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D1.5 Implementation of ICARIA holistic modelling framework - Lessons learnt

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D1.1 ICARIA holistic modelling framework

Summary

The implementation of ICARIA holistic modelling framework and lessons learnt from Case Studies development, presented in Deliverable 1.5, reflects the activities carried out within Trial and Mini-trials processes . By applying the framework through dedicated models and tools, a comprehensive risk/impact assessment across different climate-related hazard categories have been achieved, also covering complex interactions characterised by compound events and cascading effects, in the context of climate change. The successful implementation in the context of Trials and Mini-trials (Barcelona Metropolitan Area, South Aegean Region, and Salzburg Region) supports the validation of the ICARIA framework and its potential uptake by any other EU region potentially affected by such events. A consistent and harmonized methodology to build climate scenarios is provided, including guidance on modelling data collection, exposure/vulnerability analyses, risk/impact assessment covering direct and indirect damage (including cascading effects) to different risk receptors, and evaluation of the effect of adaptation solutions, supporting holistic resilience in a systemic perspective.

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Table of contents

List of Figures

List of Tables

List of Acronyms and Abbreviations

AC	Adaptive Capacity
BAU	Business-As-Usual
CBA	Cost-Benefit Analysis
CC	Coping Capacity
CCA	Climate Change Adaptation
CS	Case Study
D	Damage
DV	Dynamic Vulnerability
DRM	Disaster Risk Management
DRR	Disaster Risk Reduction
DSS	Decision Support System
E	Exposure
GHG	Greenhouse Gases
H	Hazard
MCB	Multi-Criteria Analysis
SDG	Sustainable Development Goals
SSO	Specific Sub-Objectives
TGM	Trial Guidance Methodology
TC	Transformative Capacity
V	Vulnerability
WP	Work Package

Executive summary

This document presents the implementation and validation of the ICARIA holistic modelling framework through its application in the project's Trials and Mini-trials, conducted in three heterogeneous European case study regions: the Barcelona Metropolitan Area (Spain), the South Aegean Region (Greece), and the Salzburg Region (Austria). Building upon the conceptual framework defined in Deliverable 1.1, D1.5 advances the methodology from a theoretical construct to an operational and tested modelling approach, capable of supporting multi-hazard risk/impact and resilience assessments under climate change conditions. The framework adopts a risk-based logic (Hazard × Exposure × Vulnerability) enriched through an "elementary bricks" structure that enables the representation of compound events, cascading effects, and spatio-temporal interactions across interconnected assets and services.

The implementation phase demonstrated that the framework can be consistently applied across diverse geographical, climatic, and socio-economic contexts, while maintaining flexibility to accommodate data availability, modelling capacity, and policy priorities. Trials operationalised selected event trees and modelling chains, focusing on relevant hazard–impact pathways and enabling the quantification of direct and indirect impacts on critical infrastructures, services, natural systems, and populations. A key contribution of D1.5 lies in the harmonisation of modelling workflows and data structures. Through the refinement of event trees and input–output mappings, the framework ensured coherence across hazard, exposure, vulnerability, and impact assessment stages, while explicitly addressing data gaps and uncertainties. This process confirmed the feasibility of a shared methodological backbone capable of aligning modelling approaches across regions.

The integration of resilience assessment represents a distinctive feature of the ICARIA framework. By combining impact scenario modelling with the Resilience Assessment Framework (RAF), the Resilience Assessment Tool (RAT), and the adaptation measure portfolio within the ICARIA Decision Support System (DSS), the methodology enables the evaluation of both physical and functional measures, directly affecting hazard, exposure, and vulnerability and governance and organisational measures, influencing coping, adaptive, and transformative capacities. This integrated approach supports scenario comparison (with/without adaptation measures), allowing the estimation of avoided impacts and the prioritisation of resilience strategies based on effectiveness, feasibility, and co-benefits.

The Trials also provided important lessons learnt. On the positive side, the framework proved effective in structuring complex multi-hazard assessments, supporting stakeholder engagement through Communities of Practice, and enabling decision-oriented analyses. At the same time, limitations emerged in relation to data heterogeneity, modelling complexity, representation of cascading effects, and user accessibility, highlighting the need for improved guidance, transparency, and scalability of tools and metrics.

Overall, the results of D1.5 provide a robust validation of the ICARIA holistic modelling framework as a transferable and adaptable methodology. The framework demonstrates strong potential to act as a reference approach for harmonising risk/impact assessment methods and metrics across EU regions and beyond, supporting multi-level governance and enabling local authorities to design and implement climate-resilient development pathways (IPCC, 2022).

1. Introduction

This document presents the lessons learnt from trial and Mini-Trial applications of the Holistic Modelling Framework developed within the ICARIA project, which has received funding from the European Union's Horizon Europe Research and Innovation program under Grant Agreement number 101093806. Specifically, this document corresponds to Deliverable 1.5 and is one of the results of Task 1.1 - Risk/Impact modelling framework (WP1 - Project framework, climate scenarios and modelling inputs).

1.1 ICARIA in short

The number of climate-related disasters has been progressively increasing in the last two decades and this trend could be drastically exacerbated in the medium- and long-term horizons according to climate change projections. It is estimated that, between 2000 and 2019, 7,348 natural hazard-related disasters such as heat waves, forest fires, droughts, floods, or storms caused 2.97 trillion US$ losses and affected 4 billion people worldwide. These estimates include compound and cascading events whose increasing frequency is a direct expression of ongoing climate change and related global warming (UNDRR, 2020; IPCC, 2021). For the future, by mid-century, the world stands to lose around 10% of total economic value from climate change if the temperature increases stay on the current trajectory, and both the Paris Agreement and 2050 net-zero emissions targets are not met (Guo *et al.*, 2021).

In this framework, the **ICARIA Project** (Improving ClimAte Resilience of crItical Assets) has the overall objective of promoting the definition and the use of a holistic asset-level modelling framework to achieve a better understanding of climate-related impacts produced by complex interactions, characterised by compound events and cascading effects, and the possible risk reduction provided by suitable, sustainable, and cost-effective adaptation solutions.

Special regard is devoted to critical assets and services that are particularly susceptible to climate change as its local effects can lead to significant increases in the cost of potential losses for unplanned outages and failures, as well as maintenance – unless an effort is undertaken in making these risk receptors more resilient. Therefore, ICARIA aims to understand how climate might affect the life-cycle costs of these assets and services in the coming decades and to ensure that, whenever possible, investments in adaptation solutions are made upfront to face these changes. This requires planning that considers a comprehensive multi-hazard risk/impact assessment and the uncertainties associated with climate change, rather than reliance on models solely based on past events and single climate hazards (Barr & Nider, 2015).

To achieve this goal, ICARIA has identified 7 Strategic Sub-Objectives (SSO) among which the first, second and third ones are directly linked to the WP1:

- SSO1 - Achievement of a comprehensive methodology to assess climate-related risk produced by complex, compound and cascading disasters;
- SSO2 - Obtaining tailored scenarios for the case studies regions;
- SSO3 - Quantify uncertainty and manage data gaps through model input requirements and innovative methods.

1.2 Objective of the Deliverable 1.5

Within ICARIA, Task 1.1 aims to establish a harmonised and consistent holistic modelling framework to support climate impact and resilience assessments across different climate-related hazard categories, including complex multi-hazard configurations characterised by compound events and cascading effects with respect to climate change projections and Shared Socioeconomic Pathways (SSPs, IPCC, 2022). Deliverable 1.1 developed and described this framework, clarifying the underlying taxonomies and the main modelling components ("elementary bricks") used to structure risk/impact and resilience assessments (Leone et al., 2025).

Deliverable 1.5 builds on D1.1 discussing and validating the applicability of the ICARIA holistic modelling framework based on its implementation across Trials and Mini-trials, and to reflect on the extent to which the framework can be considered a robust and transferable approach to support consistent multi-hazard risk/impact modelling across heterogeneous territorial contexts. Specifically, D1.5 advances the framework from a theoretical dimension toward a tested, aligned and replicable modelling methodology applied across ICARIA case study regions (Barcelona Metropolitan Area, South Aegean Region, and Salzburg Region), aimed at ensuring coherence in how climate scenarios are constructed, modelling inputs are collected and harmonized, exposure/vulnerability analyses and resilience assessments are performed across different hazard types (heat waves, droughts, floods, storm surges, storm wind, forest fires) and multi-hazard configurations, including compound and cascading effects.

To this aim, D1.5 discusses how the Trials and Mini-trials applied the framework in practice through modelling activities, simulations and scenario analyses, fully documented in D4.2 (Trial applications), D4.3 (Mini-Trial applications) and D3.5 (DSS applications). Lessons learned, limitations and enabling conditions emerging from implementation (e.g., data availability, modelling constraints, treatment of hazard interactions and cascading mechanisms) are discussed, outlining the potential for replication beyond ICARIA, positioning the framework as a reference approach to harmonise taxonomies and modelling workflows for climate risk/impact assessment in Europe and beyond.

2. ICARIA Holistic modelling framework

2.1 Framework logic and guiding principles

The ICARIA modelling framework is a holistic, asset-level framework developed to support a comprehensive assessment of climate-related risk, impacts and resilience in contexts characterised by multiple interacting hazards, compound events, and cascading effects. The framework is designed to overcome the limitations of traditional single-hazard approaches by explicitly accounting for the temporal, spatial and functional interactions between hazards, exposed assets and services, and their vulnerabilities under climate change conditions.

The framework provides a unifying methodological structure that harmonises existing modelling approaches and datasets within a consistent risk-based logic. Its primary purpose is to ensure comparability and coherence across different hazard categories, geographical contexts and modelling tools, while maintaining sufficient flexibility to accommodate context-specific conditions and data availability.

Designed to support multi-level decision-making of climate adaptation and resilience, its core objectives are to:

- harmonise existing hazard, exposure and vulnerability models;
- connect them through explicit spatio-temporal and causal logics;
- enable the quantification of direct and indirect impacts on critical assets and services;
- assess how resilience strategies and measures modify expected impacts under climate change scenarios.

The framework is explicitly aligned with:

- the IPCC AR6 risk-based approach and the concept of Climate Resilient Development (IPCC, 2022)
- the EU guidance on climate proofing and adaptation (European Commission, 2011; European Commission, 2021; European Commission, 2023)
- The EU Climate Risk Assessment guidelines (EEA, 2024)

The theoretical foundations and operational approaches are discussed in D1.1 and Leone et al (2025). The key theoretical concepts are reported below.

The general conceptualization of the ICARIA risk/impact/resilience assessment framework is presented in FIGURE 1.

Under the climate scenarios identified by SSPs, the risk/impact assessment is a function of:

- Hazard: depending on the climate variables and on local conditions amplifying hazard intensity (e.g., the effect of Urban Heat Island on heat wave hazards, or the effect of soil sealing or anthropogenic alteration of riverine and coastal environments in flooding hazards); to be determined taking into account the probability of occurrence of relevant compound events (see D2.4);
- Exposure: implementing a harmonized database of exposed assets and services, which includes all relevant information supporting the vulnerability analysis with respect to the multiple hazards

considered, subdivided into vulnerability classes and highlighting organizational, physical, spatial and functional interdependencies with other assets/services;

- Vulnerability: developing vulnerability functions associating for each of the assets (or for each of the asset's elements included in the vulnerability model) the hazard(s) magnitude with the expected damage threshold. This includes performing sensitivity/susceptibility analysis and developing dynamic vulnerability functions where relevant.
- Resilience capacities: developing a database of relevant measures supporting coping and adaptive capacities for the assets and services identified, and highlighting those supporting transformative approaches with respect to conventional organizational, physical, spatial and functional dimensions (see 2.1.3), clearly identifying resilience measures that can be directly embedded in the H-E-V modelling workflow, and those included in the broader resilience assessment framework (see Section 2.2).

Tangible (direct or indirect) impacts are evaluated through relevant indicators for each of the exposed assets and services considered, including where possible metrics that help to quantify economic losses. Intangible impacts and non-economic losses should be also taken into account, also including quali-quantitative approaches where fully quantitative methods are not applicable/available.

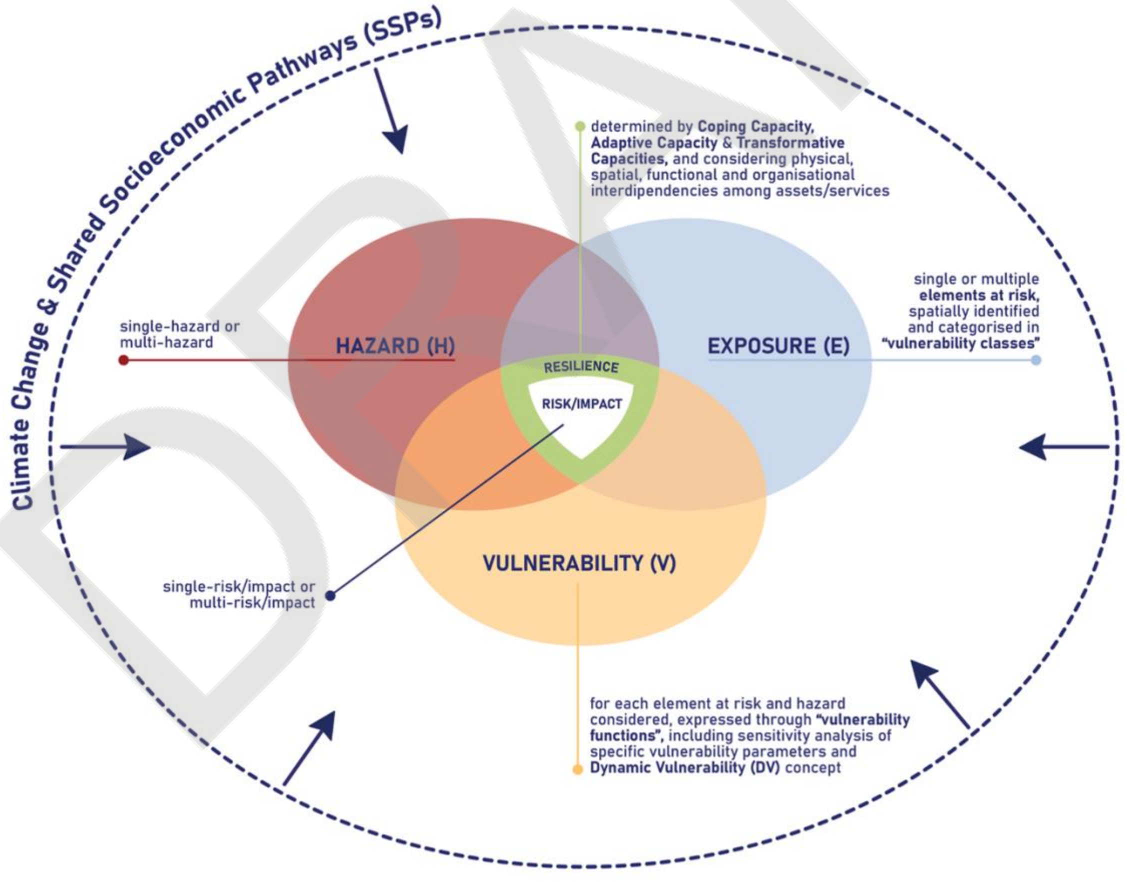


Figure 1. The risk/impact/resilience assessment framework, consolidated in the field of geophysical hazards (UNDRO, 1980; updated by the UNDRR, 2017 terminology) and harmonized in the context of climate change (IPCC, 2014; IPCC, 2022) introducing the resilience components (modified after Leone, 2020a and Turchi et al., 2023).

Specific methods to determine Hazard, Exposure, Vulnerability and Resilience can vary in relation to the specific hazards and considered assets and risk receptors. However, to ensure a harmonized multi-hazard/impact assessment, common requirements associated with each of the key elementary bricks of the ICARIA framework are identified (see Section 2.2).

A central assumption of the ICARIA framework is that climate- and weather-related hazards rarely occur in isolation. Instead, they often manifest as compound events, defined as the combination of two or more hazardous phenomena occurring simultaneously or successively, whether causally related or not. These conditions may be further exacerbated by long-term climate change trends, amplifying both hazard intensity and systemic vulnerability.

In addition to compound events, the framework explicitly addresses cascading effects, understood as sequences of impacts propagating across interdependent assets, infrastructures and services. Cascading effects may involve natural, technological or socio-economic components and frequently result in indirect and cumulative impacts that exceed those associated with the initial triggering event.

To represent these dynamics, the ICARIA framework adopts a scenario-based approach (see Section 2.2) structured around event trees and interactive causal chains (see Figure 3; D2.4; D3.1). Each scenario describes a specific sequence of hazards and impacts unfolding over time and space, allowing the assessment of probabilities, damage accumulation and cross-sectoral consequences. This approach enables the identification of critical pathways through which impacts propagate, supporting a more realistic estimation of risk in complex socio-eco-technological systems.

