

Pan-European multi-hazard risk assessment for CI assets

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Executive Summary

This deliverable outlines a comprehensive risk assessment framework that integrates harmonized datasets on hazards, exposure, and vulnerability—developed in WP1—with each Critical Infrastructure (CI) asset. It considers both single and multi-hazard scenarios and incorporates the evolving nature of vulnerability, especially in the context of compound and cascading events. By leveraging advanced modeling approaches, the methodology calculates Expected Annual Damages (EAD) or losses for each CI asset, ultimately producing a natural hazard risk profile designed to support infrastructure planning and policy making. The proposed framework is implemented both at the pan-European level and in a selected Use Case (UC4). At the pan-European scale, it evaluates exposure and risk across a variety of CI assets (i.e., roads, railway, power systems, telecommunication systems, education and healthcare) and natural hazards, including river and coastal floods, earthquakes, extreme heat, wildfires, and landslides. The Use Case application delves deeper, demonstrating the framework’s applicability in asset-level risk assessments for particular hazard scenarios—such as floods, earthquakes, and landslides—in a single and multi-hazard environment.



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1. Introduction

Deliverable 3.2 (D3.2) is a key outcome of Work Package 3 (WP3), which aims to assess multi-hazard critical infrastructure (CI) risk at multiple levels—asset, network, and system. As part of this broader effort, D3.2 focuses on asset-level risk assessment. The objective is to provide a detailed and harmonized evaluation of the risks that individual CI assets face due to single- and multi-hazard events across Europe. The assessment under D3.2 builds upon existing risk modeling frameworks developed by the consortium, incorporating state-of-the-art methodologies to estimate the potential direct impacts of infrastructure failure within a single and multi-hazard context. The goal is to develop a robust asset-level risk profile that informs infrastructure resilience planning and decision-making.

More specifically, D3.2 presents a comprehensive asset-level risk assessment methodology that overlays individual CI assets with harmonized hazard, exposure, and vulnerability datasets as developed in WP1 (Milestones MS1.1 and MS1.2, part of Deliverables D1.4 and D1.5). It accounts for both single-hazard footprints and multi-hazard event sets, explicitly integrating the dynamic nature of vulnerability due to compound and cascading events. By leveraging advanced modeling approaches, the deliverable quantifies **Expected Annual Damages (EAD)** for each identified CI asset, providing a natural hazard risk profile that can be used for infrastructure planning and policy development.

D3.2 is structured as follows: Section 2 describes the risk assessment methodologies that motivated this work, highlighting the existing gaps. Section 3 describes the Asset-Level Risk Assessment Methodology that (details the methodology used, including both single-hazard and multi-hazard approaches. The Application to European Scale (Section 4) explores the implementation of the methodology on a large (European) scale. Finally, the Application to Use-Case Scale (Section 5) further explores the applicability of the methodology analyzing asset-level risk assessment for specific hazard scenarios, such as floods, earthquakes, and landslides in a single and multi-hazard environment.

The methodology employed in D3.2 is object-based, meaning that each CI asset is assessed individually by overlaying it with hazard footprints and multi-hazard event sets. This assessment incorporates data harmonization from WP1 to ensure consistency in hazard, exposure, and vulnerability inputs, integration of existing open-access asset-level risk modeling frameworks, and explicit consideration of vulnerability dynamics arising from compound and cascading hazard events.

The findings of D3.2 will contribute to a pan-European understanding of asset-level multi-hazard risk, supporting more informed risk mitigation strategies, and will be considered as a starting point for the further development of MIRACA's interactive



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database. For the final release of the interactive database, exposure and risk estimates will be updated, based on the results of Deliverable 1.4 and Deliverable 1.5. By quantifying potential damages at an asset-specific level, this deliverable will serve as a valuable resource for policymakers, infrastructure operators, and risk analysts working towards enhancing the resilience of CI in Europe.

2. State of the art

Climate change has profound and far-reaching consequences across all sectors of society, affecting physical infrastructure, economic stability, and financial systems (van den Hurk et al., 2023; Zournatzidou et al., 2024; Koks, 2022). Natural hazards, such as floods, are becoming more frequent and severe due to climate change, posing substantial threats to CI, including transportation networks, residential areas, and commercial establishments (Nemry et al., 2012; Insana et al., 2021; Forzieri et al., 2018).

In recent years, several tools and software solutions have been developed for large-scale risk analysis of CI exposed to single natural hazards (Shadabfar et al., 2022). For example, the Retis-Risk research project developed a seismic risk assessment tool for road networks (Sextos et al., 2017). The SYNER-G3 project focused on systemic seismic vulnerability and risk analysis at urban and regional levels. Ergo¹ is an open-source platform designed for seismic risk and resilience assessment. ResMapper (Byun & D'Ayala,² is an open-source platform designed for seismic risk and resilience assessment. In addition to seismic-focused tools, several software platforms support risk assessment for other natural hazards. For instance, MyOcean Viewer PRO (2021) offers an interactive environment for analyzing marine conditions and coastal risks using data from the Copernicus Marine Environment Monitoring Service. The Thermal Stress Story Hub visualizes the impacts of extreme heat under future climate scenarios, while the Past Climate Explorer and WEKEO platforms provide access to historical and real-time climate data for assessing hazard exposure and long-term vulnerability trends. Safeland³ large-scale European project created standardized tools and approaches for quantitatively assessing and managing landslide risks across local, regional and European scales. The project also established the basis for understanding landslide risk in Europe enhancing our ability to predict landslide hazards and detect high-risk landslide zones. According to Kazantzi et al. (2025), an analytical probabilistic approach is presented for evaluating the flood fragility of bridges, taking into account various levels of foundation scour severity.

¹ <https://ergo.ncsa.illinois.edu/>

² <https://github.com/jieunbyun/resmapper>

³ <https://www.ngi.no/en/projects/safeland/>



Despite these advancements, significant gaps remain. Most available tools focus on specific hazards, such as seismic events, without considering multi-hazard interactions. Effective risk reduction requires the development of models that integrate multiple hazards and assess the vulnerability of CI comprehensively. However, addressing multiple hazards introduces additional challenges, such as varying hazard characteristics and cascading effects.

There are two primary approaches to multi-hazard assessments. The first, known as Independent Multi-Hazards, examines multiple hazards separately without considering interactions between them. The second, Interacting Multi-Hazards, acknowledges and analyzes the ways hazards influence one another, such as through cascading or triggering effects (Liu et al. 2015; De Angeli et al., 2022).

The Independent Multi-Hazard approach evaluates all relevant hazards within a specific area without assessing their interactions. Methodologies include conducting separate analyses of different hazards (et al., 1999, Garcin et al., 2008, Perry et al., 2008) or overlaying hazard maps to identify spatial intersections of different threats (Agwe et al. 2005, Wipulanusat et al. 2011, Mahendra et al. 2011, Pourghasemi et al. 2019, Bathrellos et al. 2017, Koks et al. 2019, Karatzetzou et al. 2023). Multi-hazard assessments can be conducted at different scales. On a global scale, the multi-hazard index by Agwe et al. (2005) ranks regions based on cumulative hazard intensity. Reports such as the Global Assessment Report (Desai et al., 2015) and the Global Risk Atlas (UNISDR, 2017) aggregate risk metrics using probabilistic average annual losses (AALs). GIRI⁴ (Global Infrastructure Risk and Resilience Index) is a comprehensive platform developed by the Coalition for Disaster Resilient Infrastructure (CDRI) to assess the risk to infrastructure assets across various sectors due to geological and climate-related hazards. It provides a global, probabilistic risk assessment for infrastructure, including power, telecommunications, transportation, water, energy, and essential services like health and education. On regional and local scales, spatial methodologies standardize hazard assessments to enable cross-hazard comparisons (Garcia-Aristizabal and Marzocchi, 2013). Probabilistic models use return periods of hazard events (Carpignano et al. 2009, Schmidt et al. 2011, FEMA 2007, Van Westen et al. 2002, Marzocchi et al. 2009, Asprone et al. 2009), while qualitative classifications categorize hazard frequency and intensity (NGI, 2009).

The Interacting Multi-Hazard approach, unlike the independent approach, studies relationships between hazards, including their potential to trigger, amplify, or alter each other. Due to its complexity and data requirements, this approach is less widely applied. To address data gaps, Barrantes (2018) introduced a qualitative framework for analyzing hazard interactions in data-scarce environments. Research has identified three primary interaction mechanisms (Ciurean et al., 2018): triggering (causation), where one hazard directly initiates another (e.g., an earthquake inducing a landslide); influence, where a

⁴ <https://giri.unepgrid.ch/>



hazard modifies the likelihood, intensity, or spatial distribution of another without direct causation; and independent coincidence, where multiple hazards occur simultaneously in the same area without a direct causal link. Gallina et al. (2020) introduced a semi-quantitative multi-risk methodology to assess the impact of climate change on multiple (interacting) hazards. They used an influence matrix to analyze the relationships among hazards. The proposed approach provides a rapid assessment tool able to scan areas and targets at risk from different types of hazards. At a European scale, the E.U. MYRIAD⁵ project developed a unified approach for managing risks that are multi-hazard, cross-sectoral, and systemic in nature. In the framework of the project, Claassen et al. (2023) presented MYRIAD-Hazard Event Sets Algorithm (MYRIAD-HESA), that compiles historically based multi-hazard event sets that occur on varying time, space, and intensity scales.

Although hazard interaction research is growing, no comprehensive framework systematically addresses all multi-hazard scenarios (Choi et al., 2021). Understanding these interactions is essential for improving risk predictions, as combined impacts may differ significantly from the sum of individual effects (Zuccaro et al., 2008).

Multi-hazard risk assessments evaluate the cumulative impact of multiple hazards, incorporating both hazard interactions and vulnerability dynamics (Wang et al., 2020). This field is still evolving, particularly in the development of quantitative methods that account for uncertainties. Research efforts, such as those by Marzocchi et al. (2012) and Liu et al. (2015) emphasize integrating hazard interactions into risk models. However, comprehensive frameworks remain limited.

Several large-scale initiatives have developed frameworks and tools for vulnerability and loss assessment in multi-hazard environments. HAZUS⁶ in the 1990s as a seismic risk assessment tool but has since evolved into multiple hazard platforms, including earthquakes, hurricanes, and floods. Despite their extensive fragility models, many rely on expert judgment with limited derivation consistency. The CAPRA Platform⁷, developed in collaboration with Central American governments and international organizations, integrates hazard data, exposure models, and vulnerability assessments for multi-hazard risk analysis.

Other initiatives include INFRARISK⁸, an EU-funded project that developed a stress test framework for critical European transport infrastructure, considering multi-hazard and

⁵ <https://www.myriadproject.eu/>

⁶ <https://www.fema.gov/>

⁷ <https://ecapra.org/>

⁸ <https://cordis.europa.eu/project/id/603960/reporting/es#:~:text=The%20objective%20of%20the%20INFRARISK%20project%20was%20to,stress%20tests%20for%20distributed%20road%20and%20rail%20networks>



cascading extreme events. STREST⁹ proposed a multi-level stress test framework for non-nuclear CI, incorporating interdependencies and cascading failures under various natural hazards. The Global Earthquake Model (GEM)¹⁰, founded in 2009, provides open-source databases and software for global earthquake and multi-hazard risk assessment. RiskScape, a GIS-based tool developed by NIWA¹¹ in New Zealand, integrates exposure modeling, vulnerability assessment, and loss estimation. The NIST Community Resilience Planning Guide supports multi-hazard vulnerability assessments of buildings and infrastructure systems. EU-CIRCLE¹² established the Critical Infrastructure Resilience Platform (CIRP) to analyze vulnerabilities and climate change impacts on European CI. IN-CORE, developed by the University of Southern California, provides tools for simulating hazard interactions and assessing infrastructure vulnerabilities. The INFRARES Project¹³ developed an innovative, user-friendly software for multi-hazard risk and resilience assessment of transportation infrastructure, specifically for floods and earthquakes. The INFRARES tool, implemented in Excel using VBA, facilitates easy application by operators, stakeholders, and designers.

Despite these advancements, many frameworks and tools remain at the research level, with limited practical adoption at European scale. The review of existing multi-hazard literature highlights three major gaps that hinder comprehensive multi-hazard risk assessment. Many studies on hazard interactions fail to incorporate quantitative risk assessments, limiting their practical application for risk-based decision making for infrastructure investment decisions. On the other hand, existing quantitative multi-hazard methods based on sophisticated computational models are often too complicated to permit their direct application to real case studies at large scale. Additionally, most research focuses on a limited subset of hazard types, preventing a fully integrated multi-hazard approach considering also hazard scenarios that incorporate climate change. Another key shortcoming is the lack of consideration for long-term recovery, including compound and/or residual damage from consecutive disasters, which is essential for understanding the full impact of hazard interactions. Addressing these gaps is crucial for advancing multi-hazard risk assessment methodologies and developing more effective resilience strategies.

⁹ <http://strest-eu.org/>

¹⁰ <https://www.globalquakemodel.org/>

¹¹ <https://niwa.co.nz/hazards/riskscape-software#:~:text=RiskScape%2C%20a%20collaboration%20between%20NIWA%20and%20GNS%20Science,a%20software%20application%20for%20analysing%20natural%20hazard%20consequences>

¹² <https://www.eu-circle.eu/>

¹³ <https://www.infrares.gr/>



3. Asset-level risk assessment methodology

3.1. Single-Hazard

Risk is commonly defined as a function of hazard, exposure, and vulnerability. **Hazard** is defined as the probability of the occurrence of a specified level of intensity event within a specified time period and within a given area with potential to cause damage (IPPC, 2014). **Exposure** is the spatial distribution (location) and characteristics of the assets subjected to hazard (IPPC, 2014; UNDDR, 2019). **Vulnerability** is the degree of damage or loss to a given asset or set of assets exposed to a specified hazard of a given intensity (Koks et al. 2015). Herein, these components are incorporated in the proposed object-based risk assessment approach that involves intersecting CI assets with various single natural hazards, followed by a damage and risk assessment for each impacted asset using the collected vulnerability data.

The MIRACA asset-level risk assessment methodology follows a well-structured approach to evaluate the vulnerability and risk of CI assets under various natural hazards. Fig 1 presents the flowchart of the adopted methodological framework, summarizing the main aspects to be considered and how they combine for a generic, single-source, risk assessment, while the following paragraphs outline the conceptual features of the methodology.

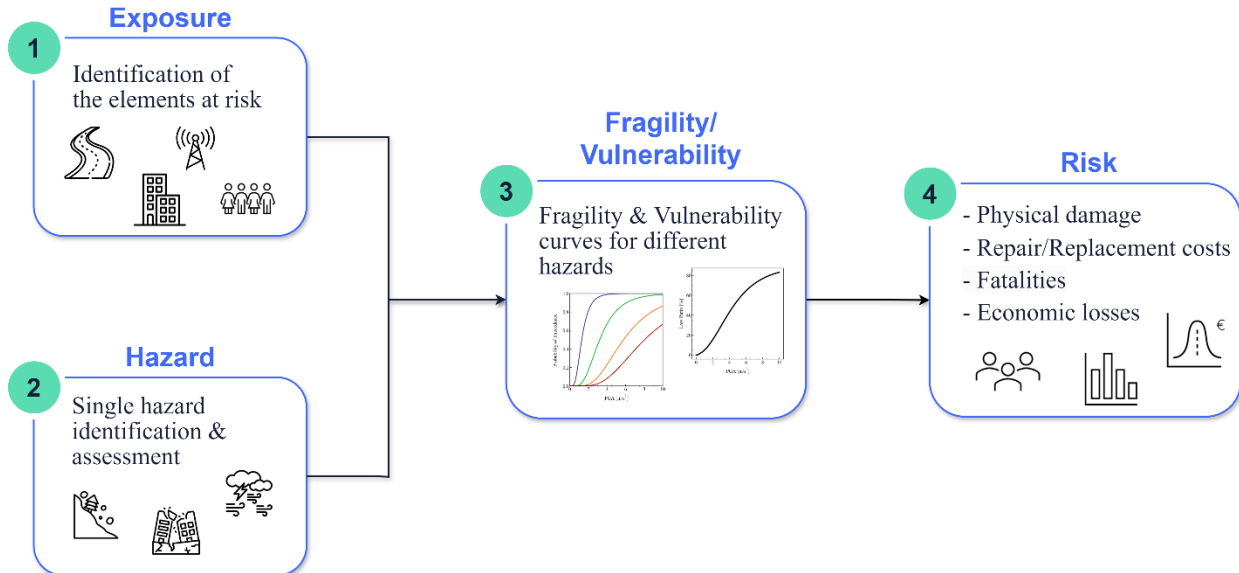


Fig 1. Graphical representation of the asset-level risk assessment methodological framework.



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In the initial phase, the **specific geographic area** and **time frame** of interest are determined.

The proposed methodology consists of **four key steps**: i) identification of the elements at risk; ii) single hazard identification and assessment; iii) fragility/vulnerability identification; and iv) risk assessment. **These steps are closely linked to the project's tasks and deliverables**, ensuring a harmonized, data-driven, and scientifically robust framework for risk assessment.

The following paragraphs provide a detailed description of each step.

- **Step 1: Identification of the elements at risk (exposure model)**

CI assets are those essential to the functioning of society, where their damage or destruction could have severe consequences on public health, safety, and the socioeconomic well-being of the population (Council Directive 2008; PCCIP 1997; Hall et al. 2016; Poudel et al. 2023). In the MIRACA asset-level risk assessment methodology, various CI assets are considered, as detailed in D1.1. Given their significance, the first step of the methodology is crucial, as it involves identifying and collecting available exposure data for critical elements at risk within the specific location of interest.

More specifically, the first step involves determining which CI assets of the area under study are exposed to natural hazards. These assets include essential facilities such as transportation networks, power grids, hospitals, and telecommunication networks. This step includes collecting available exposure data on CI assets at risk and mapping the spatial distribution of these assets to better understand their vulnerability. As part of MIRACA, a Pan-European harmonized exposure database (D1.4) is being developed, providing a standardized dataset for exposure analysis. Furthermore, existing gaps in exposure data are assessed as part of Task 1.1, ensuring that the risk assessment methodology is based on a comprehensive dataset.

At this step, we also define suitable loss metrics to quantify risks (e.g., expected annual damage, annual probability of collapse, loss of functionality etc.). Establishing suitable impact metrics is crucial and should be addressed before moving forward. This will enable decision-makers to prioritize risks based on their severity and likelihood, ensuring that the most critical risks are addressed first. This is also essential considering that some hazards can cause significant financial damage without directly leading to injuries or loss of life.

- **Step 2: Single hazard identification and assessment**

The purpose of this step is to identify the critical natural hazards that may occur at the location of the examined assets and to identify appropriate single hazard models for these hazards, which will be considered at risk assessment of the assets. For critical



hazards, appropriate intensity measures (IMs) are defined, primarily based on their computability and availability, as well as to some extent their effectiveness, efficiency, sufficiency, and robustness. It should be noted that the methodology for single hazard assessment, presented herein, can be applied also to multiple natural hazards, but with no combination of the expected results. Deliverable 1.2 - MIRACA Climate Hazard Database provides an overview of the categories of hazards included in MIRACA hazard database, highlighting the key findings and gaps of data that should be considered when using the climate hazard database as input for a climate risk assessment.

More specifically, this second step focuses on defining the natural hazards that could potentially affect the identified CI assets. Based on Task 1.2, climatological and geophysical hazards such as floods (pluvial, fluvial, coastal), windstorms, heatwaves, droughts, wildfires, earthquakes, and landslides are considered. For each hazard, appropriate intensity measures (IMs) associated with a specific frequency of occurrence are selected to quantify their severity, such as wind speed for windstorms, ground displacement for landslides, and inundation depth for floods. For specific hazards (e.g., earthquakes, landslides), a kind of assessment is performed to derive the appropriate hazard IMs. For example, in case of earthquakes, European Seismic Hazard maps (ESHM20, Danciu, et al., 2021) provide PGA and spectral accelerations at different periods ($T=0.3s, 0.6s, 1s, 1.5s$) at bedrock level for six different return periods derived from probabilistic seismic hazard analysis (PSHA). So, we then estimate median PGA and spectral accelerations at different periods ($Sa(T)$) at the ground surface for the different return periods considering a detailed site model using OpenQuake engine (Silva et. al, 2014). Similarly, for landslides, we overlap the susceptibility index map (ELSUS v2, Wilde et al. 2018) with the computed seismic hazard maps to compute the permanent displacements due to earthquake induced landslides. Additionally, existing datasets are used to collect hazard footprint data and event sets for different return periods and spatial scales, contributing to the Pan-European standardized hazard database (D1.2). This step also considers the influence of climate change by analyzing potential shifts in hazard intensity, frequency, and spatial extent, ensuring that the methodology remains adaptable to future climate scenarios.

- **Step 3: Fragility / Vulnerability assessment**

The third step evaluates how examined CI assets (Step 1) respond to different hazard intensities of critical hazards (Step 2) by assessing their susceptibility to damage. This step is combined with Task 1.5, where historical CI disruptions and socio-economic losses from past hazard events are analyzed to create vulnerability functions. The outcome is a Pan-European harmonized vulnerability database (D1.5), which includes reconstruction costs per asset, as well as vulnerability and fragility curves tailored to different hazards. Fragility curves, which quantify the probability of an asset reaching a certain damage state based on an intensity measure (IM), are developed using empirical and analytical approaches. These curves are typically expressed using probabilistic models, incorporating both aleatory and epistemic uncertainties. Moreover, in cases of



consecutive or conjoint hazards, fragility models are extended to account for cumulative damage effects, ensuring a comprehensive multi-hazard risk evaluation. The core methodology remains the same, regardless of the hazard considered or the asset examined. The fragility curves are expressed according to Equation 1 (e.g., Porter et al. 2021).

$$P_f(LS \geq LS_i | IM) = \Phi \left[\frac{1}{\beta_{tot}} \ln \left(\frac{IM}{IM_{mi}} \right) \right] \quad (\text{Eq. 1})$$

where P_f is the probability of exceeding a given limit state, for a given level of intensity of the hazard (the latter expressed via an IM), Φ is the standard cumulative probability function, IM_{mi} is the median threshold value of the intensity measure, required to cause the i^{th} limit state and β_{tot} is the total lognormal standard deviation, describing the aleatory and epistemic uncertainties related with the definition of the fragility function.

• **Step 4: Risk assessment**

The final step, Risk Assessment, integrates exposure, hazard, and vulnerability data to estimate potential risks associated with CI assets. This involves calculating both direct and indirect losses, where direct losses include physical damage, repair costs, fatalities and functionality disruptions, while indirect losses encompass economic consequences such as business interruptions and supply chain failures. The assessment also involves defining key risk metrics, such as expected annual damage (EAD), failure probabilities, and infrastructure restoration times. The results of the risk assessment will then be used to develop mitigation strategies, adaptation measures, and emergency response plans, providing stakeholders with data-driven insights for enhancing infrastructure resilience. It is acknowledged that due to the diversity of hazards and their combinations, it would be impractical to describe every possible hazard scenario. However, the proposed framework aims to be comprehensive and representative by including several critical hazard scenarios that cover a wide range of potential events.

It is noted that for specific hazards (e.g. wildfires, landslides), a comprehensive risk analysis that would require assessing the vulnerability of the CI is not possible due to the lack of appropriate fragility/vulnerability functions and detailed exposure data. In these cases, a more qualitative approach will be followed resulting in the evaluation of the potential impact by overlapping hazard or susceptibility data with exposure information.

3.2. Multi-Hazard

The concept of “multi-hazard assessment” according to the United Nations Disaster Risk Reduction (UNDRR, 2019) definition is the selection of multiple major hazards that a region faces and the specific contexts where hazardous events may occur



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simultaneously, cascading or cumulatively over time, and considering the potential interrelated effects.

Herein, building on the available literature (e.g., Marzocchi et al. 2012; Liu et al. 2015), a conceptual Bayesian network for multi-hazard risk assessment is proposed to estimate the whole risk from various hazards, considering the effects of interactions among potential hazards and at the vulnerability level (dynamic vulnerability). Fig 2 summarizes a schematic view of the general procedure followed for the multi-hazard risk assessment.

In the first step, the **space (target area) and time window** of interest are identified. This initial step also involves determining the **CI assets** of the area under study that are exposed to natural hazards as well as the **expected loss metric(s)**. Especially, the definition of appropriate loss metrics plays a key role and should precede the rest steps, as, for example, some hazards can create significant economic losses without, however, causing injuries or fatalities.

In the second step, once the space and time window, the elements at risk and the loss metrics have been defined, the **hazard sources or triggering hazardous events need to be identified** for the target area. This includes hazards that are (i) independent but threatening the same elements at risk with or without chronological coincidence, and (ii) dependent on one another or caused by the same triggering event or hazard (e.g., the case of “cascading events”). In this step, possible scenarios for cascade (or compound) events are also identified **considering also** (when appropriate) **climate change** (e.g., an earthquake can trigger a landslide, extreme precipitation may trigger landslides and floods and increase the frequency of their occurrence due to climate change).



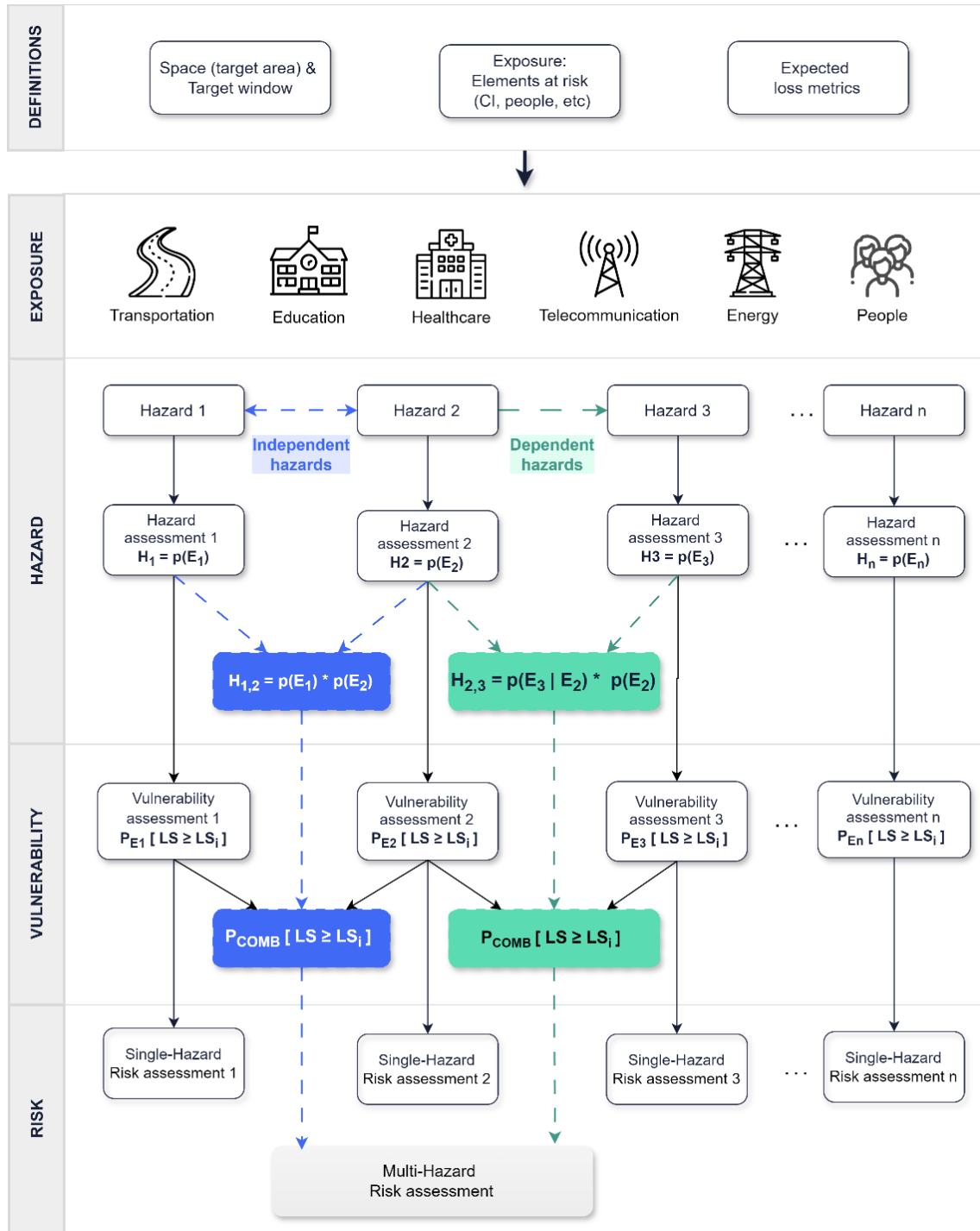


Fig 2. Graphical representation of the general procedure followed for the multi-hazard risk assessment (modified from Marzocchi et al., 2012).



