and drought policy: Water retention measures in the Warta River Basin, Poland. *Regional Environmental Change*, *15*(6), 1011–1023. https://doi.org/10.1007/s10113-014-0643-7

Loch, A., & Adamson, D. (2015). Drought and the rebound effect: A Murray–Darling Basin example. *Natural Hazards*, *79*(3), 1429–1449. https://doi.org/10.1007/s11069-015-1705-y

Lombardo, F. T. (2019). Treatment of Uncertainty for Windstorm Risk Assessment. *ASCE-ASME Journal of Risk and Uncertainty in Engineering Systems, Part A: Civil Engineering*, *5*(3), 02019001. https://doi.org/10.1061/AJRUA6.0001010

Lückerath, D., Rome, E., & Milde, K. (2023). Using impact chains for assessing local climate risk—A case study on impacts of extended periods of fluvial low waters and drought on a metropolitan region. *Frontiers in Climate*, *5*, 1037117. https://doi.org/10.3389/fclim.2023.1037117

Lund, A. J., Lopez-Carr, D., Sokolow, S. H., Rohr, J. R., & De Leo, G. A. (2021). Agricultural innovations to reduce the health impacts of dams. *Sustainability (Switzerland)*, *13*(4), 1–9. https://doi.org/10.3390/su13041869

Maggiotto, G., Miani, A., Rizzo, E., Castellone, M. D., & Piscitelli, P. (2021). Heat waves and adaptation strategies in a mediterranean urban context. *Environmental Research*, *197*, 111066. https://doi.org/10.1016/j.envres.2021.111066

Mahdi, T. W., & Hillo, A. N. (2021). Flood Control by Weir Design Using HEC-RAS Model: The Case of Al-Musandaq Escape. *IOP Conference Series: Earth and Environmental Science*, *877*(1), 012025. https://doi.org/10.1088/1755-1315/877/1/012025

Malik, H., Kändler, N., Alam, M. M., Annus, I., Le Moullec, Y., & Kuusik, A. (2018). Evaluation of low power wide area network technologies for smart urban drainage systems. *2018 IEEE International Conference on Environmental Engineering, EE 2018 - Proceedings*, 1–5. https://doi.org/10.1109/EE1.2018.8385262

Mariani, L., Parisi, S. G., Cola, G., Lafortezza, R., Colangelo, G., & Sanesi, G. (2016). Climatological analysis of the mitigating effect of vegetation on the urban heat island of Milan, Italy. *Science of The Total Environment*, *569–570*, 762–773. https://doi.org/10.1016/j.scitotenv.2016.06.111

Marinoski, A. K., Rupp, R. F., & Ghisi, E. (2018). Environmental benefit analysis of strategies for potable water savings in residential buildings. *Journal of Environmental Management*, *206*, 28–39. https://doi.org/10.1016/j.jenvman.2017.10.004

Mazdiyasni, O., Sadegh, M., Chiang, F., & AghaKouchak, A. (2019). Heat wave Intensity Duration Frequency Curve: A Multivariate Approach for Hazard and Attribution Analysis. *Scientific Reports*, *9*(1), 14117. https://doi.org/10.1038/s41598-019-50643-w

Meresa, H. K. (2020). River flow characteristics and changes under the influence of varying climate conditions. *Natural Resource Modeling*, *33*(1). https://doi.org/10.1111/nrm.12242

Moftakhari, H., & Aghakouchak, A. (2019). Increasing exposure of energy infrastructure to compound hazards: Cascading wildfires and extreme rainfall. *Environmental Research Letters*, *14*(10). https://doi.org/10.1088/1748-9326/ab41a6

This project has received funding from the European Union's Horizon Europe research and innovation programme under grant agreement No. 101093854

Moos, C., Bebi, P., Graf, F., Mattli, J., Rickli, C., & Schwarz, M. (2016). How does forest structure affect root reinforcement and susceptibility to shallow landslides? *Earth Surface Processes and Landforms*, *41*(7), 951–960. https://doi.org/10.1002/esp.3887