Given the relevance of systems' vulnerability towards multiple hazards in the characterization of frequency and intensity of cascading effects, within ICARIA the study of interactive causal chains and systems' interdependencies is incorporated in the proposed hazard and impact assessment framework and modelling tools (see D2.4 and D3.1).

2.2 The elementary brick model

The analytical core of the ICARIA framework is based on an extended interpretation of the classical risk equation:

$$R/I = H \times E \times V \qquad (1)$$

where risk/impact (R/I) is expressed as the probability of reaching a given level of damage over a defined time and space, resulting from the interaction of hazard (H), exposure (E) and vulnerability (V). While the generalized version of the formula is applicable to evaluate both Risk (R) and Impact (I) in terms of expected damage on selected exposed assets and/or services, a fundamental distinction among the two kinds of assessments concerns the way the hazard input is incorporated in the modelling workflow, where risk assessment implies that hazard is calculated as probabilistic convolution of all hazard intensities and spatial/temporal distribution in the targeted study area included in the event tree, while impact assessment (or impact scenario analysis) is performed on a selected sequence of hazard events (supported by probabilistic information about hazard transitions, see D2.4), based on specific decision-makers and/or technical-scientific study priorities.

More in detail, in relation (1), Hazard (H) represents the probability of occurrence of all possible events – or of a single event in the case of impact scenario analysis – of a given intensity level, within a defined area and time period. Exposure (E) describes the quantitative and qualitative geographical distribution of the elements at risk within the area considered. These elements may suffer damage, functional alteration or destruction as a consequence of the hazard event. Vulnerability (V) expresses the conditional probability that an exposed element, belonging to a specific vulnerability class, reaches a certain damage level according to an appropriate damage scale, given the occurrence of a hazard event of assigned intensity. In other words, while Equation (2) integrates over all possible hazard intensities to provide a full probabilistic estimate for the risk level l, Equation (3) focuses on a specific chain of hazard events and evaluates the expected damage distribution across exposure categories.

By specialising relation (1), the risk assessment can be formalized in the following way:

$$Risk_l = \int_m \quad E_m[\int_i \quad (H_i) \cdot (V_{l,i,m})] \ (2)$$

The impact scenario associated with a single event of intensity i and referring to damage level l is defined as:

$$Impact_{\ l,i} = \int_m \quad E_m[(H_i) \cdot (V_{l,i,m})] \ (3)$$

where:

- H_i is the probability of occurrence of an event with severity level i over a given time period and at a specific site;
- $V_{l,i,m}$ is the probability of reaching damage level l, conditional on the occurrence of event i, for elements belonging to category m (vulnerability class);
- E_m represents the proportion (or spatial percentage) of elements belonging to category m.

In emergency and territorial planning, both approaches serve complementary purposes:

- Risk analysis supports through synthetic indexes the comparative evaluation of risk-prone areas, informing strategic decisions related to preparedness, emergency response (e.g. evacuation planning), and the prioritisation of adaptation and mitigation measures.
- Impact scenario analysis, by focusing on selected reference hazard events and potential compounds and cascades, enables a detailed and spatially explicit quantification of expected impacts within a given territory. This allows for more precise estimation of the human and financial resources required for emergency management, recovery, and resilience-based governance and planning.

Due to the extreme complexity of full probabilistic multi-hazard risk assessments – particularly in contexts characterised by interacting hazards or cascading effects – the modelling methodology developed by ICARIA adopts a scenario-based approach. This approach enables the assessment of damage induced on assets and services (e.g. population, buildings, critical infrastructures, service networks, etc.) by sequences of interconnected hazards within complex events characterized by compound events and cascading effects. In this framework, scenario analysis measures the space- and time-dependent damage induced by a single event, or a defined chain of events of assigned intensity and probability, on the exposed elements, as a function of their vulnerability characteristics.

The outputs consist of a detailed quantification of expected impacts, including:

- human impacts (e.g. number of deaths, injured, homeless);
- physical damage to buildings and infrastructures (e.g. damage states ranging from D0 – no damage to D5 – total collapse);
- direct and indirect economic losses (e.g. rehabilitation and reconstruction costs, business interruption losses).

This structured quantification provides a robust basis for emergency management planning, resource allocation and resilience-oriented urban design.

ICARIA holistic modelling framework assumes "elementary bricks" as units of analysis: *Time (t), Space (s), Hazards (H)* within a chain, initial *Exposure (E)*, initial *Vulnerability (V), Dynamic Vulnerability (DV), Coping Capacity (CC), Adaptive Capacity (AC), Transformative Capacity (TC), Damage (D),* and *Human behaviour* (*α*) influence (see D1.1 and Leone et al., 2025).

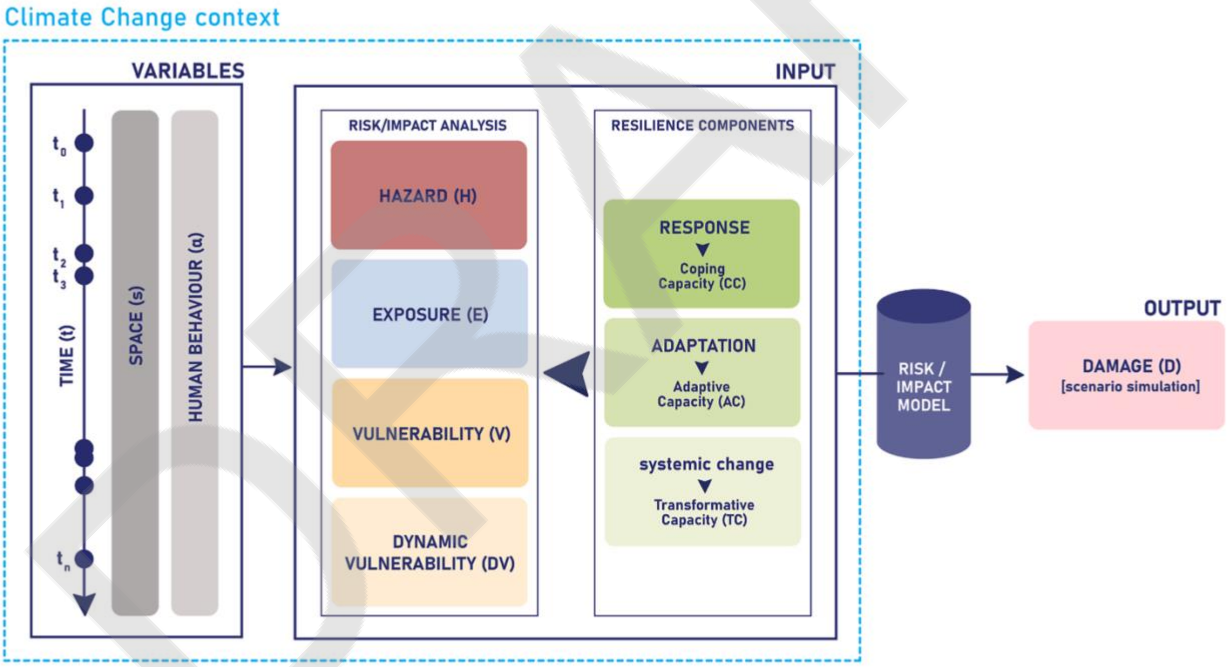


Figure 2. Holistic modelling framework for multi-hazard risk/impact/resilience assessment, covering combined events and their cascading effects. Main elementary bricks are represented (Leone et al., 2025).

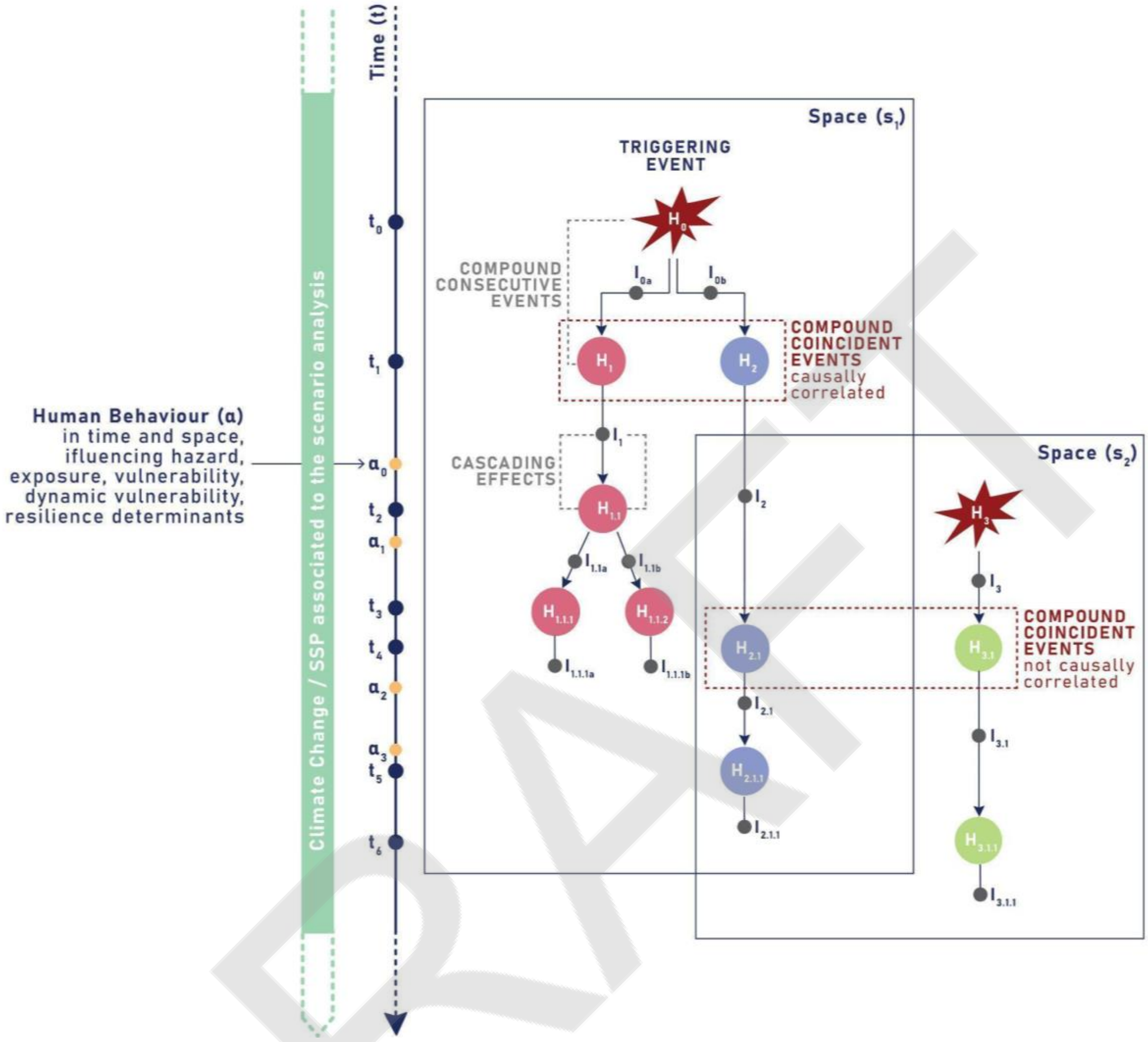


Figure 3. Timeline of events showing compound (coincident, causally or not causally correlated, and consecutive) events and cascading effects (when the impact on a critical asset or service triggers a subsequent hazard in the chain), where "H" is Hazard, and "I" is Impact. The influence of key-variables (i.e., time, space, and human behaviour) in the risk/impact/resilience assessment process has been considered (modified after Zuccaro *et al.,* 2018).

2.3 Incorporating resilience into a multi-hazard risk/impact modelling framework

A key feature of the ICARIA framework is the explicit and operational integration of resilience into the risk and impact assessment process. In line with the conceptual foundations consolidated across WP1 and WP3 (see D1.1, D3.2, Leone et al., 2025; Brito et al., 2026; Brito et al., 2025), resilience is conceptualised as the combined expression of Coping Capacity (CT), Adaptive Capacity (AT), and Transformative Capacity (TC), reflecting the ability of socio-eco-technical systems to withstand disruptions, adjust to evolving hazard conditions, and – where necessary – fundamentally reconfigure development trajectories in response to climate-related risks.

Within the ICARIA modelling framework, resilience is treated as a set of operational levers that can be embedded into impact scenario modelling and strategic planning. Accordingly, resilience measures are classified into two complementary categories.

The first category includes measures that directly affect hazard, exposure, and/or vulnerability, and can therefore be explicitly embedded within the H × E × V modelling workflow. These include, for example, physical protection measures (e.g., flood retention infrastructure, protective buffers, redundancy of critical assets), spatial reconfiguration strategies (e.g., relocation of exposed functions, nature-based solutions enhancing local microclimate regulation), and asset retrofitting or upgrading (e.g., reinforcement of infrastructure robustness, increased autonomy of critical services). When implemented in the Trials and Mini-Trials, these measures were translated into modified input parameters for Impact Scenario modelling, allowing alternative modelling runs to quantify avoided damage and shifts in risk profiles under resilience-enhanced configurations.

The second category comprises measures acting on organizational, institutional, financial, and behavioural dimensions, including governance arrangements, coordination mechanisms across services, early warning systems, emergency planning, stakeholder engagement processes, resilience budgeting, and participatory design approaches, which represent fundamental components of systemic resilience. Their assessment through multi-criteria scoring systems can orient specific scenario modelling that take into account how their implementation can be translated into a variation of the numerical parameters of the H × E × V equation, such as, for example simulating the effect of early warning systems enabling emergency management procedures that can reduce the exposure of elements at risk through evacuations or access limitations (e.g. car transit limitation or parked vehicles removing in case of incipient floods), or relocation of critical infrastructures in hazard-prone areas .

Within ICARIA resilience assessment incorporates organizational, spatial, functional, and physical dimensions in an integrated manner and it is performed at two levels by: 1) evaluating expected avoided impacts through alternative runs of risk/impact assessments with adaptation measures in place (mostly addressing physical, spatial and functional dimensions, and 2) evaluating governance and institutional preparedness, response efficiency, recovery speed, and long-term adaptive capacity, operationalised through the use of the Resilience Assessment Framework (RAF) and the Resilience Assessment Tool (RAT), both accessible via the ICARIA web-based platform and integrated into the Decision Support System (DSS) (see D3.5; D3.5; Brito et al., 2026).

The RAF supported Trials and Mini-Trials in conducting a holistic resilience diagnosis across four dimensions (organizational, spatial, functional, and physical) allowing stakeholders to identify strengths, gaps, and priority areas for improvement. Through its objective/criteria/metrics structure and development levels (incipient, progressing, advanced), the RAF provided a structured basis for defining and prioritising resilience strategies. The RAF enables the identification of governance-related weaknesses (e.g., lack of coordinated hazard scenarios, insufficient resilience budgeting, absence of resilience plans) that, although not directly embedded in impact modelling equations, significantly condition the feasibility and effectiveness of physical and functional measures. Alignment of RAF metrics to the “resilience components” defined in D1.1 (CT, AT, TC) is reported in T3.2.

The RAT focuses specifically on the resilience capabilities of critical infrastructure assets, structured around the capacities to withstand, absorb, recover, adapt, anticipate, and prepare. This asset-level perspective allowed Trials to assess operational robustness, redundancy, and autonomy of critical systems, thus informing the design of targeted physical and functional interventions directly relevant to Impact Scenario modelling.

The adaptation measure portfolio, integrated within the ICARIA DSS, acted as a bridge between assessment and action. By linking resilience diagnostics (RAF/RAT outputs) with modelling outputs (impact and risk scenarios), the DSS enabled stakeholders to explore combinations of measures—ranging from grey infrastructure upgrades to nature-based solutions and governance reforms and evaluate their contribution to resilience enhancement. A subset of RAF metrics was embedded in the DSS to provide a resilience "snapshot", and predefined summary reports can be exported to support decision-oriented comparison of strategies.

The effectiveness of resilience strategies is evaluated through alternative modelling runs, comparing baseline scenarios with resilience-enhanced scenarios in order to estimate avoided damage and changes in exposure and vulnerability patterns. Quantitative modelling outputs are complemented by Multi-Criteria Analysis tool embedded in the DSS, enabling a transparent prioritisation of measures that considers not only damage reduction but also co-benefits, feasibility, and stakeholder acceptability.