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In the third step, the process of **single and multi-hazard assessment** is performed as a function $f()$ of the hazard intensity measure, the hazard source(s), and the diffusion procedures (i.e. the pathway from the source to the receptor (exposed element)). Herein, multi-hazard assessment differentiates depending on whether the hazards are independent or not.

In the former case, **where independent hazards threaten a common area**, the different hazard sources need to be identified, and each individual hazard is estimated independently, generally using a hazard-specific assessment methodology. The objective is to identify the frequency (or probability) of the occurrence of the different hazards and the spatial distribution of their effects over a range of their respective intensity measures (IMs). For the case of three independent hazards E_1 , E_2 and E_3 , whose occurrence is H_1 , H_2 and H_3 , the joint probability of E_1 , E_2 and E_3 occurrence ($H_{(1,2,3)}$) can be written as:

$$H_{(1,2,3)} = H_1 * H_2 * H_3 = p(E_1) * p(E_2) * p(E_3) \quad (\text{Eq. 2})$$

where $p(E_1)$ represents the probability of E_1 occurrence (H_1), $p(E_2)$ the probability of E_2 occurrence (H_2), and $p(E_3)$ the probability of E_3 occurrence (H_3). In this case, the results may be single hazard maps, aggregated maps (where all maps overlap) and hazard curves (for each individual hazard) that plot the probability (or frequency) via the IM of the hazard.

In the latter case, **where hazards interact, different conditions may be considered**. Cascading events are one condition where the occurrence of a primary hazardous event could trigger a secondary hazard (e.g., an earthquake may trigger a landslide event) and thus change the probability of the occurrence of the secondary hazard. A second condition is compound events, which are hazards coinciding in space and/or time caused by the same external factors (or primary event) (e.g., a coastal flood and a river flood occurring in the same region caused by extreme precipitation, drought and wildfire both caused by lack of rainfall and extreme temperatures). In addition, consecutive disasters are a third condition, where two or more disasters occur in succession, and whose direct impacts overlap spatially before recovery from a previous event is completed. Fig 3 shows a Bayesian network that may be built to describe the interactions between hazards. As seen, one hazardous event could trigger a few other hazardous events. Generally, the joint probability of the occurrence of the interacting hazards needs to be estimated. For the case of three dependent hazards E_1 , E_2 and E_3 , whose occurrence is H_1 , H_2 and H_3 , the joint probability of the occurrence of interacting hazards ($H_{(1,2,3)}$) is estimated as:

$$H_{(1,2,3)} = p(E_1) * p(E_2|E_1) * p(E_3|E_2, E_1) \quad (\text{Eq. 3})$$



where $p(E_1)$ represents the probability of the primary event E_1 occurrence, $p(E_2|E_1)$ the conditional probability of the impacted event E_2 given the E_1 occurrence, and $p(E_3|E_2, E_1)$ the conditional probability of the impacted event E_3 given the joint occurrence of E_2 and E_1 .

This equation also includes the cases where the events E_2 and E_3 are also dependent. An example is the case where “Rainfall” is event 1 and “Flood” and “Landslide” are events 2 and 3 respectively. A flood (E_2) caused by rainfall (E_1) may increase the probability of landslide (E_3) occurrence. Thus, in this case the positive correlation between the dependent events (flood and landslide) is considered.

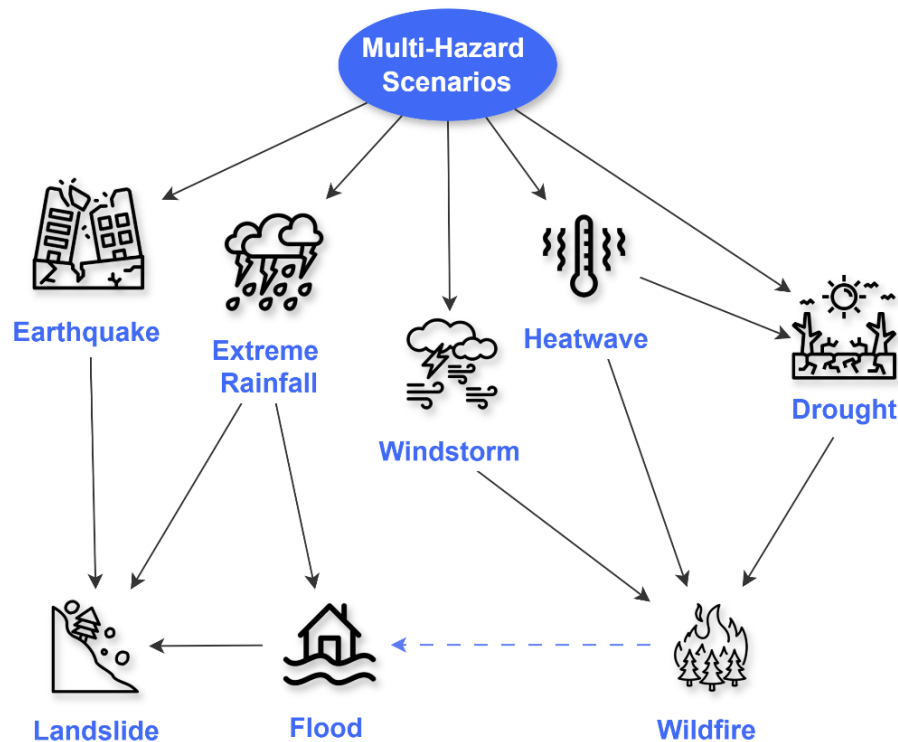


Fig 3. Possible scenarios of multi-hazard interaction, as considered within the MIRACA project.

The fourth step of the proposed framework is the **dynamic vulnerability assessment** of the exposed assets at risk, which is a function $g()$ of the hazard intensity, H , and may be modified within the context of conjoint or successive hazards. The dynamic (or time-variant) vulnerability of an asset may evolve over time due to both physical effects (e.g., ageing due to corrosion, damage accumulation from past events, etc.) and human actions (reconstruction and reinforcement, changes in use etc.) (e.g., Liu et al. 2015; Karapetrou et al. 2017). For instance, a building that suffered damage due to an



earthquake (and was not subjected to any repair) might have a greater vulnerability when subjected to another earthquake or to another hazard such as a flood or a landslide. The dynamic vulnerability can be calculated using appropriate vulnerability models (e.g., that consider aging effects or reconstruction/reinforcement) from the vulnerability database developed in MIRACA (Task 1.5). The **cumulative damage** from the different hazards (e.g., earthquake and landslides) may be evaluated using appropriate fragility surfaces that are a function of the two (or more) hazards (if they exist) from the MIRACA vulnerability database (Task 1.5).

Alternatively, the **compound damage** due to the different hazards may be estimated by combining the damage state probabilities for the different hazards.

The combined probability (P_{COMB}) of exceeding a given limit state i due to the occurrence of two different hazards is given as (e.g., Fotopoulou et al. 2022):

$$P_{\text{COMB}}[LS \geq LS_i] = P_{E_1}[LS \geq LS_i] + p(E_2|E_1) \cdot P_{E_2}[LS \geq LS_i] - P_{E_1}[LS \geq LS_i] \cdot p(E_2|E_1) \cdot P_{E_2}[LS \geq LS_i] \quad (\text{Eq. 4})$$

where $P_{E_1}[LS \geq LS_i]$ is probability of exceeding of the limit state i due to the occurrence of hazard E_1 , $P_{E_2}[LS \geq LS_i]$ is probability of exceeding of the limit state i due to the occurrence of hazard E_2 and $p(E_2|E_1)$ is the probability of occurrence of hazard E_2 given the primary hazard E_1 . In case of independent hazards $p(E_2|E_1)$ is equal to 1.0.

The final step of this methodological framework is the **scenario-based multi-hazard risk assessment in terms of expected damages**. A loss ratio (that is usually defined as the ratio of the cost of repairs to the replacement cost and can be easily quantified in direct economic terms) is finally computed based on the different intensity measures. The results are given in terms of (economic and human) loss maps for the different return periods. A loss curve per asset describing the annual probability of the occurrence of the joint hazards as a function of the expected losses may be also derived.

Overall, the MIRACA asset-level risk assessment methodology provides a robust, structured approach for evaluating risks to CI. By integrating harmonized exposure data, standardized hazard models, advanced fragility functions, and comprehensive risk analysis techniques, the methodology enables a scientifically sound evaluation of infrastructure vulnerability and potential losses. The outputs of MIRACA, including Pan-European harmonized exposure and vulnerability databases, standardized single-hazard datasets, and advanced risk quantification tools, offer valuable resources for policymakers, infrastructure managers, and emergency response teams. This ensures that decision-makers have reliable and actionable insights to enhance infrastructure resilience in the face of natural hazards and climate change.



4. Application to European Scale

On a pan-European scale, we will assess exposure and risk estimates for a wide range of natural hazards: fluvial and coastal flooding, earthquakes, windstorms, extreme heat, wildfires and landslides. Whereas exposure estimates can be estimated for all natural hazards and climate extremes involved, estimating risk is more complex. To be able to estimate risk, one requires a notion of probability, most often available through natural hazard return period footprint maps (see Section 4.1). However, such maps are still unavailable on a large-scale for Europe when it comes to extreme heat, wildfires and landslides, especially when considering potential future changes to climate. As such, due to data constraints, this report will present risk estimates for flooding and earthquakes and will provide exposure estimates for all other hazards. With respect to infrastructure systems, this section of D3.2 will focus on roads, railways, airports, power systems, telecommunication systems, education, and healthcare. Please refer to Section 4.2 and Supplementary Table S1 for a full overview of specific assets and subtypes included, as extracted from OSM.

In Section 4.1, we will explain the hazards involved in this analysis, whereas Section 4.2 will further explain the exposure and vulnerability used to perform our risk assessments. In Section 4.3, we will discuss present and future pan-European exposure estimates. In Section 4.4, risk estimates are shown for present (earthquake, windstorms, flooding) and future flooding.

The exposure and risk estimates within this deliverable will be presented in full detail within MIRACA's interactive viewer once operational. The result sections in this deliverable focus on the country-level results, as static figures are proven to be complex to visualize object-based results.

4.1. Natural hazards

Table 1 provides an overview of hazard information used in this study. River flooding is obtained from JRC¹⁴ and includes seven return periods (10, 20, 30, 40, 50, 75, 100, 200, 500). The JRC flood maps do not account for any form of river protection standards. As such, a post-processing step is applied to ensure we do consider flooding in areas where the design standards of the embankments along the river are designed to not overtop or breach under those return periods. For example, if a specific section of river embankment is designed to withstand flooding with a return period of 100 years, we set all damages below this return period (e.g., the return periods 10-100) to zero. This should prevent us from overestimating river flood risk across Europe. To implement this, we make use of a gridded map of design standards, as provided by Dottori et al. (2023).

¹⁴ <https://data.jrc.ec.europa.eu/dataset/1d128b6c-a4ee-4858-9e34-6210707f3c81>



Table 1. Overview of hazard data used within Deliverable 3.2

Hazard	Return Periods	Time Periods	Source
River flooding	10, 20, 30, 40, 50, 75, 100, 200, 500	Present day, 1, 2, 3, 4 degrees of global warming	JRC
Coastal flooding	1, 100, 1000	2010, 2030, 2050, 2100	CoCliCo project
Earthquakes	50, 101, 476, 976, 2500, 5000	Present day	EFEHR
Windstorms	5, 20, 25, 50, 100, 250, 500	Present day	Priestley et al. (2023)
Extreme heat	–	1940–2100, six climate models	CCDS
Wildfires	–	1940–2100, five climate models	CCDS
Landslides	-	-	ELSUS v2

Furthermore, as no explicit hydrodynamic modelling has been performed under future climate conditions, we will make use of changing return periods under future climate conditions. Mentaschi et al. (2020) employed the LISFLOOD distributed hydrological model forced by EURO-CORDEX climate projections to simulate daily river discharge across Europe from 1981–2100 under RCP4.5 and RCP8.5 scenarios. They applied a non-stationary extreme value analysis (tsEVA) using the entire 120-year time series to estimate time-varying return levels for high and low flow extremes, rather than traditional 30-year stationary approaches. This methodology captured changing flow statistics at global warming levels of 2.0°C, 3.0°C and 4.0°C, allowing quantification of how return periods systematically change under future climate conditions without requiring explicit hydrodynamic modelling of flood events.

For coastal flooding, we make use of state-of-the-art flood maps as delivered by the CoCliCo project¹⁵. These coastal flood maps provide three return periods (1, 100 and 1000) under multiple time windows (2010, 2030, 2050, 2100) and multiple climate scenarios (SSP126, SSP245, SSP585). Moreover, three levels of protection standards are provided: (i) no assumed design standards of coastal protection, (ii) low protection standards, and (iii) high protection standards. Due to the large uncertainty across Europe with respect to coastal defense standards, we assume lower protection standards for this analysis (Van Maanen et al., 2025). Assuming no protection standards would cause a serious overestimation of potential damage.

¹⁵ <https://stacindex.org/catalogs/coclico#/2PKVxCQE9PmNgu71GLpSgWsXVNvy?t=2>



To ensure consistency when discussing future impacts across river and coastal flooding, we following the IPCC Sixth Assessment Report¹⁶, thereby assuming that SSP245 in the year 2050 corresponds to roughly 2.0°C of global warming, SSP245 in the year 2100 to roughly 3.0°C of global warming, and SSP585 in the year 2100 to roughly 4.0°C of global warming.

For earthquakes, we make use of the data shared by the European Facilities for Earthquake Hazard and Risk (EFEHR)¹⁷. They provide the results from the Euro-Mediterranean Seismic Hazard Model (ESHM-20), which we use as the underlying hazard data for our earthquake risk assessment. More specifically, we make use of the PGA hazard maps, with six return periods (50, 101, 476, 976, 2500, 5000).

For windstorms, we rely on the return-period footprint maps as developed by Priestley et al. (2023). They developed windstorm maps with seven return periods (5, 20, 25, 50, 100, 250, 500), based on the Windstorm Information Service (WISC) database. Priestley et al. (2023) provides spatially coherent windstorm footprints at 4.4 km resolution across Europe for the period 1950-2014. The footprints are produced through a two-step downscaling process of ERA-Interim and ERA-20C reanalysis data. First, the reanalysis data acts as boundary conditions for a 12 km version of the Met Office Unified Model that is initialized on 4 consecutive days for 30 hours, followed by the 12 km model acting as boundary conditions for the 4.4 km model. Each footprint represents the maximum 3-second wind gust at 10 m elevation over a 72-hour period centered on ± 36 hours of the storm's maximum intensity, defined as the time of maximum 925 hPa wind speed over land. The final windstorm footprint maps are generated by assuming that gust speed peaks over threshold are distributed exponentially (i.e., a generalised Pareto distribution with zero shape parameter).

For wildfires and extreme heat, we make use of the “Climate indicators for Europe from 1940 to 2100 derived from reanalysis and climate projections” dataset provided by the Copernicus Climate Data Store¹⁸. For extreme heat, we make use of three global climate models (EC-EARTH, HadGEM2-ES and MPI-ESM-LR) and three regional climate models (CCLM4-8-17, RACMO22E, RCA4) to determine the number of hot days (above 30, 35 and 40 degrees Celsius) per month. For wildfires, we make use of five global climate models (EC-EARTH, CNRM-CM5, IPSL-CM5A-MR, HadGEM2-ES and MPI-ESM-LR). For both datasets, we compare the present day (1990 to 2020) with several future time windows (2040-2060, and 2080-2100).

Landslide susceptibility across Europe is assessed using the European Landslide Susceptibility Map (ELSUS) V2, as developed by Wilde et al. (2018). ELSUS V2 provides

¹⁶ <https://www.ipcc.ch/report/sixth-assessment-report-working-group-i/>

¹⁷ <https://hazard.efehr.org/en/home/>

¹⁸ <https://cds.climate.copernicus.eu/datasets/sis-ecde-climate-indicators?tab=overview>



landslide susceptibility zonation for individual climate-physiographic zones across Europe at 200 × 200 m spatial resolution, covering a larger area than the previous ELSUS 1000 version. The map is prepared using a semi-quantitative method that combines landslide frequency ratios with a spatial multi-criteria evaluation model incorporating three thematic predictors: slope angle, shallow subsurface lithology, and land cover. ELSUS V2 was developed using an extended landslide inventory containing 30% additional locations for model calibration and validation compared to the previous version, along with an updated lithological dataset derived from the International Hydrogeological Map of Europe (IHME). This updated approach increases the overall predictive performance by 8% compared to the original ELSUS 1000 map.

4.2. Exposure and vulnerability

4.2.1. Exposure

To represent the global landscape of CI, we selected a total of 60 OSM tags to identify 43 different infrastructure types (Table S1). This breakdown of CI types enables a more granular approach to risk and damage assessments by providing detailed categorizations and geospatial data on the global infrastructure network. Table S2 provides an overview of the number of unique CI assets which are being considered for each country.

Transportation

The transportation system includes three subsystems: roads, railways, and airports. Roadways are further categorized into primary, secondary, tertiary roads, and other roads. The system facilitates the movement of people, goods, and services, and its disruption can cause widespread economic and societal impacts.

Energy

The energy infrastructure is crucial for the generation, transmission, and distribution of electricity. The seven key types selected for energy representation include cables, power lines (major and minor), substations, and power plants. Disruptions to this system can result in significant economic losses and widespread outages. Key elements include power cables, power lines, minor power lines, power towers, power poles, power plants, and substations.

Telecommunication

Telecommunication networks enable communication through telephone, radio, and internet systems. This system includes communication towers and masts. Towers are generally taller and support multiple applications, while masts are used for single applications. Key infrastructure types include communication towers and masts.



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Health

Health infrastructure supports public health and medical services, ensuring the availability of hospitals, clinics, and pharmacies. A variety of facilities are considered under this system, ranging from general medical services to specialized centres. Examples include hospitals, clinics, pharmacies, doctors, laboratories, birthing centres, and rehabilitation centres.

Education

Educational infrastructure ensures the availability of facilities for learning and knowledge dissemination. The five infrastructure types in this system include schools, universities, colleges, kindergartens, and libraries.

Completeness of OpenStreetMap

While OSM provides an invaluable global dataset for infrastructure mapping, a lack of completeness needs to be discussed for the sake of correct interpretability of the data. Being aware of the level of completeness is essential for using OSM as a reliable source for exposure analysis in risk assessments. OSM completeness directly affects the quality of damage and risk models. Incomplete datasets can lead to underestimation of exposure, particularly in regions with limited mapping activity (e.g., the more rural parts of Europe). Users should therefore always be careful with using OSM for their area of interest and, if necessary, supplement with local or proprietary data sources.

Despite limited available insights on OSM completeness for critical infrastructure systems, few sources are available to better understand OSM coverage for a given region. For example, the isOSMComplete tool¹⁹ provides visualizations of global OSM coverage, highlighting areas of high and low completeness. Barrington-Leigh & Ball (2017) has found that OSM completeness for road networks exceeds 80% globally, though rural and developing regions show significant gaps. For urban centres, OSM building footprint data exceeds 80% completeness for 16% of the global urban population, but completeness remains lower than 20% for 48% of the urban population. For Europe, the percentage of building completeness is over 75% (Herfort et al., 2023). While checking for completeness can be difficult, even qualitative checks (e.g. visually comparing OSM data with satellite imagery) can help to judge the completeness of the data.

Across the various infrastructure systems considered in this deliverable, it is largely agreed upon that transportation systems have the best coverage, followed by healthcare and educational systems. Whereas transportation systems have been always been the core of OSM, several large initiatives have taken place to improve the mapping of, for example, healthcare facilities²⁰. For power infrastructure, large components (e.g.

¹⁹ <https://wvanderp.github.io/isOsmComplete/>

²⁰ www.healthsites.io



power plants, large substations) and the high-voltage transmission systems are generally well mapped across Europe, but large gaps remain across medium and low-voltage distribution systems (Xiong et al., 2025). For telecommunication systems, the mapping is relatively poor, and the results of this study should only be considered as an indication of the potential impacts. Unfortunately, no known large-scale initiatives have taken place to improve the coverage of telecommunication systems within public data.

4.2.2. Vulnerability

Despite its importance, accurately determining the vulnerability of infrastructure remains a challenge. Many assets lack detailed vulnerability studies, and existing assessments are empirical, analytical, and expert judgement approaches, or a combination of these approaches. This increases the complexity of a large-scale risk assessment with a wide variety of assets. Due to the limited information on asset-level vulnerability (relative to the available hazard intensity metrics from the hazard information available for Europe), we only perform a risk assessment for windstorms, flooding and earthquakes.

Empirical approaches rely on observational or experimental data to construct vulnerability curves, offering grounded insights based on real-world events. However, empirical data is often scarce, fragmented, or context-specific, limiting its transferability. Analytical approaches use physical modelling to simulate damage processes and develop damage models that can be systematically validated. While these methods allow for a more theoretical and transparent understanding, they are data-intensive, often reliant on simplifying assumptions, and require considerable technical resources. Expert-judgement approaches are typically quicker and less resource-demanding, especially in data-poor environments, but they can introduce biases and are more difficult to validate or replicate (Nirandjan et al., 2024).

For the European risk assessment, we make use of the intermediate vulnerability database (M1.2), as part of Deliverable 1.5. This intermediate vulnerability database complements the existing database as developed by Nirandjan et al. (2024). Supplementary Table S3 provides a list of vulnerability IDs, corresponding to M1.5. In short, vulnerability curves are used for windstorms, coastal and river flooding, whereas fragility functions are used to determine the potential impact due to earthquakes.

As the detailed characteristics of assets are largely unavailable on a European level, we use a wide range of vulnerability curves and fragility functions for all assets, where available (Supplementary Table S3). This allows us to identify the potential “mean” damages for each asset, given the potential range of vulnerability characteristics for each individual asset. A full exploration of uncertainties will be presented in MIRACA’s Deliverable 3.5.



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4.2.3. Maximum construction cost

Maximum damage estimates used in this study are based on first estimates as provided by Nirandjan et al. (2024) and further complemented through Nirandjan et al. (in review). We use the median maximum construction cost for each asset type, as presented in Table S4. The maximum damages are extracted from a wide range of sources, but often from either a European or North-American origin (as similar to the vulnerability curves and fragility functions used within this analysis).

We recognize that there is considerable uncertainty surrounding the estimation of maximum construction costs. These costs are influenced not only by the type of asset and its construction materials, but also by factors such as the asset's age and degree of deterioration. However, since our primary goal is to enable a consistent comparison of potential risks across Europe, we choose not to adjust these estimated construction costs by regional GDP levels. While GDP-based adjustments are commonly applied in European studies (e.g., Forzieri et al., 2018; Voudoukas et al., 2020), we believe such an approach oversimplifies the realities of infrastructure systems. Lower-income countries do not necessarily face proportionally lower infrastructure development costs, as key resources—such as specialized materials, expertise, and technology—are often imported. Additionally, geographic features play a significant role in shaping costs. For instance, although Slovenia's GDP per capita is lower than that of the Netherlands, its mountainous terrain can significantly increase the expense of infrastructure development.

4.3. Exposure assessment

Landslides

Fig 4 presents the susceptibility to landslides across Europe for the six infrastructure systems. Landslide susceptibility across European countries shows a strong regional variation, with implications for infrastructure risk management under current and future climate conditions. Southern and mountainous countries such as Malta, Liechtenstein, Greece, Iceland, and Portugal consistently exhibit higher proportions of infrastructure located in moderate to very high susceptibility zones (Levels 3 to 5), with countries like Malta showing approximately 80-90% of their infrastructure outside of Level 1 zones across most sectors. In contrast, northern and low-lying countries including Lithuania, the Netherlands, Latvia, and Denmark are characterized by a dominance of Level 1 susceptibility (approximately 80-90% of infrastructure), suggesting relatively limited exposure. Between these extremes lies a middle tier of countries such as Finland, Bulgaria, Belgium, and Austria that show more balanced distributions across



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susceptibility levels. These patterns reflect underlying topographic and geological variability within these countries, with steep terrain playing a key role in hazard prevalence. The geographic disparities highlight the need for spatially differentiated adaptation strategies that account for regional susceptibility baselines when planning or upgrading infrastructure.

At the sectoral level, the most exposed systems are those that traverse large spatial extents, particularly power, rail, and road networks. These sectors display greater heterogeneity in susceptibility, with many countries showing more substantial infrastructure shares in Level 4 or 5 zones. For instance, Slovenia, Greece and Switzerland exhibit substantial power and road infrastructure within high-susceptibility areas, reflecting the alignment of networks through mountainous terrain. Rail systems show similar patterns, particularly in countries with complex topographies such as Slovenia, Norway, and other mountainous regions. These sectors are inherently more vulnerable not only due to their geographic footprint but also due to the difficulty and cost of rerouting or protecting across large stretches of steep terrain.

In contrast, healthcare and telecom infrastructure are more frequently situated in lower-risk zones, though exceptions exist in smaller or densely built countries such as Malta and Liechtenstein, where spatial constraints may limit the ability to avoid hazard-prone areas. Education infrastructure shows a more mixed profile, with some countries (e.g., Cyprus, Ireland) exhibiting moderate susceptibility levels across a notable share of facilities. While these assets are generally more localized and potentially easier to protect through site-specific interventions, their exposure still warrants consideration in resilience planning. It is important to note that these patterns represent percentage distributions rather than absolute quantities, meaning that even countries with predominantly Level 1 infrastructure still maintain some assets in higher susceptibility zones, and smaller countries may appear more vulnerable due to limited geographic options for infrastructure placement.





Fig 4. Relative share of maximum landslide susceptibility exposure for all objects within each infrastructure system.



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Wildfires

Fig 5 presents the average number of days with high risk of wildfire across CI assets within each infrastructure system under the baseline period, across different climate models. Fig 6 and Fig 7 present the average increase in number of days with a high risk of wildfire occurrence, across different climate models (see Section 4.1) under RCP 4.5 and RCP 8.5 scenarios respectively. The baseline wildfire exposure reveals that many Southern European countries already experience substantial wildfire risk, with Cyprus facing approximately 80-100 days of wildfire risk annually across most infrastructure sectors, making it the most fire-prone country in Europe. Greece, Spain, and Portugal also show considerable baseline exposure, typically ranging from 40-80 days annually depending on the sector.

Under RCP 8.5, Southern European countries face the most dramatic increases in wildfire exposure, with Cyprus, Portugal, and Greece showing the largest projected changes across all infrastructure sectors. Cyprus stands out with particularly large increases, reaching 15-20 days of additional wildfire exposure annually by the far future across most sectors, and potentially pushing annual wildfire exposure to over 120 days for telecommunication infrastructure. Portugal and Greece also show substantial increases, typically ranging from 10-20 additional days, representing 25-50% increases over their baseline exposure of 40-60 days. In contrast, RCP 4.5 presents more moderate increases for these same countries, with Cyprus still leading but with roughly half the magnitude of change seen under RCP 8.5.

Northern European countries including the Nordic and Baltic states show minimal wildfire exposure changes under both scenarios, with most countries projecting increases of fewer than 5 additional days annually. These countries currently experience fewer than 10 days of baseline wildfire exposure annually, meaning that even modest increases represent relatively small absolute risks. This pattern holds consistently across both RCP scenarios, though RCP 8.5 shows slightly higher increases for countries like Hungary and Romania compared to RCP 4.5.

The progression from mid-future to far-future periods show accelerating wildfire exposure across most countries and sectors. Under RCP 8.5, the far-future period consistently shows substantially higher exposure increases than the mid-future period, with the gap being particularly pronounced for high-risk Southern European countries. Under RCP 4.5, this temporal progression is more gradual, with smaller differences between the two time periods.

Telecom infrastructure shows the most extreme exposure increases, particularly under RCP 8.5, with Cyprus reaching nearly 60 additional days annually in the far future. This sector consistently shows the highest baseline exposure across most countries, which



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amplifies the significance of projected increases. Power, rail, and road infrastructure show relatively similar exposure patterns within countries, typically ranging from moderate to high increases in Southern Europe. Healthcare and education infrastructure generally show lower exposure increases compared to network-based sectors, though they still follow the same regional patterns as Southern European countries experiencing the most significant changes.

The difference between RCP 4.5 and RCP 8.5 is most pronounced in Southern European countries, where RCP 8.5 projects roughly double the wildfire exposure increases of RCP 4.5. For Northern European countries, both scenarios show minimal differences, suggesting that even under moderate climate change, these regions remain relatively protected from wildfire risk. The accelerated warming under RCP 8.5 appears to create “tipping points” that disproportionately affect fire-prone Mediterranean climates.