Mortazavi-Naeini, M., Bussi, G., Elliott, J. A., Hall, J. W., & Whitehead, P. G. (2019). Assessment of Risks to Public Water Supply From Low Flows and Harmful Water Quality in a Changing Climate. *Water Resources Research*, *55*(12), 10386–10404. https://doi.org/10.1029/2018WR022865

Mortensen, E., Tiggeloven, T., Haer, T., van Bemmel, B., Le Bars, D., Muis, S., Eilander, D., Sperna Weiland, F., Bouwman, A., Ligtvoet, W., & Ward, P. J. (2023). The potential of global coastal flood risk reduction using various DRR measures. *Natural Hazards and Earth System Sciences Discussions*, *2023*, 1–33. https://doi.org/10.5194/nhess-2022-284

Mourad, K. A., Nordin, L., & Andersson-Sköld, Y. (2022). Assessing flooding and possible adaptation measures using remote sensing data and hydrological modeling in Sweden. *Climate Risk Management*, *38*. https://doi.org/10.1016/j.crm.2022.100464

Mugume, S. N., Gomez, D. E., Fu, G., Farmani, R., & Butler, D. (2015). A global analysis approach for investigating structural resilience in urban drainage systems. *Water Research*, *81*, 15–26. https://doi.org/10.1016/j.watres.2015.05.030

Muis, S., Verlaan, M., Winsemius, H. C., Aerts, J. C. J. H., & Ward, P. J. (2016). A global reanalysis of storm surges and extreme sea levels. *Nature Communications*, *7*. https://doi.org/10.1038/ncomms11969

Mulholland, E., & Feyen, L. (2021). Increased risk of extreme heat to European roads and railways with global warming. *Climate Risk Management*, *34*, 100365. https://doi.org/10.1016/j.crm.2021.100365

Nguyen, M. N., & Wang, X. (2011). *An investigation of extreme heatwave events and their effects on building and infrastructure*. CSIRO National Research Flagship Climate Adaptation. http://www.csiro.au/resources/CAF-working-papers.html

Noguera, I., Domínguez-Castro, F., Vicente-Serrano, S. M., & Reig, F. (2023). Near-real time flash drought monitoring system and dataset for Spain. *Data in Brief*, *47*, 108908. https://doi.org/10.1016/j.dib.2023.108908

Nouasse, H., Rajaoarisoa, L., Doniec, A., Duviella, E., Chiron, P., Archimède, B., & Chuquet, K. (2015). *Study of drought impact on inland navigation systems based on a flow network model Open Archive Toulouse Archive Ouverte (OATAO) Study of Drought Impact on Inland Navigation Systems based on a Flow Network Model*. http://www.vnf.fr/vnf/img/cms/Tourisme

Oberascher, M., Rauch, W., & Sitzenfrei, R. (2022). Towards a smart water city: A comprehensive review of applications, data requirements, and communication technologies for integrated management. *Sustainable Cities and Society*, *76*. https://doi.org/10.1016/j.scs.2021.103442

Peng, X., Heng, X., Li, Q., Li, J., & Yu, K. (2022). From Sponge Cities to Sponge Watersheds: Enhancing Flood Resilience in the Sishui River Basin in Zhengzhou, China. *Water (Switzerland)*, *14*(19). https://doi.org/10.3390/w14193084

This project has received funding from the European Union's Horizon Europe research and innovation programme under grant agreement No. 101093854

Pezza, D. A., & White, J. M. (2021). Impact of the Duration of Coastal Flooding on Infrastructure. *Public Works Management & Policy*, *26*(2), 144–163. https://doi.org/10.1177/1087724X20915918

R M Slomp, J P De Waal, E F W Ruijgh, T Kroon, E Snippen, & J S L J Van Alphen. (2014). *The Dutch Delta model for policy analysis on flood risk management in the Netherlands.* https://doi.org/10.13140/2.1.1206.0161