This integrated approach aligns with the IPCC (2022) concept of Climate Resilient Development, which emphasises that adaptation, mitigation, and sustainable development must be pursued through integrated solutions. In ICARIA, governance-oriented measures - such as cross-sector coordination mechanisms, participatory planning, resilience monitoring, and integration of natural areas as strategic services - are explicitly recognised as enabling conditions for long-term transformative change. Even when not directly parameterised in the H × E × V workflow, these measures shape institutional capacity to implement, maintain, and upscale physical interventions over time.

3. Framework implementation: ICARIA Trials and Mini-trials

3.1 Operationalization of the ICARIA Holistic Modelling Framework

As outlined in Section 2, within ICARIA the impact scenario assessment of complex events consists in the quantification of damage, in time and space, caused by different interactive causal chains represented in a time-history of events, with assigned intensity and probability, on specific exposed assets in relation to their vulnerability. ICARIA Trials and Mini-Trials have developed their event trees connected to probabilistic-based simulation tools, performing at the local level i) the characterization of hazards, taking into account the regional climate scenarios and the local conditions influencing the hazard magnitude; ii) the transition probabilities among different compound hazards which are causally correlated; iii) the presence in the hazard(s)-prone area considered of assets and services that can become source of cascading effects due to the magnitude of hazard and/or specific vulnerability analyses; iv) the quantification of direct and indirect impacts on critical assets and services along the time history of the event tree. To assess how resilience strategies and measures modify expected impacts under climate change scenarios, alternate run of models with adaptation measures in place have been performed, supported by the ICARIA Adaptation Measures Portfolio and Resilience Assessment Framework and Tool (RAF and RAT, Brito et al., 2026), quantifying the effect in terms of avoided damages and improved governance and response strategies.

In summary, the ICARIA Trials and Mini-Trials have developed customized operational modelling workflows based on the following common methodological steps:

1) EVENT TREE DEFINITION
    a) identification of a time-space window for the compound events and cascading effects scenario assessment, and definition of risk/impact metrics;
    b) identification of the triggering hazards affecting the case study regions;
    c) identification of selected cascading effects scenarios which covers all possible interactive causal chains of events and interactions between relevant hazards;
2) HAZARD CHARACTERIZATION
    a) probabilistic assessment of triggering hazard under different SSP scenarios;
    b) probabilistic assessment of compound event/cascading effects scenario, considering the occurrence of a triggering hazard with a certain magnitude;
3) EXPOSURE AND VULNERABILITY ANALYSIS
    a) Identification of relevant risk receptors potentially damaged by the sequence of hazards and cascading effects along the timeline;
    b) exposure and vulnerability assessment for each selected scenario, taking into account the influence of time and space dependencies;
4) IMPACT SCENARIO ANALYSIS
    a) loss estimation and risk/impact assessment. This includes the cumulative damage on risk receptors following the sequence of events.
5) RESILIENCE ASSESSMENT
    a) definition of resilience measures with the support of adaptation measures' portfolio;
    b) comprehensive resilience assessment, with focus on multi-level governance and critical infrastructure, supported respectively by RAF and RAT;

c) alternate run of impact scenario analysis with adaptation measures in place to assess avoided impacts and co-benefits.

3.2 Trial and Mini-trial modelling architecture review

The implementation of ICARIA Trials and Mini-Trials across the three case study regions, Barcelona Metropolitan Area (AMB), Archipelago of South Aegean Region, and Salzburg Region) provided a critical opportunity to test the modelling architecture originally defined in D1.1 and understand limitations in its full applicability. While the overall conceptual structure of the multi-hazard risk/impact framework remained valid, the practical deployment of modelling workflows, together with continuous stakeholder engagement within the Communities of Practice (CoPs), required targeted adjustments to the initial plan.

Trials and Mini-Trials operationalised selected hazard/impact chains that were both policy-relevant and technically feasible within available data and time constraints. This required differentiated modelling depths, tailored data integration strategies, and context-specific scenario configurations. In several cases, simplified vulnerability representations or partial cascading pathways were adopted, while additional interactions were identified through stakeholder discussions as priorities for future refinement.

Despite these contextual differences and operational limitations, the underlying modelling structure – event-tree building, hazard characterisation, exposure mapping, vulnerability analysis, impact quantification, and comparison between baseline and adaptation scenarios – remained consistent across Case Studies.

The preliminary mapping carried out within Task 1.1 (see D1.1) identified the relevant "elementary bricks", their key parameters, and associated datasets. It also defined the input/output structure of hazard and impact modelling for single hazards, and highlighted the main potential cascading effects related to the analysed event trees.

This work provided a common basis for understanding and implementing the subsequent Trials. It also supported an initial harmonisation of the modelling framework, contributing to the definition of a shared taxonomy and methodology across case studies. .

During the Trials implementation phase, several constraints emerged:

- Data heterogeneity and availability gaps, especially at asset level;
- Operational limitations in harmonising hazard-specific models across regions;
- Temporal and computational constraints affecting full coupling of hazard interactions;
- Stakeholder-driven prioritisation, which redirected modelling efforts toward the most policy-relevant impact chains rather than purely theoretical completeness.

This resulted in a final revision of modelling architecture and event-trees object of analysis, defining the final applications documented in D4.2.

The Communities of Practice played a key role in this revision process. CoP discussions helped clarify which modelling components were most relevant for decision-making, which impact pathways required higher resolution, and where simplifications were acceptable. This iterative exchange between modellers and stakeholders led to a more operational, decision-oriented configuration of the modelling architecture.

As a result, the Trial and Mini-trial architecture evolved from a primarily hazard-driven structure toward a risk-informed and decision-support-oriented architecture, better aligned with:

- Asset-level vulnerability representation;
- Integration with resilience assessment tools (RAF and RAT);
- Linkage with the adaptation measure portfolio within the ICARIA DSS;
- Feasible replication within Mini-Trials under realistic resource constraints.

In particular, the revised implementation approach:

- Strengthened the representation of risk receptors and critical assets, ensuring that impact modelling outputs could directly inform resilience strategies.
- Clarified the separation between core hazard modelling components and scenario-based adaptation simulations, allowing more flexible combinations during Mini-trials.
- Improved the interface between modelling outputs and resilience metrics, enabling quantitative results to feed the RAF snapshot and DSS comparative evaluations.
- Introduced a staged modelling logic, distinguishing between baseline risk assessment, resilience-enhanced scenario modelling, and adaptation optimisation cycles.

Mini-trials benefited from this revision by adopting a modular architecture, where selected components of the full modelling chain could be activated depending on local priorities and data maturity. While simplified in terms of modelling complexity with respect to Trials, Mini-trials focused on targeted hazard(s)/asset(s)/impact combinations validated through CoP engagement.

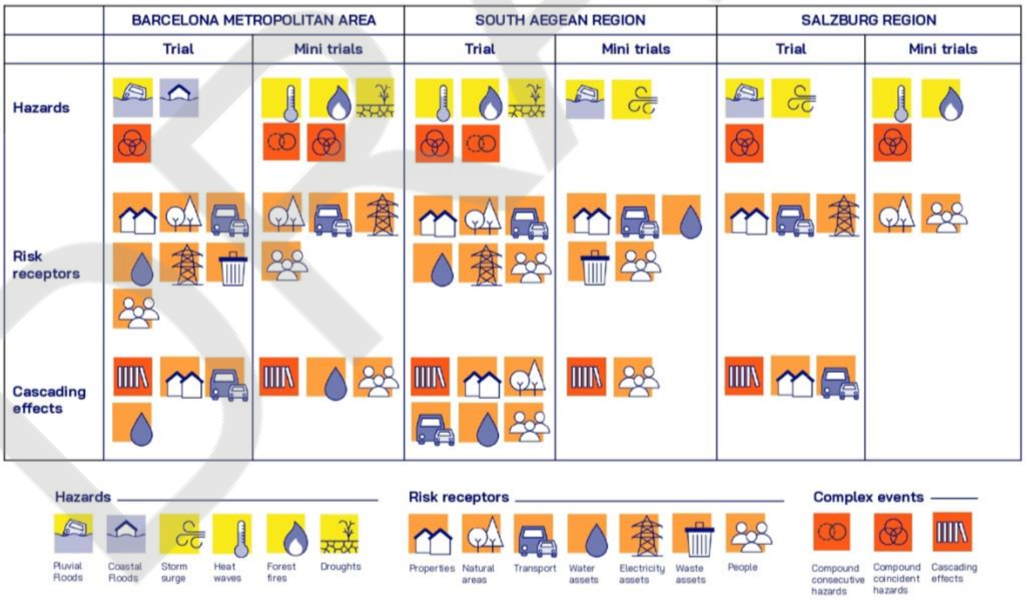


Figure 4. Updated ICARIA Trials and Mini-trials modelling architecture in the three case study regions.

Overall, the implementation phase demonstrated that a fully integrated multi-hazard architecture must remain flexible, scalable, and stakeholder-informed. The updated modelling architecture therefore reflects a balance between scientific robustness and operational feasibility, ensuring consistency across regions while allowing context-specific adaptation.

The revised ICARIA Trial and Mini-trial modelling architecture is illustrated in Figure 4.

3.3 Update of event trees and input-output data mapping

Building on the preliminary mapping developed in Task 1.1 (see D1.1), the implementation of Trials and Mini-trials required a systematic update and refinement of event trees and associated input–output data structures. This process was driven by the need to align the initial conceptual modelling framework with the actual availability of data, modelling tools, and policy-relevant priorities identified in each case study region.

While D1.1 defined a comprehensive set of potential hazard interactions and cascading mechanisms, the Trial phase operationalised selected event trees, focusing on those hazard–impact chains that could be consistently modelled and validated within the project constraints. This resulted in a progressive refinement of both the structure of event trees, and the input/output data mapping across the H–E–V modelling workflow, ensuring coherence with the ICARIA holistic modelling framework while maintaining feasibility and comparability across case studies.

3.3.1 Barcelona Metropolitan Area (AMB)

In the AMB case study, the updated event tree focused on pluvial flooding as the triggering hazard, with cascading effects on the electricity networks.

The hazard modelling stage integrates high-resolution precipitation data (historical and synthetic storms achieved from projected IDF curves), terrain models, and land-use datasets, producing flood hazard maps (water depth and velocity) and derived indicators such as risk levels for pedestrians and vehicles.

The exposure and vulnerability mapping extends beyond buildings and population to include critical infrastructures and services (water, electricity, transport, waste, natural areas), explicitly capturing interdependencies across networks. For example, the mapping of water and electricity systems includes both structural and operational data, allowing the representation of cascading failures.

The refinement of the event tree required addressing several data gaps, leading to the adoption of data harmonisation and gap-filling strategies, such as the statistical generation of missing infrastructure data (e.g., sewer networks), the temporal enrichment of land-use datasets, the integration of heterogeneous data sources from operators and public agencies.

These adjustments allowed the modelling workflow to be aligned with the ICARIA framework, ensuring consistency between hazard outputs, exposure classification, and vulnerability functions, while preserving the ability to simulate cascading effects across interconnected services, allowing scenario comparisons with resilience measures in place.

The refinement process led to a clearer structuring of modelling steps across the H–E–V chain, supported by a detailed definition of input/output datasets (see Tables 1-3 in Annex 3).

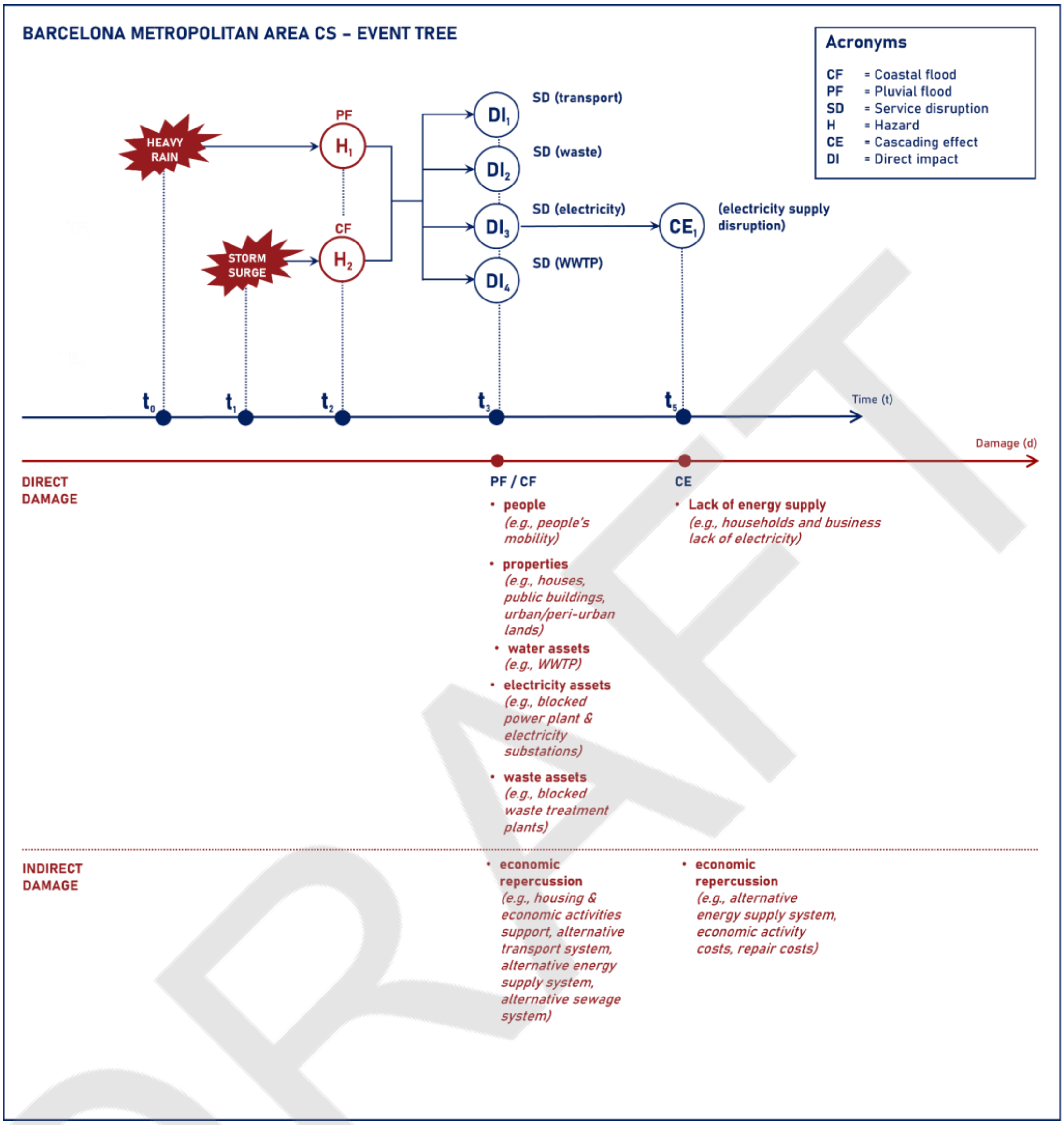


Figure 5. Updated event tree for Barcelona Metropolitan area.

3.3.2 Salzburg Region

In the Salzburg case study, the refinement of event trees resulted in the definition of two main modelling chains, reflecting the priorities identified during Trial implementation, focused on road network disruption triggered by fluvial flooding and on electricity network disruption due to windstorm, analysing cascading effects on population in affected areas due to power outage of buildings.

The Salzburg modelling workflow, explicitly focused on asset-level vulnerability and service continuity, particularly for critical infrastructure systems combines for the hazard modelling stage precipitation or wind datasets with terrain and infrastructure information, producing hazard maps (e.g., flood depth, wind speed) and identifying affected network components (e.g., roads, power lines). The exposure and vulnerability stages are characterised by simplified but robust representations of asset classes (e.g., generalized building vulnerability curves due to limited typological data); explicit modelling of infrastructure networks (transport and energy) and linkage between network failures and downstream impacts on buildings and services.

The refinement process highlighted several constraints, including limited availability of detailed vulnerability data (e.g., building typologies), the need to rely on generalized or literature-based fragility curves, and a partial representation of cascading mechanisms (e.g., indirect impacts of infrastructure disruption). Despite these limitations, the updated event trees allowed a consistent integration of hazard, exposure and vulnerability components, enabling the simulation of cascading impacts and supporting scenario-based analysis aligned with the ICARIA framework.

Table 4-9 in Annex 3 synthesizes the input/output datasets for the Salzburg area.