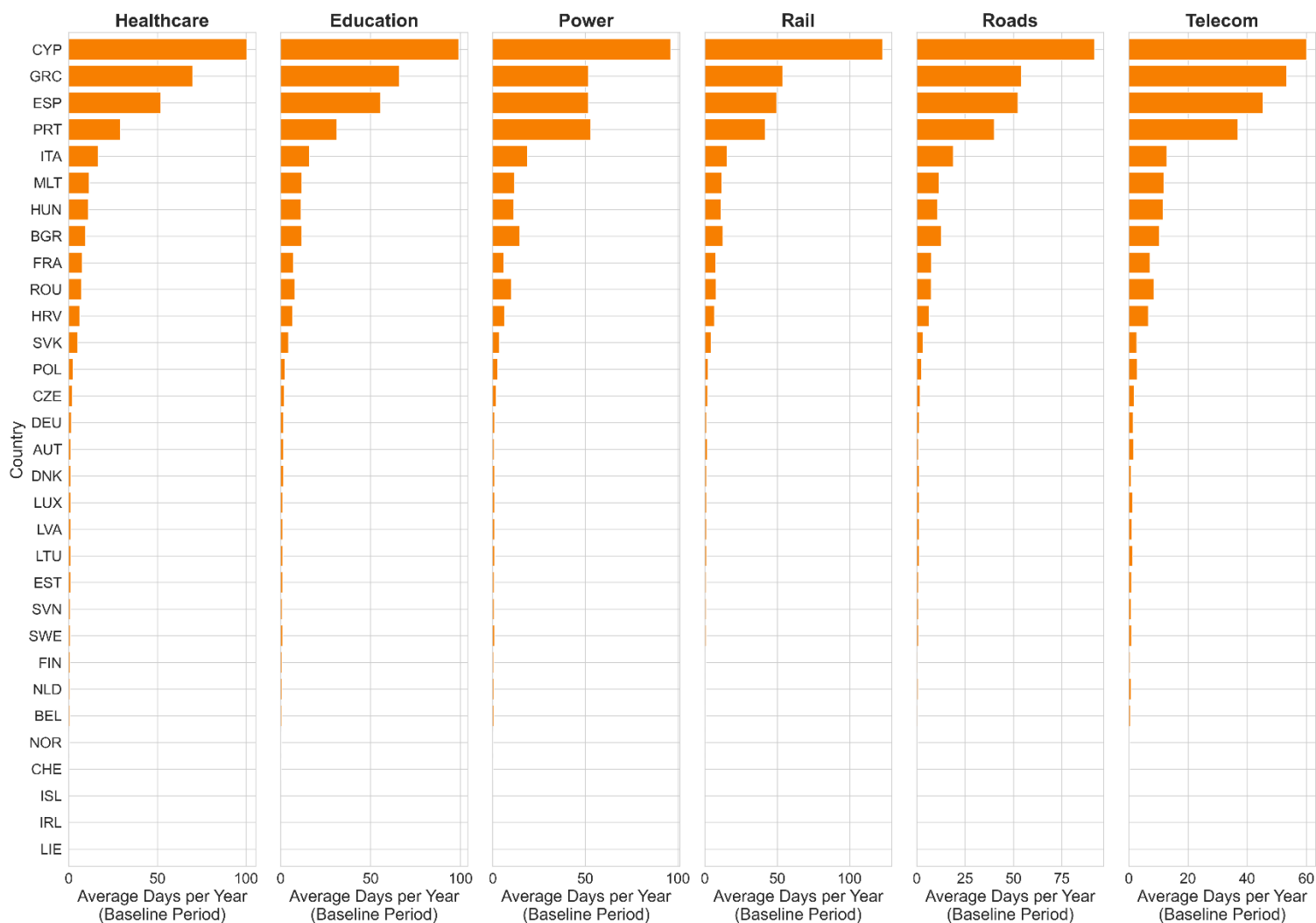


Fig 5. Average number of days with high risk of wildfire across the assets within each infrastructure system.



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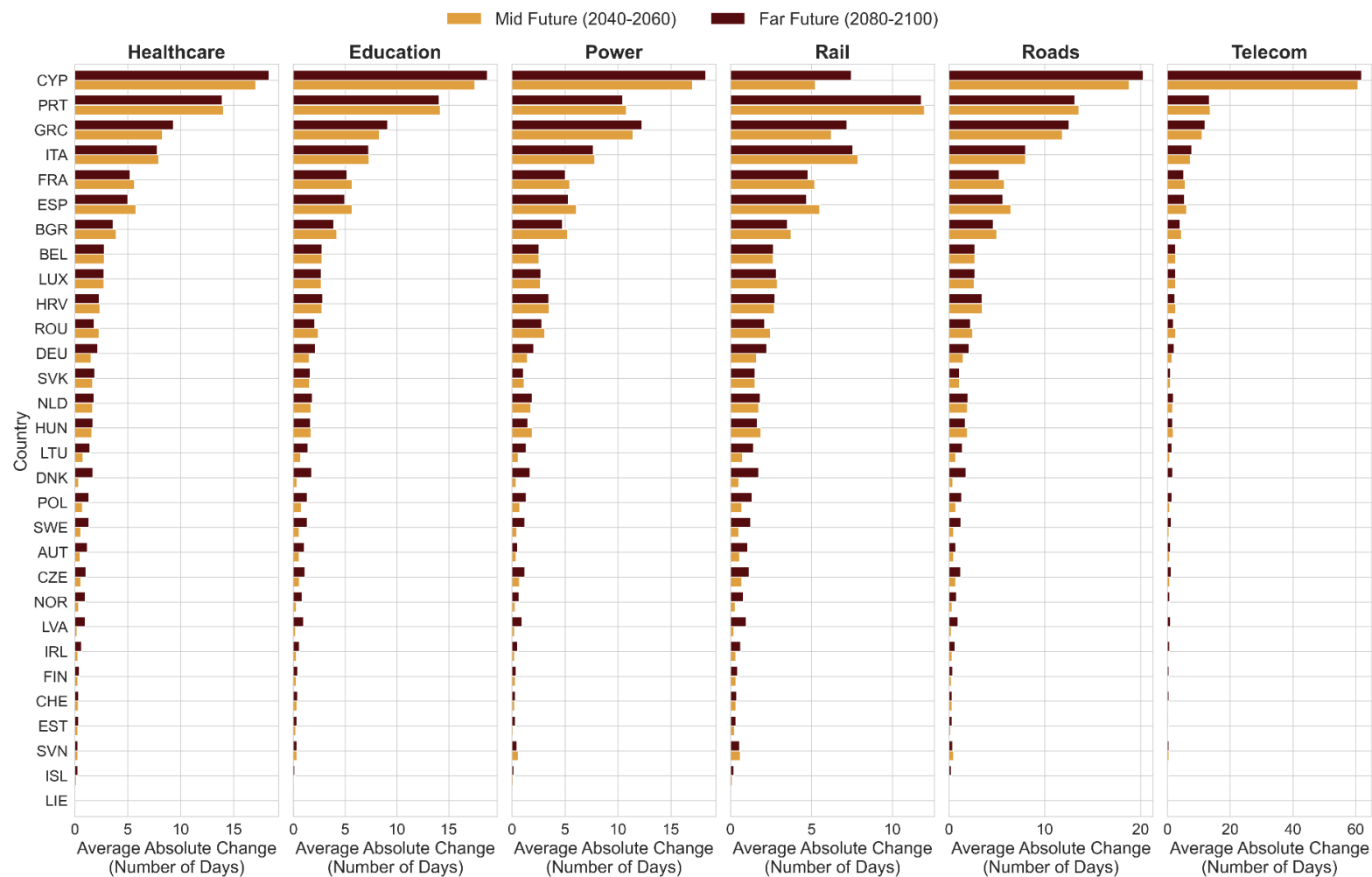


Fig 6. Absolute increase in number of days with high probability of wildfires within the proximity of the assets within RCP4.5



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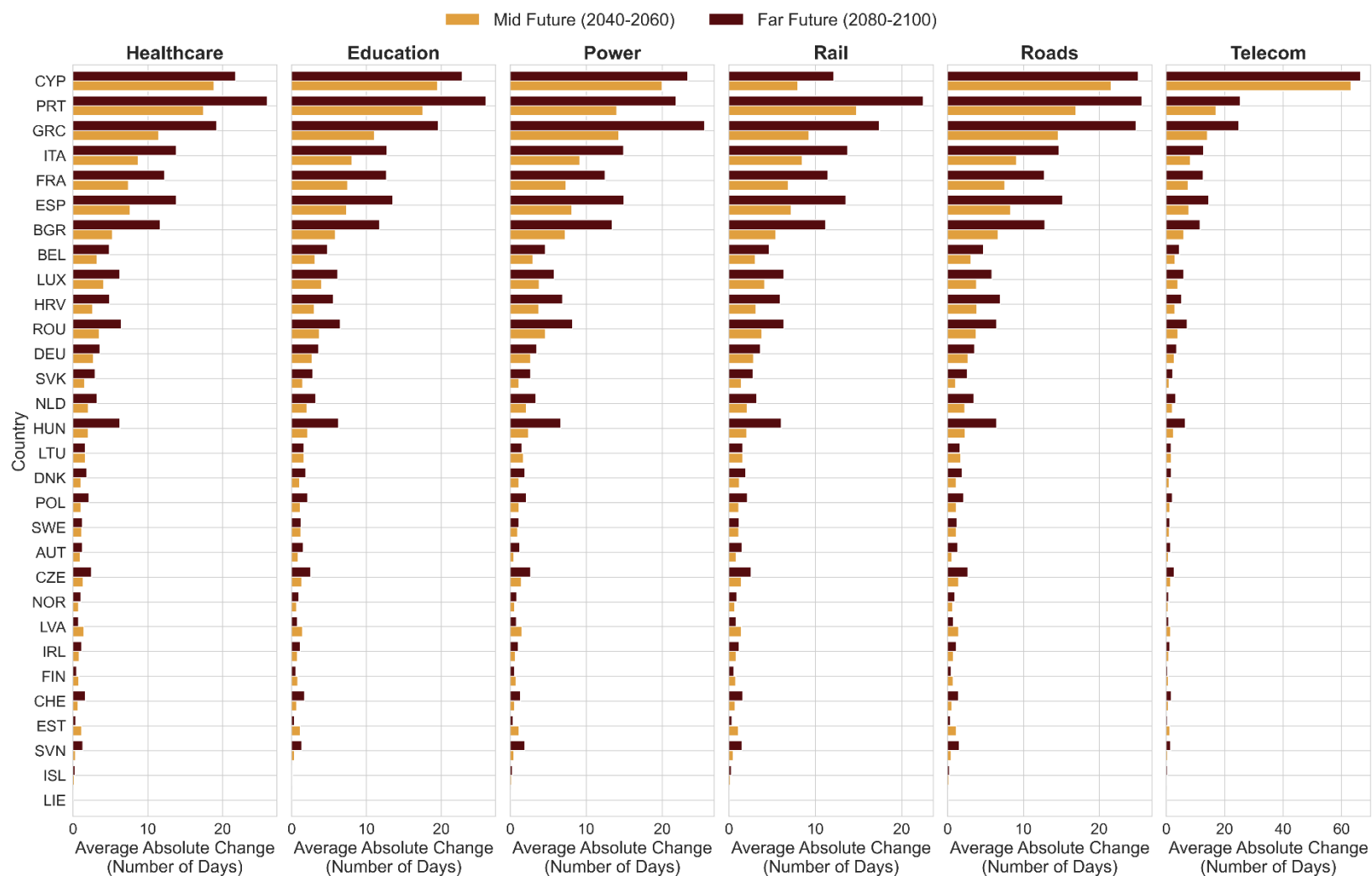


Fig 7. Absolute increase in number of days with high probability of wildfires within the proximity of the assets within RCP8.5



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Heat

Fig 8 presents the average number of hot days (days experiencing temperatures greater than 30°C, 35°C and 40°C) within the proximity of CI systems, across different climate models. Fig 9 and Fig 10 present the absolute increase in average number of hot days across CI systems for RCP 4.5 and RCP 8.5 scenarios respectively. Southern European countries face the most severe heat exposure increases, with Cyprus, Greece, Spain, and Italy showing the largest projected changes across all temperature thresholds. The baseline heat exposure (Fig 8) reveals significant existing disparities, with Cyprus already experiencing more than 60 days above 30°C annually across most infrastructure sectors, along with 15-20 days above 35°C and occasional days above 40°C. Greece and Spain also show substantial baseline exposure, typically experiencing 60-80 days above 30°C and 5-15 days above 35°C annually.

Under RCP 8.5, Greece experiences particularly extreme increases, with projections reaching approximately 30-40 additional days above 30°C annually by the far future, representing a 50-65% increase over baseline conditions of approximately 60-70 days and potentially pushing total exposure to around 100-110 days annually. The days exceeding 35°C and 40°C are increasing as well, with Greece potentially experiencing 15-25 additional days above 35°C over its baseline of 5-10 days. Cyprus and Spain show similar but varying magnitudes, with notable increases across all temperature categories that represent substantial increases over their baseline exposure. Under RCP 4.5, these same countries still lead in heat exposure increases, but with roughly half the magnitude seen under RCP 8.5, particularly for the higher temperature thresholds.

Northern European countries including the Nordic and Baltic states show relatively small heat exposure changes under both scenarios, with most countries projecting increases of fewer than 10 additional days above 30°C annually, and virtually no increases in days exceeding 35°C or 40°C. These countries currently experience minimal baseline heat exposure, with most showing fewer than 5 days above 30°C annually and virtually no exposure to higher temperature thresholds, meaning that even modest increases represent relatively small absolute risks. This pattern is consistent across both RCP scenarios, though RCP 8.5 shows slightly higher increases for Central European countries like Hungary, Bulgaria, and Romania.

The 30°C threshold dominates the projections across most countries and scenarios, representing the largest absolute increases in extreme temperature days. The 35°C threshold shows more moderate increases but still represents significant changes for



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Southern European countries, particularly under RCP 8.5. The 40°C threshold shows the largest relative changes, with Southern European countries potentially experiencing dozens of additional days at this extreme temperature level under RCP 8.5, while such conditions remain virtually absent in Northern Europe under both scenarios.

Healthcare infrastructure shows particularly concerning exposure patterns, as it must remain operational during extreme heat events when demand typically peaks. The projected increases are substantial enough to require significant adaptation measures in Southern European countries, including enhanced cooling systems and emergency preparedness protocols. Moreover, heat can have substantial impacts on railway segments. Exposure to extreme heat can cause railway buckling and technical failures, causing large-scale disruptions across railway systems. For power and telecom systems, new design standards will be required to ensure sufficient cooling of the respective systems during periods of extreme heat. Across all sectors, the patterns remain consistent within countries.

The temporal progression from mid-future to far-future periods show accelerating heat exposure, with the far-future consistently showing substantially higher increases than the mid-future period under both scenarios. The difference between RCP 4.5 and RCP 8.5 becomes increasingly pronounced for higher temperature thresholds and Southern European countries, highlighting the importance of emission reduction pathways in determining future heat exposure levels.



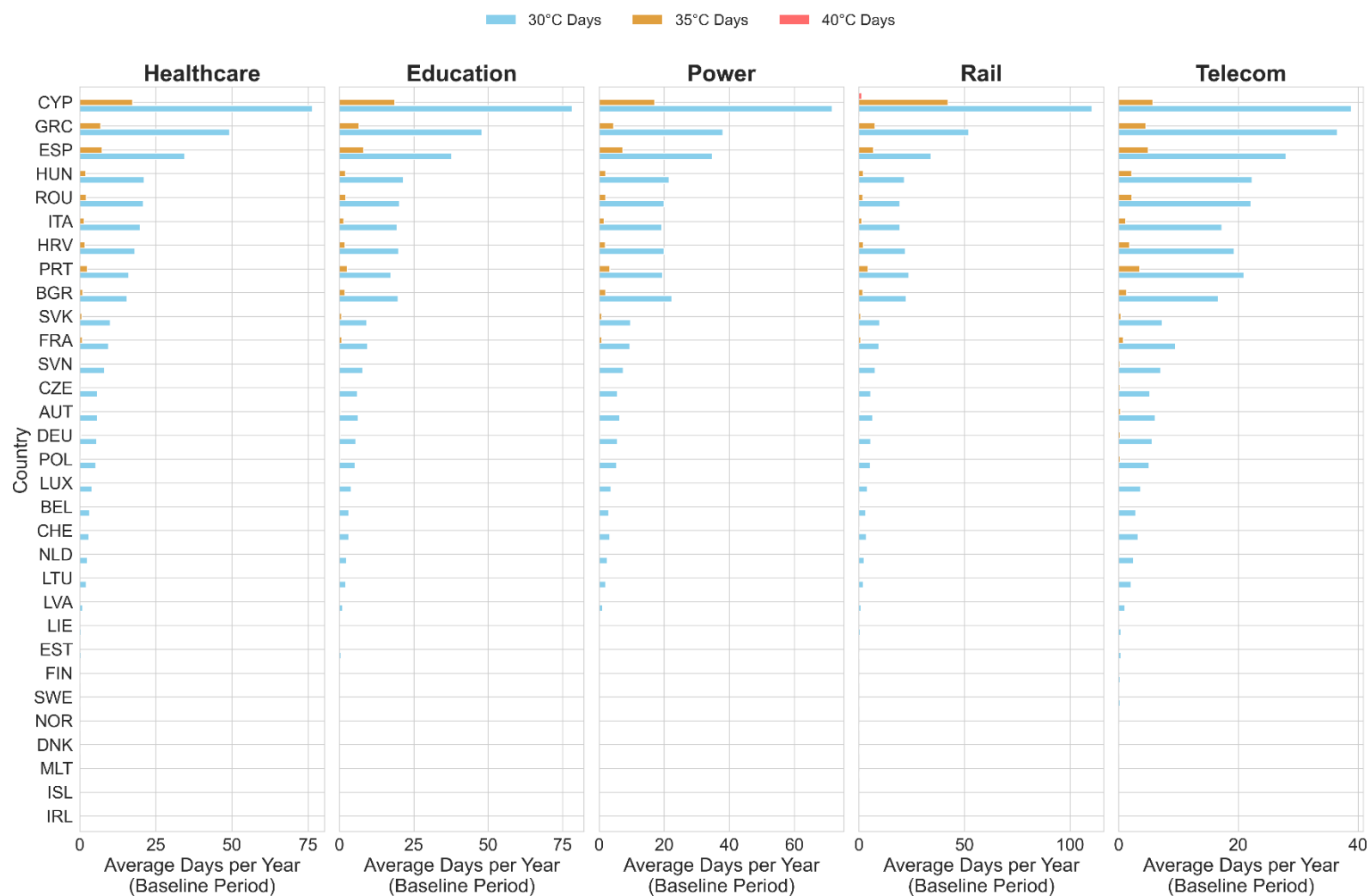


Fig 8. Average number of days in the current situation above 30, 35 and 40 degrees Celsius within the proximity of the assets within each infrastructure system.



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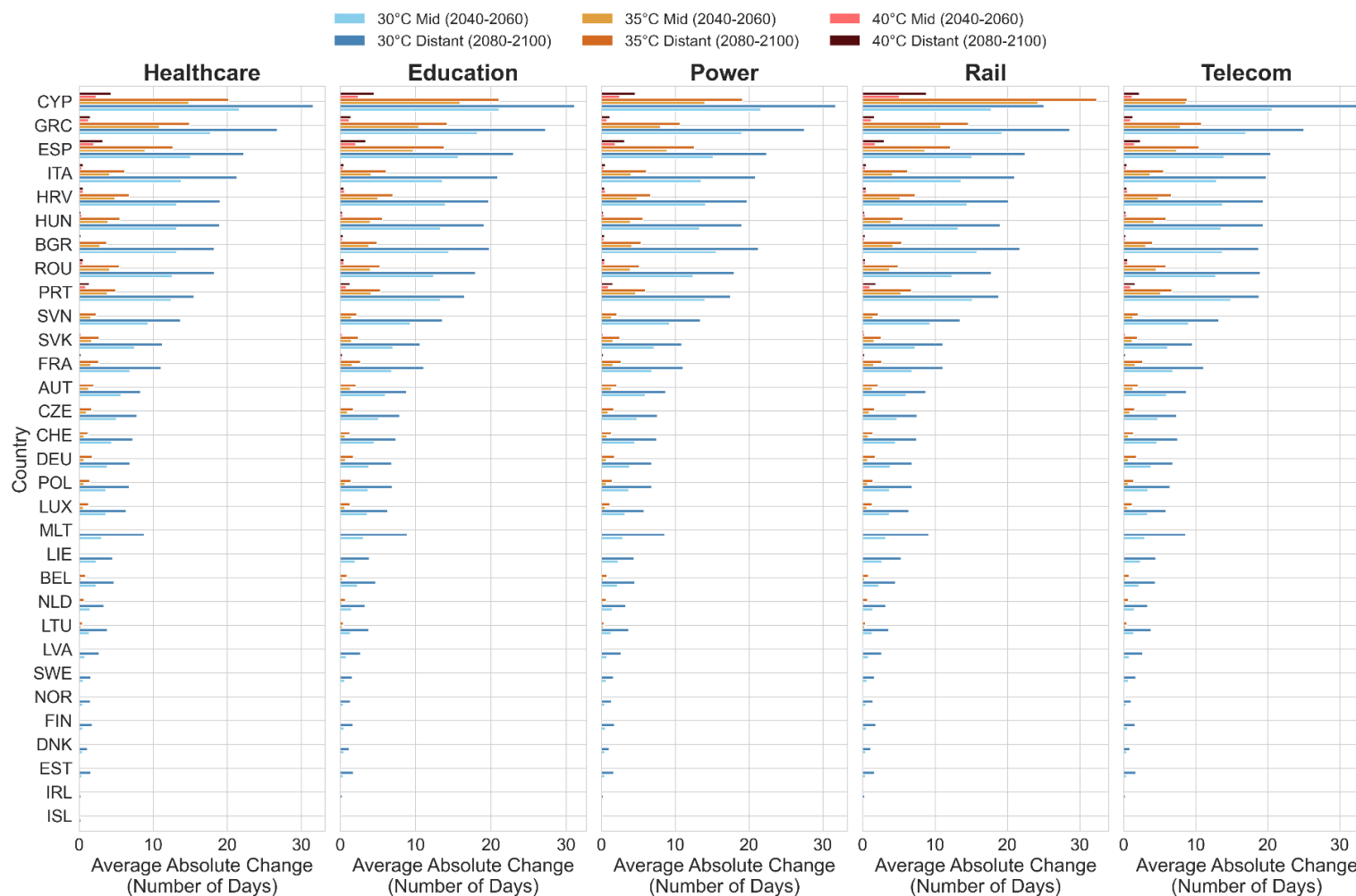


Fig 9. Absolute increase in average number of days above 30, 35 and 40 degrees Celsius within the proximity of the assets within RCP4.5



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

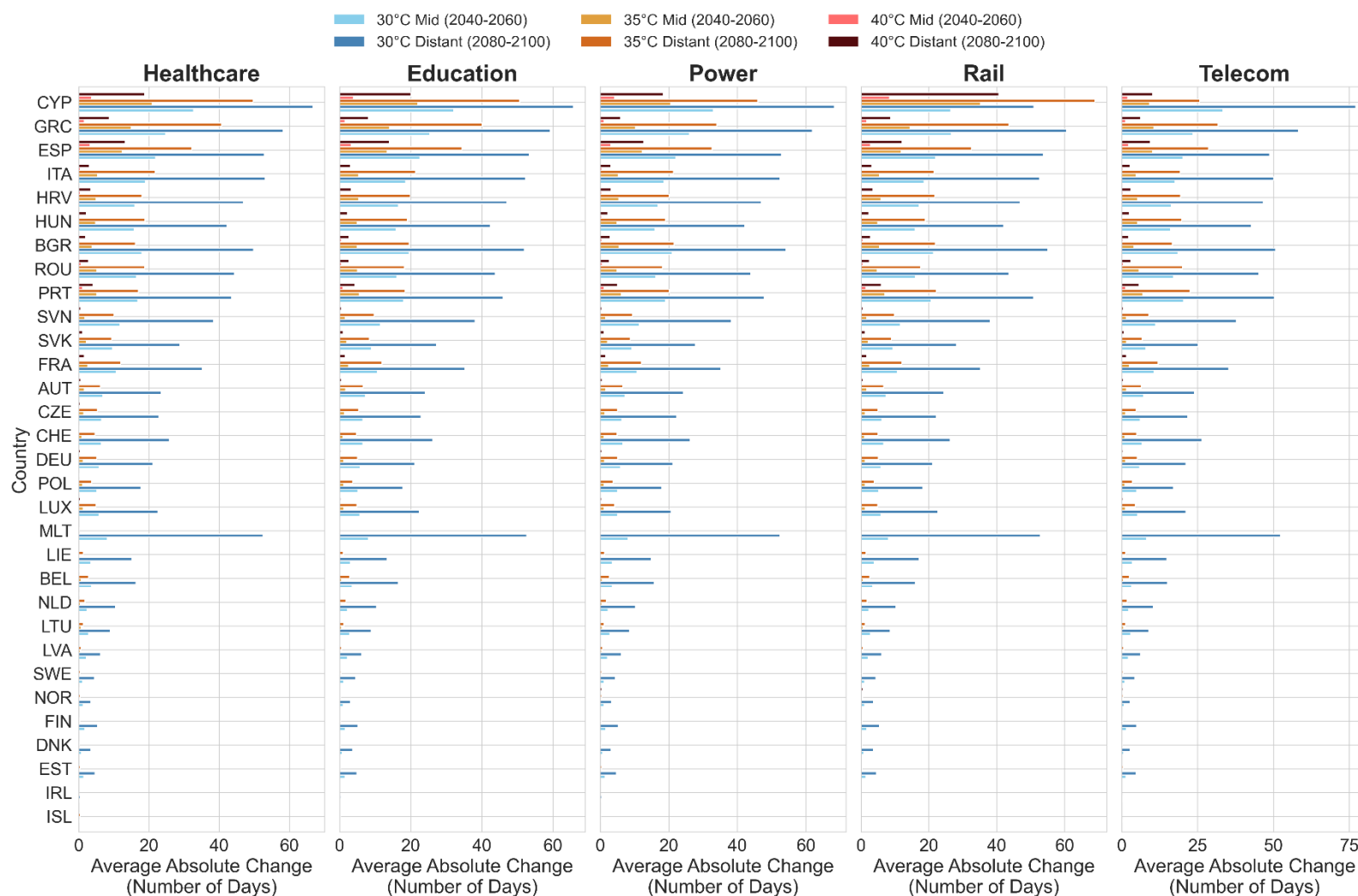


Fig 10. Absolute increase in average number of days above 30, 35 and 40 degrees Celsius within the proximity of the assets within RCP8.5



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4.4. Present-day risk assessment

Fig 11 presents an overview of the total present-day risk estimates by CI system and hazard types. From a system perspective, power systems dominate the risk landscape, accounting for 40.8% of total expected annual damages at approximately \$2.7 billion. This substantial share reflects both the extensive spatial coverage of electrical networks and their high economic value, making them particularly vulnerable to multiple hazard types. Education infrastructure represents the second-largest risk category at 25.3% (~\$1.7 billion), followed by rail systems at 14.1% (~\$932 million). The relatively high-risk share for education infrastructure reflects the widespread distribution of schools and universities across hazard-prone areas, combined with their significant replacement costs.

Transportation networks show a mixed pattern, with rail infrastructure accounting for 14.0% of risks while roads represent 9.3% (\$619 million). This difference may reflect the higher unit costs and more concentrated nature of rail infrastructure compared to the more distributed but potentially lower-value road networks. Healthcare and telecom infrastructure show lower risk shares at 7.5% and 2.9% respectively. For telecommunication infrastructure, this can be explained by its relatively low number of assets compared to other systems.