Rana, I. A., Sikander, L., Khalid, Z., Nawaz, A., Najam, F. A., Khan, S. U., & Aslam, A. (2022). A localized index-based approach to assess heatwave vulnerability and climate change adaptation strategies: A case study of formal and informal settlements of Lahore, Pakistan. *Environmental Impact Assessment Review*, *96*, 106820. https://doi.org/10.1016/j.eiar.2022.106820

Reale, A. S. (2023). *Assessing the burdens of urban heat: A description of functional economic and public health impacts of increasing heat in cities.*

Renewables Grid Initiative. (2023). *Implementing Integrated Vegetation Management across Europe Workshop Summary Report*. https://renewables-grid.eu/fileadmin/user_upload/Nature/IVM_Workshop_Summary_Report_fin.pdf

Rijke, J., van Herk, S., Zevenbergen, C., & Ashley, R. (2012). Room for the river: Delivering integrated river basin management in the netherlands. *International Journal of River Basin Management*, *10*(4), 369–382. https://doi.org/10.1080/15715124.2012.739173

Romero-Calcerrada, R., Novillo, C. J., Millington, J. D. A., & Gomez-Jimenez, I. (2008). GIS analysis of spatial patterns of human-caused wildfire ignition risk in the SW of Madrid (Central Spain). *Landscape Ecology*, *23*(3), 341–354. https://doi.org/10.1007/s10980-008-9190-2

Rosenzweig, C., Solecki, W. D., Blake, R., Bowman, M., Faris, C., Gornitz, V., Horton, R., Jacob, K., LeBlanc, A., Leichenko, R., Linkin, M., Major, D., O'Grady, M., Patrick, L., Sussman, E., Yohe, G., & Zimmerman, R. (2011). Developing coastal adaptation to climate change in the New York City infrastructure-shed: Process, approach, tools, and strategies. *Climatic Change*, *106*(1), 93–127. https://doi.org/10.1007/s10584-010-0002-8

Röthlisberger, M., & Papritz, L. (2023). Quantifying the physical processes leading to atmospheric hot extremes at a global scale. *Nature Geoscience*, *16*(3), 210–216. https://doi.org/10.1038/s41561-023-01126-1

Saco, P. M., McDonough, K. R., Rodriguez, J. F., Rivera-Zayas, J., & Sandi, S. G. (2021). The role of soils in the regulation of hazards and extreme events. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *376*(1834). https://doi.org/10.1098/rstb.2020.0178

Saengsupavanich, C., Pranzini, E., Ariffin, E. H., & Yun, L. S. (2023). Jeopardizing the environment with beach nourishment. *Science of The Total Environment*, *868*, 161485. https://doi.org/10.1016/j.scitotenv.2023.161485

Sánchez-Almodóvar, E., Olcina-Cantos, J., Martí-Talavera, J., Prieto-Cerdán, A., & Padilla-Blanco, A. (2023). Floods and Adaptation to Climate Change in Tourist Areas: Management Experiences on the Coast of the Province of Alicante (Spain). *Water*, *15*(4), 807. https://doi.org/10.3390/w15040807

This project has received funding from the European Union's Horizon Europe research and innovation programme under grant agreement No. 101093854

Santoso, M. A., Christensen, E. G., Yang, J., & Rein, G. (2019). Review of the Transition From Smouldering to Flaming Combustion in Wildfires. *Frontiers in Mechanical Engineering*, *5*, 49. https://doi.org/10.3389/fmech.2019.00049

Savonis, M. J., Burkett, V. R., & Potter, J. R. (2008). *Impacts of climate change and variability on transportation systems and infrastructure*. U.S. Climate Change Science Program and the Subcommittee on Global Change Research. https://rosap.ntl.bts.gov/view/dot/17351

Schanze, J. (2018). Pluvial flood risk management: An evolving and specific field. *Journal of Flood Risk Management*, *11*(3), 227–229. https://doi.org/10.1111/jfr3.12487

Schelhaas, M.-J., Hengeveld, G., Moriondo, M., Reinds, G. J., Kundzewicz, Z. W., Ter Maat, H., & Bindi, M. (2010). Assessing risk and adaptation options to fires and windstorms in European forestry. *Mitigation and Adaptation Strategies for Global Change*, *15*(7), 681–701. https://doi.org/10.1007/s11027-010-9243-0