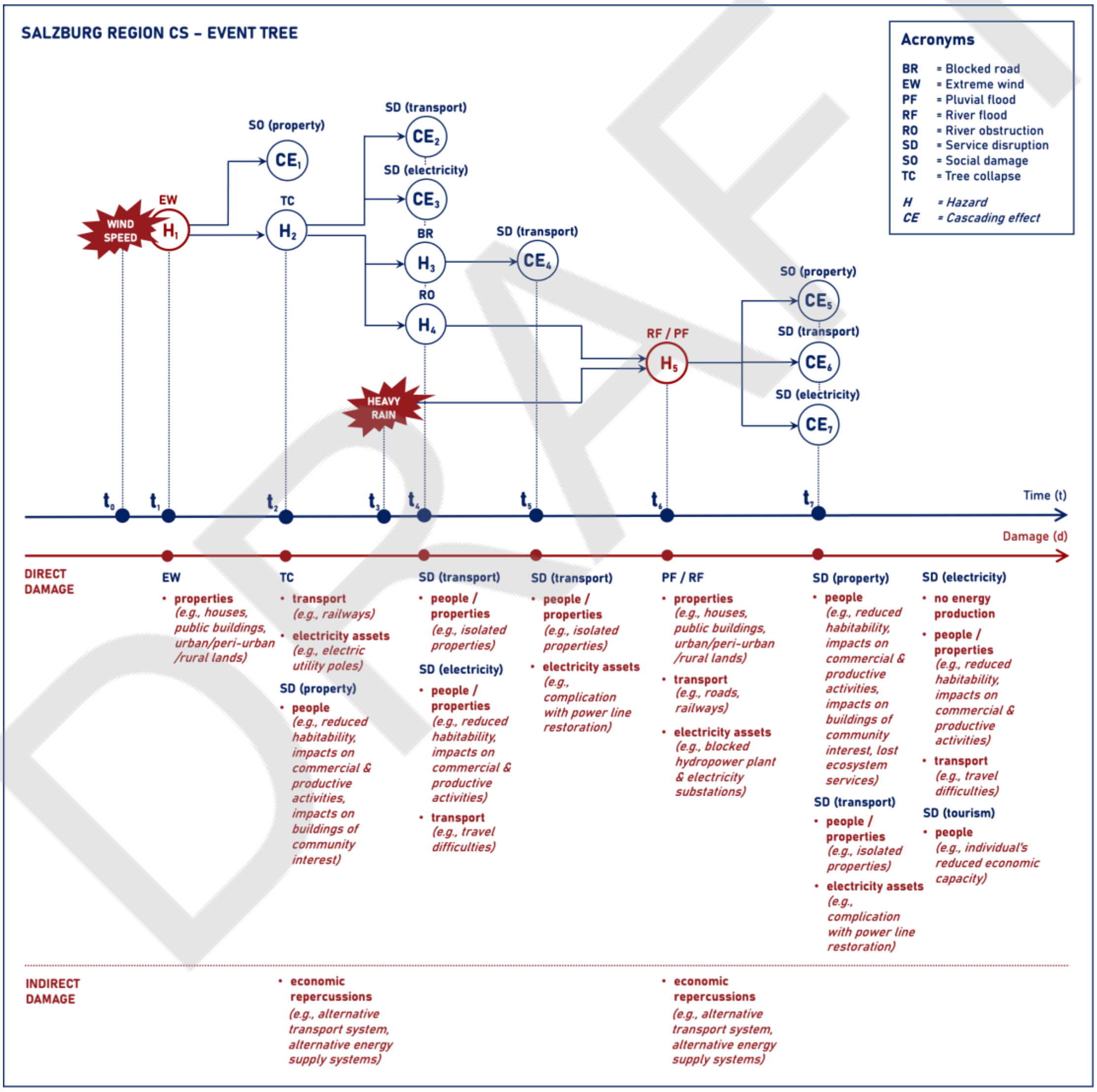


Figure 6. Updated event tree for Salzburg Region, focusing on the combined impact of windstorm and heavy rains on transport and electricity networks, properties and people.

3.3.3 South Aegean Region (SAR)

In the South Aegean case study, the updated event trees focused on the role of compound hazards (heat waves and drought) in determining the probability and intensity of wildfire hazard, assessing impacts on population, property and environment, testing the effectiveness of NBS for wildfire risk reduction across the different exposed assets considered.

The hazard modelling stage integrates climate projections, land-use data, and terrain information to derive hazard indicators. Exposure and vulnerability mapping is strongly oriented toward multi-sectoral impacts, including population, buildings and economic assets, natural areas and ecosystems, transport and energy infrastructures. In the wildfire case, particular attention is given to ecosystem and environmental impacts, highlighting the role of natural areas both as risk receptors and as components influencing hazard dynamics. The refinement of event trees in SAR required adapting the input/output data structure to ensure consistency across modelling steps, while accommodating the specific characteristics of island systems and available datasets.

Tables 10-11 in Annex 3 synthesize the input/output datasets for the South Aegean Region Area.

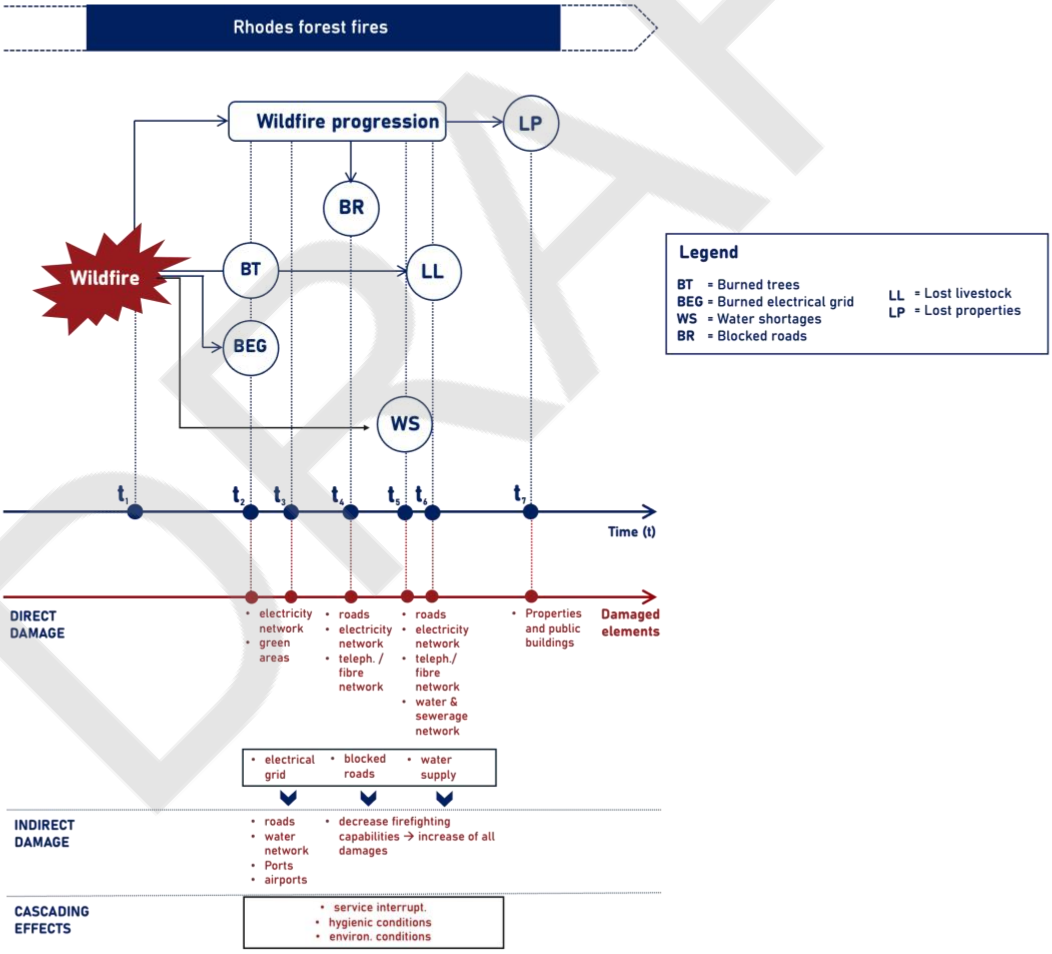


Figure 7. Updated event tree for South Aegean Region, focusing on climate drivers affecting wildfire hazards, and propagation of impacts across aspects over time following wildfire progression due to Fire Weather Index and fuel type conditions.

3.4 Cross-case harmonisation and implications for the modelling workflow

Across the three case studies, the update of event trees and input-output data mapping played a crucial role in aligning the conceptual ICARIA framework with operational modelling workflows.

The main outcomes of this process can be summarised as follows:

- Selection and prioritisation of event trees based on data availability, modelling feasibility, and policy relevance;
- Standardisation of input/output structures across hazard, exposure, vulnerability and impact modelling stages, as reflected in the harmonised tables;
- Integration of cascading effects where feasible, with simplified representations adopted when full coupling was not possible;
- Explicit treatment of data gaps and uncertainties, through harmonisation, statistical reconstruction, or use of proxy datasets;
- Alignment of modelling outputs with decision-support needs, ensuring that results could be directly used in DSS analyses and resilience assessments.

The use of event trees as operational modelling constructs that evolve through iteration between conceptual design, data availability, and stakeholder-driven priorities has allowed to implement a key intermediate step between the conceptual framework defined in D1.1 and its operational implementation in the Trials (D4.2), tailoring assessment to decision making and resilience priorities identified by CoP participants .

Section 3.4 illustrates how the ICARIA modelling framework informed the Trials implementation, with concrete examples from the different case studies with respect to the key steps and outputs included in the workflow.

3.5 Applying the ICARIA holistic modelling framework in the Trials: Lessons learnt

The application of the ICARIA holistic modelling framework in the three Trials (AMB, Salzburg, South Aegean) provided a first, robust validation of its applicability as a unifying logic for multi-hazard risk and resilience assessment across heterogeneous European contexts and specific assessment, governance and planning objectives. While the Trials were not designed to exhaustively test every possible hazard interaction from the initially designed event-trees, they did demonstrate that the framework can be operationalised through a consistent modelling architecture (Figure 8) that remains risk-based (H×E×V), delivering quantitative and spatialized output with respect to targeted impact indicators, while allowing a more holistic and multidimensional interpretation of risk and resilience outcomes.

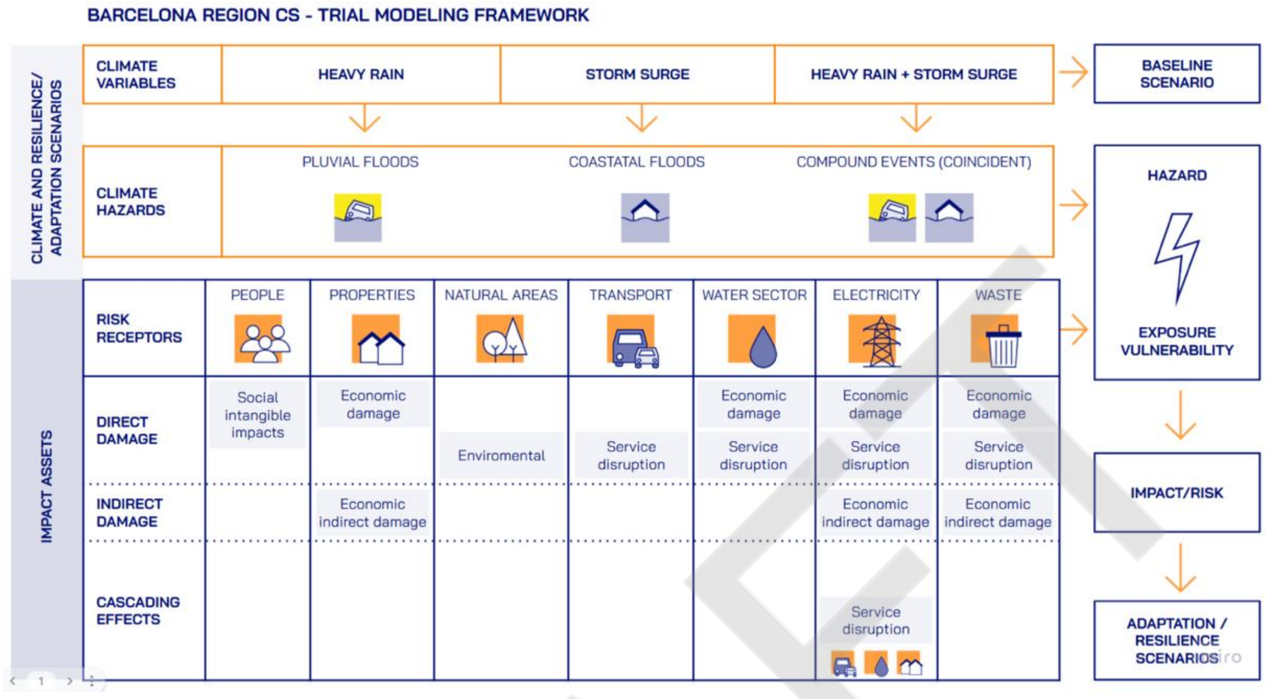


Figure 8. Final modelling architecture of ICARIA AMB Trial.

A key lesson concerns the framework's ability to act as a common backbone to align methods and metrics. Across Trials, the modelling workflow was organised around consistent inputs (hazard layers, exposure layers, vulnerability curves and maps, Figures 9-11) and a structured logic for producing risk/impact layers and indicators, which could then be visualised, compared and reported through the ICARIA DSS. Stakeholders consistently recognised the value of having climate projections, impact/risk results and scenario comparison integrated in a single platform, even when they did not expect "everyday operational use" in its current prototype form. This reinforces the framework's potential to support a shared evidence base for risk governance and investment planning across the EU and beyond, provided that local data readiness and guidance are strengthened.

From a modelling perspective, the Trials showed that the "elementary bricks" approach can effectively structure asset- and service-oriented impact scenario analysis (Figure 12). As reported in D4.2, risk receptors span from buildings and people to strategic services and critical infrastructures (e.g., electricity, transport, waste, water, natural areas), demonstrating that the same modelling logic can be applied to diverse assets and services by tailoring exposure representations and vulnerability/fragility functions to the relationships between hazards and assets/services. This was particularly evident where the modelling chain had to remain transparent under data constraints (e.g., simplified but physically consistent fragility modelling for wind impacts on electricity components in Salzburg, see D4.2), highlighting the practical value of a framework that can remain coherent across different levels of modelling complexity.

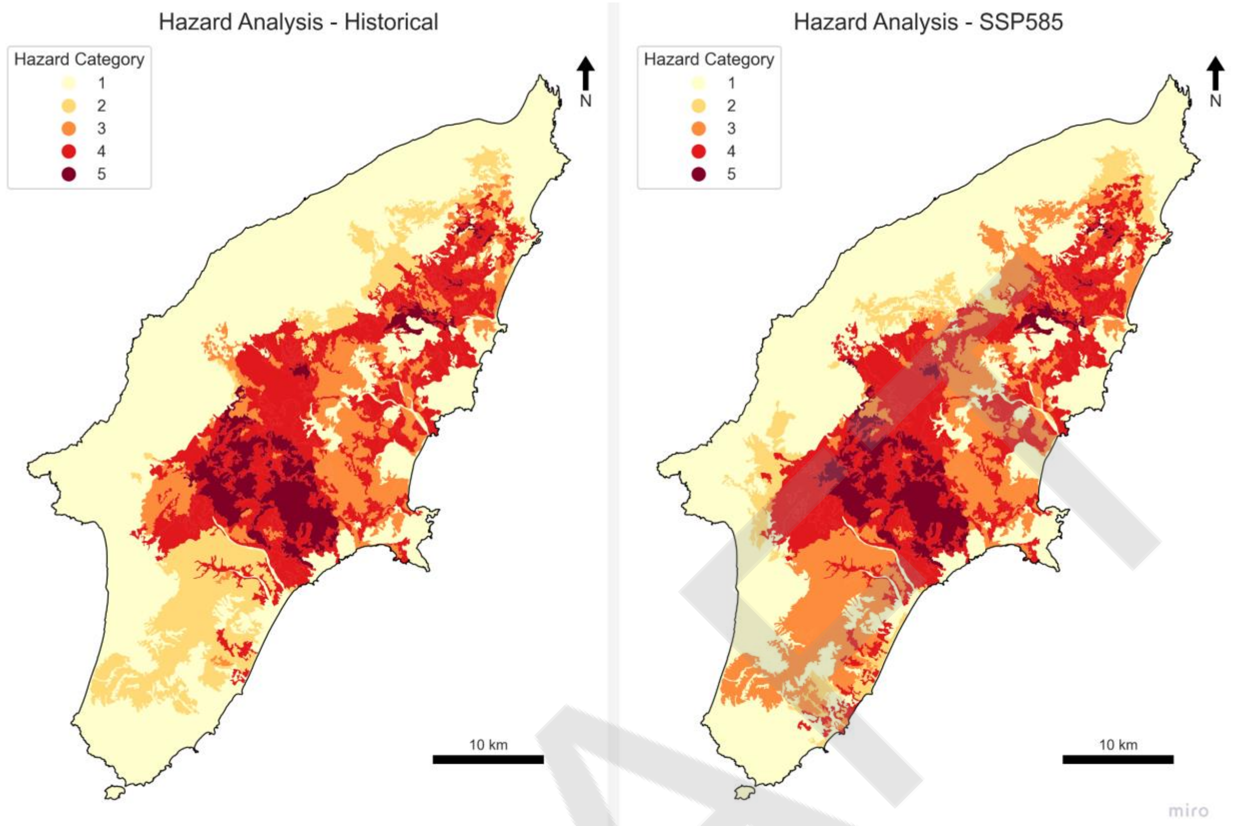


Figure 9. Hazard maps illustrating consecutive compound hazards (heat wave + forest fire) under historical and future (SSP585) climate for the ICARIA Rhodos Trial.