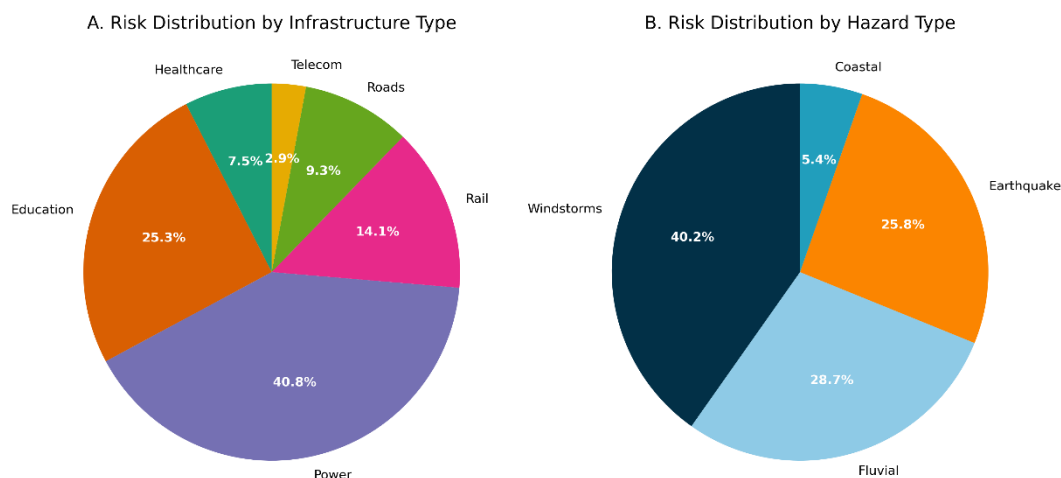


Fig 11. Overview of total risk estimates across infrastructure systems and natural hazards.

The hazard distribution reveals windstorms as the dominant threat, responsible for 40.2% of total risks (\$2.7 billion), highlighting the pan-European exposure to these extreme weather events. Fluvial flooding represents the second-largest hazard at 28.7% (\$1.9 billion), emphasizing the importance of river-based risks across the continent.



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Earthquakes account for 25.8% (~\$1.7 billion) of total risks, concentrated in seismically active regions but representing substantial absolute damages. While not a climate extreme by itself, its large share in the total risk estimates emphasize how important it is to include earthquakes in climate adaptation strategies. Not including other major risks could result in possible maladaptation practices (see Deliverable 4.2). Coastal hazards, while geographically limited, still contribute 5.4% (\$354 million) to total risks, reflecting the high value of infrastructure in coastal zones.

The relatively balanced distribution between windstorms, fluvial flooding, and earthquakes suggests that European infrastructure faces a diverse risk portfolio, with no single hazard type overwhelming the others. This pattern underscores the need for comprehensive, multi-hazard adaptation strategies rather than approaches focused on individual threat types.

A comparison with Forzieri et al. (2018), which remains the only other European-wide study on multiple hazard damages to infrastructure, reveals both the evolution of risk assessment methodologies and the impact of improved data resolution on infrastructure vulnerability estimates. Our analysis shows substantially higher risk estimates across all categories. For power infrastructure, our estimate of \$2.7 billion significantly exceeds Forzieri et al. (2018) combined estimates across all hazards. Transportation infrastructure shows similarly elevated risk levels, with our separate estimates of \$932 million for rail and \$603 million for roads totaling \$1.5 billion, compared to Forzieri et al. (2018) combined road and railway risks of 403 million euros for river flooding, 4 million for coastal flooding, and 66 million for winter windstorms. The healthcare and education sector comparison are particularly striking, with our analysis estimating \$2.2 billion for these sectors combined compared to Forzieri et al. (2018) total of approximately 534 million euros across all hazards.

These differences underscore how advances in asset mapping and hazard modelling can fundamentally alter our understanding of infrastructure vulnerability. Our analysis incorporates substantially more comprehensive asset databases and high-resolution hazard maps that can capture localized risk hotspots previously undetected. The high-resolution approach captures fine-scale exposure patterns that aggregate-level assessments might not consider, while comprehensive asset databases ensure that the full scope of infrastructure at risk is properly accounted for in vulnerability assessments.

Figure 12a and Figure 12b present the country-level risk estimates per infrastructure system for windstorms, fluvial and coastal flooding, and earthquakes. The country-level risk estimates reveal substantial variations in both absolute damage levels and hazard-specific vulnerability patterns across Europe, with the logarithmic scale highlighting the several orders of magnitude difference between different nations.



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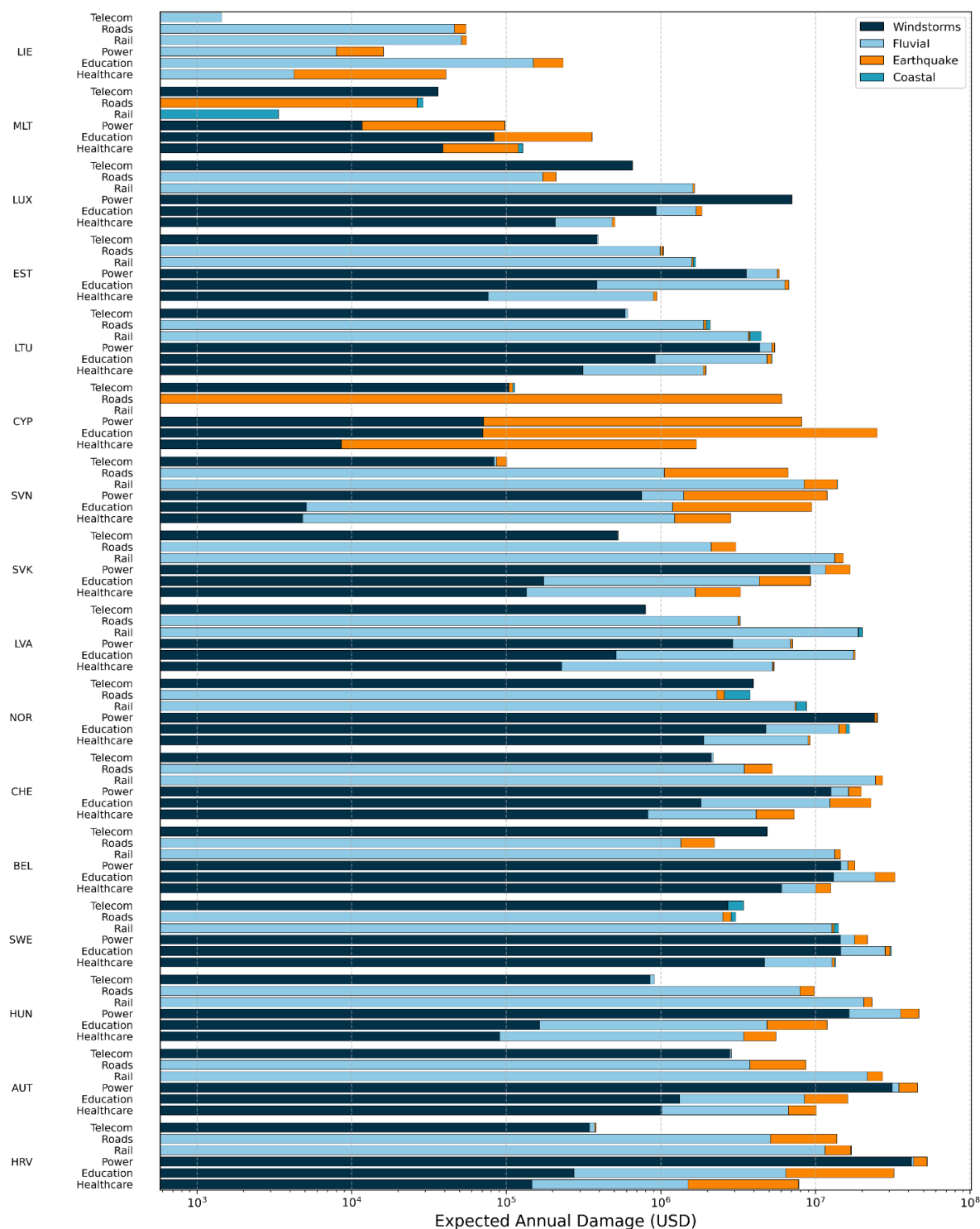


Fig 12a. Expected annual damages across different hazards and CI systems (Part1)



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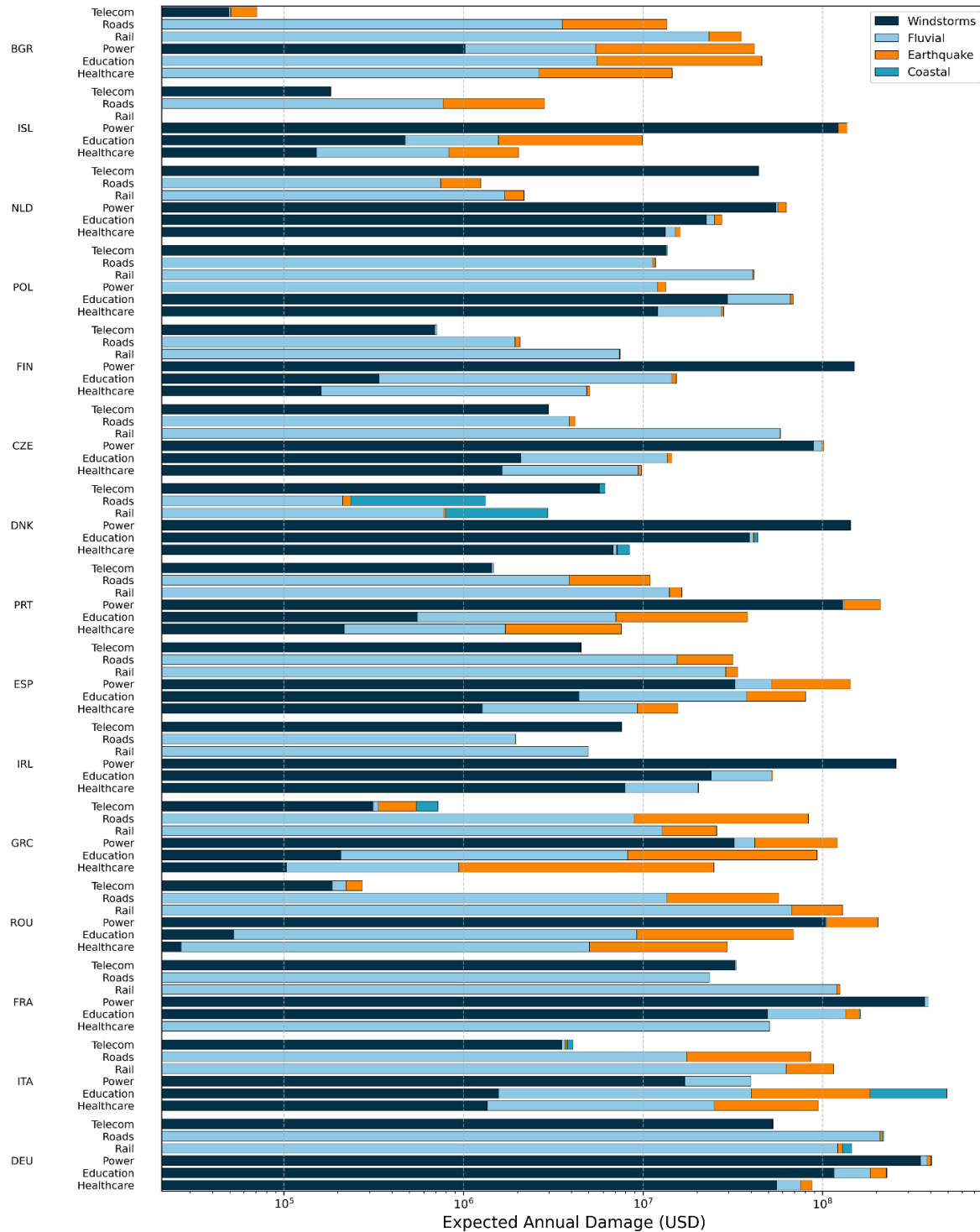


Fig 12b. Expected annual damages across different hazards and CI systems (Part2)



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Germany, France, and Italy show the highest absolute infrastructure risks, with total EAD reaching hundreds of millions to over a billion dollars across all sectors and hazards. Germany shows notable risks to windstorms across power and education infrastructure, with power systems facing damages in the hundreds of millions range.

Romania, Greece, and Spain also show significant absolute risks, with Romania demonstrating high fluvial flood risk across transportation and power infrastructure. Greece shows earthquake dominance across all sectors, with seismic risks often exceeding windstorm and flood risks combined. Spain shows a mixed hazard profile with notable earthquake risks and substantial windstorm risks for power and telecom infrastructure.

The hazard-specific patterns reveal clear sectoral vulnerabilities. Windstorms demonstrate their impact on power and telecom infrastructure across most countries, with these sectors consistently showing high windstorm-related damages. This pattern is evident in countries like Belgium, the Netherlands, and Nordic countries, where windstorms represent the dominant threat to power and telecommunication networks. The extensive spatial coverage and above-ground nature of these networks makes them vulnerable to wind damage.

Fluvial flooding shows its characteristic impact on transportation infrastructure, with roads and rail systems bearing substantial river-related damage across most countries. This pattern is evident in countries like Poland, Czech Republic, and Latvia, where considerable portions of transportation infrastructure face flood risks. The linear nature of transportation networks and their necessity to cross river systems explains their heightened vulnerability to fluvial hazards.

Earthquake risks demonstrate a clear geographic concentration in Southern European countries, with Greece, Italy, Romania, and parts of the eastern European countries showing substantial seismic exposure across all infrastructure sectors. In these countries, earthquake damage often represents the largest single hazard threat, sometimes exceeding the combined impacts of other hazards. Cyprus and Slovenia also show notable earthquake exposure, though at lower absolute levels.

Figure 12a shows that smaller countries display more varied patterns. Malta shows earthquake dominance across most sectors, while Baltic states like Estonia, Latvia, and Lithuania face primarily windstorm risks with notable fluvial risks for transportation infrastructure.



4.5. Future risk assessment

Fig 13 presents current and future EAD of river flooding across three warming levels (2.0, 3.0 and 4.0 degrees). The logarithmic scale highlights the wide range of Expected Annual Damage (EAD) values, spanning several orders of magnitude across countries and sectors. France, Germany, and Italy emerge as the countries with the highest absolute flood risks, showing EAD values in the range of tens to hundreds of millions of euros across most infrastructure sectors under baseline conditions. Poland and Sweden also show a substantial absolute risk, though at somewhat lower levels in the range of millions to tens of millions of euros.

Several countries demonstrate particularly large relative increases in flood risk with increasing warming. Eastern European countries including Czech Republic, Hungary, and Romania show substantial relative increases under several higher warming scenarios. However, a notable and counterintuitive pattern emerges at the 4°C warming level, where several countries show decreases in flood risk compared to the 3°C scenario. This is particularly evident in southern European countries like Spain, Portugal and Greece. Italy also shows this pattern in some sectors, where the 4°C scenario projects lower EAD than the 3°C scenario. This non-linear response likely reflects complex changes in precipitation patterns, seasonal distribution of rainfall, and potentially shifts from snow-dominated to rain-dominated hydrological regimes that could alter peak flow timing and magnitude.

Smaller countries like Luxembourg, Denmark, and the Baltic states generally show lower absolute risks in the range of hundreds of thousands to low millions of euros but can still experience significant relative increases.

Across sectors, the patterns remain consistent within countries, indicating that river flooding risk is primarily driven by national-scale hydrological and climatic factors rather than infrastructure-specific vulnerabilities. However, the absolute magnitude of impacts varies substantially, with power and transportation networks typically showing higher EAD values than healthcare and education infrastructure, reflecting both the spatial extent and economic value of these systems.

Fig 14 and Fig 15 present the coastal flooding risk estimates across European countries and infrastructure sectors, showing baseline conditions and projections for 2050 and 2100, under SSP245 and SSP585 respectively. The coastal flooding projections show relatively modest absolute damage levels but substantial relative increases toward the future for several countries (e.g., Portugal and Spain), particularly compared to river flooding patterns. While river flooding projections often show more gradual increases or even some decreases at higher warming levels, coastal flooding consistently shows accelerating damage trends from baseline through 2100. This pattern reflects the



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compounding effects of sea level rise, changing storm patterns, and potential increases in coastal storm intensity.

The absolute coastal flooding risks remain relatively small across most countries and sectors, with many infrastructure systems showing expected annual damages in the range of thousands to low millions of dollars. This contrasts sharply with the higher absolute risks observed for windstorms and river flooding. However, the temporal progression reveals acceleration patterns of concern, with the 2100 projections often showing substantial multiples of baseline conditions.

Northern European countries including Norway, Germany, and Denmark show the highest absolute coastal flooding risks across most infrastructure sectors, with damages reaching millions of dollars for power, rail, and road systems. Norway demonstrates particularly notable exposure across all sectors, with healthcare and education infrastructure also showing meaningful coastal flood risks. Germany and Denmark follow similar patterns, with power and transportation infrastructure bearing the highest exposure levels.

Several countries show modest baseline coastal flooding risks, but substantial relative increases toward 2100. Belgium demonstrates this pattern clearly, with power and transportation infrastructure showing notable acceleration in damages from baseline to 2100. Poland and Sweden also exhibit this characteristic, where relatively small baseline coastal risks translate into meaningful damage levels by the end of the century. The Netherlands shows a distinctive risk profile, with relatively moderate baseline coastal flooding risks but substantial projected increases by 2100. This pattern reflects the country's unique coastal protection systems and low-lying geography, where future sea level rise and storm surge changes could dramatically alter flood risk.

The sectoral patterns reveal that power and transportation infrastructure face the highest coastal flood risk, consistent with their extensive spatial coverage and presence in coastal zones. Telecom infrastructure shows more varied patterns across countries, with some nations like Norway and Italy demonstrating notable coastal risks for communication networks. Healthcare and education infrastructure generally show lower coastal flood risks, though several countries including Norway and Germany demonstrate meaningful exposure levels for these sectors.



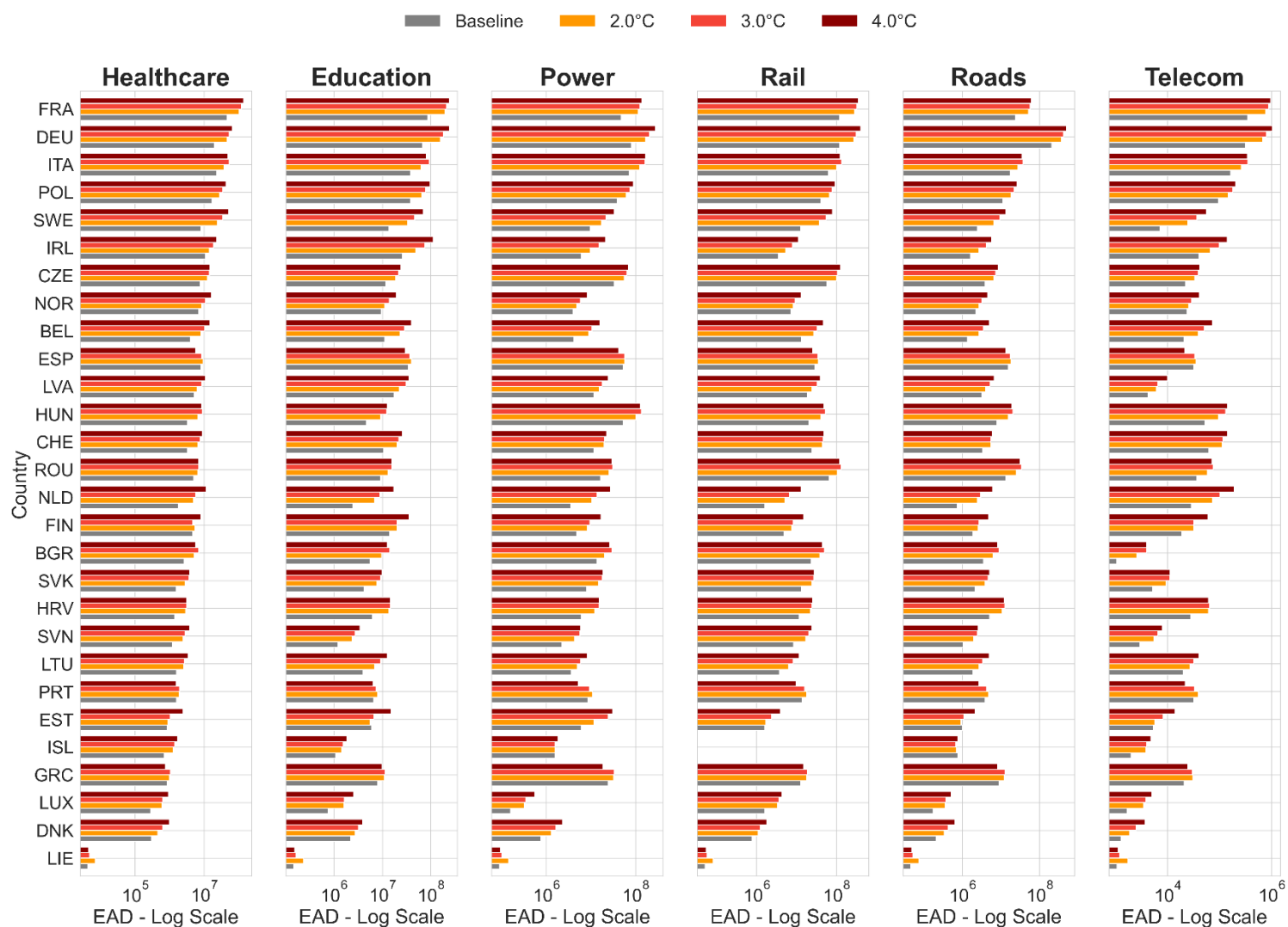


Fig 13. Absolute EAD due to river flooding for the baseline, and under 2.0, 3.0 and 4.0 degrees of global warming.



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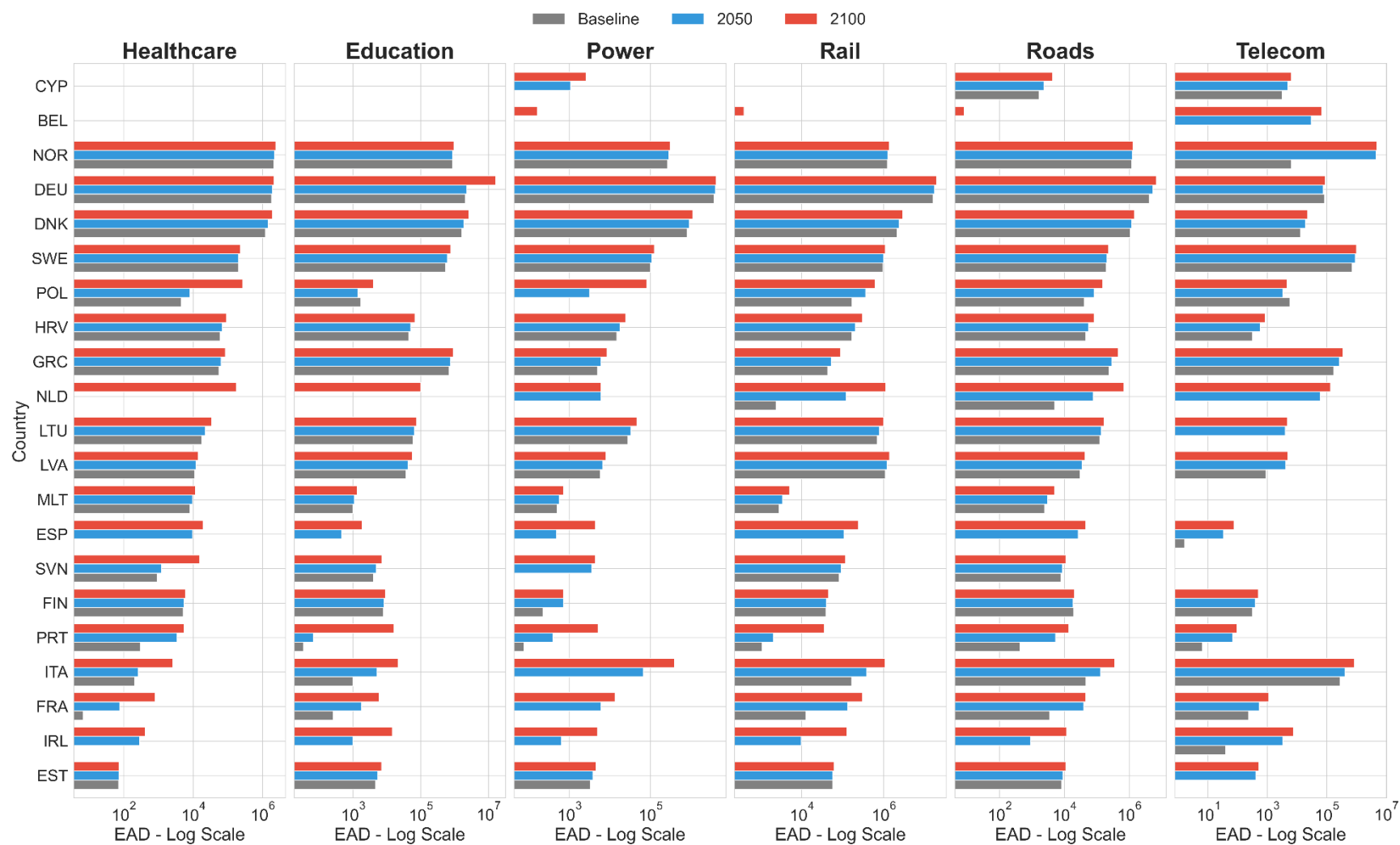


Fig 14. Absolute EAD due to coastal flooding under SSP245



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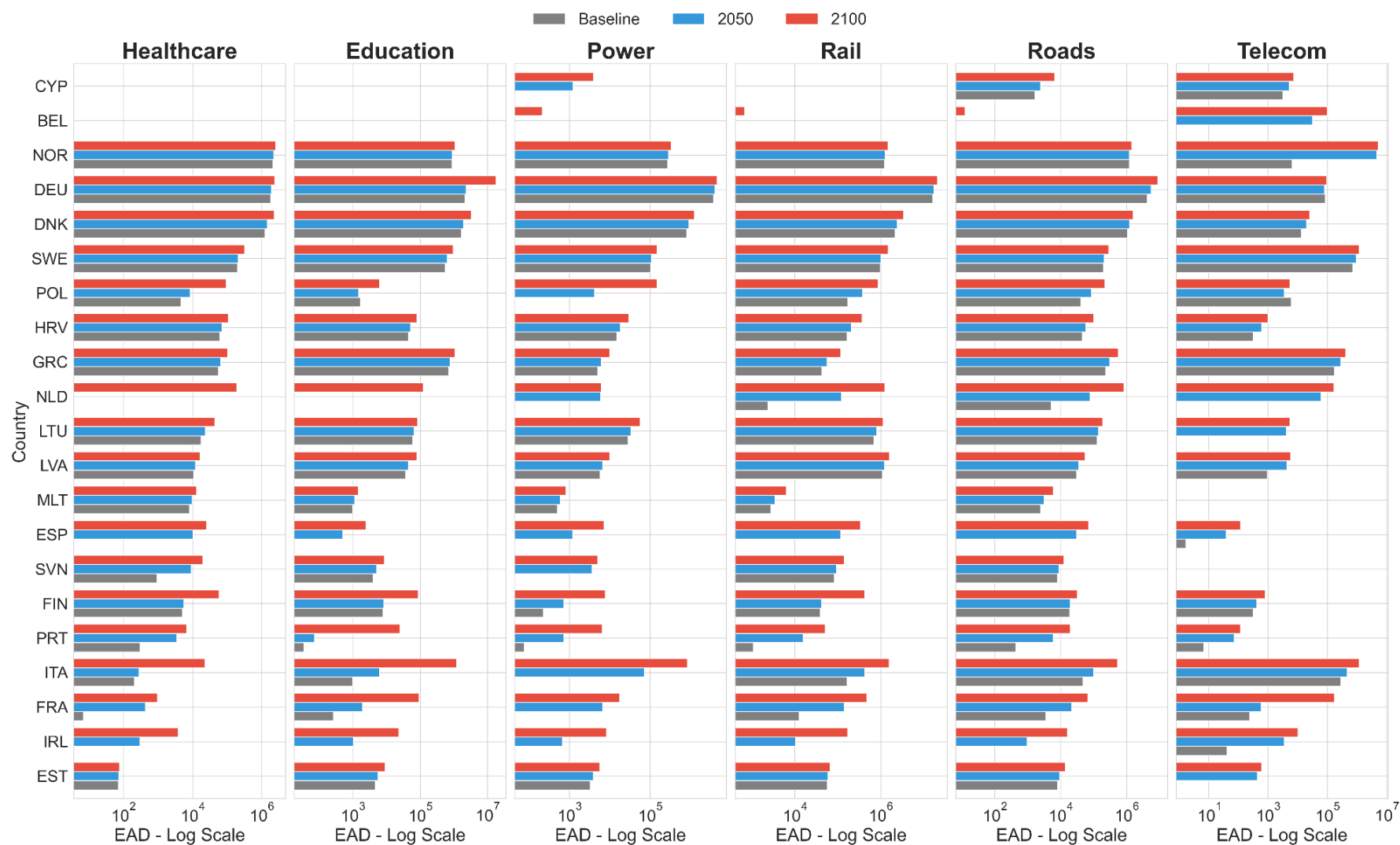


Fig 15. Absolute EAD due to coastal flooding under SSP585



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5. Application to Use-Case Scale

The proposed single and multi-hazard methodologies developed in MIRACA and presented in Section 3 are demonstrated through their application to the educational and healthcare facilities of the Region of Central Macedonia, Greece (UC4). Fig 16 presents the study area in blue, while Fig 17 shows the locations of the educational and healthcare facilities within the study area. It should be noted that not all existing schools and hospitals are included on the map. Regarding educational facilities, a high coverage rate is achieved. As for healthcare facilities, the analysis focuses on the most significant hospitals located within the urban fabric of the Metropolitan area of Thessaloniki, rather than across the entire regional unit. This selection was based on the availability of reliable data, which in turn ensures more robust and meaningful results. Nevertheless, as the aim of this deliverable is to present the methodological framework, the exposure assessment can be further enhanced in future stages.