Schulz, C., & Adams, W. M. (2019). Debating dams: The World Commission on Dams 20 years on. *Wiley Interdisciplinary Reviews: Water*, *6*(5), 1–19. https://doi.org/10.1002/wat2.1369

Serra-Llobet, A., Kondolf, G. M., Magdaleno, F., & Keenan-Jones, D. (2022). Flood diversions and bypasses: Benefits and challenges. *WIREs Water*, *9*(1), e1562. https://doi.org/10.1002/wat2.1562

Severino, L. G., Kropf, C. M., Afargan-Gerstman, H., Fairless, C., De Vries, A. J., Domeisen, D. I. V., & Bresch, D. N. (2023). *Projections and uncertainties of future winter windstorm damage in Europe* [Preprint]. Atmospheric, Meteorological and Climatological Hazards. https://doi.org/10.5194/egusphere-2023-205

Spinoni, J., Formetta, G., Mentaschi, L., Forzieri, G., & Feyen, L. (2020). *Global warming and windstorm impacts in the EU*. JRC PESETA IV project-Task 13. https://doi.org/10.2760/039014

Sun, X., Wang, J., Ma, M., & Han, X. (2023). Attribution of Extreme Drought Events and Associated Physical Drivers across Southwest China Using the Budyko Framework. *Remote Sensing*, *15*(11), 2702. https://doi.org/10.3390/rs15112702

Tedim, F., Leone, V., & Xanthopoulos, G. (2016). A wildfire risk management concept based on a social-ecological approach in the European Union: Fire Smart Territory. *International Journal of Disaster Risk Reduction*, *18*, 138–153. https://doi.org/10.1016/j.ijdrr.2016.06.005

Thompson, J. R., Frezza, D., Necioglu, B., Cohen, M. L., Hoffman, K., & Rosfjord, K. (2019). Interdependent Critical Infrastructure Model (ICIM): An agent-based model of power and water infrastructure. *International Journal of Critical Infrastructure Protection*, *24*, 144–165. https://doi.org/10.1016/j.ijcip.2018.12.002

Tiggeloven, T., de Moel, H., van Zelst, V. T. M., van Wesenbeeck, B. K., Winsemius, H. C., Eilander, D., & Ward, P. J. (2022). The benefits of coastal adaptation through conservation of foreshore vegetation. *Journal of Flood Risk Management*, *15*(3). https://doi.org/10.1111/jfr3.12790

Valerio, C., Giuliani, M., Castelletti, A., Garrido, A., & De Stefano, L. (2023). Multi-objective optimal design of interbasin water transfers: The Tagus-Segura aqueduct (Spain).

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Journal of Hydrology: Regional Studies, *46*, 101339. https://doi.org/10.1016/j.ejrh.2023.101339

Van Der Werf, J. A., Kapelan, Z., & Langeveld, J. (2023). Real-time control of combined sewer systems: Risks associated with uncertainties. *Journal of Hydrology*, *617*, 128900. https://doi.org/10.1016/j.jhydrol.2022.128900

Van Loon, A. F. (2015). Hydrological drought explained. *WIREs Water*, *2*(4), 359–392. https://doi.org/10.1002/wat2.1085

Van Steen, P. J. M., & Pellenbarg, P. H. (2004). Water management challenges in the Netherlands. *Tijdschrift Voor Economische En Sociale Geografie*, *95*(5), 590–599. https://doi.org/10.1111/j.0040-747X.2004.00343.x

van Zelst, V. T. M., Dijkstra, J. T., van Wesenbeeck, B. K., Eilander, D., Morris, E. P., Winsemius, H. C., Ward, P. J., & de Vries, M. B. (2021). Cutting the costs of coastal protection by integrating vegetation in flood defences. *Nature Communications*, *12*(1). https://doi.org/10.1038/s41467-021-26887-4

Varnes, D. J. (1984). *Landslide Hazard Zonation: A review of theory and practice* (Vol. 3). United Nations. http://worldcat.org/isbn/9231018957