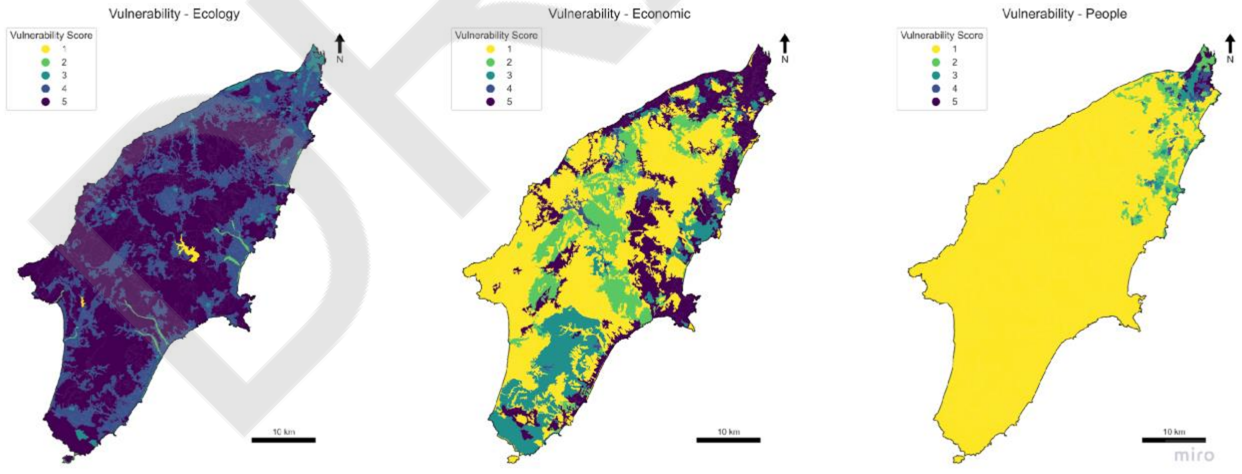


Figure 10. Vulnerability analysis for identified exposed assets (ecology, economy, people) for the ICARIA Rhodos Trial.

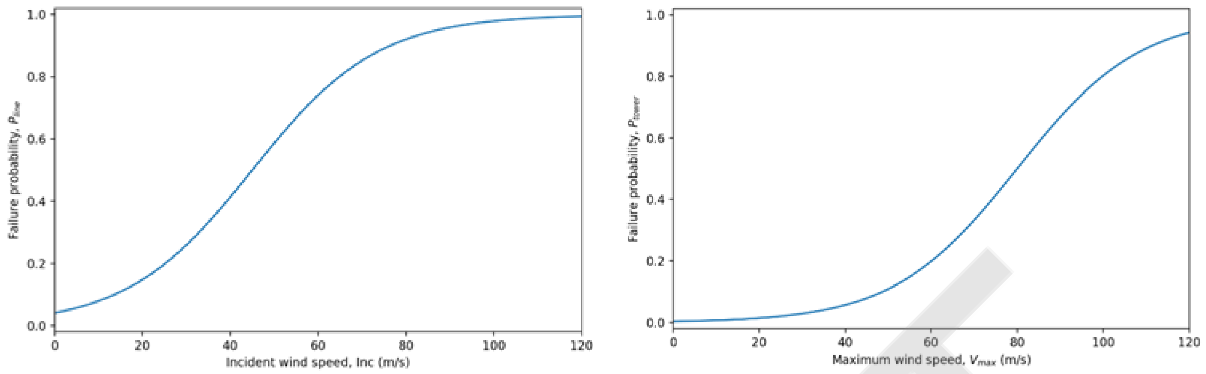


Figure 11. Vulnerability curves for overhead power lines (left) and electrical substations (right) developed for the ICARIA Salzburg Trial.

Modelling experts involved in trial activities explicitly recognised the importance of representing hazard interactions and cascading effects (Figure 12), validating both the capacity of the framework to effectively depict complex events characterized by hazard- and exposure/vulnerability-dependent causal chains and cascading consequences in service sectors under different SSPs. While acknowledging specific time/data constraints, Trials could navigate operational trade-offs between H-E-V interactions that can be modelled explicitly and other relevant expected impact components represented through simplified linkages or identified as a priority for future refinement. An example emerging from Salzburg discussions concerns secondary mechanisms (e.g., storm impacts aggravated by drought/insect-driven forest weakening) that were recognised as relevant but not foreseen in the original modelling plan, pointing to the need for follow-up modelling extensions.

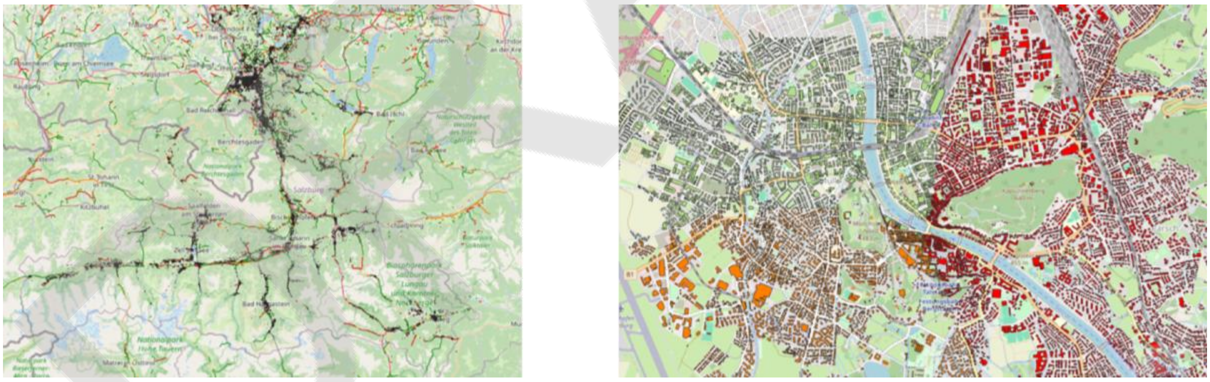


Figure 12. Areas (left) and detail of individual buildings (right) affected by the cascading effect of electricity network failure due to windstorm in the ICARIA Salzburg Trial.

The Trials also validated the framework's practical usefulness for scenario-based decision support, particularly through systematic comparison between conditions with and without resilience measures (Figure 13). Trial applications have been structured around (i) single-hazard assessment, (ii) multi-hazard assessment, and (iii) adaptation scenario assessment for each case study, explicitly embedding a logic of baseline vs resilience-enhanced simulation that is central to validating adaptation effectiveness. This structure proved to be intelligible and compelling for stakeholders, who consistently highlighted scenario comparison as one of the most valuable DSS functionalities for exploring future pathways and trade-offs.

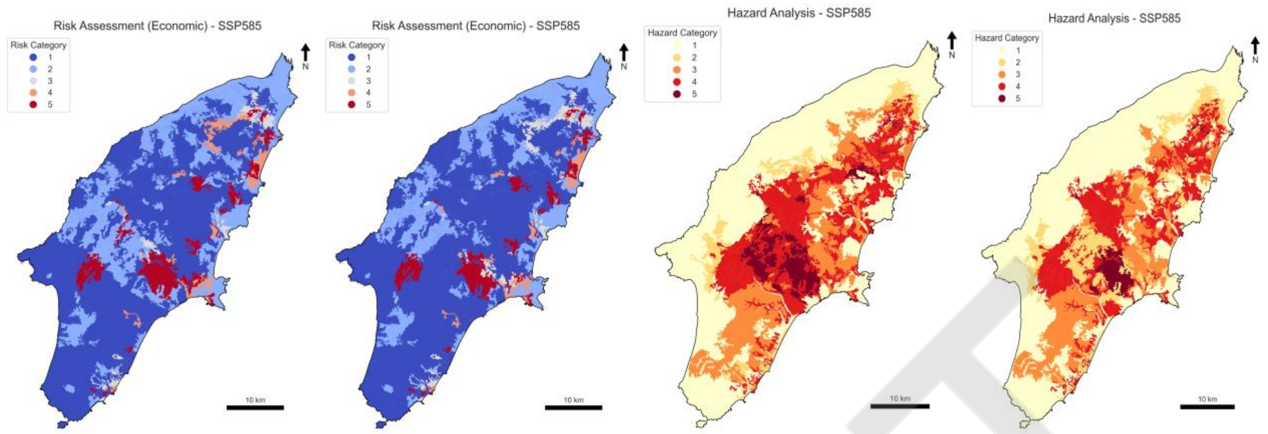
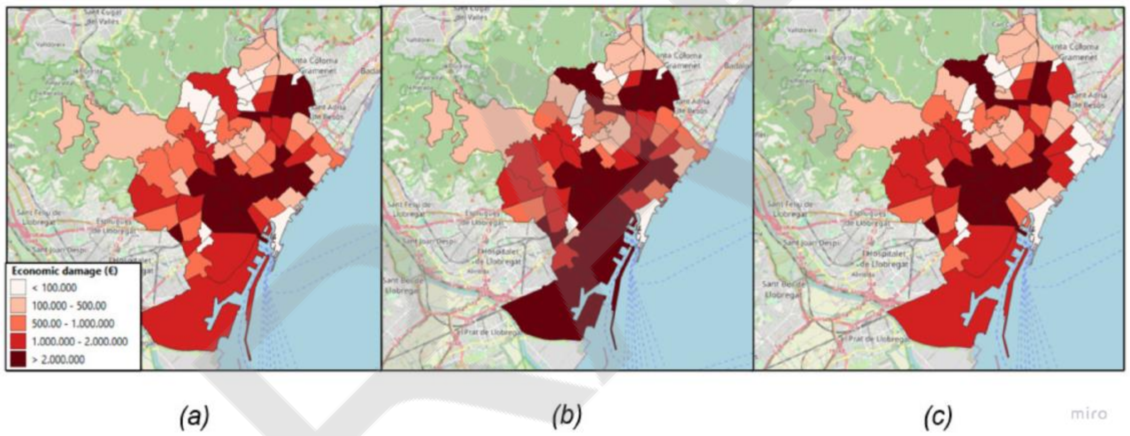


Figure 13. Scenario comparisons without and with adaptation measures in place addressing wildfire risk in the ICARIA Rhodos Trial. Left-side plots show risk reduction for the exposed asset "economy", while the right-side plots show how identified measures (namely an extensive replacement of the existing vegetation with Ceratonia siliqua) determine a significant variation of the "Hazard" elementary brick, thus leading to an overall risk reduction.



(a) (b) (c)

Figure 14. DSS output displaying the economic damage of floods on buildings aggregated per neighbourhood for Baseline (a), Business as Usual (b), and Adaptation (c) scenarios in the ICARIA AMB Trial.

Trials also showed that the ICARIA framework becomes most actionable when modelling is connected to a resilience strategy defined and prioritised through the DSS tools (Figure 14). The adaptation measures' portfolio and DSS functionalities (review, filtering, prioritisation, comparison, assignment to scenarios) enabled Trial teams and CoP members to move beyond "what is the risk?" toward "what can we do about it, and with what co-benefits?". This capability is essential for local authorities operating under multilevel governance constraints, because it supports transparent discussions on why certain measures are prioritised (cost, hazard relevance, co-benefits, feasibility), and how these measures map onto specific assets/services and impact pathways.

The integration of resilience assessment through the ICARIA RAF and RAT added a concrete validation layer to the framework's "multidimensional" ambition. The application of the holistic framework first highlighted the strategic importance of early identification and engagement of the right stakeholders, assembling a cohesive coordination team with access to relevant data and ensuring continuity of participation throughout the assessment process. It also demonstrated the value of a step-by-step structure (essential, complementary, comprehensive metrics), enabling organizations with different levels of maturity, data availability, and resources to calibrate the depth of the assessment while maintaining methodological coherence. Through its structured metric system, RAF and RAT applications helped identifying opportunities for resilience improvement across organizational, spatial, functional, and physical dimensions, directly supporting decision making and clarifying how specific qualities of regional to local assets and services (including natural areas, as highlighted by SAR wildfire Trial) contribute to climate resilience. Furthermore, the assessment sessions themselves acted as a platform for communication, fostering dialogue among departments, utilities, and local authorities that are usually fragmented.

As an example, in the AMB Trial the holistic RAF application for flooding (Figure 15) showed that roughly one third of metrics reached advanced or progressing levels in the organizational and spatial dimensions, supported by established hazard maps, early warning systems, and coordination mechanisms (Brito et al., 2025). However, the assessment also exposed structural gaps, such as the absence of comprehensive multi-hazard exposure scenarios, limited formal integration of climate change into service-level strategic planning (e.g., mobility and waste), and insufficient post-event learning mechanisms. The application of RAF to Baseline, Business as Usual, and Adaptation scenarios in AMB allowed to assess the potential increase in resilience following the implementation of targeted adaptation measures, also emphasizing how a BaU approach is likely to undermine current resilience levels of the city due to increased frequency and intensity of flood events induced by climate change (Figure 15).

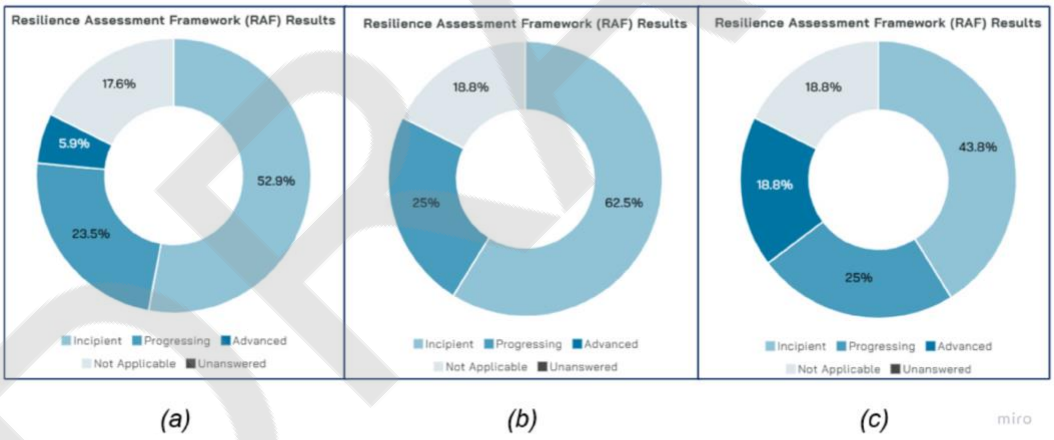
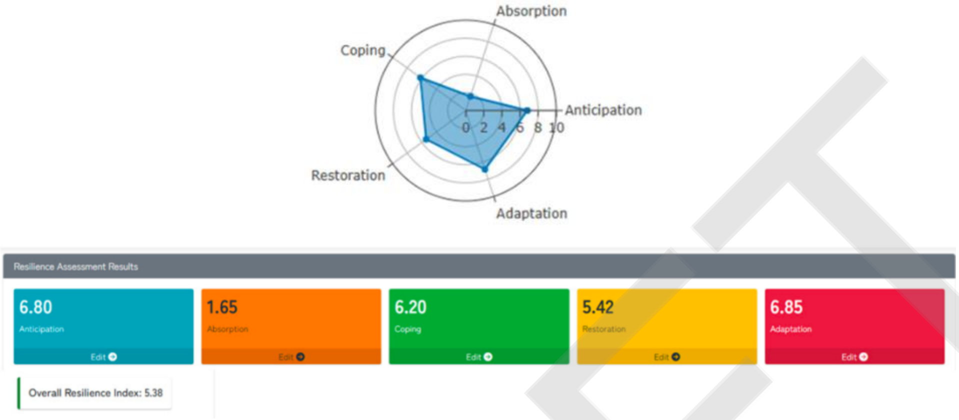


Figure 15. DSS/RAF output displaying flood resilience for Baseline (a), Business as Usual (b), and Adaptation (c) scenarios in the ICARIA AMB Trial.