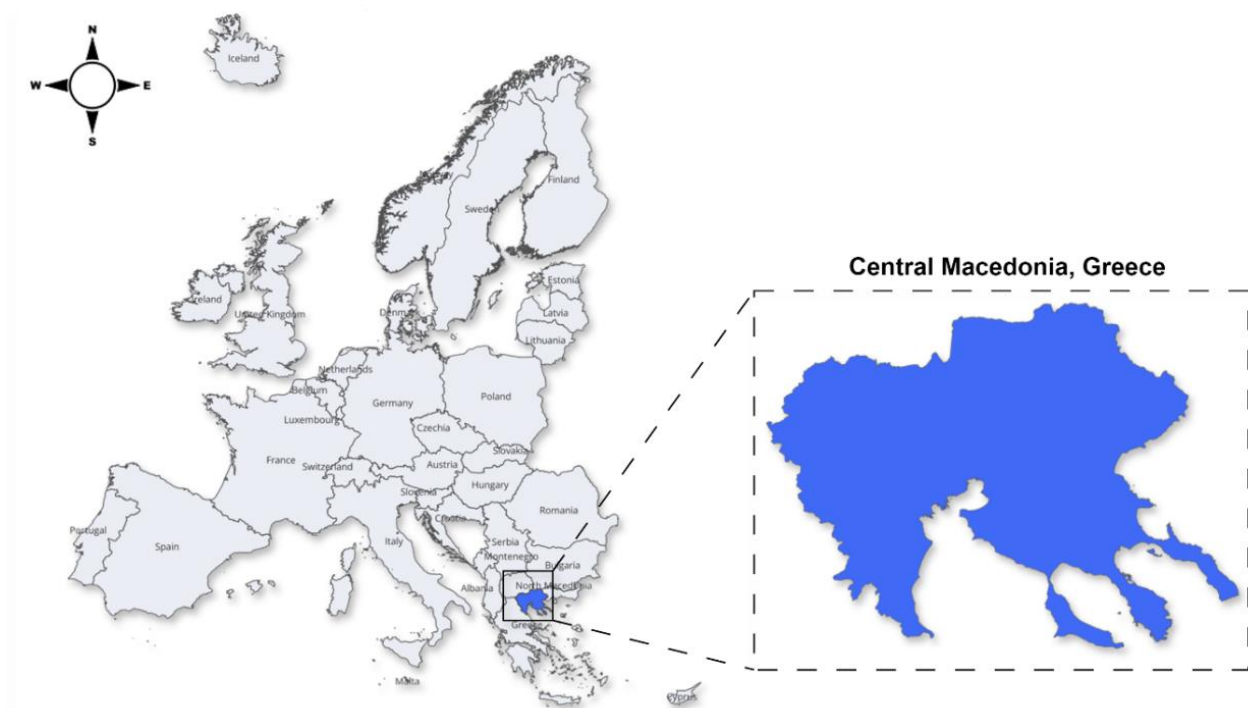


Fig 16. Study area - Region of Central Macedonia, Greece



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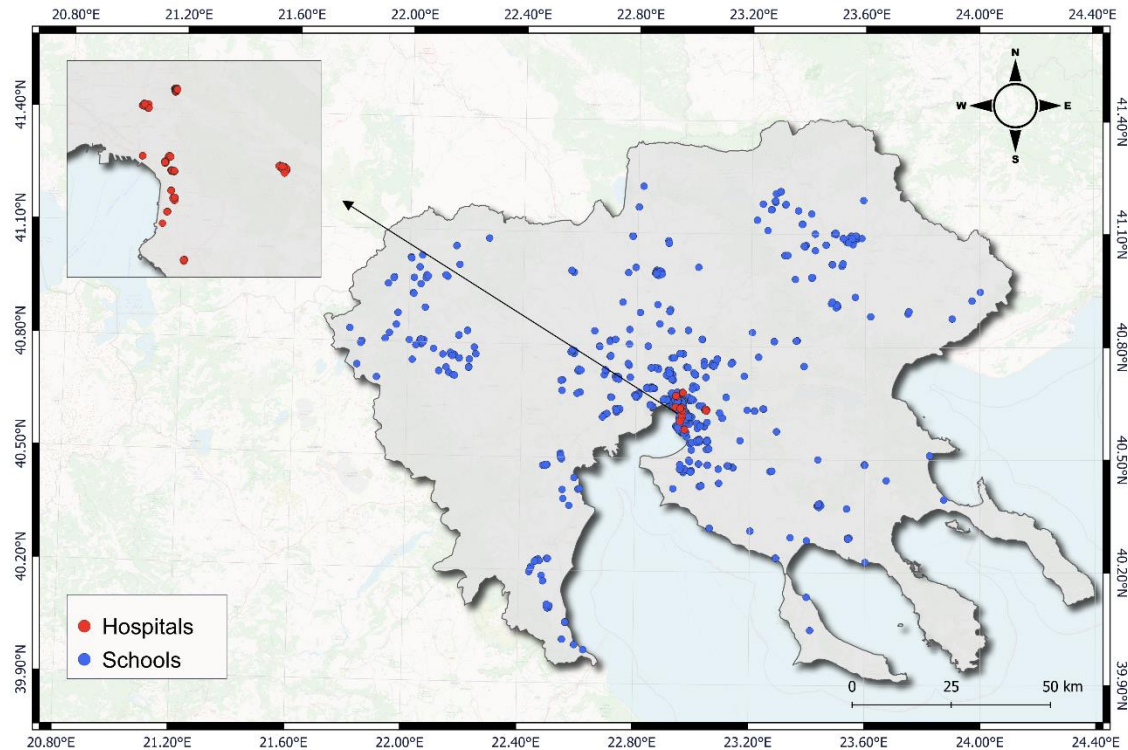


Fig 17. School (in blue) and hospital (in red) buildings in the study area

More specifically, the exposure model for schools includes data of 1718 school buildings from 27 Municipalities of the 6 Regional Units of the Region of Central Macedonia, Greece. Regarding the healthcare facilities, information of the main public hospitals in Thessaloniki city, Greece has been collected and archived including 255 statically independent buildings. Following the GEM building taxonomy v3.2 (Silva et al. 2022), several exposure indicators are considered for the asset level risk assessment of the schools and hospitals, namely: the main construction material, the structural system, the number of storeys, the seismic design/ductility level and the building area.

Fig 18 and Fig 19 provide statistics of the school and hospital buildings respectively regarding the construction material, the code design level, the lateral loading system and the number of stories.

As shown in the figures, more than 35% of the school buildings examined have been designed either with a low-level seismic code (CDL) or without any seismic code at all (CDN). The situation appears even more critical in the case of hospitals, where this percentage exceeds 60%. This means that a considerable proportion of the essential building stock lacks adequate seismic design provisions.

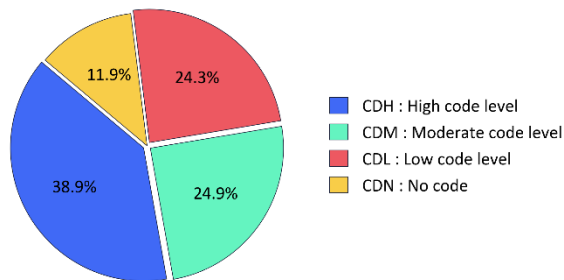


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The statistics in terms of the lateral load-resisting system reveal that approximately 40% of school buildings and 45% of hospital buildings are constructed as infilled frames. This finding further indicates the prevalence of structures designed according to older seismic codes, which did not require the inclusion of shear walls or other structural elements that would enhance their lateral strength and stiffness. As a result, these buildings exhibit reduced seismic capacity, increasing their vulnerability during earthquake events. Regarding the other two selected attributes, the data indicate that most of school and hospital buildings are low-rise reinforced concrete (RC) structures, typically consisting of one to three storeys, while there is also a not negligible number of mid-rise and high-rise RC hospital buildings.

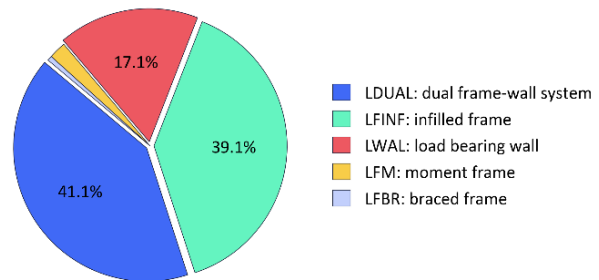
Expected loss metrics are also defined at this stage in terms of expected damage, loss ratio (that can be also quantified in direct economic losses) and loss of life.

Distribution of Code Design Level



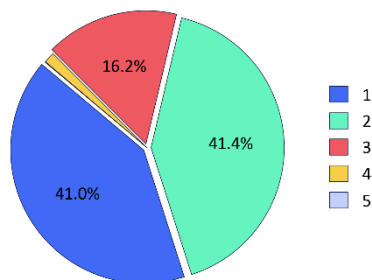
(a)

Distribution of Lateral Loading system



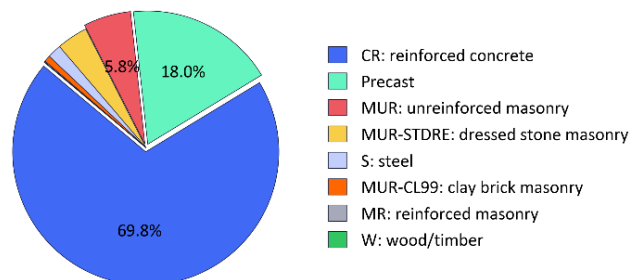
(b)

Distribution of Number of Floors



(c)

Distribution of Construction Material



(d)

Fig 18. Statistics of the school buildings with respect to a) the seismic code design level, b) the lateral loading system, c) the number of floors and d) the construction material.



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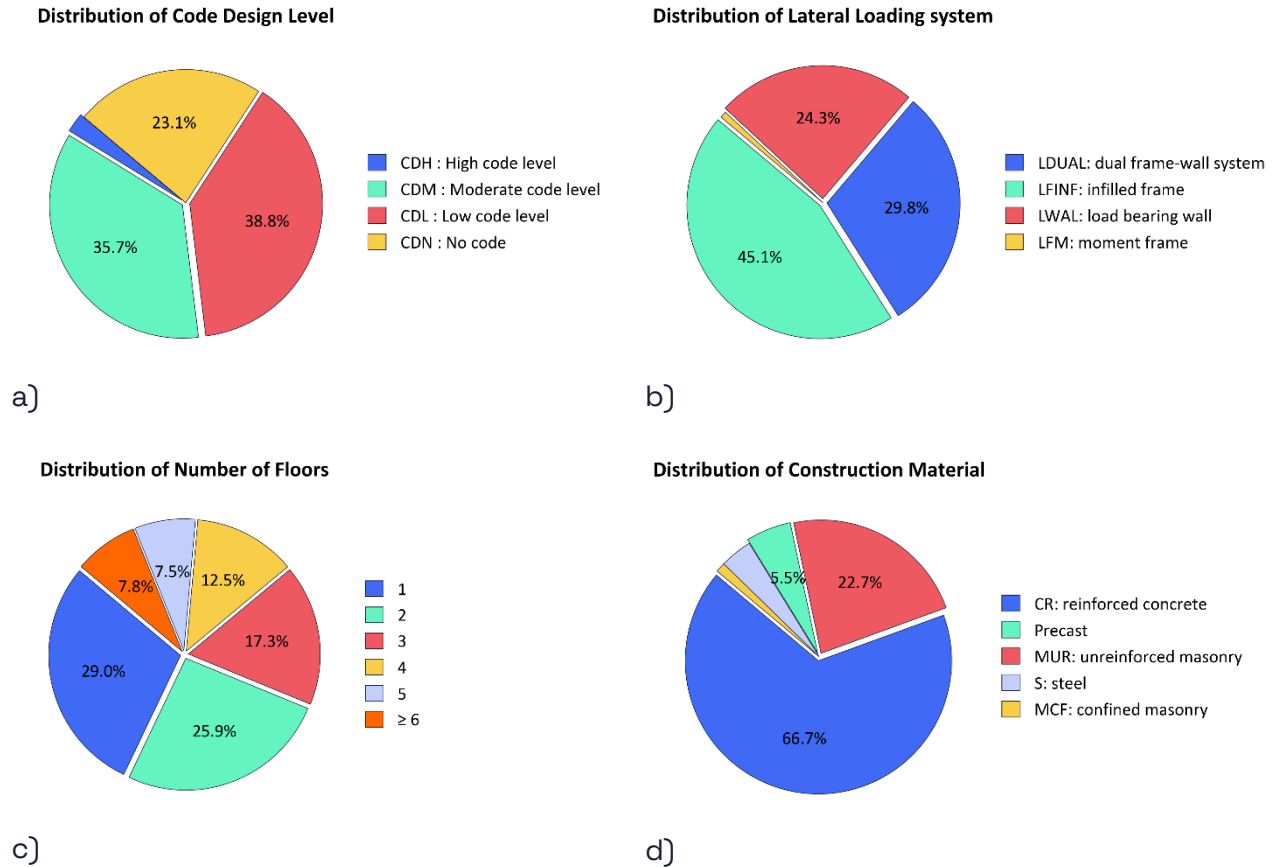


Fig 19. Statistics of the hospital buildings with respect to a) the seismic code design level, b) the lateral loading system, c) the number of floors and d) the construction material.

5.1. Single-Hazard

Initially, following the methodology presented in Section 3.1, a risk assessment is performed for schools and hospitals subjected to floods, earthquakes and landslides considered as single hazards.

5.1.1. Floods

For the single-hazard flood risk assessment, appropriate hazard and fragility models need to be identified. Two flood hazard models are considered for this application to tackle the uncertainty in hazard modelling for various climate scenarios: the European Commission - Joint Research Centre (JRC) river flood hazard maps for Europe and the Mediterranean Basin region (Baugh et al. 2024) and the GIRI global flood hazard model (Alfieri et al.).



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The JRC model is a gridded data set representing water depth (in m) along the river network, for nine different flood return periods (from 1-in-10-years to 1-in-500-years). The input river flow data have been produced by means of the open-source hydrological model LISFLOOD, while inundation simulations are performed with the hydrodynamic model LISFLOOD-FP for river basins > 150km². The dataset has been created as part of the Copernicus Emergency Management Service.

The GIRI model provides 90m resolution global flood hazard maps representing flood depth (in cm) for different flood magnitudes under present and future (upper and lower bound) climate scenarios (in total 3x9 different return periods). The approach relies on calibrated meteorological-hydrological-hydraulic models and integrates global datasets of atmospheric variables for the present climate and from bias corrected projections of future climate from the ISIMIP3b initiative.

Fig 20 and Fig 21 present the flood hazard maps for the study area when considering the JRC and GIRI flood models, respectively for the same mean return period of 100 years, which has 1/100=0.01% of chance to occur or be exceeded every year. There are some differences between the two models indicating the uncertainty in flood hazard modelling. These might be attributed to uncertainties in data, modeling approaches, parameters, and geo-processing tools.

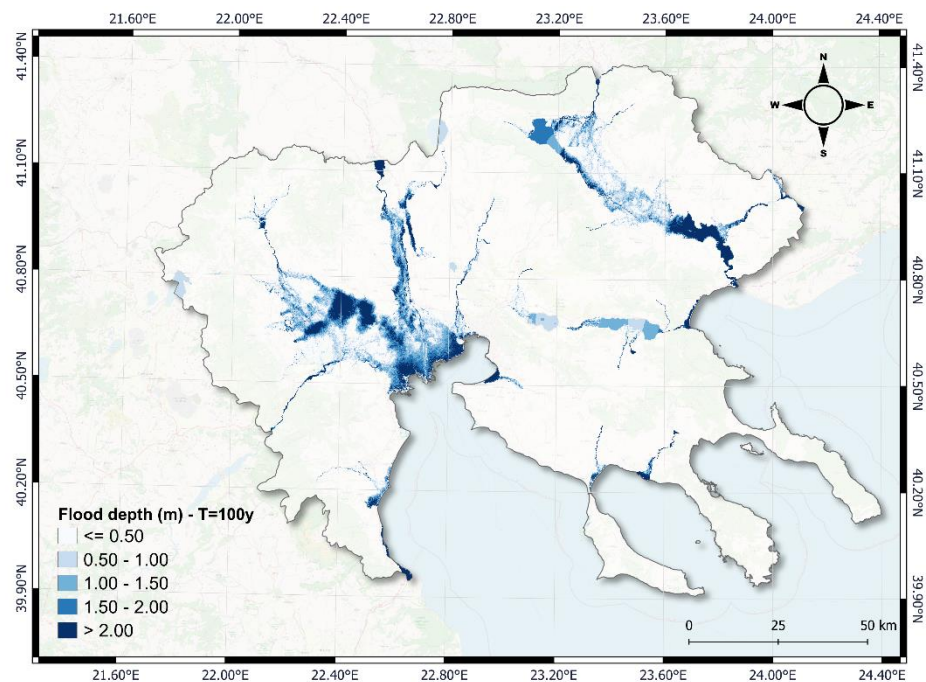


Fig 20. Flood hazard map for the study area when considering the JRC flood model for the mean return period of 100 years.



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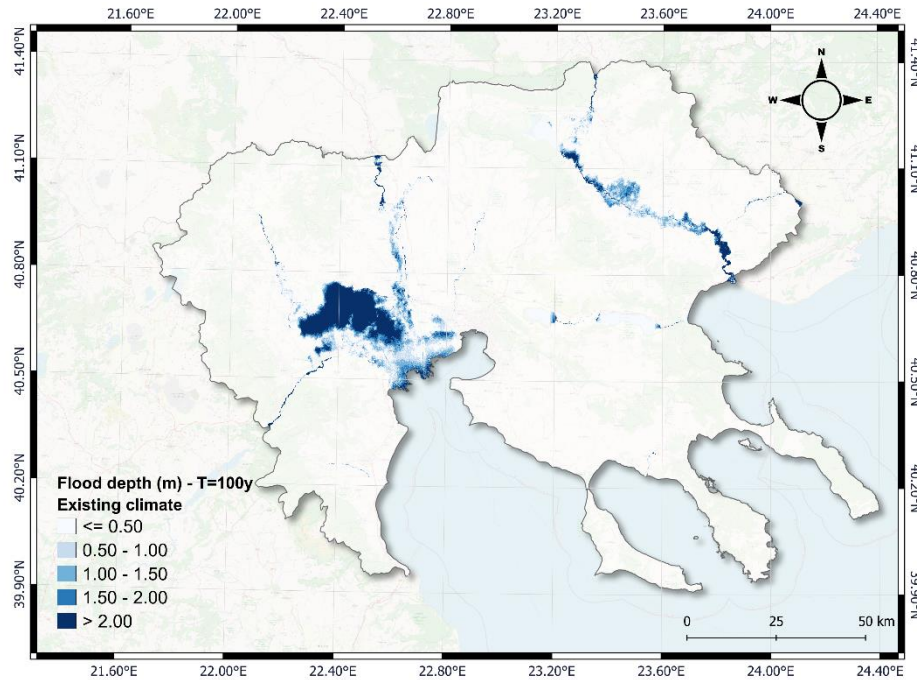


Fig. 21. Flood hazard map for the study area when considering the GIRI flood model for the mean return period of 100 years.

To assess the vulnerability of educational and healthcare buildings in the region of Central Macedonia, Greece, the fragility functions developed by Nofal and van de Lindt (2020) for schools (One-Story and Two-Story School) and hospitals (Hospital/Clinic) in terms of flood depth, have been utilized. These functions describe flood-induced damage to buildings in terms of five damage states (DSs) ranging from insignificant damage (DS0) up to complete damage (DS4). To calculate the mean flood losses in monetary terms, the so-called fragility-based flood loss approach as described in Nofal and van de Lindt (2020) has been used.

Flood risk analysis is performed for 9 return periods with the JRC hazard model and for 27 (9x3) return periods with the GIRI hazard model for the present and future climate. The results of the flood risk assessment, expressed in terms of loss maps are presented in Fig 22 – Fig 26 . These results are indicative for a mean return period of 100 years and are based on both JRC and GIRI flood models (for present and future climate scenarios). The analysis reveals that only a limited number of school buildings - primarily those located next to the expected flood basins – are affected by the flood hazard. In general, we observe that there are very few buildings (ranging from 0 to 6) for which significant flood-related losses are recorded. This outcome is primarily attributed to the selected hazard models; thus, the flood hazard values are concentrated in specific locations. Additionally, we note that hospitals exhibit virtually no losses, which again relates to



their geographic location on the map in relation to the hazard zones, rather than to their overall vulnerability to floods.

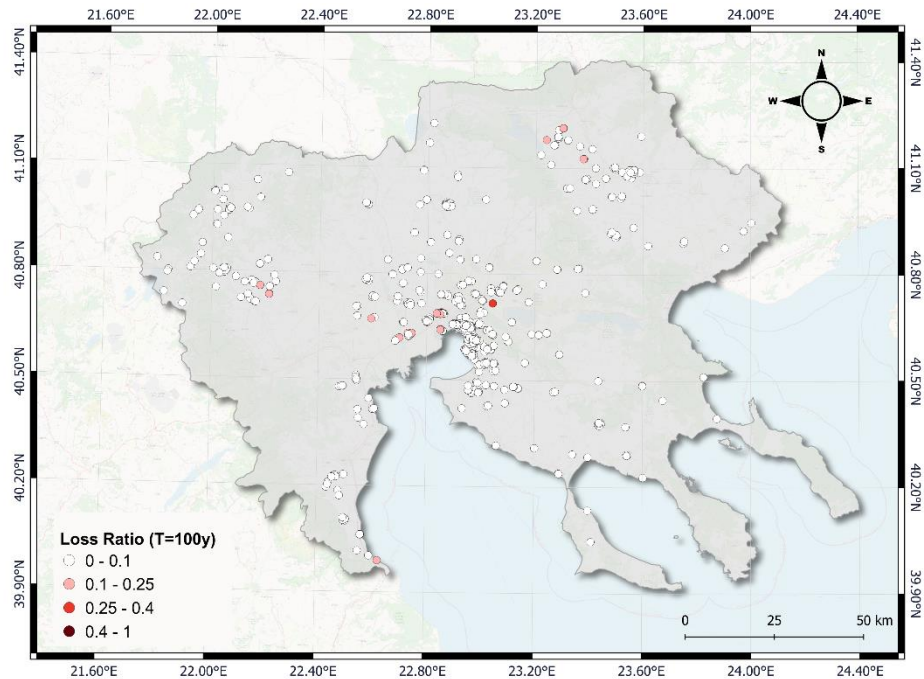


Fig 22. Loss ratio map for a return period of 100 years using JRC flood model, for the school buildings in the study area



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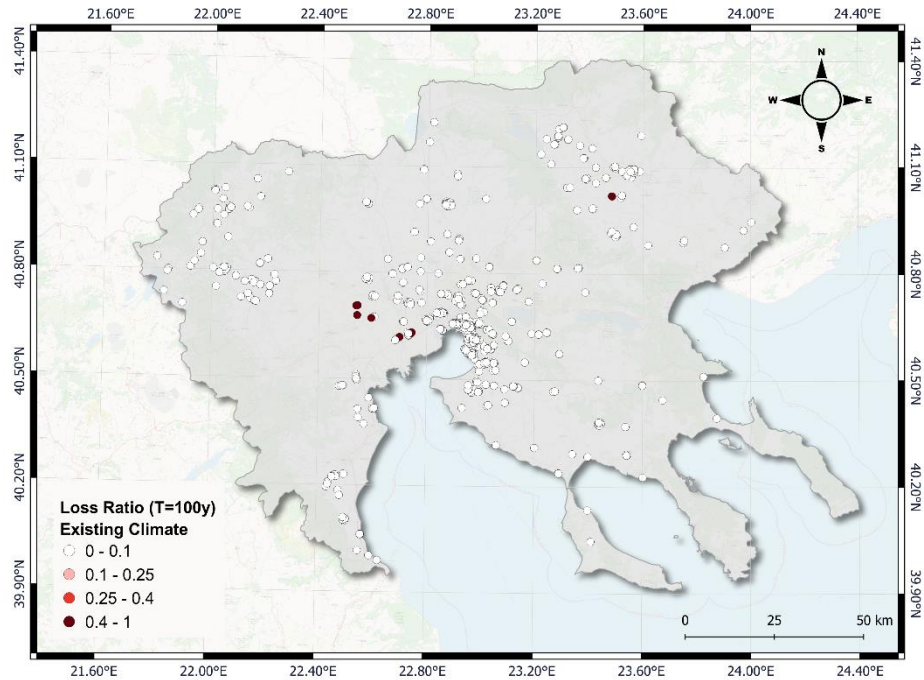


Fig 23. Loss ratio map for a return period of 100 years using GIRI flood model (existing climate), for the school buildings in the study area

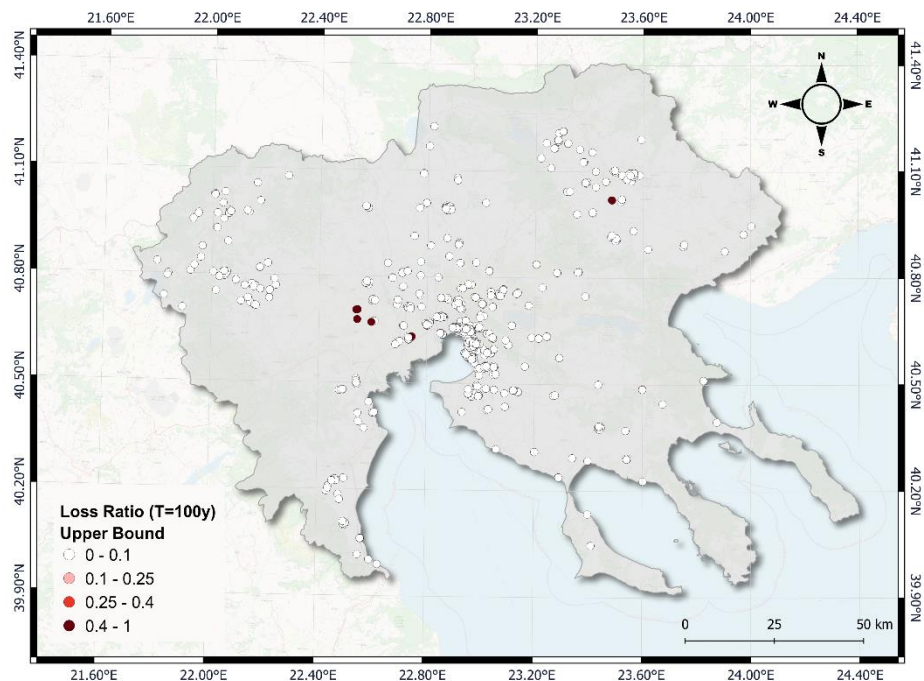


Fig 24. Loss ratio map for a return period of 100 years using GIRI flood model (future climate – upper bound), for the school buildings in the study area



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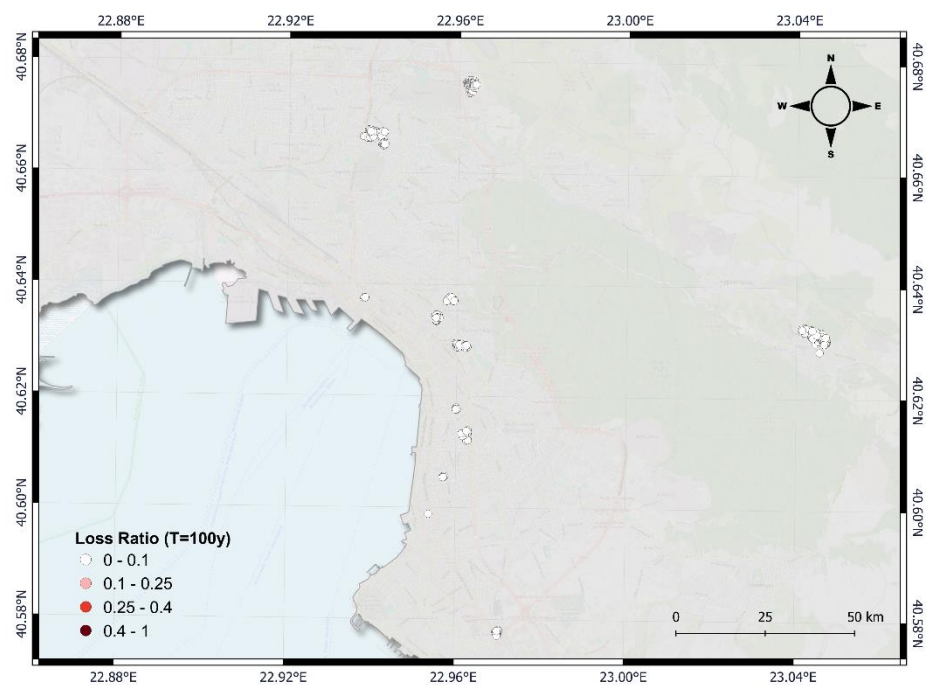


Fig 25. Loss ratio map for a return period of 100 years using JRC flood model, for the hospitals in the study area



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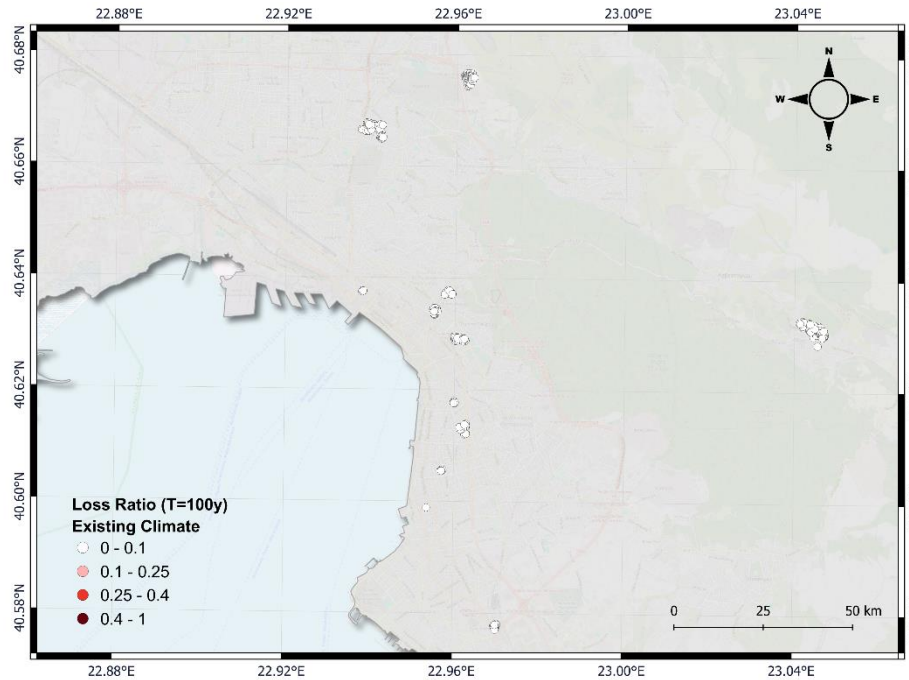


Fig 26. Loss ratio map for a return period of 100 years using GIRI flood model (case of existing climate), for the hospitals in the study area

5.1.2. Earthquakes

To conduct a seismic risk assessment for schools and hospitals, appropriate hazard and fragility models need to be identified.