Verbrugghe, N., & Khan, A. Z. (2023). Water harvesting through fog collectors: A review of conceptual, experimental and operational aspects. *International Journal of Low-Carbon Technologies*, *18*, 392–403. https://doi.org/10.1093/ijlct/ctac129

Wang, H., Lei, X., Wang, C., Liao, W., Kang, A., Huang, H., Ding, X., Chen, Y., & Zhang, X. (2023). A coordinated drainage and regulation model of urban water systems in China: A case study in Fuzhou city. *River*, *2*(1), 5–20. https://doi.org/10.1002/rvr2.36

Wang, M., Sweetapple, C., Fu, G., Farmani, R., & Butler, D. (2017). A framework to support decision making in the selection of sustainable drainage system design alternatives. *Journal of Environmental Management*, *201*, 145–152. https://doi.org/10.1016/j.jenvman.2017.06.034

Wang, X., & Bocchini, P. (2023). Predicting wildfire ignition induced by dynamic conductor swaying under strong winds. *Scientific Reports*, *13*(1), 3998. https://doi.org/10.1038/s41598-023-30802-w

Ward, P. J., Blauhut, V., Bloemendaal, N., Daniell, J. E., De Ruiter, M. C., Duncan, M. J., Emberson, R., Jenkins, S. F., Kirschbaum, D., Kunz, M., Mohr, S., Muis, S., Riddell, G. A., Schäfer, A., Stanley, T., Veldkamp, T. I. E., & Winsemius, H. C. (2020). Review article: Natural hazard risk assessments at the global scale. *Natural Hazards and Earth System Sciences*, *20*(4), 1069–1096. https://doi.org/10.5194/nhess-20-1069-2020

Ward, P. J., Jongman, B., Aerts, J. C. J. H., Bates, P. D., Botzen, W. J. W., Dlaz Loaiza, A., Hallegatte, S., Kind, J. M., Kwadijk, J., Scussolini, P., & Winsemius, H. C. (2017). A global framework for future costs and benefits of river-flood protection in urban areas. *Nature Climate Change*, *7*(9), 642–646. https://doi.org/10.1038/nclimate3350

Wilde, M., Günther, A., Reichenbach, P., Malet, J.-P., & Hervás, J. (2018). Pan-European landslide susceptibility mapping: ELSUS Version 2. *Journal of Maps*, *14*(2), 97–104. https://doi.org/10.1080/17445647.2018.1432511

This project has received funding from the European Union's Horizon Europe research and innovation programme under grant agreement No. 101093854

Winterwerp, J. C., Albers, T., Anthony, E. J., Friess, D. A., Mancheño, A. G., Moseley, K., Muhari, A., Naipal, S., Noordermeer, J., Oost, A., Saengsupavanich, C., Tas, S. A. J., Tonneijck, F. H., Wilms, T., Van Bijsterveldt, C., Van Eijk, P., Van Lavieren, E., & Van Wesenbeeck, B. K. (2020). Managing erosion of mangrove-mud coasts with permeable dams – lessons learned. *Ecological Engineering*, *158*. https://doi.org/10.1016/j.ecoleng.2020.106078

Xie, K., Kim, J. S., Hu, L., Chen, H., Xu, C. Y., Lee, J. H., Chen, J., Yoon, S. K., Zhu, D., Zhang, S., & Liu, Y. (2023). Intelligent Scheduling of Urban Drainage Systems: Effective Local Adaptation Strategies for Increased Climate Variability. *Water Resources Management*, *37*(1), 91–111. https://doi.org/10.1007/s11269-022-03357-0

Zhang, M., Liu, R., & Li, Y. (2022). Diversifying Water Sources with Atmospheric Water Harvesting to Enhance Water Supply Resilience. *Sustainability*, *14*(13), 7783. https://doi.org/10.3390/su14137783

Zimmerman, R. (2020). Heat measures for climate and infrastructure services. *Urban Climate*, *34*, 100658. https://doi.org/10.1016/j.uclim.2020.100658

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