In Salzburg, the RAT-based pilot assessment of critical energy infrastructure (Figure 15) revealed relatively strong anticipation and restoration capacities, but weaker absorption capacity under climate-related stress, partly due to nationally regulated standards not fully reflected in the assessment logic. Across the Trials, stakeholders stressed the need to streamline essential metrics in multi-municipal contexts and to clarify interdependencies across governance scales. These lessons confirm that operationalizing resilience dimensions in real decision contexts requires adaptive metric scaling and explicit treatment of interdependencies, especially where data availability and institutional coordination are uneven.

From a stakeholder-engagement perspective, finally, the Trials provided evidence that Communities of Practice can effectively support co-production and validation of modelling workflows, outputs and resilience strategies, as an iterative process of alignment between decision-making goals and support from expert modelling.



Resilience Assessment Results

6.80 Anticipation

1.65 Absorption

6.20 Coping

5.42 Restoration

6.85 Adaptation

Overall Resilience Index: 5.38

Figure 16. DSS/RAT output displaying resilience of electricity critical infrastructure in the ICARIA Salzburg Trial.

Conclusions

The ICARIA holistic modelling framework (D1.1) provides a harmonized and consistent methodology to support risk/impact and resilience assessment across different climate-related hazard categories, adopting a multi-hazard perspective that explicitly accounts for compound events and cascading effects. A key contribution of the framework lies in its asset- and service-oriented approach, which enables hazard/impact modelling to be performed at the level of specific risk receptors (e.g. buildings, infrastructures, networks, natural areas), while capturing how impacts propagate across interdependent systems and governance levels.

The framework ensures that data and modelling algorithms are structured to represent direct impacts on individual assets and cascading effects across connected services (e.g. energy, water, transport, waste), where disruptions in one system may trigger secondary impacts in others. The use of the ICARIA framework allows to explicitly link hazard intensity, exposure conditions, and vulnerability characteristics at asset level with time- and space-dependent impact propagation, providing a more realistic representation of risk in complex socio-eco-technical systems. Starting from the evaluation of both direct and indirect damage, the methodology enables the correlation between suitable, sustainable, and cost-effective resilience strategies and their potential risk reduction benefits (social, environmental and economic), including the mitigation of cascading failures.

The Trial applications provide a positive validation of the ICARIA holistic modelling framework as a coherent structure for integrating hazard–exposure–vulnerability modelling across multiple hazards and risk receptors at asset/service level. The scenario-based methods allows to consistently quantifying and comparing impacts with/without resilience measures, including their effects on cascading mechanisms, supporting decisions by translating modelling outputs into locally grounded resilience strategies through the DSS functionalities, including customizable hazard/impact assessments, the selection of suitable resilience strategies through adaptation measures portfolio, and RAF/RAT-based resilience diagnostics.

Trial applications highlighted that achieving this level of modelling detail requires appropriate data availability, explicit representation of asset interdependencies, and careful selection of event trees to ensure that cascading effects are captured where most relevant for decision-making. The main limitations emerging through Mini-Trial applications, such as data readiness for complex interdependent multi-hazard scenarios, user guidance for DSS functionalities, become relevant input for refinement and subsequent exploitation, in order to strengthen operational uptake and long-term use in multilevel governance for multi-hazard resilience.

The lessons emerging from the Trials provide concrete evidence that the ICARIA holistic modelling framework can function as a harmonisation backbone for risk and resilience assessment across EU regions and beyond, particularly when applied with a clear focus on asset- and service-level modelling and their interdependencies. By structuring modelling around shared “elementary bricks”. embedding consistent scenario comparison logic (with/without resilience measures), and reconnecting quantitative outputs to multidimensional resilience diagnostics (RAF/RAT) within a common DSS environment, the framework establishes a reproducible methodological pathway adaptable to diverse climatic, socio-economic and institutional contexts.

Annex 1: Glossary

Adaptation: Process of adjustment to actual or expected climate and its effects. In human systems, adaptation seeks to moderate or avoid harm or exploit beneficial opportunities. In some natural systems, human intervention may facilitate adjustment to the expected climate and its effects (IPCC, 2014).
This can be specific to climate change (United Nations Framework Convention on Climate Change, UNFCCC), but also applicable to other challenges such as soil erosion, migration and structural economic changes. Adaptation can occur in autonomous fashion, for example through market changes, or as a result of intentional adaptation policies and plans at the international, national, or local scale (UNISDR, 2009).

Adaptation measures (or actions): Technologies, processes, and activities directed at enhancing our capacity to adapt (building adaptive capacity) and at minimizing, adjusting to and taking advantage of the consequences of climatic change (delivering adaptation) (Climate-ADAPT, 2012). Adaptation measures can be separated in: i) hard and source-oriented measures, ii) hard and receptor-oriented measures, and iii) soft measures.
In the context of European Guidelines (EU-GL), the term generally refers to the Actions reducing vulnerability to climate change and climate variability by preventing negative effects or by enhancing resilience to climate change (European Commission, 2011; Climat-ADAPT, 2012).

Annotation: In the EU guidelines, the terms "adaptation options/measures" and "resilience measures" are used interchangeably.

Adaptation strategy: Broad plan of action that is implemented through policies and measures. A climate change adaptation strategy for a country, region or municipality refers to a general plan of action for addressing the impacts of climate change, including climate variability and extremes. It may include a mix of policies and measures, selected to meet the overarching objective of reducing the country's vulnerability (UNDP, 2005).

Adaptive Capacity (AC): Strategies/measures adopted by individuals, organizations, and/or systems to anticipate future drastic changes before they turn into disasters, taking into account past events. AC manifests itself progressively, in the long-term, through action/practices that introduce incremental changes to ensure future well-being (Lemos & Tompkins, 2008; Birkmann *et al.,* 2009; Berman *et al.,* 2012; Keck & Sakdapolrak, 2013; IPCC, 2014; Wolfram, 2016; IPCC, 2022). It represents one of the key-components of resilience (Leone, 2020a; Leone 2020b; Turchi *et al.,* 2023).

Affected: People who are affected, either directly or indirectly, by a hazardous event. Directly affected are those who have suffered injury, illness, or other health effects, who were evacuated, displaced, relocated, or have suffered direct damage to their livelihoods, economic, physical, social, cultural and environmental assets. Indirectly affected are people who have suffered consequences, other than or in addition to direct effects, over time, due to disruption or changes in the economy, critical infrastructure, basic services, commerce or work, or social, health and psychological consequences.

Annotation: People can be affected directly or indirectly. Affected people may experience short-term or long-term consequences to their lives, livelihoods, or health and to their economic, physical, social, cultural and environmental assets. In addition, people who are missing or dead may be considered directly affected (UNISDR, 2017).

Affected area: Area under the consequences of the impacts predicted by the scenario (CRISMA Project glossary; CRISMA, 2012).

Algorithm: Effective method (formula) expressed as a finite list of well-defined parameters for calculating the quantification of the effects caused by a hazardous event (i.e., cost or damage function, direct or indirect).

Assets: Natural or human-made resources that provide current or future utility, benefit, economic or intrinsic value to natural or human systems.

Business-As-Usual (BAU): Scenario that does not assume additional policies beyond those currently in place and that socioeconomic development patterns are consistent with recent trends. Today the term is used less frequently than in the past (IPCC, 2022).

Capacity: Combination of all the strengths, attributes, and resources available within an organization, community or society to manage and reduce disaster risks and strengthen resilience.

Annotation: Capacity may include infrastructure, institutions, human knowledge and skills, and collective attributes such as social relationships, leadership, and management (UNISDR, 2017).

Cascading effect: Dynamics present in disasters, whereby a natural (originated by climate or geophysical conditions) or anthropogenic (originated by the failure of socioeconomic and/or technological systems) hazard generates a sequence of events and interactive causal chains with potential critical affection on different interdependent assets and services. Their repercussions on society and the environment are particularly severe (Garcia-Aristizabal *et al.,* 2014; Pescaroli & Alexander, 2015). For this reason, even circumscribed and low-intensity hazards could generate broad cascading effects over time and space. The domain of existing organizational, spatial, functional, and physical interrelations between the environmental, socioeconomic, and technological systems that determine the occurrence of cascading effects are mostly associated with the vulnerability dimension and resulting in a non-linear disaster escalation process and potential cumulative impacts on exposed assets (Zuccaro *et al.,* 2018).

Climate: Average weather, or more rigorously, the statistical description in terms of the mean and variability of relevant quantities over a period of time ranging from months to thousands or millions of years. The classical period for averaging these variables is 30 years, as defined by the World Meteorological Organization (WMO). The relevant quantities are most often surface variables such as temperature, precipitation, and wind. Climate in a wider sense is the state, including a statistical description, of the climate system.

Climate Change: Change in the state of the climate that can be identified by changes in the mean and/or the variability of its properties, and that persists for an extended period, typically decades or longer. Climate change may be due to natural internal processes or external forcings such as modulations of the solar cycles, volcanic eruptions, and persistent anthropogenic changes in the composition of the atmosphere or in land use. Note that the UNFCCC, in its Article 1, defines climate change as: “a change of climate which is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and which is in addition to natural climate variability observed over comparable time periods”. The UNFCCC thus makes a distinction between climate change attributable to human activities altering the atmospheric composition, and climate variability attributable to natural causes (IPCC, 2014).

Climate resilient development: Process of implementing greenhouse gas mitigation and adaptation measures to support sustainable development (IPCC, 2022).

Climate scenario: Plausible and often simplified representation of the future climate, based on an internally consistent set of climatological relationships that has been constructed for explicit use in investigating the potential consequences of anthropogenic climate change, often serving as input to impact models. Climate projections often serve as the raw material for constructing climate scenarios, but climate scenarios usually require additional information such as about the observed current climate. A climate change scenario is the difference between a climate scenario and the current climate (IPCC, 2014).

Compound event: Specific category of extreme events due to their growing frequency and intensity. Compound events are the result of the combination of two or more natural events (causally correlated or not), that can i) occur simultaneously (i.e., compound coincident), ii) successively (i.e., compound consecutive), or iii) be combined with the evolutionary trends represented by the Shared Socioeconomic Pathways (SSPs) that drastically amplify their impact (IPCC, 2012). Compound events, which pertain to the natural environment and climate change domains, can be associated with the hazard dimension in its physical and statistical components (Pescaroli & Alexander, 2018). Their analysis mostly involves physical modelling and forecasting activities.

Coping Capacity (CC): Strategies/measures adopted by individuals, organizations, and/or systems to handle abrupt adverse conditions, allowing them to absorb impacts and respond retroactively. CC manifests itself immediately, in the short-term, through all available resources with the aim of restoring the state of well-being prior to the crisis (Birkmann *et al.,* 2009; Berman *et al.,* 2012; Keck & Sakdapolrak, 2013; IPCC, 2022). It represents one of the key-components of resilience (Leone, 2020a; Leone 2020b; Turchi *et al.,* 2023).

Co-benefits: The positive effects that a policy or measure aimed at one objective might have on other objectives, irrespective of the net effect on overall social welfare. Co-benefits are often subject to uncertainty and depend on local circumstances and implementation practices, among other factors. Co-benefits are also referred to as ancillary benefits (IPCC, 2014).

Cost-Benefit Analysis (CBA): Analysis aimed at providing a structured process for integrating climate change risks and uncertainty into adaption options appraisal, with a view to selecting the "optimal" options that maximise the net benefits in terms of increased resilience to current and future climate. In the context of climate change, the focus widens to select not only efficient options but also those that perform robustly in the context of the uncertainties associated with future climate change (European Commission, 2011).

Cost-effectiveness: Calculated by using a ratio by dividing the costs of an investment (e.g., adaptation/mitigation measures) by units of effectiveness. The number of lives saved is an example of unit of effectiveness for risk adaptation/mitigation measures (CRISMA project Glossary; CRISMA, 2012).

Crisis (from the Greek κρίσις - krisis; plural: "crises"; adjectival form: "critical"): Event that is, or is expected to lead to, an unstable and dangerous situation affecting an individual, group, community, or whole society. Crises are deemed to be negative changes in security, economic, political, societal, or environmental affairs, especially when they occur abruptly, with little or no warning. More loosely, it is a term meaning an “emergency event” (CRISMA project Glossary, CRISMA, 2012).

Critical infrastructure: Physical structures, facilities, networks, and other assets which provide services that are essential to the social and economic functioning of a community or society (UNISDR, 2017).

Damage (D): Distribution of damage occurred on one or more elements at risk (e.g., people, buildings, infrastructure, services, activities, etc.), expressed in number of damaged elements for each damage class and/or monetary value of their restoration (Zuccaro *et al.,* 2018).

Damage class: Evaluation, recording, and categorization of damage to people, building structures and infrastructures, services, activities, etc., according to several categories (e.g., for buildings: 0 = No damage, 1 = Non-structural damage, 2 = Light damage, 3 = Heavy damage, 4 = Partial collapse, 5 = Total collapse) (Grünthal *et al.,* 1998).

Decision-making: Cognitive process resulting in the selection of a course of action among several alternative scenarios. Every decision-making process produces a final choice. The output can be an action or an opinion of choice. (adapted from: Wikipedia, 2013).

Decision Support System (DSS): Specific class of computerized information systems that support business and organizational decision-making activities. A properly designed DSS is an interactive software-based system intended to help decision-makers compile useful information from raw data, documents, personal knowledge, and/or business models to identify and solve problems and make decisions.

Decision-making process: Process of examining possibilities and options, comparing them, and choosing the way of action.

Disruption: Incident, whether anticipated (e.g., hurricane) or unanticipated (e.g., a blackout or earthquake) which disrupts the normal course of operations at an organization location (ISO/PAS 22399, 2007).

Disaster: Serious disruption of the functioning of a community or a society at any scale due to hazardous events interacting with conditions of exposure, vulnerability, and capacities, leading to one or more human, material, economic and environmental losses and impacts.

Annotations: The effect of the disaster can be immediate and localized but is often widespread and could last for a long period of time. The effect may test or exceed the capacity of a community or society to cope using its own resources, and therefore may require assistance from external sources, which could include neighbouring jurisdictions, or those at the national or international levels (UNISDR, 2017).

In literature disasters are also defined as "severe alterations in the normal functioning of a community or a society due to hazardous physical events interacting with vulnerable social conditions, leading to widespread adverse human, material, economic, or environmental effects that require immediate emergency response to satisfy critical human needs and that may require external support for recovery (IPCC, 2014).

Disaster risk: Potential loss of life, injury, or destroyed or damaged assets which could occur to a system, society, or a community in a specific period of time, determined probabilistically as a function of hazard, exposure, vulnerability and capacity.

Annotation: The definition of disaster risk reflects the concept of hazardous events and disasters as the outcome of continuously present conditions of risk. Disaster risk comprises different types of potential losses which are often difficult to quantify. Nevertheless, with knowledge of the prevailing hazards and the patterns of population and socioeconomic development, disaster risks can be assessed and mapped, in broad terms at least. It is important to consider the social and economic contexts in which disaster risks occur and that people do not necessarily share the same perceptions of risk and their underlying risk factors (UNISDR, 2017).

Disaster Risk Management (DRM): Application of Disaster Risk Reduction policies and strategies/plans to prevent new disaster risk, reduce existing disaster risk and manage residual risk, contributing to the strengthening of resilience and reduction of disaster losses (UNISDR, 2017). As well as the processes for designing, implementing, and evaluating strategies, policies, and measures to improve the understanding of disaster risk, foster disaster risk reduction and transfer, and promote continuous improvement in disaster preparedness, response, and recovery practices, with the explicit purpose of increasing human security, well-being, quality of life, and sustainable development (IPCC, 2014).

Annotation: Disaster Risk Management actions can be distinguished between prospective disaster risk management, corrective disaster risk management and compensatory disaster risk management, also called residual risk management.

Disaster Risk Reduction (DRR): Policies and strategies/plans aimed at preventing new and reducing existing disaster risk and managing residual risk, all of which contribute to strengthening resilience and therefore to the achievement of sustainable development.

Annotation: Disaster Risk Reduction is the policy objective of Disaster Risk Management, and its goals and objectives are defined in Disaster Risk reduction strategies/plans (UNISDR, 2017).

Dynamic Vulnerability (DV): "Procedure" that updates the vulnerability of one or more elements at risk, following of a sequence of events of given intensities. Sequences of multiple events progressively increase the vulnerability of the elements in relation to the evolution process of damage. Implementing a dynamic vulnerability model means updating both exposure and vulnerability step-by-step, taking into account how each event could increase the vulnerability compared to the previous event. The vulnerability class is assigned proportionally to the level of damage, indicating the damage probability curves to be used when the next event occurs (Zuccaro *et al.,* 2018).