The 2020 European Seismic Hazard Model (ESHM20, Danciu, et al., 2021), which provides an update on the earthquake hazard assessment of the Euro-Mediterranean region, has been considered in this study to model the seismic hazard of the Region of Central Macedonia, Greece. A fully probabilistic framework was adopted in the hazard model implementation, and all datasets and inputs are fully cross-border harmonised. The scientific data and input models are accessible in the publicly available EFEHR ESHM20 GitLab repository²¹. Seismic hazard maps for peak ground acceleration (PGA) and spectral accelerations $S_a(T)$ at selected periods equal to $T=0.3s, 0.6s, 1s, 1.5s$ for six return periods T_m (73, 102, 475, 1000, 2500, 5000 years) on rock are provided for the whole Europe and extracted for the region of interest.

Considering the significant contribution of site effects in altering the seismic response at the ground surface (Anastasiadis et al. 2001; Riga et al. 2023; Karafagka et al. 2024), OpenQuake engine (Pagani et al. 2014) is then used to estimate the different intensity

²¹ <https://gitlab.seismo.ethz.ch/efehr/eshm20>



parameters (i.e., PGA and spectral accelerations for the different return periods) on the ground surface through a fully probabilistic seismic hazard analysis, considering an appropriate site model to account for site effects. The amplification model was constructed using the Exposure to Site python tool²² for the seismic hazard analysis in OpenQuake. It is worth noting that different descriptive measures of the intensity parameters (PGA, $S_a(T)$) are used such as the mean, the median, and selected quantiles. Fig 27 and Fig 28 show the derived seismic hazard maps for median PGA and $S_a(T=0.6s)$ for a 1000-year return period on ground surface, respectively. The points on the maps presented in Fig 27 and Fig 28, represent the locations of schools and hospitals, while the color gradient indicates the intensity of the median Peak Ground Acceleration (PGA) in g at the ground surface and the spectral acceleration $S_a(T=0.6s)$, respectively. In terms of PGA, maximum values reach up to 0.7 g, and notably, many buildings fall within the highest range of values, specifically between 0.5 and 0.69 g. A similar pattern is observed in terms of spectral values (Fig 28). These results are consistent with expectations, as the area is known for its high seismicity. Moreover, the 1000-year return period scenario is more severe than the one typically used in seismic design according to building codes, which is based on a 475-year return period.

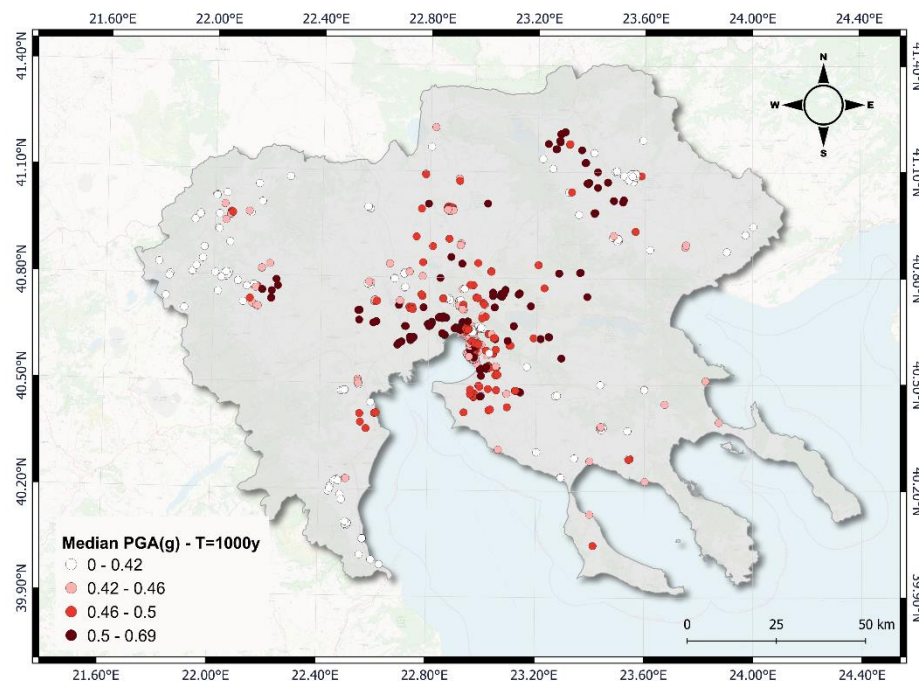


Fig 27. Seismic hazard map for median PGA for a 1000-year return period on ground surface

²² https://gitlab.seismo.ethz.ch/efehr/esrm20_sitemodel



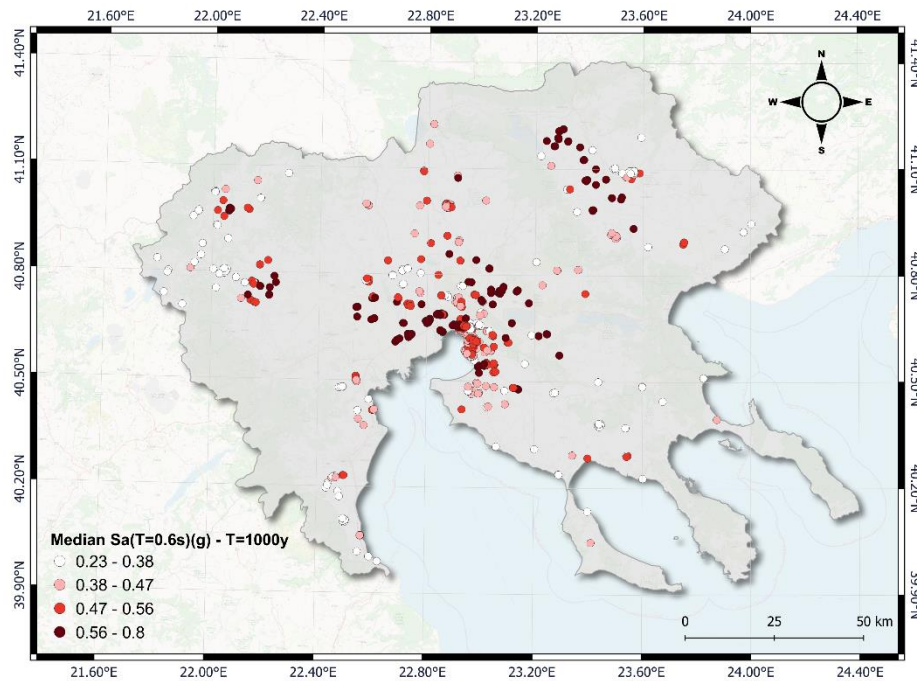


Fig 28. Seismic hazard map for median $Sa(T=0.6s)$ for a 1000- year return period on ground surface

To account for the epistemic uncertainty in fragility modelling, different sets of seismic fragility functions are used to assess the seismic vulnerability of the school and hospital buildings. Specifically, the European Seismic Risk Model (ESRM20, Romão et al. 2021) is used to estimate seismic damages and losses for both schools and hospitals, while complementary Di Ludovico et al. (2023) and Shooraki et al. (2024) seismic fragility models are used for school and hospital buildings respectively. The maps and curves below (Fig 29 to Fig 32) present indicative results derived using the ESRM20 model.

ESRM20 fragility models have been derived for simplified equivalent single degree-of-freedom oscillators and their use is recommended for large-scale applications (such as the European building stock). They are therefore a suitable option for a large-scale analysis at city or region scale, as they include fragility curves for all the different typologies of school and hospital buildings in Greece (except for precast ones). The ESRM20 fragility curves have been derived for four damage levels (slight, moderate, extensive and complete damage) and for different seismic intensity measures depending on the building typology, namely, the peak ground acceleration (PGA), and the spectral accelerations $Sa(0.3s)$, $Sa(0.6s)$ and $Sa(1.0s)$. The ESRM20 vulnerability curves have been obtained from the respective fragility functions using the following



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loss indices based on a review of recent European damage/ loss models: 0.05 for the slight damage, 0.15 for the moderate damage, 0.6 for the extensive damage) and 1.0 for the complete damage (Crowley et al. 2021). These loss ratios represent the repair cost (or cost of damage) as a proportion of the total replacement cost, which covers structural damage, non-structural damage and damage to contents. Thus, the total direct economic loss (in terms of repair cost) may be estimated by simply multiplying the loss ratios with the building area (in m^2) and the replacement cost/ m^2 . For the precast reinforced concrete school and hospital buildings, for which fragility curves are not available in ESRM20, the fragility curves by Yesilyurt et al. (2021) as a function of spectral acceleration $S_a(T)$ are used where T corresponds to the structure's fundamental period. The latter curves have been initially developed for industrial precast reinforced concrete buildings for four damage levels and for three construction categories: poor, typical, and superior. Calibrated damage indices for each damage state are considered according to Yesilyurt et al. (2021), namely 0.05 for the slight damage, 0.30 for the moderate damage, 0.7 for the extensive damage and 1.0 for the complete damage.

Considering that ESRM20 fragility curves have been developed for the residential building stock, the fragility curves proposed by Di Ludovico et al. (2023) and Shooraki et al. (2024) which refer specifically to schools and hospitals respectively, are used additionally.

Di Ludovico et al. (2023) proposes empirical/heuristic fragility curves for reinforced concrete and unreinforced masonry public school buildings typical of the Italian building stock, based on the damage observed in the aftermath of the 2009 L' Aquila earthquake. Three different approaches (i.e. empirical, empirical-binomial, heuristic) have been used by the authors to derive the fragility curves for five damage states (using the EMS-98 damage grade) as a function of PGA. In this study, the fragility functions derived with the heuristic approach have been applied for the school buildings of the region of Central Macedonia, Greece to assess their vulnerability to seismic loads.

Shooraki et al. (2024) developed empirical fragility curves for hospitals based on damage data of 341 hospital buildings in previous earthquakes. Fragility curves in terms of PGA have been constructed for different typologies of hospital buildings worldwide, namely low-rise concrete moment frame, medium-rise concrete moment frame, and masonry hospital buildings. Due to the lack of sufficient damage data for masonry hospitals, the Bayes theorem was used to update the existing curves with the collected data. Considering the significant contribution of non-structural-component damage to earthquake-induced losses in hospital buildings, the authors also provided seismic fragility curves for non-structural components of hospitals. In this study, the seismic vulnerability of the hospital buildings of the region of Central Macedonia, Greece has been assessed using the above-mentioned fragility curves.



Fig 29 and Fig 30 present a comparison of the ESRM20 fragility curves with the ones of Di Ludovico et al. (2023) and Shooraki et al. (2024) respectively, for one of the most common typologies of school and hospital buildings (i.e., low rise RC frame building) in the target area. A large variability between the curves is generally shown. Further comparative results (with the use of the alternative sets of fragility curves) in terms of damages and losses at asset and system level will be shown in the next stages of MIRACA project (Task 3.5).

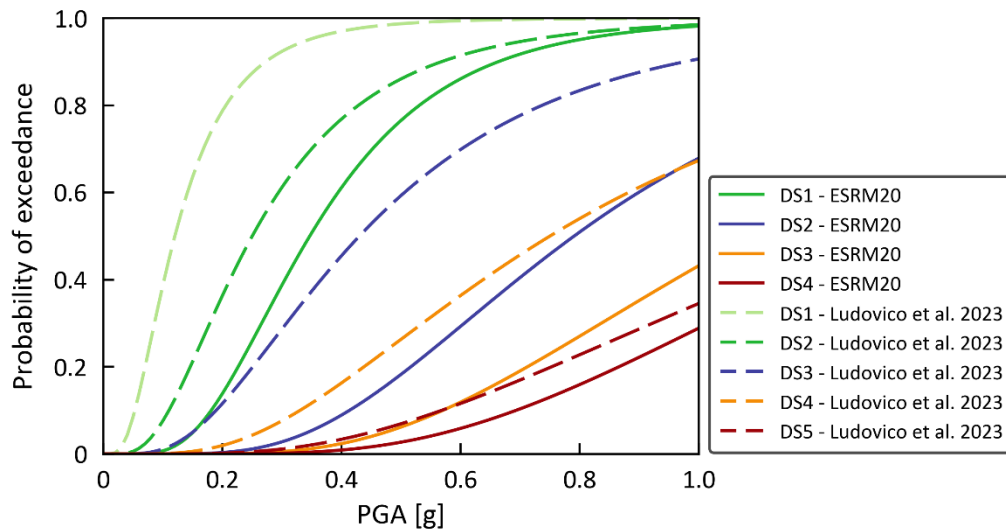


Fig 29. Comparative plots of seismic fragility curves for schools and specifically for RC low rise buildings



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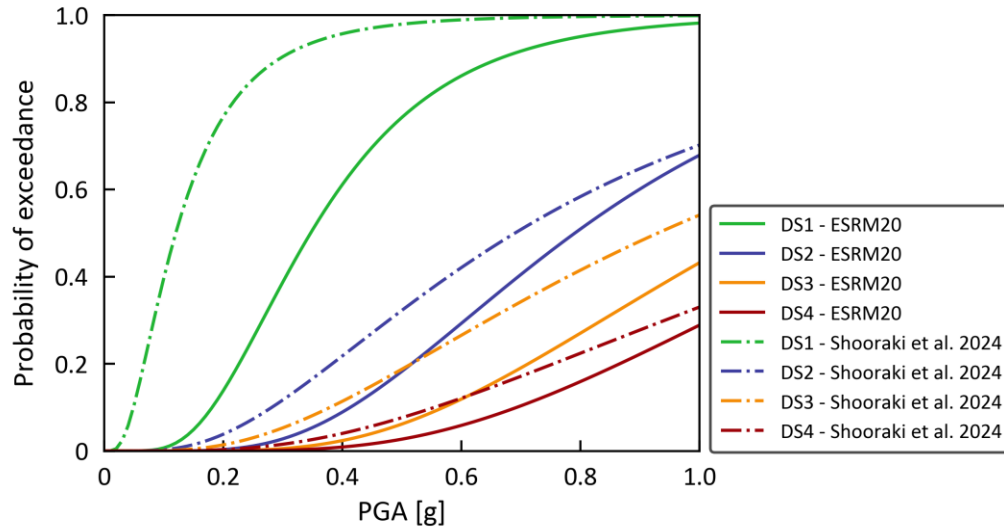


Fig 30. Comparative plots of seismic fragility curves for hospitals and specifically for RC low rise buildings

To account for human losses, the ESRM20²³ fatality model initially derived for residential buildings is properly adopted for the case of schools and hospitals in the study area. Specifically, the fatality indices are obtained by multiplying the complete damage fragility functions by 1.0% (based on empirical data from previous earthquakes), the collapse factor (that varies from 0.5 to 5 as a function of the building class), the probability of entrapment given collapse (Reinoso et al. 2017), and the probability of loss of life given entrapment (Reinoso et al. 2017). Human losses are finally calculated per building by multiplying the derived fatality index with the expected number of people in each building.

Damage and risk analyses are performed for the six different return periods ($T_m=73, 102, 475, 1000, 2500, 5000$ years) derived from the precomputed probabilistic hazard analyses. Probabilistic damage and risk analyses are also conducted.

Risk results are given in terms of loss maps describing the losses of all exposed assets for a specific return period. Loss exceedance curves per asset that provide the probability of exceeding the loss as a function of the expected losses (in terms of loss ratio) are also directly derived from classical probabilistic seismic risk analysis in OpenQuake. Fig 31 and Fig 32 illustrate the expected loss maps for a return period of 1000 years using ESRM20 fragility curves for the school and hospital buildings respectively. As shown in the figures, a large majority of school and hospital buildings

²³ <https://gitlab.seismo.ethz.ch/efehr>



are expected to sustain significant damages for the specific seismic scenario, given that, as described above, the expected seismic hazard in the area is high. More specifically, most school buildings (1,125) are in areas with low loss ratios (0–0.1), followed by 329 in the 0.1–0.25 range. Still, 87 schools fall in the highest loss ratio category (>0.4), which is notable given their critical function. Hospitals show a more balanced distribution: 76 in the lowest range, 87 in the 0.1–0.25 range, and 64 with loss ratios above 0.4, suggesting increased seismic exposure for a portion of healthcare facilities. Hospitals appear more seismically vulnerable than schools, as a higher proportion have been constructed under outdated or no seismic codes. This is consistent with the distribution of the loss ratio, where a relatively larger number of hospital buildings fall into higher risk categories. Fig 33 and Fig 34 show the spatial distribution of economic (in thousand euros) and human losses (loss of lives) for the schools, aggregated per municipality, for the return period of 1000 years. Municipalities, shown as blank on the maps, indicate areas where data for school buildings was not available. The losses are classified into five categories, with the highest economic losses (above €11.36 million) observed in the central and western regions, particularly in urban and densely populated areas, such as Thessaloniki, Neapolis-Sykeon, Pavlou Mela, Lagkada, Delta, Kilkis. Concerning the human losses, the red areas concern the Municipalities of Thessaloniki, Pavlou Mela, Lagkada and Delta. It is important to note that the municipalities marked as red differ between the two maps. This is because the economic losses are derived based on the loss ratio applied to the asset value of each building, whereas the human losses result from the probability of collapse, as computed through the fragility curves. Therefore, these two maps reflect different loss mechanisms and should not be directly compared.

Fig 35 shows the derived loss exceedance curves for specific typologies of school buildings with the ESRM20 vulnerability models. The results show significant variability in damage estimates across different building typologies. For instance, the curve of the high-code infilled RC building (CR_LFINF-CDH-10_H2) indicates a better seismic performance compared to the low-code infilled RC building (CR_LFINF-CDL-10_H2).



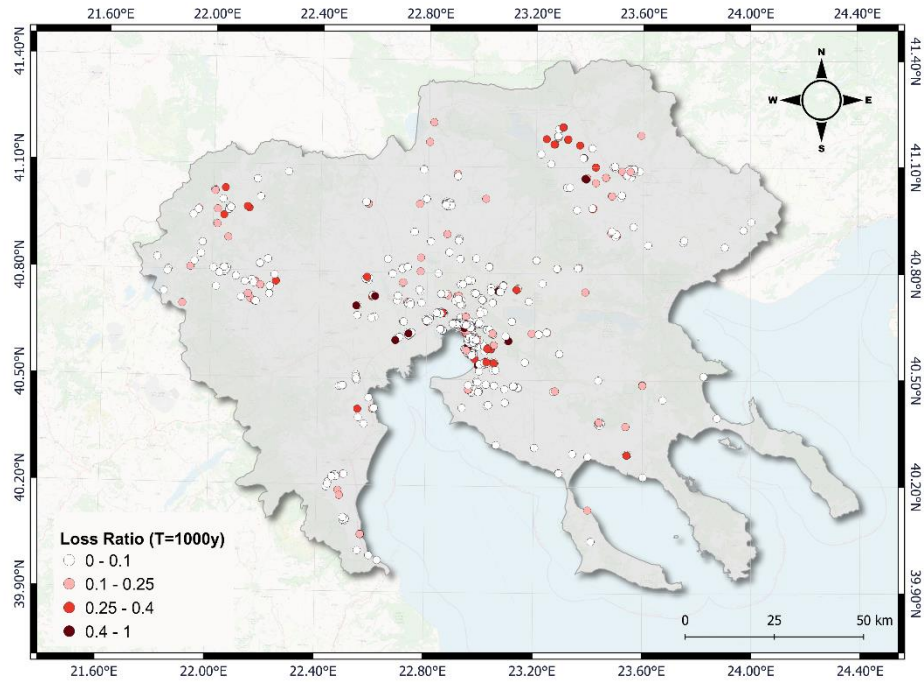


Fig 31. Loss ratio map for a return period of 1000 years using ERSM20 fragility curves, for the school buildings in the study area

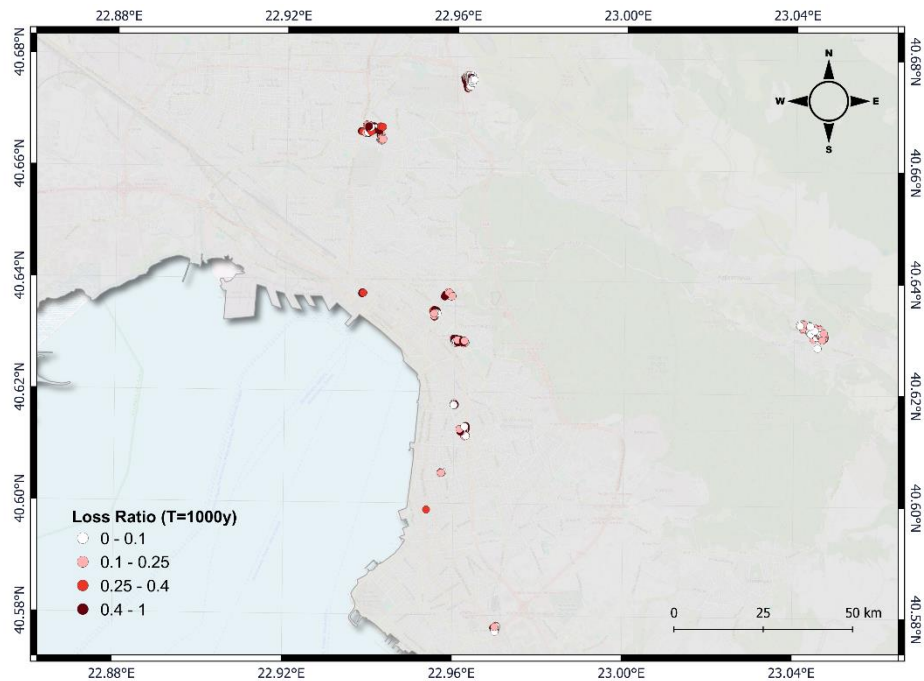


Fig 32. Loss ratio map for a return period of 1000 years using ERSM20 fragility curves, for the hospital buildings in the study area



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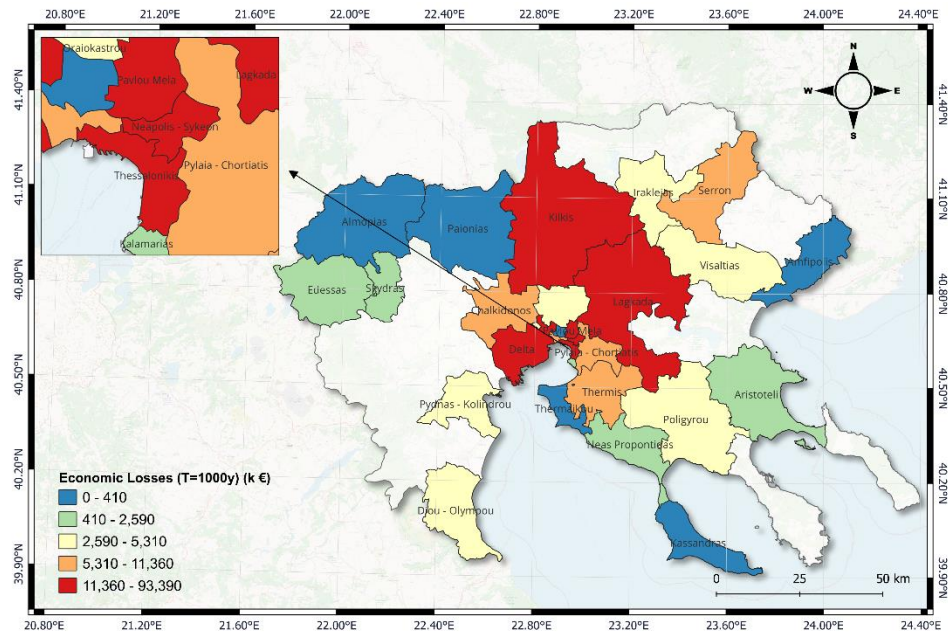


Fig 33. Economic losses for a return period of 1000 years using ESRM20 methodology, for the school buildings in the study area

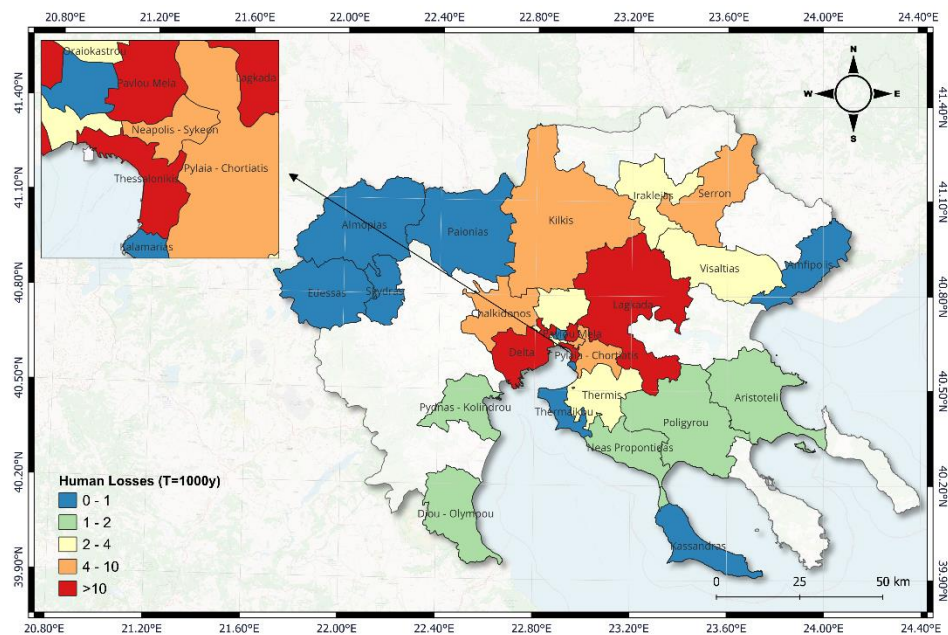


Fig 34. Human losses for a return period of 1000 years using ESRM20 methodology, for the school buildings in the study area



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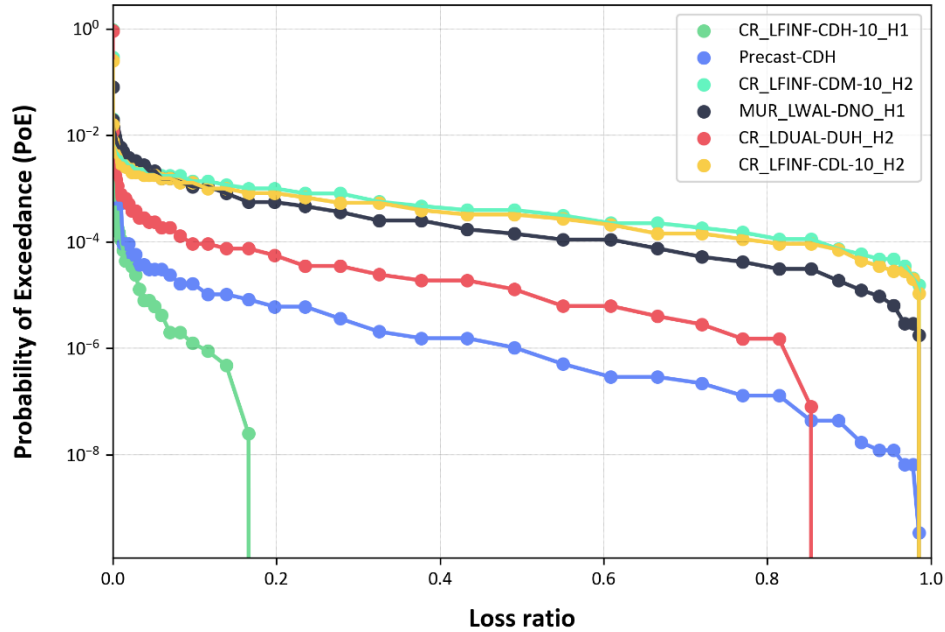


Fig 35. Seismic loss exceedance curves for different typologies of school buildings

5.1.3. Landslides

To assess the potential impact of landslides on schools and hospitals, a semi-quantitative procedure is followed by overlapping landslide susceptibility data with exposure characteristics of the exposed single assets (schools and hospital buildings). The European Landslide Susceptibility Map version 2 (Elsus v2, Wilde et al. 2018) is used as a basis for the susceptibility analysis of the region of central Macedonia in Greece. The map with a resolution of 200 m has been derived from heuristic-statistical modelling of the main landslide contributing factors (slope angle, shallow sub-surface lithology, and land cover spatial datasets) using also when available landslide location data for model calibration and map validation. It covers all European Union member states except Malta, and several neighbouring countries. Fig 36 shows the landslide susceptibility levels for the region of interest.