Drivers: Aspects which change a given system. They can be short-term but are mainly long-term. Changes in both the climate system and socioeconomic processes including adaptation and mitigation are drivers of hazards, exposure, and vulnerability. Drivers can, thus, be climatic or non-climatic. Climatic drivers include warming trends, drying trends, extreme temperatures, extreme precipitations, snow cover, damaging cyclones, sea levels, ocean acidification, and carbon dioxide fertilisation. Non-climatic drivers include land use change, migration, population and demographic change, and economic development (based on IPCC 2014 (SPM)).

Early warning system: Integrated system of hazard monitoring, forecasting and prediction, disaster risk assessment, communication and preparedness activities systems and processes that enable individuals, communities, governments, businesses, and others to take timely action to reduce disaster risks in advance of hazardous events (UNISDR, 2017).

Economic loss: Total economic impact that consists of direct economic loss and indirect economic loss. Direct economic loss is the monetary value of total or partial destruction of physical assets in the affected area, nearly equivalent to physical damage. Indirect economic loss is a decline in economic value added as a consequence of direct economic loss and/or human and environmental impacts.

Annotations: Examples of physical assets that are the basis for calculating direct economic loss include homes, schools, hospitals, commercial and governmental buildings, transport, energy, telecommunications infrastructures and other infrastructure, business assets and industrial plants; and production such as crops, livestock and production infrastructure. They may also encompass environmental assets and cultural heritage (UNISDR, 2017).

Effectiveness: Ability to be successful and produce the intended results (Cambridge Dictionary, 2023).

Elements at risk: Set of elements, also groupable in categories, (e.g., population, buildings, infrastructures, environmental features, services, cultural values, economic activities, etc.) in an area exposed to damage due to the occurrence of a given event.

Emergency: State of the system following any natural, technological, or human-caused incident that requires responsive action to protect life or property (FEMA Glossary; FEMA, 2013)

Emergency management: Organization and management of resources and responsibilities for addressing all aspects of emergencies, in particular preparedness, response, and initial recovery steps (UNISDR, 2009).

Evacuation: Moving people and assets temporarily to safer places before, during or after the occurrence of a hazardous event in order to protect them.

Annotation: Evacuation plans refer to the arrangements established in advance to enable the moving of people and assets temporarily to safer places before, during or after the occurrence of a hazardous event. Evacuation plans may include plans for the return of evacuees and options to shelter in place (UNISDR, 2017).

Event tree: Inductive analytical diagram wherein an event is analysed with Boolean logic to investigate a chronological series of subsequent events and/or consequences, identifying and measuring the aftermath of an initial event. Indeed "event trees" are constructed using the "forward logic" (Zuccaro *et al.* 2018).

Exposure (E): Evaluation of the quantity, quality, and sensitivity of the elements at risk (e.g., people, buildings, infrastructure, services, activities, etc.) exposed to damage in hazard-prone areas, considering their spatial and temporal distribution. Exposure is usually combined with the vulnerability and capacities of the elements, in order to estimate the quantitative risks/impact associated with one or more hazards occurred (UNISDR, 2017).

Annotation: The measurement of exposure requires both the quantification and spatial distribution of the elements in the area to be analysed. Being closely linked to vulnerability, exposure estimation also involves vulnerability analysis that gives information on the capacity response by the elements in case of hazardous events. For this reason, the elements are usually grouped into homogeneous classes according to the expected damage following one or more events, in order to "estimate in quantitative terms the risks and/or the impacts associated with a given hazard intensity in the area of interest" (UNDRR, 2017).

Alternative definitions could be:

- presence of people, livelihoods, species or ecosystems, environmental functions, services, and resources, infrastructure, or economic, social, or cultural assets in places and settings that could be adversely affected (IPCC, 2014);
- distribution of the probability that one or more risk receptors (e.g., people, buildings, infrastructures, services, etc.), identified by assigned qualitative and quantitative characteristics, occupy a specific geographical area (i.e., space) in a specific moment (i.e., time) (Zuccaro *et al.*, 2018).

Extreme weather event: Rare event in a particular place and time of year. Definitions of 'rare' vary, but an extreme weather event would normally be as rare as, or rarer than, the 10th or 90th percentile of a probability density function estimated from observations.

Framework: Information architecture that comprises, in terms of software design, a reusable software template, or skeleton, from which key enabling and supporting services can be selected, configured, and integrated with application code.

Greenhouse gases (GHGs): Gaseous constituents of the atmosphere, both natural and anthropogenic, that absorb and emit radiation at specific wavelengths within the spectrum of radiation emitted by the Earth's surface, by the atmosphere itself, and by clouds. Includes Water vapour (H2O), carbon dioxide (CO2), nitrous oxide (N2O), methane (CH4) ozone (O3) sulphur hexafluoride (SF6), hydrofluorocarbons (HFCs), chlorofluorocarbons (CFCs) and perfluorocarbons (PFCs).

Hazard (H): Potential occurrence of a natural or human-induced physical event that may cause loss of life, injury, or other health impacts, as well as damage and loss to property, infrastructure, livelihoods, service provision, ecosystems, and environmental resources (IPCC, 2014). In the IPCC context, the term hazard usually refers to "climate-related physical events or trends or their physical impacts" (IPCC, 2014).

Alternative definitions could be:

- time-space distribution of the intensity of an event, characterized by an assigned probability of occurrence in a given time and space (Zuccaro *et al.,* 2018);
- dangerous phenomenon, substance, human activity, or condition" - characterized by its location, intensity, frequency and probability - that may cause adverse impacts on a social (e.g., loss of life, injury or other health impacts, property damage, social and economic services disruption) or environmental (e.g., ecological damages) system (Pelling *et al.,* 2004; Birkmann *et al.,* 2013; Dewan, 2013).

Annotations: Hazards may be natural, anthropogenic, or sociocultural in origin. Natural hazards are predominantly associated with natural processes and phenomena. Anthropogenic hazards, or human-induced hazards, are induced entirely or predominantly by human activities and choices. This term does not include the occurrence or risk of armed conflicts and other situations of social instability or tension which are subject to international humanitarian law and national legislation. Several hazards are socio-natural, in that they are associated with a combination of natural and anthropogenic factors, including environmental degradation and climate change. Hazards may be single, sequential, or combined in their origin and effects. Each hazard is characterized by its location, intensity or magnitude, frequency, and probability. Biological hazards are also defined by their infectiousness or toxicity, or other characteristics of the pathogen such as dose-response, incubation period, case fatality rate and estimation of the pathogen for transmission (UNISDR, 2017).

Hazardous event: Manifestation of a hazard in a particular place during a particular period of time.

Annotation: Severe hazardous events can lead to a disaster as a result of the combination of hazard occurrence and other risk factors (UNISDR, 2017).

Human behaviour: People's response to a particular situation (e.g., climate-related event). The human behaviour covers the range of actions by individuals, communities, organisations, and governments at different levels. It influences all factors of risk (Zuccaro *et al.,* 2018).

Impact: Probable spatial/temporal damage distribution according to a predefined scale of damage expected on the element at risk under consideration.

Alternative definitions could be:

- the impact scenario therefore represents the probabilistic distribution, in a given geographical area, of the damage caused by a single hazardous event with an assigned probability of occurrence (assumed as the reference hazard scenario) (Zuccaro *et al.,* 2018).

The impact can be measured in several ways: physical, economic, social, functional etc. and it can be evaluated as a direct and/or indirect consequence of the event at a given time (snapshot) or projected in the future. In literature impact is defined as "consequences of a hazardous event, on natural and human systems, once it materializes, i.e., actually affects a societal system. The term impacts is used primarily to refer to the effects on natural and human systems of extreme weather and climate events and of climate change. Impacts generally refer to effects on lives, livelihoods, health, ecosystems, economies, societies, cultures, services, and infrastructure due to the interaction of climate changes or hazardous climate events occurring within a specific time period and the vulnerability of an exposed society or system". The impacts of climate change on geophysical systems, including floods, droughts, and sea level rise, are a subset of impacts called physical impacts (IPCC, 2014).

Impact scenario analysis: Choosing one or more significant events, among past events or resulting from numerical hazard simulation models, it can be possible to obtain a damage evaluation following a specific event. The event chosen has, obviously, its own probability of occurrence to be considered.

Indicator: Single or aggregated parameters describing in a synthetic form the impact on the elements exposed involved in the study.

Intensity: Quality of being intense. The measurable amount of a property, such as force, brightness, or a magnetic field (Oxford Learner's Dictionaries, 2023).

Interdependence: According to the Hazur® terminology, relationship between different services or infrastructures given when one service or infrastructure (donor) fails and makes fail another one (the receptor) (RESCCUE, 2016).

Losses: Amount of realized damages as a consequence of an occurred hazard. A typical subdivision of the type of losses is between direct losses (as consequences of the damage caused by adverse events) and indirect losses (business interruptions caused by an occurred hazard).

Mitigation: In the climate change domain, the term is used to indicate "a human intervention to reduce the sources or enhance the sinks of greenhouse gases (GHGs)" (IPCC, 2014), that are the source of climate change.
In general, it consists of the lessening or minimizing of the adverse impacts caused by a hazardous event (UNISDR, 2017), through actions that reduce hazard, exposure, and vulnerability (IPCC, 2014).

Annotation: The adverse impacts of hazards, especially natural hazards, cannot be completely prevented, but their scale or severity can be substantially reduced by various strategies and actions. Mitigation measures include engineering techniques and hazard-resistant construction as well as improved environmental and social policies and public awareness.

Model: Hypothetical simplified description of a complex entity or process (Sterling & Taveter, 2009). A model can be considered as "an abstract representation of a system or process" (Carson, 2005). A model is a physical, mathematical, or otherwise logical representation of a system, entity, phenomenon, or process that has been designed for a specific purpose. Stachowiak (1973) describes a model using three features: the mapping feature (reproduction of the original), the reduction feature (abstraction of the original) and the pragmatic feature (addressing a purpose for its user).

Multi-Criteria Analysis (MCA): Any structured approach used to assess overall preferences among alternative options, which are designed to fulfil several objectives. In MCA, predefined desirable objectives are delineated, and corresponding attributes or indicators are identified. The measurement of indicators does not necessarily need to be expressed in monetary terms. Rather, it often involves quantitative analysis through scoring, ranking, and weighting across a diverse array of qualitative impact categories and criteria. Known as multi-objective decision-making, the MCA serves as a decision analysis tool specifically well-suited for all those situations where a single-criterion approach (e.g., cost-benefit analysis) results inadequate. This is particularly evident when substantial environmental and social impacts cannot be easily quantified in monetary terms. In this sense, the MCA empowers decision-makers to incorporate a comprehensive spectrum of criteria, spanning social, environmental, technical, economic, and financial considerations.
Adaptation options can be ranked according to multiple criteria. MCA is useful to evaluate measures or interventions for which several criteria are deemed relevant and when is not feasible to quantify and assign them a monetary value in terms of costs and/or benefits. Using weighted criteria, an overall score can be determined for each adaptation option, facilitating the decision-making process to identify the most urgently needed option. The MCA prioritization process begins with a set of adaptation options, each expected to fulfil desired adaptation objectives. The primary goal is to prioritize these options based on the preferences of decision-makers or their representative proxies (UNFCC, 2012).

Multi-hazard: Selection of multiple major hazards that the country faces, and (2) the specific contexts where hazardous events may occur simultaneously, "cascadingly" or cumulatively over time, and taking into account the potential interrelated effects (UNISDR, 2017).

Multi-hazard assessment: To determine the probability of occurrence of different hazards either occurring at the same time or shortly following each other, because they are dependent on one another or because they are caused by the same triggering event or hazard, or merely threatening the same elements at risk without chronological coincidence. (European Commission, 2010).

Multi-risk assessment: To determine the whole risk from several hazards, taking into account possible hazards and vulnerability interactions (a multi-risk approach entails a multi-hazard and multi-vulnerability perspective).

This would include the following events:

1) occurring at the same time or shortly following each other, because they are dependent on one another or because they are caused by the same triggering event or hazard; this is mainly the case of cascading events;
2) or threatening the same elements at risk (vulnerable/exposed elements) without chronological coincidence (MATRIX project Glossary; MATRIX, 2010)

Natural hazard: Natural process or phenomenon that may cause loss of life, injury or other health impacts, property damage, loss of livelihoods and services, social and economic disruption, or environmental damage (UNISDR, 2009).

Parameter: Element included in the method of calculation of an algorithm. It can assume different values, depending on the kind of scenario simulated.

Preparedness: Knowledge and capacities developed by governments, response and recovery organizations, communities, and individuals to effectively anticipate, respond to and recover from the impacts of likely, imminent or current disasters.

Annotation: Preparedness action is carried out within the context of disaster risk management and aims to build the capacities needed to efficiently manage all types of emergencies and achieve orderly transitions from response to sustained recovery (UNISDR, 2017).

Prevention: Activities and measures to avoid existing and new disaster risks.

Annotations: Prevention (i.e., disaster prevention) expresses the concept and intention to completely avoid potential adverse impacts of hazardous events. While certain disaster risks cannot be eliminated, prevention aims at reducing vulnerability and exposure in such contexts where, as a result, the risk of disaster is removed. Examples include dams or embankments that eliminate flood risks, land-use regulations that do not permit any settlement in high-risk zones, seismic engineering designs that ensure the survival and function of a critical building in any likely earthquake and immunization against vaccine-preventable diseases. Prevention measures can also be taken during or after a hazardous event or disaster to prevent secondary hazards or their consequences, such as measures to prevent the contamination of water (UNISDR, 2017).

Probability: Chance or relative frequency of occurrence of particular types of events, or sequences or combinations of such events (Willows *et al.,* 2003) (European Commission, 2011).

Reconstruction: Medium- and long-term rebuilding and sustainable restoration of resilient critical infrastructures, services, housing, facilities and livelihoods required for the full functioning of a community, or a society affected by a disaster, aligning with the principles of sustainable development and "build back better", to avoid or reduce future disaster risk (UNISDR, 2017).

Recovery: Restoring or improving of livelihoods and health, as well as economic, physical, social, cultural, and environmental assets, systems and activities, of a disaster-affected community or society, aligning with the principles of sustainable development and "build back better", to avoid or reduce future disaster risk (UNISDR, 2017).

Rehabilitation: Restoration of basic services and facilities for the functioning of a community or a society affected by a disaster (UNISDR, 2017).

Resilience: Ability of a system, community or society exposed to hazards to resist, absorb, accommodate, adapt to, transform, and recover from the effects of a hazard in a timely and efficient manner, including through the preservation and restoration of its essential basic structures and functions through risk management (UNISDR, 2017). The resilience is also defined by IPCC as "the capacity of social, economic, and environmental systems to cope with a hazardous event or trend or disturbance, responding or reorganizing in ways that maintain their essential function, identity, and structure, while also maintaining the capacity for adaptation, learning, and transformation" (IPCC, 2014).

Representative Concentration Pathways (RCPs): Based on what stated by the IPCC (2023), "four RCPs produced from integrated assessment models are used in the Fifth and the Sixth IPCC Assessments for comparison, spanning the range from approximately below 2°C warming to high (>4°C) warming best-estimates by the end of the 21st century: RCP2.6, RCP4.5, RCP6.0 and RCP8.5."

Response: Actions taken directly before, during or immediately after a disaster in order to save lives, reduce health impacts, ensure public safety and meet the basic subsistence needs of the people affected. Annotation: Disaster response is predominantly focused on immediate and short-term needs and is sometimes called disaster relief. Effective, efficient, and timely response relies on disaster risk-informed preparedness measures, including the development of the response capacities of individuals, communities, organizations, countries and the international community (UNISDR, 2017).

Risk (R): Potential for consequences where something of value is at stake and where the outcome is uncertain, recognizing the diversity of values. Risk is often represented as the probability of occurrence of hazardous events or trends multiplied by the impacts if these events or trends occur. Risk results from the interaction between hazard (H), exposure (E) and vulnerability (V), defined as the product (in terms of probabilistic convolution) of the three factors, according to the well-known relationship $R=H \times E \times V$ (IPCC, 2014). The risk therefore represents the probability that a given level of damage (e.g., on people, buildings, infrastructures, etc.), due to a hazard, will be reached in a given period of time, in a specific geographical area. Therefore, the risk must be understood as a cumulative assessment that considers the total potential damage that can be induced in the same area by several dangerous events (with different intensity or return periods) in a pre-set time window.

Risk analysis: Systematic use of available information to determine how often specified events may occur and the magnitude of their likely consequences (CRISMA project Glossary; CRISMA, 2012).