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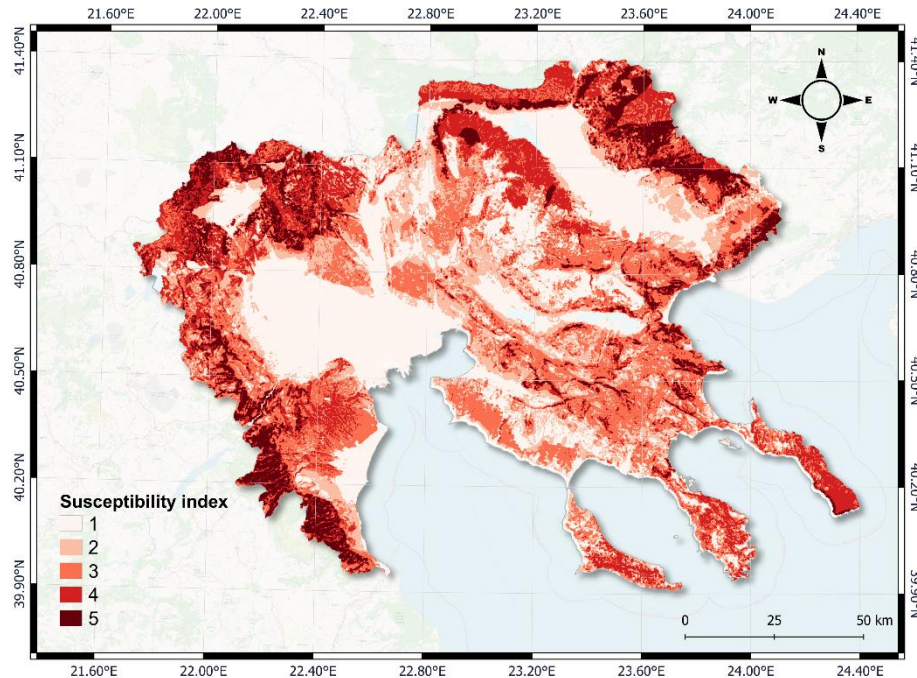


Fig 36. Landslide susceptibility map of the Region of Central Macedonia, Greece (where susceptibility index 1=very low; 2=low; 3=medium; 4=high; 5=very high)

The vulnerability of schools and hospitals due to landslide is assessed through a semi-quantitative index-based approach initially proposed by Papathoma et al. (2007) and updated by Arnaouti et al. (2013). As shown in Table 2, various contributing factors are considered (i.e., construction material, outdatedness, age, number of floors) and different weightings are assigned to each of them based on their relative importance in the vulnerability assessment. A different score is also specified to each category of the given factors and the total vulnerability value is computed for each building utilizing the Weighted Linear Combination Method (Papathoma et al. 2007). To calculate landslide risk, based on the function of the asset, a different value of the building is also considered as seen in Table 3. Fig 37 and Fig 38 illustrate the computed landslide risk map of the schools and hospitals in the study area. The majority of school buildings (830) fall within the 0.1-0.25 risk range, while hospital buildings show higher vulnerability, with 197 facilities in the highest category of loss ratio range (0.4-1), indicating greater vulnerability of healthcare infrastructure to landslide hazards. It should be noted, however, that the derived normalized risk values are based on a rather qualitative approach and should not be transformed into absolute economic values. Therefore, a comparison with the other hazards in terms of losses is not recommended.



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

Table 2. Factors contributing to building vulnerability to landslides, the score of each category and their relevant weightings (Arnaouti et al. [2013])

Factor	Categories	Score	Weighting
Construction material	masonry	0.6	4
	reinforced concrete	0.3	
	steel	0.3	
	wood	0.8	
	mixed	0.7	
Number of floors	1	0.5	1
	2-3	0.3	
	≥4	0.1	
Outdatedness	good	0.1	4
	average	0.3	
	bad	0.6	
	destroyed	0.9	
Age of building	before 1900 (DCN)	0.9	3
	1900-1950 (DCN)	0.7	
	1950-1970 (DCL)	0.5	
	1970-1990 (DCL)	0.3	
	1990-2000 (DCH)	0.1	
	after 2000 (DCH)	0	

Table 3. Function and the corresponding value of the building (Arnaouti et al. [2013])

Function	Value of the element (E)
residential	1
commercial	1.1
industrial and craft	1
agricultural	1
leisure and sportive	1.1
hotel	1.1
place of religious worship	1.2
private service	1.2
public service	1.3
education	1.3
civil service	1.3
urgency service	1.3



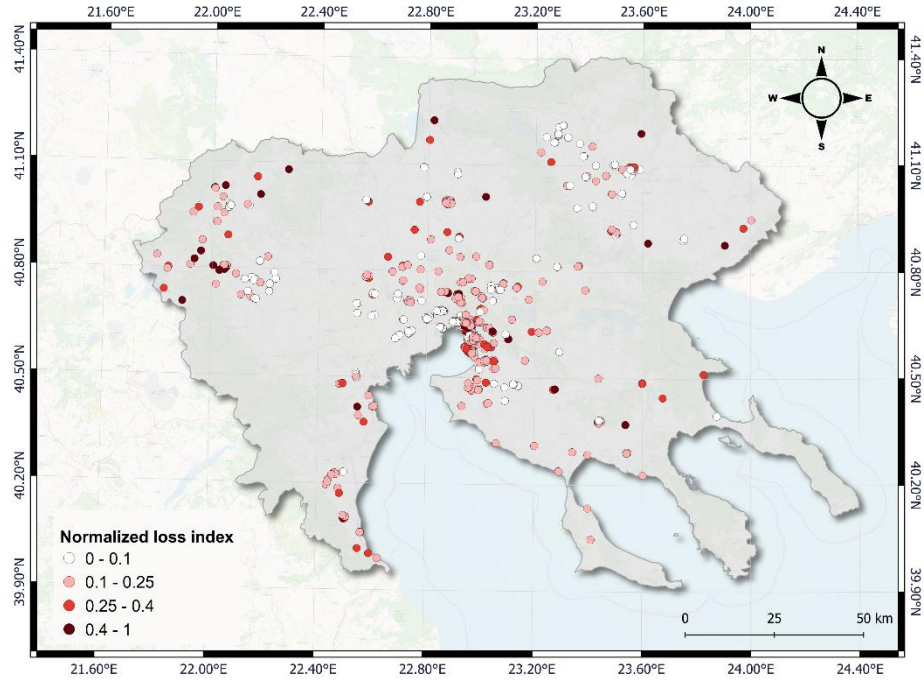


Fig 37. Landslide risk map of the schools in the study area

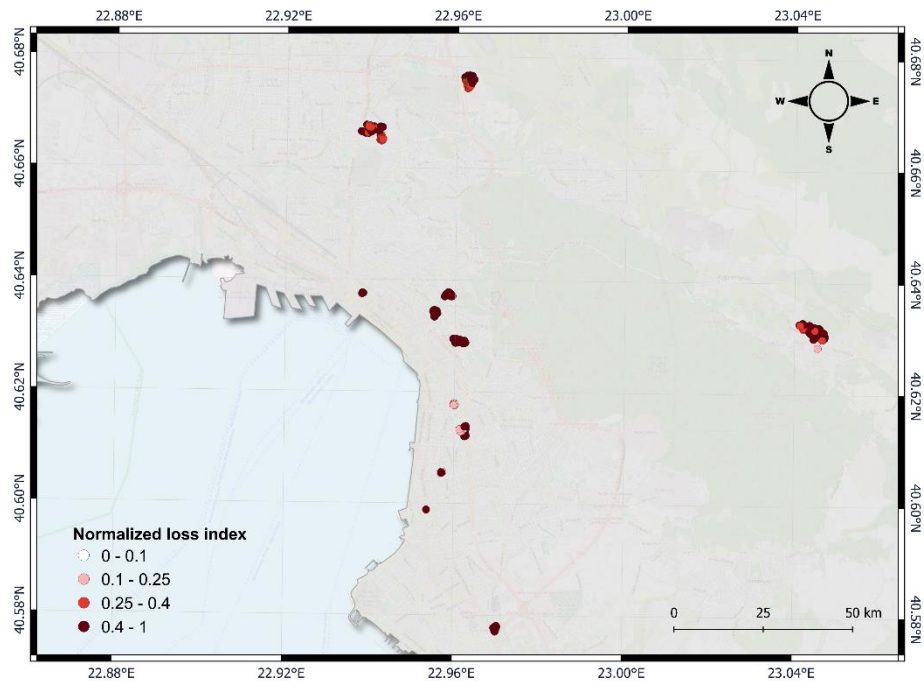


Fig 38. Landslide risk map of the hospitals in the study area.



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5.2. Multi-Hazard

Multi-hazard assessment differentiates depending on whether the hazards that may occur at the location of the examined assets are independent or not. In this study, following the existing literature (e.g., Arrighi et al. 2023), flood and earthquake are treated as independent hazards, while earthquake and landslide as dependent hazards. Specifically, the earthquake is considered as the primary hazard and the landslide as the secondary hazard triggered by the earthquake.

5.2.1. Floods & Earthquakes

In case of floods and earthquakes, a hazard-specific risk assessment as described in the previous section is initially performed. Following the methodology presented in Section 3.2, Eq. 2 referring to the case of three independent hazards) is modified to compute the joint probability of the occurrence $H_{(1,2)}$ for the case of two independent hazard events E_1 (flood) and E_2 (earthquake):

$$H_{(1,2)} = p(E_1) * p(E_2) \quad (\text{Eq. 5})$$

Where $p(E_1)$ represents the probability of occurrence of the flood E_1 , $p(E_2)$ the probability of occurrence of the earthquake E_2 ; both derived from the hazard-specific assessment presented in section 5.1.

As discussed in the methodology Section 3.2, the cumulative damage from the different hazards (flood and earthquake) impacting the same assets may be evaluated using appropriate fragility surfaces that are a function of two (or more) intensity parameters describing each hazard. Such fragility surfaces have been incorporated (when available) in MIRACA vulnerability database (Task 1.5).

In this study, due to the lack of appropriate fragility surfaces for all typologies of the exposed assets, the compound damage due to the flood and earthquake is alternatively estimated by combining the damage state probabilities of the fragility functions described in Section 5.1 for the different hazards. The combined probability (P_{COMB}) of exceeding a given limit state i in the case of the occurrence of two independent hazards is given as (e.g., Fotopoulou et al. 2022):

$$P_{\text{COMB}} [LS \geq LS_i] = P_{E1} [LS \geq LS_i] + P_{E2} [LS \geq LS_i] - P_{E1} [LS \geq LS_i] * P_{E2} [LS \geq LS_i] \quad (\text{Eq.6})$$

The corresponding compound loss ratios have been obtained from the respective damage probabilities using the appropriate damage factors based on existing European consequence models (Crowley et al. 2021).



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The multi-hazard risk analysis is performed for all different combinations of return periods of flood and earthquake. Specifically, 9x6 combinations of flood-earthquake were considered when using the JRC flood model and 9x3x6 combinations when using the GIRI model for the present and future climate. Results are given in terms of compound loss maps for the different combinations of return periods of the flood and earthquake for all assets (schools and hospitals).

Fig 39 to Fig 42 show representative loss maps for two different combinations of flood (using JRC model) and earthquake for the considered educational and healthcare facilities. Most school buildings exhibit low expected loss (0–0.1 range), while hospitals are more evenly distributed, with a significant number (92 in Fig 42) falling in the highest loss category (0.4–1), indicating increased multi-hazard vulnerability of healthcare facilities. Generally, it is seen that the earthquake hazard has a greater impact on the multi-hazard risk of schools and hospitals compared to the flood hazard, something that has already been commented on earlier in the paragraph discussing the single hazards. This is because earthquakes typically affect the entire area under study, impacting all assets to varying degrees. In contrast, floods generally affect only those assets located within or near the flood-prone zones, such as areas close to river basins. However, in cases where school or hospital buildings are situated near river basins (Fig 20), flood hazards may contribute more significantly to the overall multi-hazard risk.



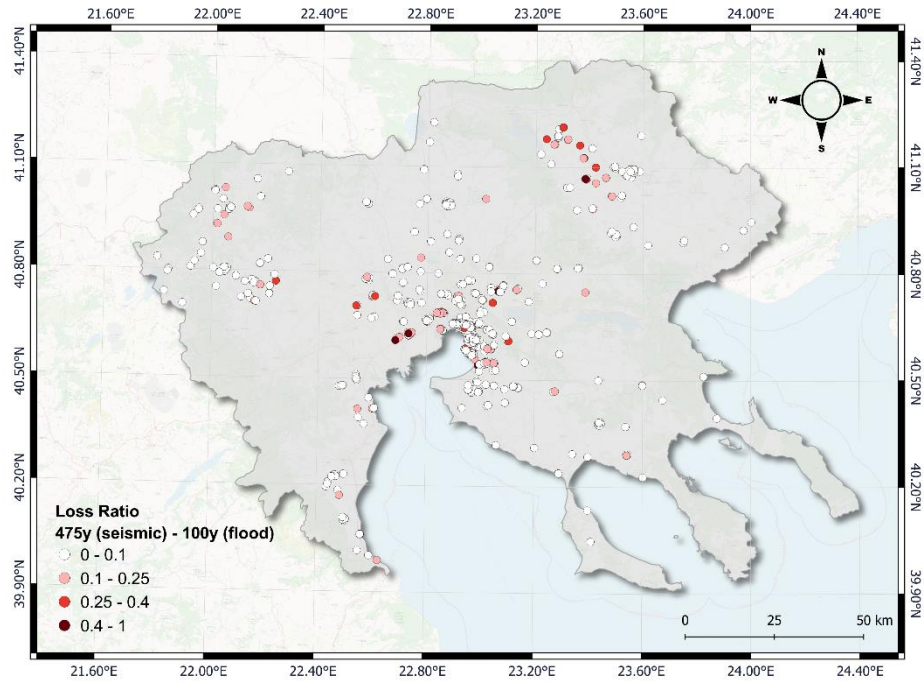


Fig 39. Loss ratio map for the school buildings for the combination of 475 years (seismic) - 100 years (flood)



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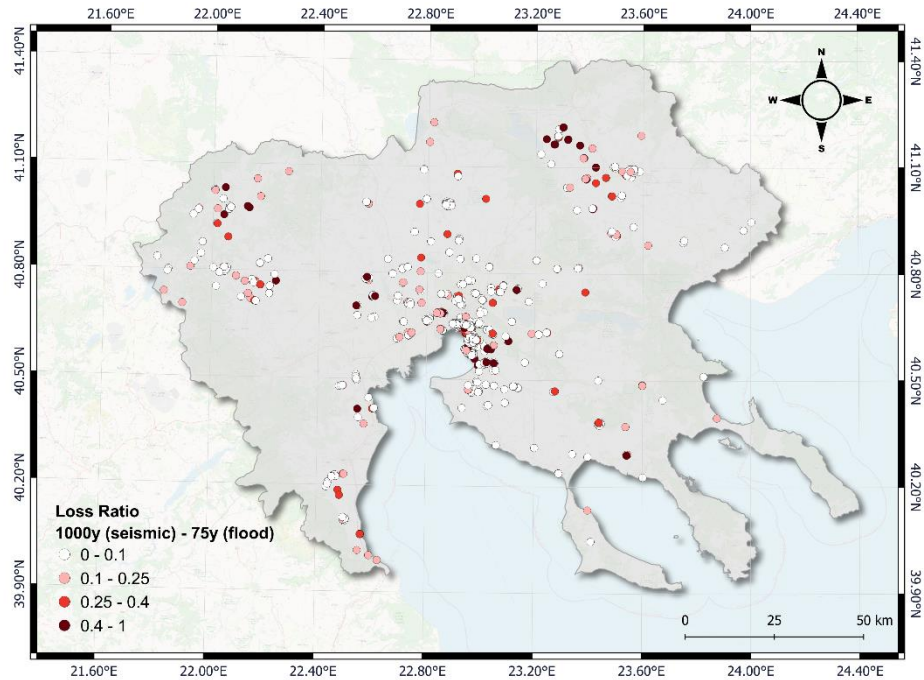


Fig 40. Loss ratio map for the school buildings for the combination of 1000 years (seismic) – 75 years (flood)

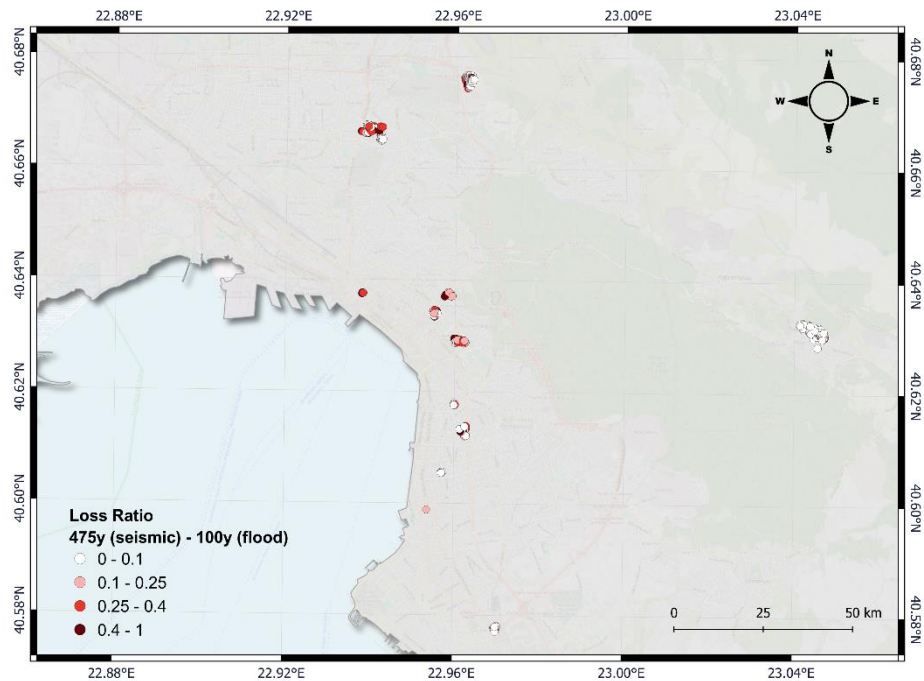


Fig 41. Loss ratio map for the hospital buildings for the combination of 475 years (seismic) – 100 years (flood)



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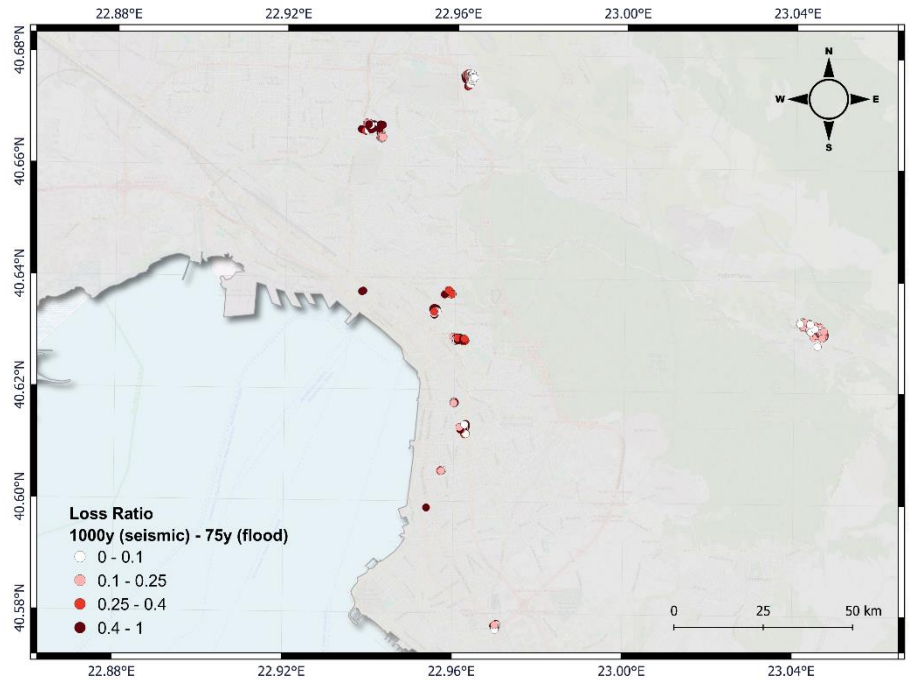


Fig 42. Loss ratio map for the hospital buildings for the combination of 1000 years (seismic) – 75 years (flood)

Loss curves are also developed per asset describing the joint annual probability of the occurrence of the two hazards as a function of the compound economic losses. The integral of the loss curves (the area underneath the curve) is the Expected Annual Damage (EAD). Fig 43 shows comparative plots of the loss curves for a specific school building subjected only to floods (using the JRC model), subjected only to earthquakes and subjected to both earthquake and flood hazards. The calculation of the EAD in Euro is also illustrated indicatively for the multi-hazard case. It is seen that for the case of the multi-hazard events (flood-earthquake), the probability of occurrence is much lower compared to the case of the single-hazard events (only flood or only earthquake). However, in the former case the expected losses are much higher, highlighting the importance of incorporating multi-hazard threats in the risk assessment. Table 4 presents the computed Expected Annual Damages (EAD) in Euro for the representative school buildings shown in Fig 43, under three hazard scenarios: earthquake only, flood only (based on the JRC model), and combined earthquake–flood events. As illustrated, the EAD is highest when only floods are considered, amounting to 2,241.47€, followed by 242.65€ for earthquakes alone. Interestingly, the combined hazard scenario results in a significantly lower EAD of 23.94€.

This outcome is explained by the very low joint annual probability of occurrence of both hazards, despite the higher losses when such compound events occur. Moreover, the higher EAD associated with floods as a standalone hazard, compared to earthquakes, is



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likely due to their more frequent nature and higher recurrence rates, as floods typically occur more often than significant seismic events.

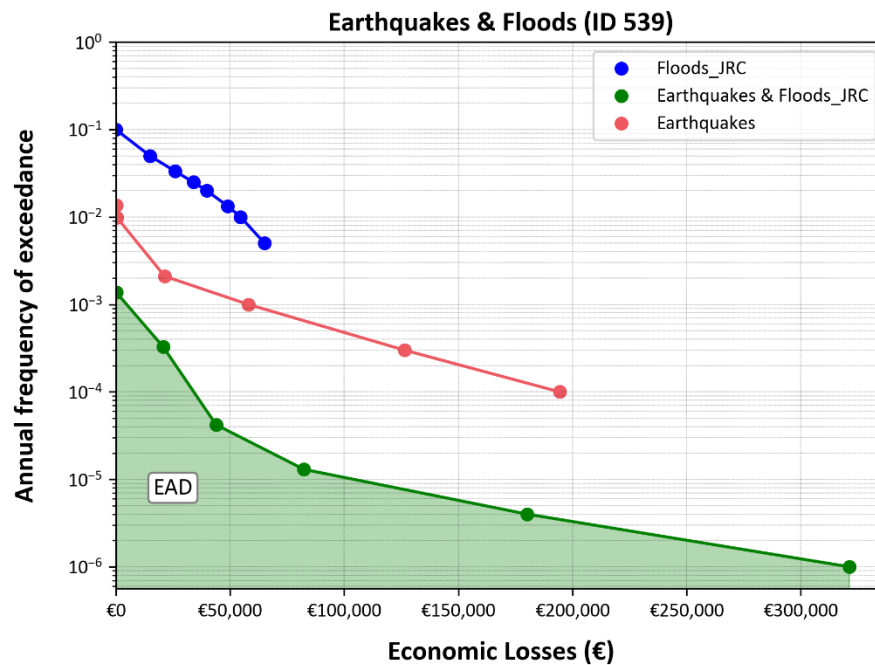


Fig 43. Loss curves for a specific school building (ID 539) impacted only by floods (using the JRC model), impacted only by earthquakes and impacted to both earthquake and flood hazards

Table 4. Expected annual damage (EAD) in Euro, for a specific school building (ID 539)

Hazard scenario	EAD (€)
Earthquakes	242.65
Floods_JRC	2,241.47
Earthquakes & Floods_JRC	23.94

5.2.2. Earthquakes & Landslides

In the case of earthquakes and landslide hazards threatening the same elements at risk, we consider a hazard interaction effect. Specifically, cascading events are modelled, where the earthquake is the primary hazardous event and the landslide the secondary one triggered by the earthquake.

A hazard-specific assessment is initially performed for the earthquake based on ESHM20 hazard model and probabilistic analysis in OpenQuake as described in Section 5.1. PGA



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and different spectral ordinates for the different return periods on the ground surface are derived to describe the ground shaking. To assess earthquake induced landslide hazard, ELSUS v2 susceptibility classes (Wilde et al. 2018) are related to yield acceleration ratio (k_y) values based on FEMA (2024) methodology and expert judgement. Then, the Permanent ground displacement (PGD) of (earthquake induced) landsliding is estimated using an analytical expression (Fotopoulou and Pitilakis 2015) that relates the PGD with PGA (taken from the seismic hazard analysis presented in Section 5.1) and yield acceleration ratio (k_y). The probability of the occurrence of the earthquake induced landslide is assumed to be that of the earthquake itself ($P_L=1.0$, meaning that the landslide will certainly occur given the occurrence of the earthquake) or lower compared to the one of the earthquake ($P_L<1.0$). In the latter case, the probability of the occurrence of the earthquake induced landslide (P_L) is taken from the study of Nadim et al. (2023), presented in Table 5.

Specifically, to be on the safe side, and given that the PGA has already been included in the analysis through the calculation of PGD, only the last row of the table, corresponding to the highest PGA range ($PGA \geq 0.45g$), was used to derive the probabilities of landslide occurrence. Thus, the probability of landslide occurrence given the earthquake is assumed to be linked to the landslide susceptibility category.

Following the methodology presented in Section 3.2, the joint probability of the occurrence of the interacting hazards needs to be estimated. (Eq. 3 (referring to the case of three dependent hazards) is modified to compute the joint probability of the occurrence $H_{(2,3)}$ for the case of two interacting hazard events E_2 (earthquake) and E_3 (landslide):

$$H_{(2,3)} = p(E_2) * p(E_3|E_2) \quad (\text{Eq. 7})$$

where $p(E_2)$ represents the probability of the occurrence of the earthquake event E_2 and $p(E_3|E_2)$ the conditional probability of the impacted landslide event E_3 given the occurrence of the earthquake (E_2) that equals P_L .

Table 5. Probability of occurrence of a significant earthquake-induced landslide as a function of PGA of the earthquake scenario at that location and the Susceptibility Category (adapted from Nadim et al. 2023)

PGA (g)	Susceptibility category				
	Susc. 1	Susc. 2	Susc. 3	Susc. 4	Susc. 5
$0.05g \leq PGA < 0.15g$	~ 0	~ 0	~ 0	0.1%	0.5%



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$0.15g \leq PGA < 0.25g$	~ 0	~ 0	0.1%	0.5%	1%
$0.25g \leq PGA < 0.35g$	~ 0	0.1%	0.5%	1%	5%
$0.35g \leq PGA < 0.45g$	~ 0	0.5%	1%	5%	10%
$PGA \geq 0.45g$	~ 0	1%	5%	10%	40%

The next step is the compound vulnerability assessment of the interacting hazards. In this study, the **compound damage** due to the earthquake and landslide is estimated by combining the damage state probabilities for the different hazards using Eq. 4. The seismic fragility functions described in Section 5.1 are used to account for the damage due to seismic ground shaking and FEMA (2024) fragility functions for the damage due to seismically induced landslides.

The corresponding compound loss ratios have been obtained from the respective damage probabilities using appropriate damage factors based on existing European models (Crowley et al. 2021).

The multi-hazard risk analysis is performed for the six return periods of the earthquake for $P_L < 1.0$ and $P_L = 1.0$. Results are given in terms of compound loss maps for the different return periods of the earthquake and landslide for all assets (schools and hospitals).

Fig 44 to 47 show representative loss maps for the same return period of the earthquake and a different assumption for the landslide occurrence given the earthquake ($P_L < 1.0$ and $P_L = 1.0$) for the considered educational and healthcare facilities. Fig 48 shows comparative plots of the loss curves for a specific school building subjected only to earthquake and subjected to earthquake and landslide with a different occurrence probability of the landslide given the earthquake ($P_L < 1.0$ and $P_L = 1.0$). The calculation of the EAD is also illustrated indicatively for the multi-hazard case with $P_L < 1.0$. It is seen that the assumption for the probability of the landslide occurrence given the earthquake P_L is critical in assessing the annual expected losses with the case of $P_L = 1.0$ showing much higher loss ratios and annual frequencies of exceedance compared to the case of $P_L < 1.0$. In the latter case, although the annual frequency of exceedance is much lower compared to the one of the earthquake, the expected losses are higher compared to the case where only the earthquake is considered highlighting the importance of including multi-hazard interacting impacts in the risk assessment. Table 6 presents the computed Expected Annual Damage (EAD) for a school building under different hazard scenarios: single earthquake and multi-hazard cases (earthquake-landslide with $P_L < 1.0$ and $P_L = 1.0$). As anticipated, the highest EAD (5,840.88€) corresponds to the multi-hazard scenario assuming that a landslide will certainly occur following an earthquake ($P_L = 1$). In contrast, significantly lower values are observed for



the earthquake-only case (4,067.36 €) and especially for the multi-hazard scenario with a conditional probability less than 1 ($P_L < 1$), yielding just 207.80€. These results highlight the sensitivity of risk estimates to assumptions regarding hazard interaction and underline the importance of an accurate assumption for the probability of the landslide occurrence given the earthquake in assessing the multi-hazard risk.

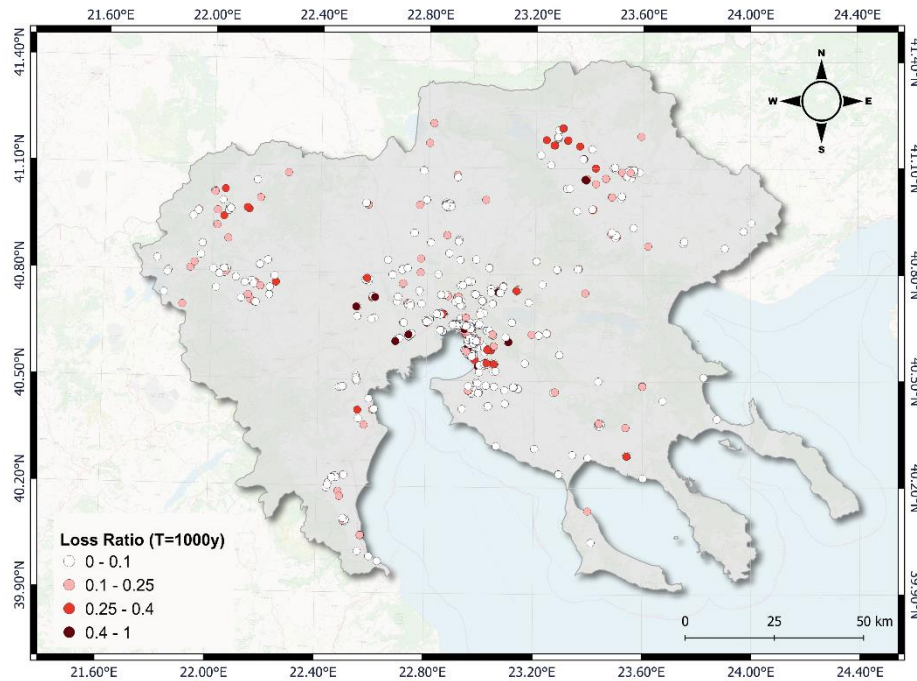


Fig 44. Loss ratio map of the interacting (earthquake-landslide) hazards considering a return period of 1000 years for the earthquake and a landslide occurrence given the earthquake lower than unity ($P_L < 1.0$), for the school buildings in the study area



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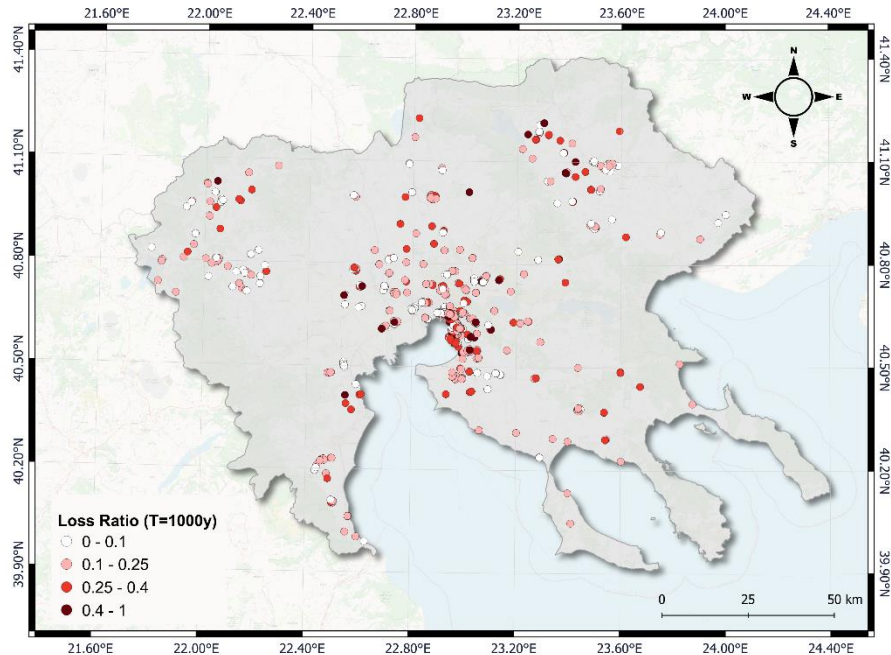


Fig 45. Loss ratio map of the interacting (earthquake-landslide) hazards considering a return period of 1000 years for the earthquake and a landslide occurrence given the earthquake equal to unity ($P_L=1.0$), for the school buildings in the study area

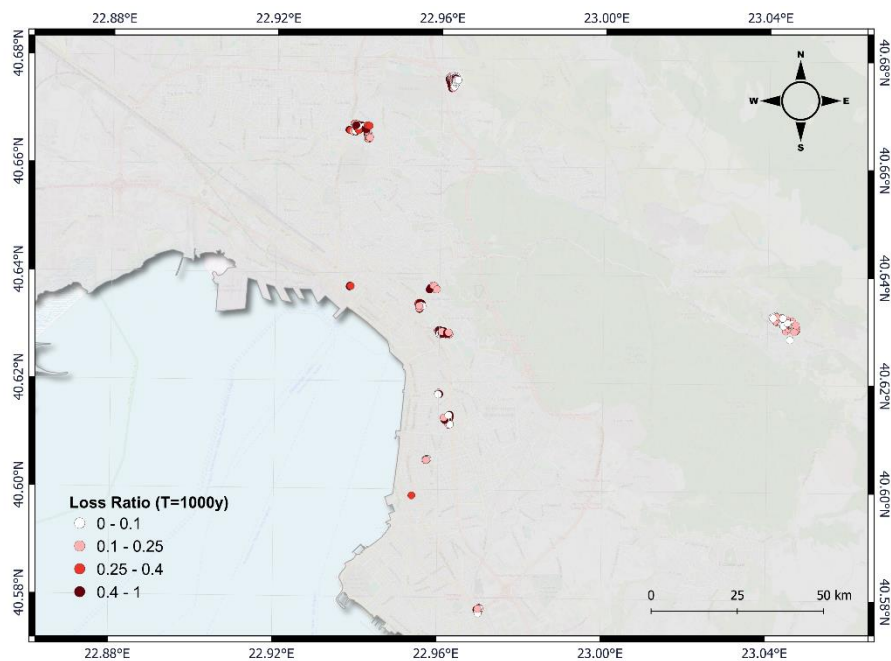


Fig 46. Loss ratio map of the interacting (earthquake-landslide) hazards considering a return period of 1000 years for the earthquake and a landslide occurrence given the earthquake lower than unity ($P_L<1.0$), for the hospital buildings in the study area



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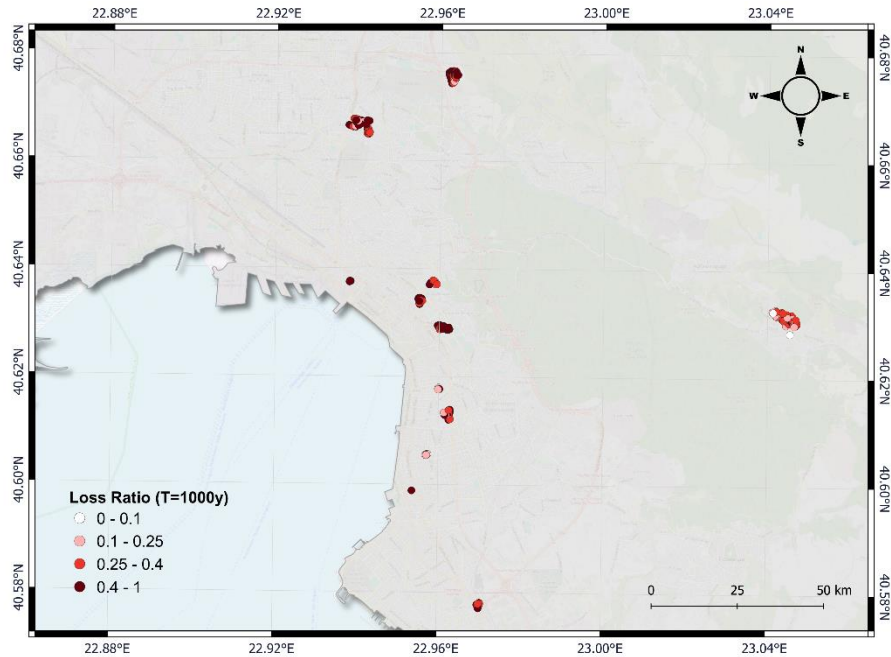
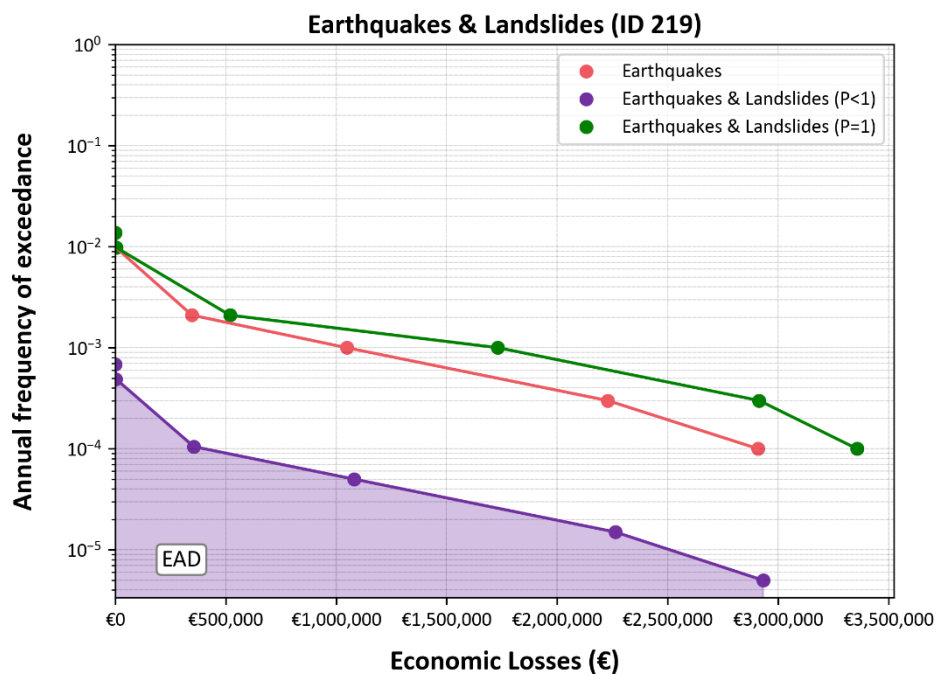


Fig 47. Loss ratio map of the interacting (earthquake-landslide) hazards considering a return period of 1000 years for the earthquake and a landslide occurrence given the earthquake equal to unity ($P_L=1.0$), for the hospital buildings in the study area



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Fig 48. Loss curves for a specific school building (ID 219) impacted only by earthquake and impacted by both earthquake and landslide hazards with varying occurrence probability of the earthquake induced landslide: $P_L < 1$ and $P_L = 1$

Table 6. Expected annual damage (EAD) in Euro for a specific school building (ID 219) for the three different cases (single & multi hazard)

Hazard scenario	EAD (€)
Earthquakes	4067.36
Earthquakes & Landslides ($P < 1$)	207.80
Earthquakes & Landslides ($P = 1$)	5840.88



6. Conclusions

Deliverable 3.2 presents a comprehensive, structured and scalable framework for assessing the risk of critical infrastructure (CI), like schools and hospitals, to natural hazards at the asset level, covering both single and multi-hazard scenarios across Europe, on a regional and European scale. The approach combines harmonized data on hazard, exposure, and vulnerability and is applied at both the European and regional scale.

At the European level, flood, windstorm and earthquake risk assessments were conducted, while exposure estimates were provided for other hazards such as wildfires, landslides, and extreme heat. The analysis included 43 infrastructure types grouped under transport, energy, telecommunications, health, and education systems, using more than 130 OpenStreetMap (OSM) tags to represent their geospatial distribution, including over 35 million unique infrastructure assets.

Power infrastructure dominates European risk profiles, accounting for 40.8% of total expected annual damages (\$2.7 billion), while windstorms represent the largest hazard threat at 40.2% of total risks. This can mostly be attributed to the reduction of river and coastal risk due to flood protection measures in place. Southern European countries face severe wildfire and heat exposure increases, with Cyprus potentially experiencing 15-20 additional wildfire days and 50-65% increases in extreme heat days under high emission scenarios. Northern countries show relatively little exposure to these climate hazards. Landslide susceptibility varies strongly by topography, with mountainous countries showing 80-90% of infrastructure in moderate to high-risk zones. River flooding projections reveal some non-linear responses, with some countries showing decreased risks at 4°C warming. Coastal flooding demonstrates accelerating damage trends through 2100, contrasting the more gradual increases towards the future for river flooding.

In the regional, use-case study in Central Macedonia, Greece, the methodology was applied to 1,718 school buildings and 255 hospital buildings. Risk assessment was performed for the aforementioned schools and hospitals subjected to floods, earthquakes and landslides considered as single hazards. Seismic hazard analysis using PGA and spectral acceleration maps showed that many buildings are located in zones with ground acceleration values up to 0.7g for a 1000-year return period. Over 35% of school buildings and more than 60% of hospitals were found to be built with low or no seismic design provisions. As a result, significant expected losses were identified: 87 schools and 64 hospitals were estimated to have a loss ratio exceeding 0.4 in the case of a severe earthquake scenario. At the municipal level, economic losses in schools exceeded €11.3 million in some areas, while expected human losses were concentrated



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in highly urbanized zones such as Thessaloniki, Pavlou Mela, and Delta. For floods, fewer buildings were directly affected, with up to 6 schools showing significant damage under a 100-year return period scenario, and virtually no hospital buildings impacted, primarily due to their location with respect to the expected flood basins. Landslide risk was assessed using a semi-quantitative method, identifying 197 hospital buildings falling into the highest risk category, pointing out a higher vulnerability.

Multi-hazard analyses combined flood and earthquake or earthquake and landslide scenarios. For independent hazards (flood and earthquake), combined loss probabilities were computed using available fragility functions. For dependent events like earthquake-triggered landslides, appropriate fragility functions and Bayesian models were applied to estimate cascading impacts.

Overall, the study confirmed that multi-hazard interactions can lead to more severe impacts than those predicted by single-hazard models alone. Despite limitations—such as data gaps for certain asset types or hazard interactions—the D3.2 framework demonstrates a scalable and scientifically sound method to support infrastructure risk assessment and resilience planning across Europe.



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Supplementary Materials

Table S1. Overview of OpenStreetMap tags used for each infrastructure system

Infrastructure System	OSM Tags
roads	motorway, motorway_link, trunk, trunk_link, primary, primary_link, secondary, secondary_link, tertiary, tertiary_link, residential, road, unclassified, track, service
main_roads	motorway, motorway_link, trunk, trunk_link, primary, primary_link, secondary, secondary_link, tertiary, tertiary_link
rail	rail
air	aerodrome, terminal, runway
telecom	mast, communications_tower, tower
education	school, kindergarten, college, university, library
healthcare	hospital, clinic, doctors, pharmacy, dentist, physiotherapist, alternative, laboratory, optometrist, rehabilitation, blood_donation, birthing_center
power	line, cable, minor_line, plant, generator, substation, transformer, pole, portal, tower, terminal, switch, catenary_mast

Table S2. Overview of number of CI assets considered for each country

	Healthcare	Education	Power	Rail	Roads	Telecom	Total
<i>AUT - Austria</i>	12044	10226	403416	51581	1179556	5795	1662618
<i>BEL - Belgium</i>	8038	12088	93760	24953	708453	3727	851019
<i>BGR - Bulgaria</i>	3459	4224	109825	8685	376384	685	503262
<i>CHE - Switzerland</i>	5863	11217	190022	40712	747398	4562	999774
<i>CYP - Cyprus</i>	1137	1067	5785	2	123747	378	132116
<i>CZE - Czech Republic</i>	4549	10301	746737	59317	870304	3456	1694664
<i>DEU - Germany</i>	84902	94934	1498758	221592	7106492	38930	9045608
<i>DNK - Denmark</i>	1658	5532	70047	6940	395230	2396	481803



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<i>ESP - Spain</i>	<i>32217</i>	<i>29591</i>	<i>622502</i>	<i>33347</i>	<i>0</i>	<i>9104</i>	<i>726761</i>
<i>EST - Estonia</i>	<i>734</i>	<i>1415</i>	<i>76612</i>	<i>2284</i>	<i>131079</i>	<i>1023</i>	<i>213147</i>
<i>FIN - Finland</i>	<i>2512</i>	<i>6564</i>	<i>219814</i>	<i>19221</i>	<i>851938</i>	<i>7186</i>	<i>1107235</i>
<i>FRA - France</i>	<i>0</i>	<i>81468</i>	<i>0</i>	<i>131053</i>	<i>0</i>	<i>44874</i>	<i>257395</i>
<i>GRC - Greece</i>	<i>7094</i>	<i>6976</i>	<i>58610</i>	<i>5285</i>	<i>979610</i>	<i>1673</i>	<i>1059248</i>
<i>HRV - Croatia</i>	<i>2067</i>	<i>3638</i>	<i>42649</i>	<i>5666</i>	<i>281591</i>	<i>1198</i>	<i>336809</i>
<i>HUN - Hungary</i>	<i>5668</i>	<i>9095</i>	<i>464488</i>	<i>20041</i>	<i>626051</i>	<i>4718</i>	<i>1130061</i>
<i>IRL - Ireland</i>	<i>3897</i>	<i>6512</i>	<i>622670</i>	<i>4908</i>	<i>488950</i>	<i>5657</i>	<i>1132594</i>
<i>ISL - Iceland</i>	<i>186</i>	<i>547</i>	<i>59113</i>	<i>0</i>	<i>40243</i>	<i>199</i>	<i>100288</i>
<i>ITA - Italy</i>	<i>26871</i>	<i>42411</i>	<i>0</i>	<i>83476</i>	<i>3567346</i>	<i>16379</i>	<i>3736483</i>
<i>LIE Liechtenstein</i>	<i>- 27</i>	<i>46</i>	<i>388</i>	<i>43</i>	<i>3843</i>	<i>0</i>	<i>4347</i>
<i>LTU - Lithuania</i>	<i>1532</i>	<i>2297</i>	<i>87555</i>	<i>4547</i>	<i>240037</i>	<i>1545</i>	<i>337513</i>
<i>LUX Luxembourg</i>	<i>- 490</i>	<i>573</i>	<i>12124</i>	<i>2158</i>	<i>67542</i>	<i>559</i>	<i>83446</i>
<i>LVA - Latvia</i>	<i>1262</i>	<i>1951</i>	<i>94025</i>	<i>6131</i>	<i>147510</i>	<i>1389</i>	<i>252268</i>
<i>MLT - Malta</i>	<i>200</i>	<i>233</i>	<i>6817</i>	<i>11</i>	<i>20739</i>	<i>51</i>	<i>28051</i>
<i>NLD - Netherlands</i>	<i>6790</i>	<i>12199</i>	<i>104041</i>	<i>26457</i>	<i>1034774</i>	<i>20879</i>	<i>1205140</i>
<i>NOR - Norway</i>	<i>4630</i>	<i>17295</i>	<i>375062</i>	<i>12635</i>	<i>493385</i>	<i>8388</i>	<i>911395</i>
<i>POL - Poland</i>	<i>27558</i>	<i>34122</i>	<i>1022768</i>	<i>73590</i>	<i>2145131</i>	<i>12193</i>	<i>3315362</i>
<i>PRT - Portugal</i>	<i>6725</i>	<i>10830</i>	<i>325705</i>	<i>8347</i>	<i>1029820</i>	<i>10107</i>	<i>1391534</i>
<i>ROU - Romania</i>	<i>7568</i>	<i>7747</i>	<i>165923</i>	<i>23363</i>	<i>659541</i>	<i>2709</i>	<i>866851</i>
<i>SVK - Slovakia</i>	<i>3141</i>	<i>6023</i>	<i>294555</i>	<i>21275</i>	<i>416356</i>	<i>2376</i>	<i>743726</i>



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<i>SVN - Slovenia</i>	788	1850	63028	6202	234245	1040	307153
<i>SWE - Sweden</i>	3332	12269	224350	23227	926972	5221	1195371
TOTAL	266939	445241	8061149	927049	25894267	218397	35813042

Table S3. Overview of Vulnerability IDs for each infrastructure system for windstorms, earthquakes and floods

Infrastructure System	Asset Type	Windstorm IDs	Earthquake IDs	Flood IDs
Roads	motorway, motorway_link, trunk, trunk_link, primary, primary_link, secondary, secondary_link, tertiary, tertiary_link, residential, road, unclassified, track, service	W7.2	E7.2 – E7.10	F7.4 – F7.9
Rail	Rail	W7.2	E8.1 – E8.20	F8.1 – F8.7
Air	Aerodrome	W7.2	E9.2 – E9.4	F9.1 – F9.3
	terminal	W21.13, W21.14	E9.2 – E9.4	F9.1 – F9.3
	runway	W7.2	E7.2 – E7.10	F7.4 – F7.7



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Telecom	mast	W4.1–W4.80 (except W4.40, W4.50, W4.60, W4.70)	E11.1	F10.1
	communications_tower	W10.3–W10.9	E3.1 – E3.2	F6.1 – F6.2
Education	school, kindergarten, college, university, library	W21.11– W21.14	E21.26-C – E21.43-C, E21.48-C – E21.61-C	F21.6 – F21.13
	hospital, clinic, doctors, pharmacy, dentist, physiotherapist, alternative, laboratory, optometrist, rehabilitation, blood_donation, birthing_center	W21.11– W21.14	E21.67-C – E21.72-C	F21.6, F21.8, F21.9, F21.12
Power	line, minor_line	W6.1, W6.2, W6.3	E6.1 – E6.4	F6.1 – F6.2
	cable	W7.2	E6.1 – E6.4	F5.1
	plant, generator		E1.1 – E1.7	F1.1 – F1.7
	substation, transformer, portal, terminal, switch	W1.10, W1.13 (some also W1.11–W1.14)	E2.1 – E2.9	F2.1 – F2.3
	pole	W4.1–W4.80 (same as mast)	E4.1 – E4.4	F6.1 – F6.2



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tower	W3.5–W3.14	E3.1 – E3.2	F6.1 – F6.2
catenary_mast	W4.1–W4.5	E4.1 – E4.4	F10.1

Table S4. Overview of the maximum reconstruction costs used for each infrastructure object. Nirandjan et al. (in review).

Category	Type	Min	Median	Max
Roads	motorway	1106	2895	3931
	motorway_link	1106	2895	3931
	trunk	848	1242	1636
	trunk_link	848	1242	1636
	primary	917	1137	1357
	primary_link	917	1137	1357
	secondary	257	452	678
	secondary_link	257	452	678
	tertiary	203	271	339
	tertiary_link	203	271	339
	residential	66	136	305
	road	66	136	305
	unclassified	66	136	305
	track	66	136	305
	service	66	136	305
Railway	rail	491	2858	14186
Air	aerodrome	113	135	165
	terminal	113	165	4271
	runway	4133	5511	9078
Telecommunications	mast	67506	76630	111998
	communications_tower	139610	152468	229376
Education	school	267	713	1294
	kindergarten	267	713	1294
	college	267	713	1294
	university	267	713	1294
	library	267	713	1294
Healthcare	hospital	591	1294	2227



	clinic	591	1294	2227
	doctors	591	1294	2227
	pharmacy	591	1294	2227
	dentist	591	1294	2227
	physiotherapist	591	1294	2227
	alternative	591	1294	2227
	laboratory	591	1294	2227
	optometrist	591	1294	2227
	rehabilitation	591	1294	2227
	blood_donation	591	1294	2227
	birthing_center	591	1294	2227
Power	line	108	183	1151
	cable	215	1818	5497
	minor_line	71	102	103
	plant	649	1558	11110
	generator	1299	1904	6349
	substation	1299	1904	6349
	transformer	1299	1904	6349
	pole	73005	97627	369547
	portal	1299	1904	6349
	tower	6171	103928	275472
	terminal	1299	1904	6349
	switch	1299	1904	6349
	catenary_mast	67506	76630	111998



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