Risk management: Policies and strategies/plans to reduce the likelihood and/or magnitude of adverse potential consequences, based on assessed or perceived risk (IPCC, 2022).

Risk perception: Subjective judgement that individuals make about the characteristics, likelihood, and severity of a risk. (IPCC, 2022). It concerns how people perceive and interpret information regarding potential hazards, weighing factors such as uncertainty, potential consequences, and/or their own attitudes and beliefs.

Scenario: Plausible description of how the future may develop according to a coherent and internally consistent set of assumptions about key-driving forces (e.g., rate of technological change, prices) and relationships.

Annotations: scenarios, which describe the evolution of a situation over time, are neither predictions nor forecasts, but are useful to provide a view of the implications of developments and actions.

According to the IPCC (2023). "to explore and investigate climate futures, climate change projections are developed using sets of different input projections. These consist of sets of projections of greenhouse gas emissions, aerosols or aerosol precursor emissions, land use change, and concentrations designed to facilitate the evaluation of a large climate space and enable climate modelling experiments. For AR5, the input projections were referred to as representative concentration pathways (RCPs). For AR6, new sets of inputs are used and referred to as SSP scenarios, where SSP refers to socioeconomic assumptions called the shared socioeconomic pathways (SSPs)".

Shared Socioeconomic Pathways (SSPs): Based on what was stated by the IPCC (2023), "five SSP scenarios, namely SSP1–1.9, SSP1–2.6, SSP2–4.5, SSP3–7.0 and SSP5–8.5, was selected in the AR6 WGI report to fill certain gaps identified in the RCPs. The first number in the label is the particular set of socioeconomic assumptions driving the emissions and other climate forcing inputs taken up by climate models and the second number is the radiative forcing level reached in 2100."

Simulation: Manipulation of a model in such a way that it represents the expected behaviour of an individual actor or an entire system over time.

Simulation tool: Software that implements a model and allows simulation, no matter if it provides its own user interface or operates integrated in a larger software.

System: Set of entities connected together to make a complex whole or perform a complex function (Sterling & Taveter, 2009). A system can also be defined as a complex of interacting components and relationships among them that permit the identification of a boundary-maintaining entity or process (Laszlo & Krippner, 1998).

Stakeholder: Person or organization that can affect, be affected by, or perceive themselves to be affected by a decision or activity. Note: A decision maker can be a stakeholder (adapted from: ISO 31000, 2009).

Uncertainty: It comes out when we are not sure about the outcome of a process (like a measure of a physical quantity, or the occurrence of a destructive event). Several factors, acting simultaneously or separately, are responsible for the existence of uncertainty; we can group those factors in two groups:

those due to the intrinsic stochasticity of the process (the so-called aleatory uncertainty), and those due to the lack of or imprecise knowledge of the process (epistemic uncertainty) (Marzocchi *et al.,* 2010)

Urban: The categorisation of areas as “urban”, carried out by government statistical departments, is generally based either on population size, population density, economic base, provision of services, or some combination of the above. Urban systems are networks and nodes of intensive interaction and exchange including capital, culture, and material objects. Urban areas exist on a continuum with rural areas.

Urban system: System of urban areas (Urban settlements from a systemic viewpoint).

Time periods: Pre-industrial period is the multi-century period prior to the onset of large-scale industrial activity around 1750. The reference period 1850–1900 is used to approximate pre-industrial global mean surface temperature (GMST). The ‘modern’ period is defined as 1995 to 2014 in AR6, while three future reference periods are used for presenting climate change projections, namely near-term (2021–2040), mid-term (2041–2060) and long-term (2081–2100), in both the AR6 WGI and WGII reports (IPCC, 2023).

Transformative Capacity (TC): Encompasses the ability and potential of individuals, organizations and/or systems to access assets/funds and engage in the decision-making process, aiming at defining shared pathways for preventing future adverse conditions, and radically transforming the functioning of communities involved. TC manifests gradually, in the long-term, enhancing future well-being (Berman *et al.,* 2012; Keck & Sakdapolrak, 2013; Wolfram, 2016). Programs for emergency preparedness or strategic multi-stakeholder and civil society engagement concern the transformative side of resilience including operational tools organized within the framework of participation. It represents one of the key-components of resilience (Leone, 2020a; Leone 2020b; Turchi *et al.,* 2023).

Validation: Process to assure that project results are coherent and in line with the project goals and to demonstrate and validate the tools developed.

Vulnerability (V): The propensity or predisposition to be adversely affected. Vulnerability encompasses a variety of concepts and elements, including sensitivity or susceptibility to harm and lack of capacity to cope and adapt (IPCC, 2023).

Alternative definitions could be:

- Distribution of the probability that one or more elements at risk of assigned characteristics, classified as belonging to a specific vulnerability class, will be affected by a level of damage (according to a pre-set damage scale) following the occurrence of a dangerous event of a given intensity (Zuccaro et *al.,* 2018).

Vulnerability thus represents the relationship between i) the severity of the hazard, ii) the typology of the element at risk considered, and iii) the degree of damage caused, and it can therefore be represented as a “damage function” or “vulnerability function”, in the form of vulnerability curves or damage probability matrices, obtained for different correlations between hazard, element at risk and level of damage, starting from the scientific literature or by carrying out dedicated specialized studies (Zuccaro *et al.,* 1985; Coburn & Spence, 1993; Woo, 1999; Spence *et al.,* 2005; Huizinga *et al.,* 2017).

Vulnerability class: Categorization of the elements at risk, grouped according to selected properties (e.g., age, health status, crop resistance to droughts, maximum runoff capacity, etc.) able to identify a given behaviour of the element under the hazardous action.

Annex 2: Data Management Statement

No data have been used or produced in preparation of ICARIA Deliverable 1.5. Datasets and maps included in the deliverable have been developed under other ICARIA WPs and Tasks.

Annex 3: Input/output datasets from Trial modelling workflows

Table 1. Excerpt of input/output of the hazard assessment models for the Trial in the Barcelona Metropolitan Area case study. Hazards considered from the event tree: Pluvial flood (t1, t2), urban drainage network disruption (t3), Energy supply network disruption (t3).

DATASETS	**Natural Hazards**		**Cascading effects**		**Gap / Uncertainty treatment**
	Pluvial floods		**Service disruption (electricity assets)**		
	Data	**Source**	**Data**	**Source**	
INPUT DATASET					
Historic climatic variables	Precipitation (1' or 5' resolution)	National weather agency	-	-	Data validation pre-processes
Future climate projections	Precipitation IDFs curves	ICARIA project	-	-	Climate statistical downscaling
Land use & Terrain information	Land use	CORINE Land Cover	Land use	CORINE Land Cover	Temporal series regarding CORINE Land Cover Data improved through ARSINOE methodology
	DTM (2x2m)	National geographic agency	DTM (2x2m)	National geographic agency	--
	Building location	National geographic agency	Building location	National geographic agency	--
Infrastructure (water assets)	Drainage networks (structural data)	Municipalities	Drainage networks (structural data)	Municipalities	Statistical method to generate synthetic data for the physical and topographic data of sewer networks
	Drainage networks (operation data)	Network operator	Drainage networks (operation data)	Network operator	--
Infrastructure (electricity assets)	Energy networks (structural data)	Municipalities	Energy networks (structural data)	Municipalities	

	Energy networks (operation data)	Network operator	Energy networks (operation data)	Network operator	
OUTPUT DATASET					
Hazard	Flood hazard maps (indicating water depth and velocity)		Energy supply network failure (indicating branches of the network and duration of service interruption)		--

Table 2. Excerpt of input/output of the exposure and vulnerability analysis for the Trial in the Barcelona Metropolitan Area. Hazards considered from the event tree: Pluvial flood (t1, t2), urban drainage network disruption (t3), Energy supply network disruption

DATASETS	**Natural Hazards**		**Cascading effects**		**Gap / Uncertainty treatment**
	Pluvial floods		**Service disruption (electricity assets)**		
	Data	**Source**	**Data**	**Source**	
INPUT DATASET					
Exposure PEOPLE	Population distribution	National statistics agency	Population distribution Building occupancy	National statistics agency	-
Exposure PROPERTIES	Use of ground floors and basements	National statistics agency	-	-	-
Exposure NATURAL AREAS	Location of natural areas	Asset operator	-	-	Temporal series regarding CORINE Land Cover Data improved through ARSINOE methodology
Exposure TRANSPORT	Location of transport network	Open data	-	-	--
Exposure WATER ASSETS	Location of critical infrastructures	Asset operator	-	-	--
Exposure ELECTRICITY ASSETS	Location of critical infrastructures	Asset operator	Location of critical infrastructures	Asset operator	Statistical method to generate synthetic data for the physical and topographic data of sewer networks

Exposure WASTE ASSETS	Location of critical infrastructures	Asset operator	-	-	--
OUTPUT DATASET					
Vulnerability classes/functions/data	Map of risk receptor location subdivided by vulnerability class		Map of the network with information about network sections interdependencies, emergency generators and local storage units (e.g. batteries)		--

Table 3. Excerpt of input/output of the risk/impact assessment models for the Trial in the Barcelona Metropolitan Area. Hazards considered from the event tree: Pluvial flood (t1, t2), urban drainage network disruption (t3), Energy supply network disruption

DATASETS	**Natural Hazards**		**Cascading effects**	
	Pluvial floods		**Service disruption (electricity assets)**	
	Data	**Source**	**Data**	**Source**
INPUT DATASET				
Vulnerability PEOPLE	Risk curves for pedestrians	RESCCUE project	Risk curves for occupancy/building type	ICARIA project
Vulnerability PROPERTIES	Damage curves for buildings	RESCCUE project	-	-
Vulnerability NATURAL AREAS	Damage curves for natural areas	ICARIA project	-	-
Vulnerability TRANSPORT	Risk curves for cars	ICARIA project	-	-
Vulnerability WATER ASSETS	Damage curves for water infrastructure	ICARIA project	-	-
Vulnerability ELECTRICITY ASSETS	Damage curves for electricity supply infrastructure	RESCCUE project	Risk curves for electricity asset type failure; functions to assess “energy non supplied costs”, functions to assess “auxiliar	ICARIA project

			generation cost"; reparation cost functions	
Vulnerability WASTE ASSETS	Damage curves for industrial buildings	RESCCUE project	-	-
OUTPUT DATASET				
Risk/Impact	Risk maps and economic impact quantification		Impact maps of areas affected and economic impact quantification (time-dependent)	

Table 4. Excerpt of input/output of the hazard assessment models for the Trial in the Salzburg Area case study. Hazards considered from the event tree: Fluvial flood (t1), Road network disruption (t2), Properties damaged (t2).

DATASETS	**Natural Hazards**		**Cascading effects**						**Gap / Uncertainty treatment**
	Fluvial floods		**Service disruption (transport)**				**properties damaged**		
	Data	**Source**	**Data**	**Source**	**Data**	**Source**	**Data**	**Source**	
INPUT DATASET									
Historic climatic variables	Precipitation 1km²	National weather agency	-	-	-	-	-	-	Data validation pre-processes
Future climate projections	Precipitation	ICARIA project	-	-	-	-	-	-	Climate dynamical downscaling
Land use & Terrain information	Land use	CORINE Land Cover	Land use	CORINE Land Cover			Land use	CORINE Land Cover	CORINE Land Cover Data
	DTM (2x2m)	Federal agency	DTM (2x2m)	federal agency			DTM (2x2m)	federal agency	--
OUTPUT DATASET									
Hazard	Flood hazard maps (indicating water depth)								--

Table 5. Excerpt of input/output of the exposure analysis for the Trial in the Salzburg Area. Hazards considered from the event tree: Fluvial flood (t1), Road network disruption (t2), Properties damaged (t2).

DATASETS	**Natural Hazards**	
	Fluvial floods	
	Data	**Source**
INPUT DATASET		
Exposure **PROPERTIES**	Building distribution and use type	Federal agency
Exposure **TRANSPORT**	Location of transport network	Open data
OUTPUT DATASET		
Vulnerability classes/functions/data	Map of risk receptor location	

Table 6. Excerpt of input/output of the vulnerability analysis for the Trial in the Salzburg Area. Hazards considered from the event tree: Fluvial flood (t1), Road network disruption (t2), Properties damaged (t2).

DATASETS	**Natural Hazards**		**Cascading effects**						**Gap / Uncertainty treatment**
	Fluvial floods		**Road**		**Service disruption (road network)**		**Properties**		
	Data	**Source**	**Data**	**Source**	**Data**	**Source**	**Data**	**Source**	
INPUT DATASET									
Vulnerability PROPERTIES	Damage curves for buildings	JRC report	-	-	-	-	-	-	No different building types available as for AMB, generalized vulnerability curve
Vulnerability TRANSPORT	Risk curves for cars	ICARIA project	-	-	-	-	-	-	-
OUTPUT DATASET									
Risk/Impact			Impact maps of areas affected		Impact maps of areas affected		Risk maps and economic impact quantification		--

Table 7. Excerpt of input/output of the hazard assessment models for the Trial in the Salzburg Area case study. Hazards considered from the event tree: wind storm (t1), electricity network disruption (t2), Properties damaged (t2). Cascading potential impact on buildings (t3)

DATASETS	**Natural Hazards**		**Cascading effects**						**Gap / Uncertainty treatment**
	Wind storm		**Service disruption (energy)**				**properties damaged**		
	Data	**Source**	**Data**	**Source**	**Data**	**Source**	**Data**	**Source**	
INPUT DATASET									
Future climate projections	Wind speed and direction	ICARIA project	-	-	-	-	-	-	Climate dynamical downscaling
Infrastructure (electricity assets)	Energy networks (structural data)	OSM	Energy networks (structural data)	OSM	Energy networks (structural data)	OSM	Building location	federal agency	
OUTPUT DATASET									
Hazard	Wind hazard maps (speed and direction)		Energy lines/towers affected		Energy supply network failure (indicating branches of the network)				--

Table 8. Excerpt of input/output of the exposure analysis for the Trial in the Salzburg Area case study. Hazards considered from the event tree: wind storm (t1), electricity network disruption (t2), Properties damaged (t2). Cascading potential impact on buildings (t3)

DATASETS	**Natural Hazards**		**Cascading effects**						**Gap / Uncertainty treatment**
	Wind storm		**Service disruption (energy)**		**Service disruption (electricity assets)**		**properties**		
	Data	**Source**	**Data**	**Source**	**Data**	**Source**	**Data**	**Source**	
INPUT DATASET									
Exposure PROPERTIES	Use of building distributrion	Federal agency	-	-	-	-	-	-	-

Exposure Energy network	Location of energy network (lines, towers)	Open data	-	-	-	-	-	-	--
OUTPUT DATASET									
Vulnerability classes/functions/data	Map of risk receptor location				Map of buildings related to different parts of the electricy system (energy distribution lines)				--

Table 9. Excerpt of input/output of the vulnerability analysis for the Trial in the Salzburg Area case study. Hazards considered from the event tree: wind storm (t1), electricity network disruption (t2), Properties damaged (t2). Cascading potential impact on buildings (t3)

DATASETS	**Natural Hazards**		**Cascading effects**						**Gap / Uncertainty treatment**
	Wind storm		**Service disruption (energy)**		**Service disruption (electricity assets)**		**Properties**		
	Data	**Source**	**Data**	**Source**	**Data**	**Source**	**Data**	**Source**	
INPUT DATASET									
Vulnerability PROPERTIES	Damage curves for buildings	Scientific literature	-	-	-	-	-	-	
Vulnerability Energy System	Risk curves for towers and lines	Scientific literature	-	-	-	-	-	-	-
OUTPUT DATASET									
Risk/Impact			Impact maps of infrastructure affected		Impact maps of cascading effects => areas affected		Risk maps and economic impact quantification		--

Table 10. Excerpt of input/output of the hazard assessment models for the Trial in the SAR case study.

DATASETS	**Natural Hazards**	
	Heatwave	
	Data	**Source**

INPUT DATASET		
Historic climatic variables	Max Temperature	National weather agency
Future climate projections	Max Temperature	ICARIA project
Land use & Terrain information	Land use	CORINE Land Cover
	DEM (25x25m)	Copernicus
Infrastructure (Buildings)	Buildings (structural data)	Open Street maps and CENSUS
OUTPUT DATASET		
Hazard	Land Surface Temperature (LST)	

Table 11. Excerpt of input/output of the impact assessment of wildfire on properties for the SAR Trial.

DATASETS	**Natural Hazards**	
	Wildfires	
	Data	**Source**
INPUT DATASET		
Exposure/Vulnerability PROPERTIES	Building locations and construction period	Open street maps, CENSUS, Technical Champer of Greece
OUTPUT DATASET		
Risk/Impact	Risk maps and economic impact quantification	

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